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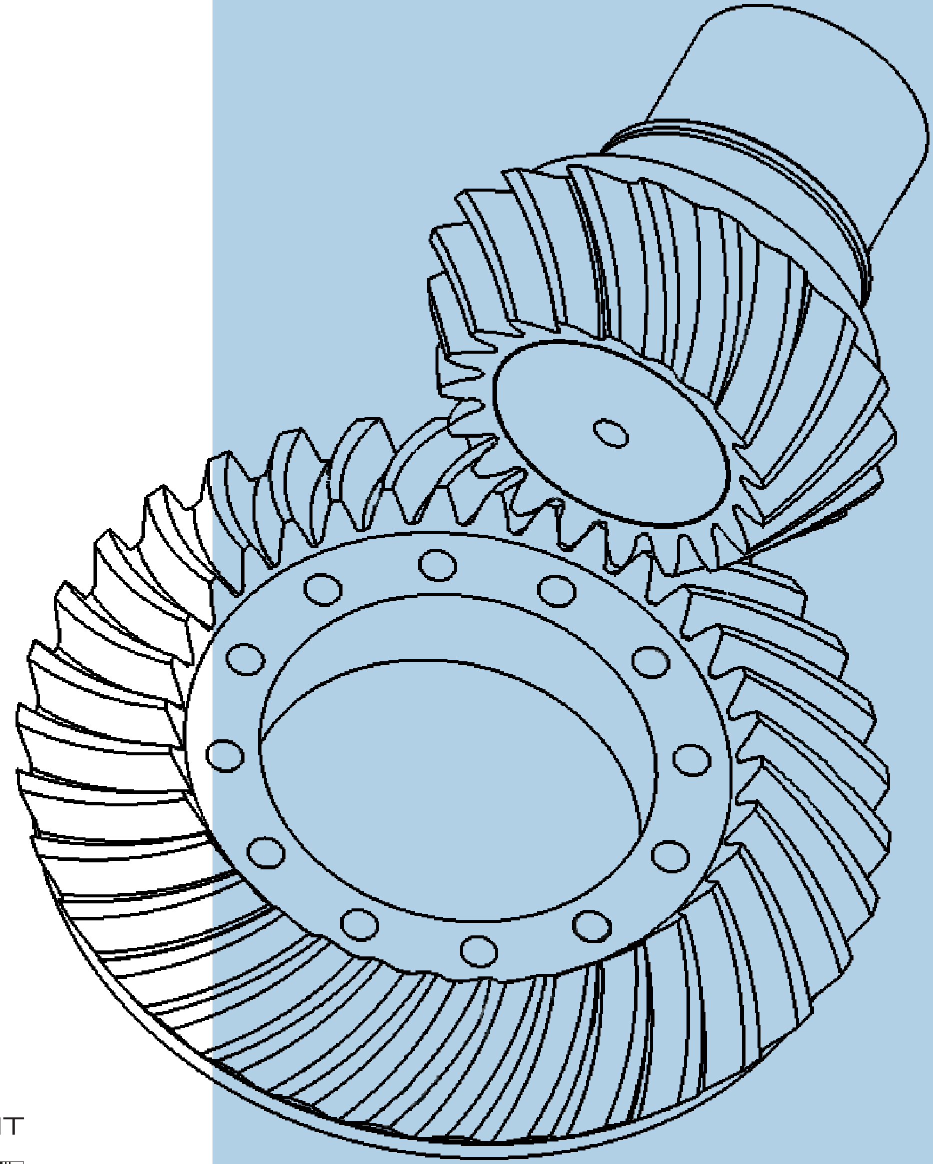

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Spremljanje obrabe vijačnega svedra (S390) z uporabo nevronskih mrež

Using Neural Networks to Follow the Wear of a S390 Twist Drill

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([1]University of Montenegro, Montenegro; [2] Industrija alata, Bosnia and Herzegovina)

Prispevek opisuje uporabo nevronskih mrež za zbiranje informacij ter postopkovnih parametrov odrezovalnega procesa (hitrost, podajanje in premer). Opazovan je vpliv dveh načinov ostrenja pri različnih časih obdelave na parametre obrabe. Material vijačnih svedrov (S390) je pridobljen s tehnologijo sintranja. Postopek za modeliranje pojava je učenje nevronske mreže z uporabo eksperimentalno pridobljenih podatkov. Nevronske mreže delujejo na načelu algoritma vzvratnega razširjanja napake. Nevronske mreže so učene s testnimi oblikami (posredno). Prikazani so dobljeni rezultati.

(Ključne besede: mreže nevronalne, vrtanje, svedri vijačni, procesi obrabe)

This paper deals with the use of neural networks for the integration of information as well as the parameters of the cutting process (speed, feed and diameter). Two sharpening methods and different working times related to the wear parameters are studied. The material used for the twist drill (S390) is obtained with power technology. Experimental results are used to train the neural networks, as one approach to the modeling of this process. The back-propagation algorithm is used as a model for neural networks. The neural networks with test shapes are trained (offline). The obtained results are presented.

(Keywords: neural networks, drilling, twist drill, wear processes)

0 INTRODUCTION

A great deal of attention has recently been paid by researchers to the application of neural networks in following the wear process of drilling ([1] to [5]).

The application of neural networks for the information integration of the cutting-process parameters, the drill-sharpening method and the operation time in relation to the tool-wear parameters is treated in this paper. The experimental results obtained in the laboratory of the School of Mechanical Engineering were used for the neural-network training. The following train of effects was studied in particular: knowledge degree, the number of layers and the number of neurons in a discrete layer. The transformation function in f-number in the function of the neurons in a layer was analyzed as well.

1 NEURAL NETWORKS

There are quite a number of neural network architectures. The back-propagation neural network model is among the most widely used in the state-following process. In this model, data are processed from the input to the output layer, whereas knowledge is performed by the algorithm of minimizing the square error by backward movement. The knowledge is controlled. It is the simplicity of the algorithm for this model that makes this architecture an attractive one, and the reason why it is analyzed in this paper.

Fig. 1 shows the architecture of neural networks specific to the back-propagation model. The basic structure of this network is made up of three layers: input, secret and output. The data from the external environment are taken over by the input layer, whereas the output to the environment is generated by the output layer. It is the secret layer, one or more of them, that makes the transformation by extracting the input data, by means of the chosen transformed function (f).

A procedure for determining the output values resulting from the observed neurons is shown in Fig. 2.

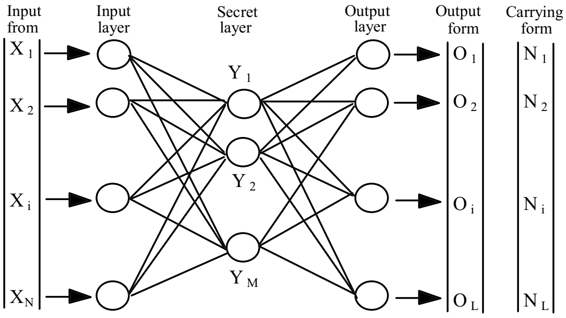

Fig. 1. *Neural network architecture*

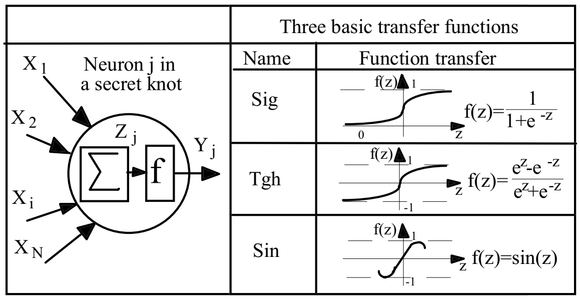

Fig. 2. *Neural network functioning algorithm*

2 EXPERIMENT PROJECTION

The experiment was carried out according to the Box–Wilson method of complex processes modeling using a complete multifactorial first-order plan with repeating in the central point of the multifactorial orthogonal plan. The characteristics employed in the experiment are listed in Table 1**.**

The scheme for carrying out the experiment is illustrated in Figure 3.

On the basis of the relation between the flank wear and the drilling duration (working time - stability) of the twist drill, for different cutting regimes, as illustrated in Figure 4 and Figure 5, it can be seen that it is very difficult to establish a relationship between the wearing belt and the drilling duration, so this paper presents an approach based on the employment of neural networks, as one of the possible approaches for establishing this relationship.

Table 1.

Characteristic		Value/type
Twist drill	Standard	DIN 338
	Dimension	Ø6; Ø7,75; Ø10
	Material	S –390 MICROCLEAN
	Point angle	135°
	Spiral grad. angle	15°
	Way of sharpening	KRI / KO
Material for examination	Standard	Č.4237
	Thermal treatment	Hardening/loosening
	Hardness HB/HRc	410 to 425 / 43 to 45
	Tension hardness [dN/mm^2]	1400-1450
Cutting regimes	Drilling depth [mm]	l = 3xd
	Number of revolutions [r.p.m.]	250; 355; 500
	Feedrate [mm/r]	0.027, 0.053, 0.107
Cooling medium		Yes
Machine for examination		FGU-32
Measuring device of flank wearing		DORMER

3 ANALYSIS OF THE RESULTS

Five parameters were used to train the neural network, as follows: three parameters for the cutting process (nominal diameter, r. p. m., and feedrate), the sharpening method, and the drilling length, while the value of the flank wear (h_a) served as an output value, as illustrated in Figure 6.

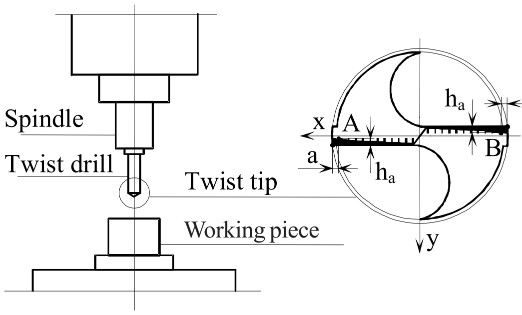

Fig. 3. *The scheme for carrying out the experiment*

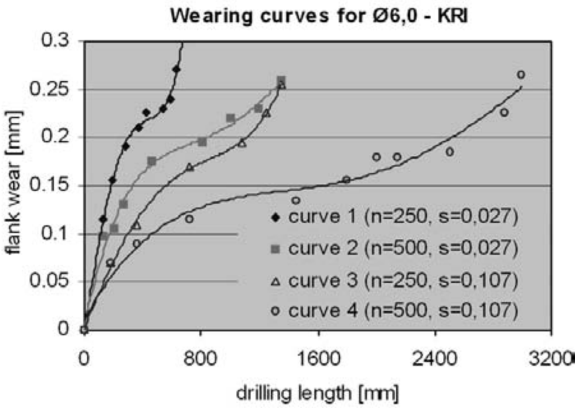

Fig. 4. *Wearing curves during drilling with the Ø6 twist drill, sharpened with a corrected cutting edge (KRI)*

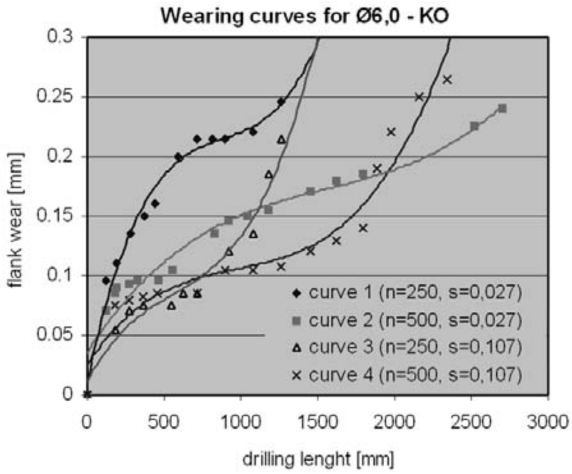

Fig. 5 *Wearing curves during drilling with Ø6 crossly sharpened twist drill (KO)*

In order to perform the training of a neural network, 90 data were chosen from the set of experimental results, as follows: 40 Ø6 data, 40 Ø10 data, and 10 Ø7.75 data, as presented in Table 2.

Table 2. *Data for training the neural network*

	INPUT					OUTPUT
	d [mm]	N	n [r.p.m.]	s [mm/r]	l [mm]	ha [mm]
1	6.00	1	500	0.027	1350	0.260
2	10.00	1	250	0.027	375	0.245
3	10.00	1	500	0.027	2400	0.230
4	6.00	2	500	0.107	0	0.000
5	10.00	1	250	0.107	0	0.000
. .						
42	6.00	2	250	0.027	540	0.190
43	6.00	1	500	0.027	460	0.175
44	7.75	1	355	0.053	580	0.160
45	6.00	2	500	0.027	1000	0.150
46	10.00	1	500	0.107	60	0.095
47	10.00	2	500	0.027	750	0.130
48	6.00	1	500	0.107	720	0.115
. .						
85	7.75	1	355	0.053	230	0.086
86	10.00	2	250	0.107	1350	0.230
87	7.75	2	355	0.053	1860	0.220
88	10.00	1	250	0.107	1350	0.270
89	10.00	1	500	0.027	1230	0.195
90	10.00	1	500	0.027	3000	0.295
Sharpening method:	1- corrected cutting edge (KRI) 2 - crossly sharpening (KO)					

Neural network of the feed-forward back-propagation type was used during training, where the following parameters were changed within the available software:

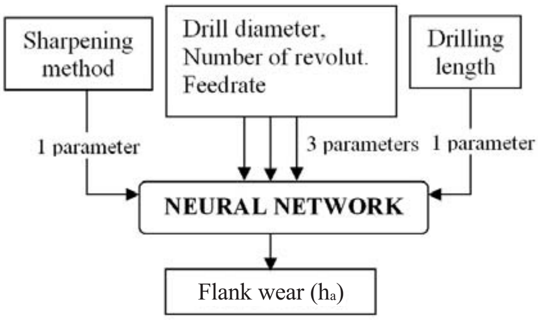

Fig. 6. *Access scheme of neural-network training*

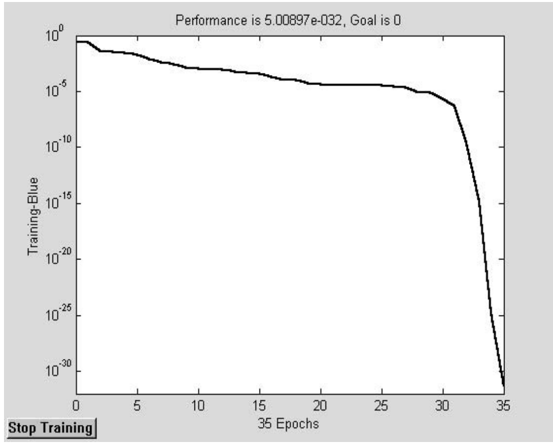

Fig. 7.

Table 3. *Parameters of neural-network training*

Trained function		TRAINLM
Adaptation of function learning		LEARNGDM
Function performance		MSE
Number of layers		3
Number of neurons	I layer	18
	II layer	15
	III layer	1
Transfer function	I layer	TANSIG
	II layer	
	III layer	

- Transformation function (trained function),
- Adjustment of function learning,
- Function performance,
- Number of layers,
- Number of neurons and the transmission function for all layers.

The neural network converged with a performance of 5.00897×10^{-032} with 35 epochs (Fig. 7), wherein the parameters specified in Table 3 were employed.

Table 4 presents the output values of flank wear (h_a), column A targeted values, column B values gained through training of the neural network, as well as the appropriate errors.

The testing of the trained network was performed for Ø6 – KO with the drilling parameters, n=500 r.p.m., s=0.027 mm/r, and the drilling lengths that were not trained. The results of the work (simulation) are represented by a wearing curve in relation to the wearing curve derived based on the experimental data (Figure 8).

Figure 9 presents a wearing curve for BV Ø6.00 – KO, which was obtained by the simulation of a trained network for the cutting parameters, n=500r.p.m. and s=0.053mm/r, in relation to the wearing curve for cutting parameters, n=500r.p.m. and s=0.027mm/r, as well as n=500r.p.m. and s=0.107mm/r, obtained on the basis of experimental data.

4 CONCLUSION

The modern conditions of processing by cutting and the growing requirements concerning the quality of cutting materials make the study of cutting regimes very important. The incorrect choice of cutting-regime values – in addition to the fact that a tool has all the other qualities – brings about rapid wear and a decrease of durability, and even the breakage of certain parts.

Traditional methods of experimental work demand a significant waste of time and resources, because of the subject of reference, i.e., the influence of every factor is being examined separately, with a fixation on other factors' meaning.

In modern conditions of production, where there are no algorithmic solutions and there are no completely defined theoretical solutions, or where

Table 4.

Record number	A	B	Error
1	0.260	0.26	2.2204e-016
2	0.245	0.245	-6.3838e-016
3	0.230	0.23	-2.2204e-016
4	0.000	2.2204e-016	4.4409e-016
5	0.000	-4.4409e-016	1.6653e-016
. . .			
42	0.190	0.19	2.7756e-016
43	0.175	0.175	-5.5511e-017
44	0.160	0.16	3.0531e-016
45	0.150	0.15	-1.3878e-016
46	0.095	0.095	-4.1633e-016
47	0.130	0.13	1.1102e-016
48	0.115	0.115	1.3878e-017
. . .			
85	0.086	0.086	1.3878e-016
86	0.230	0.23	4.7184e-016
87	0.220	0.22	2.7756e-017
88	0.270	0.27	0
89	0.195	0.195	1.6653e-016
90	0.295	0.295	5.5511e-017

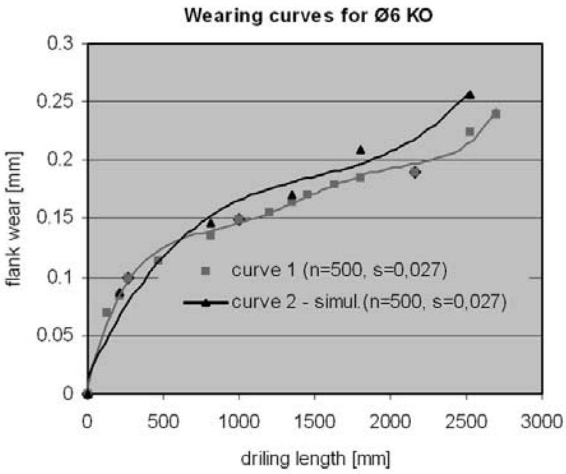

Fig. 8.

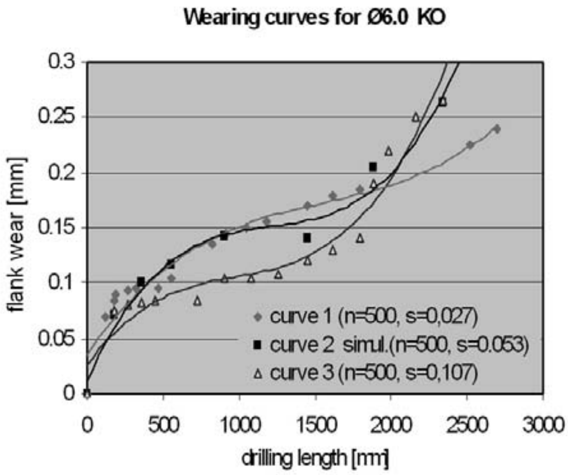

Fig. 9.

there is a theory but it is not possible in practice to process all theoretical cases using an algorithm in a satisfactorily time interval, expert systems are used.

This paper presents a performed training of a neural network based on experimental data with five input parameters and one output parameter. The inputs were the cutting process parameters, the method of sharpening and the drilling length, and the output (targeted) dimension was the value of the wearing parameter.

The trained network was tested on experimental data, and then employed in the determination of a wearing belt under regimes that were not used in the experiment.

These initialized studies should serve as the initial starting point for the tracking of tool conditions using artificial intelligence, i.e., the intelligent tracking of tool conditions.

5 REFERENCES

[1] Purushothaman, S., Srinivasa, G.Y. (1994) A back-propagation algorithm applied to tool wear monitoring, *Int. J. Mach. Manufact.*, 1994, Vol. 34, No. 5, pp. 625-631.

[2] Byrne, G., et al. (1995) Tool condition monitoring - The status of research and industrial application, *Annals of CIRP*, Vol. 44/2, 1995, pp. 541-567.

[3] Rangawala, S., Dornfeld, D. (1990) Sensor integration using neural network for intelligent tool condition monitoring, *Journal of Engineering for Industry*, August 1990, Vol. 112.

[4] Lin, C.S., Ting, J.C. (1996) Drill wear monitoring using neural network, *Int. J. Mach.Manufact.*, 1996, Vol. 36, No. 4, pp. 465-475.

[5] Krivokapic, Z., Zogovic, V. (1998) Following the twist drill wear using the neural networks, *24. JUPITER Conference with foreign participants*, Beograd.

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Vpliv spreminjanja tlaka na rezalno zmožnost vodnega curka

The Effect of Pressure Fluctuations on the Cutting Ability of Pure Water Jet

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Tehnologija obdelave z vodnim in abrazivno vodnim curkom je predmet obsežnih raziskav. To področje raziskav je usmerjeno k boljšemu razumevanju mehanizmov odnašanja materiala in optimizaciji postopkovnih parametrov (hidravličnih in tehnoloških) v primeru različnih uporab. Optimizacija postopkovnih parametrov je posebej težavna zaradi njihove nestabilnosti med samim postopkom. Številne raziskave so usmerjene v fizikalno-mehansko interakcijo med curkom in mehanskimi lastnostmi materiala, iz česar so se razvili modeli z različnimi razlagami. Kljub temu pa sedanji modeli popisujejo večinoma rezalne mehanizme pri rezanju z abrazivnim vodnim curkom (AVC). Razlaga nastanka strij pri rezanju z AVC ne pojasnjuje podobnega pojava pri rezanju z VC. V resnici se pokaže, da se pojavijo nepravilnosti (raze), kadar režemo s čistim vodnim curkom po vsej odrezani površini, med tem ko se pri rezanju z AVC pojavijo raze le v spodnjem delu rezalne cone. Predhodne študije so pokazale, da je površina nastala pri rezu samo z vodo odvisna le od endogenih in eksogenih vibracij in ne od sprememb tlaka v curku ali pa od oblike tlačnega signala. Pri zmanjšanju teh vibracij lahko zaznamo občutno izboljšanje na odrezani površini, še posebej v smislu zmanjšanja strijavosti.

Kljub temu, da spreminjanje tlaka pri rezanju z VC nima vpliva na kakovost površine, bi morala imeti vpliv na globino reza. V tem prispevku je bila raziskana prav slednja teza. Da bi prišli do naslednjih rezultatov, smo morali preučiti usmeritev potiska vodnega curka na ravno površino. Cilj tega preizkusa je bil analizirati zmožnost prodiranja vodnega curka pri izhodnem rezu. Za tem je bila preučena povezava med signalom potiska in obliko profila v spodnjem delu reza.

(Ključne besede: rezanje s curkom, curek vodni, spreminjanje tlaka)

Water jets and abrasive water-jet technology are the focus of concentrated research. This research area is oriented to understand the material-removal mechanisms and to optimise the process parameters (fluid dynamical and technological) of various applications. The optimisation of the process parameters is especially difficult because of their instability during the process. Many authors have inquired into the physical-mechanical aspects of the interaction between the jet and the mechanical properties of the material and they have developed models and different interpretations. However, the existing models, mostly try to describe the cutting mechanism only for abrasive water-jet (AWJ) technology. The interpretation of the mechanism of striation formation in AWJ cutting does not explain the striation formation in the pure WJ process. In fact, whereas in the cutting surface realised by a pure WJ cutting along the whole surface there are irregularities (striations); the surface generated by AWJ cutting is characterized by a streaked morphology in the bottom zone of the cutting surface. Previous studies have demonstrated that the cutting surface realised by WJ is not influenced either by the pressure fluctuations or the pressure signal form, but depends strongly on the exogenous and endogenous vibrations. In fact, a considerable reduction of these vibrations makes it possible to obtain remarkable improvements in the surface quality, especially as regards the striation morphology.

Although the pressure fluctuation does not have substantial effects on the WJ surface quality, it should have an influence on the depth of cut. In this work the effect of the pressure fluctuation on the depth of cut in no-passing WJ cuts has been analysed. In order to do this, the thrust trend of the water jet on a plane surface has been analyzed. The aim of this experiment has been to analyze the penetration ability trend of the jet at the exit of a passing cut; afterwards, the correlation between the thrust signal and the bottom profile generated by a no-passing cut on polycarbonate slabs has been analyzed.

(Keywords: water jet cutting, pressure fluctuation)

0 INTRODUCTION

The WJ/AWJ (water-jet/abrasive-water-jet) removal process is influenced by several technological and fluid dynamics parameters. The anticipatory models proposed in the literature usually set process parameters (stand-off distance, feed rate, pressure, mass flow rate and mesh of the abrasive, etc.) to an established value ([1] and [2]). However, the instability of some in-process parameters might prejudice the validity of such models. In particular, the water pressure is subjected to cyclical fluctuations mainly due to the intensification mechanism.

The control of cyclical pressure fluctuation is very important. In fact, the pressure fluctuation has many effects:

- it causes a periodic stress state in the whole system: every mechanical component of the high-pressure circuit is subjected to a fatigue stress that can be brought about by forced vibrations [3];
- the jet is pulsating, with possible effects on the cutting quality ([3] and [4]);
- it causes a reduction in the life of many WJ-system components [5], for example, the nozzle;
- it is often a constraining factor that limits the applications of the WJ technology [5].

Other causes of the variability of the parameters can be considered, directly or indirectly, connected to the pressure fluctuation. Examples among many are the mass-flow-rate fluctuation and the vibrations on the structure of the system [6] and [7].

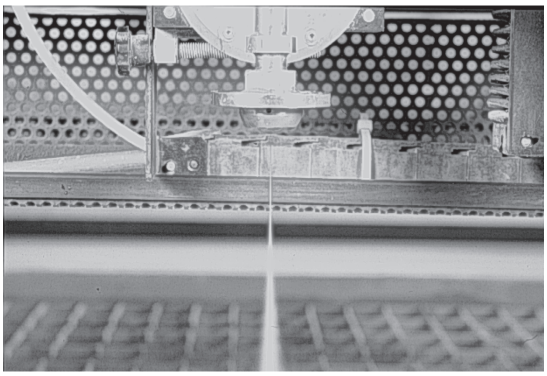
In order to investigate only the effects of pressure fluctuation on the cutting quality, leaving out the effects of the abrasive, only pure water-jet (WJ) has been considered. Therefore, the tests have been carried out on workable materials (polycarbonate, rubber, plasticine), even with high thicknesses, but without the abrasive injection. The effect of the pressure fluctuation on the penetration ability, measured in terms of the depth of cut, has been studied.

1 THE WJ/AWJ PROCESS

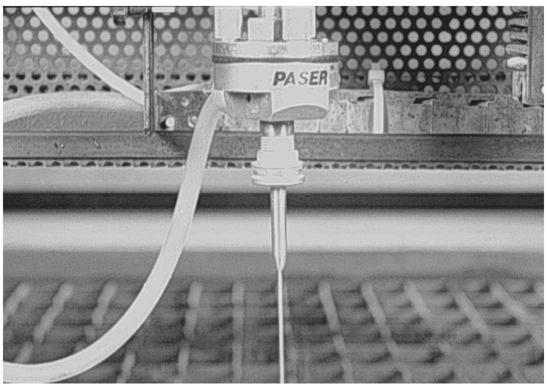
In WJ/AWJ technology, the high energy of the jet makes the cut. In pure WJ cutting, the material removal is due to the high speed of the jet; in AWJ cutting, in contrast, the jet only transfers its momentum to the abrasive particles, whose abrasive and erosive action causes the material removal.

The water pressure is increased up to the operating pressure through a pump system (intensifier). The usual pressure at present is 380-400 MPa, but the world trend is to increase the pressure: there are already proposed and realized systems that reach higher pressures [8]. Then, the high-pressure fluid is directed into the cutting head, where the pressure energy of the jet is converted into kinetic energy. The energetic conversion is obtained by means of an orifice in sapphire or synthetic ruby; at the exit of the orifice the jet reaches a rate of up to 900 m/s, depending on the selected pressure. The specific energy of the jet depends on the diameter of the orifice, which changes between 0.05 and 0.40 mm (Figure 1-a).

In AWJ systems the abrasive is added to the fluid in a mixing chamber (Figure 1-b), placed under the orifice.



(a)



(b)

Fig. 1. *WJ (a) and AWJ (b) cutting*

2 GENERATION OF HIGH PRESSURE

Intensifier systems operate on the principle of the conservation of hydraulic energy. A low-pressure, high-flow hydraulic region acts on a piston with a large area. A large force is generated, which in turn acts on a small plunger area, creating a much higher pressure. An exchange of energy is made where the low-pressure, high-flow hydraulic fluid is converted to high-pressure, low-flow water. The ratio of the low-pressure piston area to the high-pressure plunger area is called the intensification ratio.

The first intensifier for water-jet application was introduced in 1971, and the basic intensifier design did not change; that is, until the introduction of the phased intensification concept in 1991. Both types create an ultra-high pressure in essentially the same way, but they minimize the output pressure fluctuation differently.

The basic design of a standard intensifier consists of a double-acting, hydraulically actuated piston-plunger ram in which the two opposite-facing cylinders are mechanically coupled and the fluid compression and suction strokes alternate between the two cylinders (Figure 2-a).

As it strokes, creating pressure and output flow in a direction, the opposite side is in its suction stroke. When the piston reaches the end of its stroke, the directional valve is shifted. The output pressure decays due to the response time of the valve and the plunger stroke required to compress the water to the output pressure. When the water pressure in the high-pressure cylinder equals the pump's output pressure, the high-pressure check valve opens [9]. Because of the compressibility of water, the first 15% of the stroke of the piston is used to pressurise and compress the water in the cylinder without delivering water to the system [10]. This causes unacceptable pressure fluctuations that give rise to cutting inaccuracies and shortens the life of the system components. In order to reduce the pressure fluctuations, an accumulator of high-pressure water is installed. Its volume controls the range of fluctuations.

If the accumulator's volume increases, the fluctuation decreases, but the cost of the accumulator increases to more than a proportional extent. The choice of the volume results from a compromise solution between the benefits from a stable pressure signal and a sensible increase in costs ([11] and [12]).

In order to minimize the pressure fluctuation due to the intensifier, without resorting to the expensive solution of the accumulator, some constructors have opted for the use of a *phased pump* (Figure 2-b).

The phased concept is based on at least two (six in [13]) single-acting cylinders in parallel in which the plungers' motion can be arbitrarily phased through a combination of hydraulic and electronic circuitry. These systems are timed such that, at the end of the delivery stroke of a piston, there is already another piston in the phase of pressurization of the water. This implies the contributory presence of a peak of absorbed power. The concept offers several advantages in addition to the absence of a need for an accumulator, compact size, design flexibility, to name just a few [14].

3 CAUSES OF PRESSURE FLUCTUATIONS

The main cause of water-jet pressure fluctuation is intrinsic due to the architecture of the intensifier. The alternating motion of the piston brings about, in fact, an oscillating periodic trend in the pressure of the fluid. This phenomenon can be

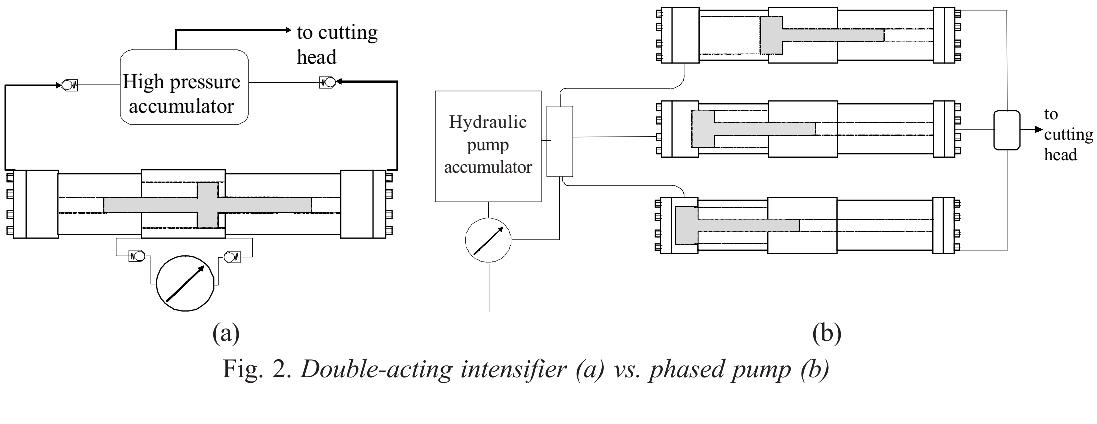


Fig. 2. *Double-acting intensifier (a) vs. phased pump (b)*

removed, only theoretically, by using an accumulator of infinite dimensions [11].

There are at least three factors [14] that have an effect on the stability of the pressure for both of the architectures mentioned above. The first one is the reversion time of the check valves which, in spite of their rapidity, have a finish time to respond. The second one concerns the speed of the return stroke of the intensifier piston: a high speed tends to reduce the pressure fluctuations because it reduces the time during which there is not a feed outflow [16]. Last, but not least, is the volume of the compression chamber: it has to be designed so as to balance these requirements:

- to obtain a higher flow rate than that of the outflow at every stroke;
- to have a short stroke in order to obtain high speed delivery.

In consideration of the compressibility of the water, which can reach up to 15% at 350 MPa [10], every piston covers a part of its working stroke in order to compress the water, without this there is water discharge while the jet is fed thanks to the accumulator and to the additional capacity supplied from the pipes.

In the single-acting system with phased pumping in parallel, the pressure fluctuation due to the compressible water is partly compensated for by the pre-compression of the piston at the end of the suction phase.

Moreover, in a double-acting intensifier the pressure developed by the pump in the forward stroke is different from the pressure developed in the backward stroke [5].

4 THE EFFECT OF PRESSURE FLUCTUATION: STATE OF THE ART

The surface morphology generated by WJ/AWJ is the subject of concentrated research.

Based on a flow visualization study of the water-jet cutting process, Hashish proposed that a water-jet cut surface consists of two cutting regions ([17] and [18]). The first region (the top cut of the surface) is dominated by the cutting wear mode, where penetration occurs at a small impact angle. The second region (the bottom part of the surface) is dominated by the deformation wear mode where penetration occurs at a large impact angle. The surface is smooth in the first region, but it is marked by striations in the second region.

In [19] and [20] it is concluded that a pressure fluctuation causes a cyclical fluctuation in the jet power density, which influences directly the diameter of the jet: the final effect is the periodic fluctuation of the dimension of the kerf.

Afterwards, Hashish proposed that in addition to jet-induced striations, which are due to the deformation wear mode of the waterjet cutting, traverse-induced striations also exist. These are due to the unsteadiness of the water-jet pressure or the motion of the AWJ traverse system and may appear in both the cutting and deformation wear zones [21].

In [4] it was found that the pressure fluctuations have a contribution to the striation formation mechanism in the lower part of the cuts generated by AWJ. In fact, using the two high-pressure generation systems, having a different amplitude fluctuation, at the same level of pressure, the streaked morphology is similar in frequency but not in amplitude. The amplitude of the striations is higher when using the pressure generation system with a higher fluctuation.

As regards pure water-jet cutting, no correlation has been found between the roughness profiles and the pressure signal [22]. Moreover, the pressure signal form does not have a substantial influence on the surface quality of waterjet cutting: in fact, for the process parameters used during the penetration time, the pressure can be considered continuous. The striations along the entire surface presuppose that there are other factors, the vibration of the cutting head and of the work piece [23], that directly influence the quality of the water-jet cutting.

Although the pressure fluctuation does not have substantial effects on the WJ surface quality, it should have an influence on the depth of cut. In fact, the water pressure determines the jet's power and is directly proportional to the energy transfer to the surface.

5 EXPERIMENTAL RESEARCH

5.1 The acquisition of the pressure signal

The trend of the pressure is a characteristic of the intensification system that generates it.

The intensification system that was used is a double-acting intensifier (30 kW).

The pressure was measured through a digital pressure transducer (Inter-Probes HP-48) that is placed in proximity to the cutting head and connected to an acquisition card (Figure 3).

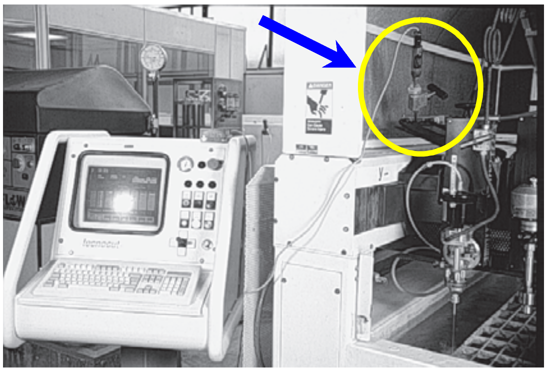


Fig. 3. *Arrangement of the pressure transducer*

The pressure measured at the exit of the intensifier system differs from that acquired only by a constant. This constant represents the pressure losses' load inside the pipe lines.

For every measurement the acquired pressure signal was analyzed in the time and frequency domains.

5.2 The penetration ability

Using a mono-axial load cell (DS Europe 535-Q), the thrust trend of the water jet on a plane surface was analyzed either with a motionless cutting head or in motion (Figure 4)

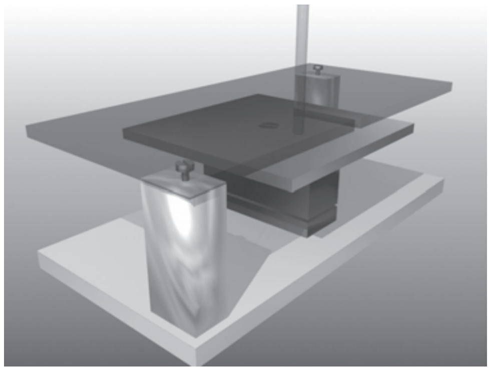


Fig. 4. *Plant description of the arrangement of the system used for the experiment with the load cell*

The aim of this experiment was to analyze the penetration ability trend of the jet at the exit of a passing cut; afterwards, the correlation between the thrust signal and the bottom profile generated by a no-passing cut was analyzed.

The material used was polycarbonate, the chemical and mechanical characteristics of which are given in Table 1.

6 ANALYSIS OF THE EXPERIMENTAL RESULTS

Figures 5 and 6 show the pressure signal and the thrust signal with the cutting head not in movement in the time and frequency domains.

Table 1. *Chemical and mechanical characteristics of polycarbonate*

Density	1200 kg/m^3
Relative saturation humidity	0.3%
Thermal conductivity	0.18 W/(m K)
Failure resistance	68.6 MPa
Melting point	220 to 240 °C

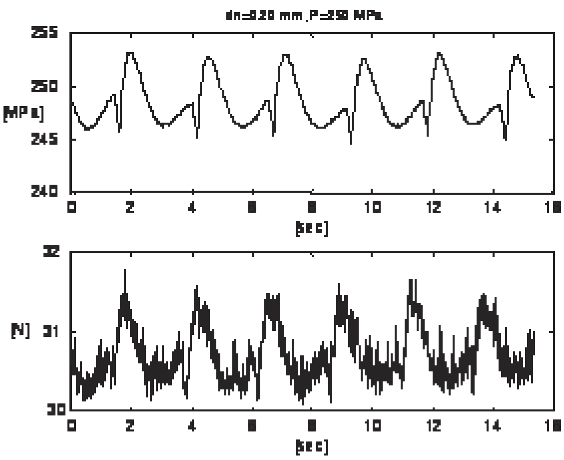


Fig. 5. *Pressure and thrust signals in the time domain*

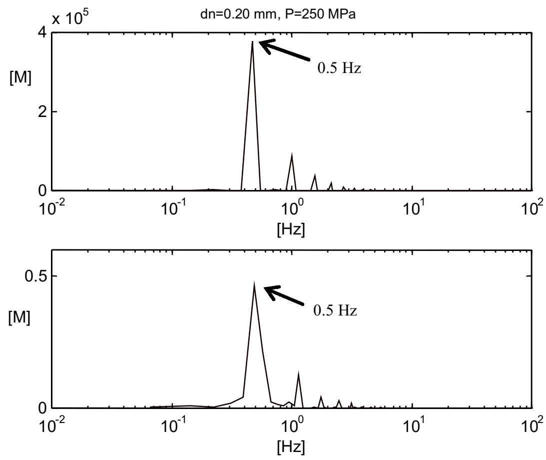


Fig. 6. *Pressure and thrust signals in the frequency domain*

It can be seen that the thrust signal, which represents the penetration ability, is comparable to the pressure signal: the main frequency of the force signal is the same of that of the pressure. Therefore, the fluctuation of the jet energy density causes cyclical areas in which the cut reaches greater depths.

Figures 7 and 8 show the thrust profile in the time and in the frequency domains, measured at the exit of a passing cut.

The main frequency of the thrust is the same as that of the pressure signal.

Figure 9 shows the profile of a no-passing cut on polycarbonate.

Figure 10 shows a frequency analysis of the no-passing profile.

The spatial frequency, which at 200 mm/min coincides with the pulsation of the pressure signal of 0.5 Hz, is 0.15 1/mm.

Figures 11 and 12 show the thrust signal in the time and in the frequency domains of the no-passing cut on polycarbonate.

It can be seen that there is a strong correlation between the dominant frequencies of the two signals and therefore with the pressure signal too.

7 CONCLUSION

This work has analysed the effect of the pressure on pure water-jet cutting.

As regards the effect on the surface quality, in a previous study [22] no correlation was found between the roughness profiles and the pressure signal. The striations along all of the surface presuppose that there are other factors, for example, the vibration of the cutting head and of the workpiece [23], that directly influence the quality of the pure water-jet cutting.

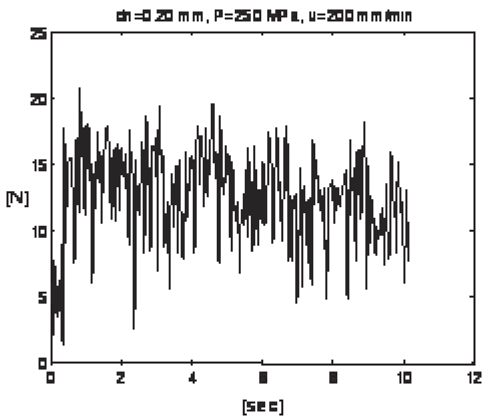


Fig. 7. *Thrust profile of the jet at the exit of a passing cut in the time domain*

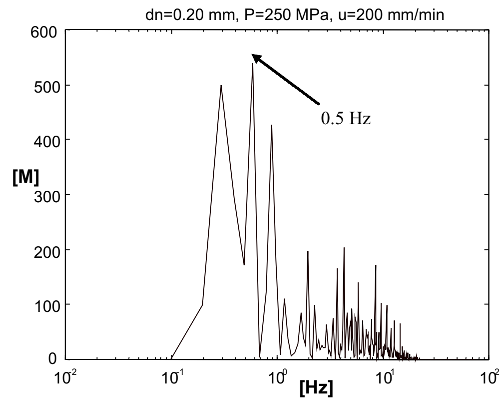


Fig. 8. *Thrust profile of the jet at the exit of a passing cut in the frequency domain*

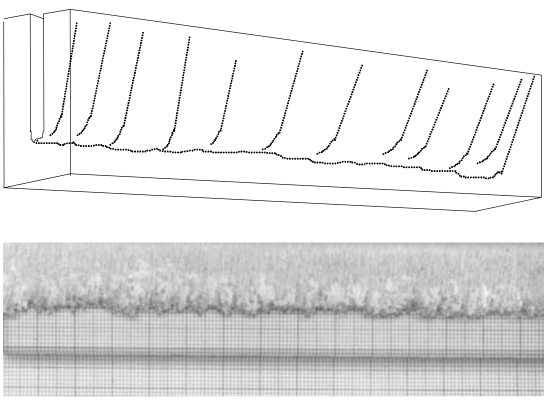


Fig. 9. *Bottom part of a profile of a no-passing cut on polycarbonate (P=250MPa, u=200mm/min, dn=0.2mm)*

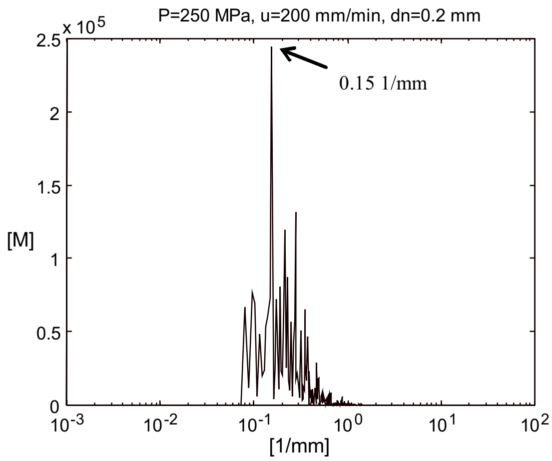


Fig. 10. *FFT of the bottom part of the profile of a no-passing cut on polycarbonate*

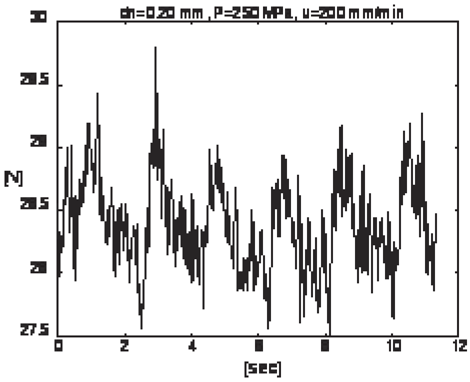


Fig. 11. *Thrust signal in the time domain of a no-passing cut on polycarbonate*

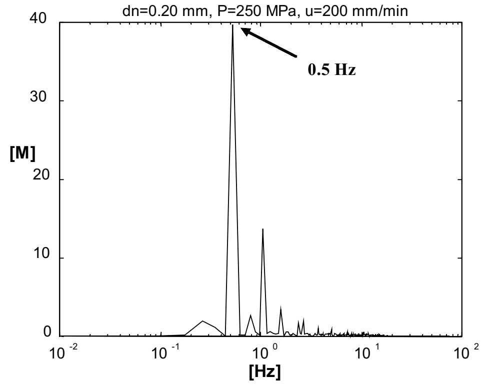


Fig. 12. *Thrust signal in the frequency domain of a no-passing cut on polycarbonate*

In contrast, in this work it was found that the pressure fluctuation causes a periodic trend in the water-jet specific energy and therefore a fluctuation in the cutting ability. In fact a strong correlation between the pressure signal and the bottom part of the profile of a no-passing cut realized on WJ suitable materials was found.

This result is very important for applications in which the jet does not pass all the way through the workpiece, rather it leaves a no-passing track (turning, milling, surface treatment).

It would be interesting to extend this research to abrasive water-jet cutting as well.

Acknowledgments

Mr. M. Dinale and Mr. L. Ferrari are acknowledged for carrying out accurate laboratory tests.

8 NOMENCLATURE

P	Pressure [MPa]
u	Feed rate [mm/min]
dn	Nozzle diameter [mm]
sod	Stand-off distance [mm]
M	Power Spectrum Density Modulus
ρ	Density of the water at atmospheric pressure

9 REFERENCES

[1] M. Hashish (1993) Prediction models for AWJ machining operations, *7th American Water Jet Conference*, pp. 205-216, Seattle, Washington, 28-31 August, 1993.

[2] N.S. Guo, H. Louis, G. Meier (1993) Surface structure and kerf geometry in abrasive waterjet cutting: formation and optimization, *7th American Water Jet Conference*, pp. 1-25, Seattle, Washington, 28-31 August, 1993.

[3] E. Chalmers (1993) Pressure fluctuation and operating efficiency of intensifier pumps, *7th American Water Jet Conference*, pp. 327-336, Seattle, Washington, 28-31 August, 1993.

[4] A. Karpinski, H. Louis, M. Monno, D. Peter, C. Ravasio, C. Scheer, U. Südmersen (2004) Effects of pressure fluctuations and vibration phenomenon on striation formation in AWJ cutting, *17th International Conference on Water Jetting Technology*, pp.123-136, Mainz, Germany, 7-9 September 2004.

[5] B.C. Fabien, M. Ramulu, M. Tremblay (2003) Dynamic modelling and identification of a water jet cutting system, *Mathematical and Computer Modelling of Dynamical Systems*, Volume No: 9, Issue: 1, pp. 45-63.

[6] J. Chao, E.S. Geskin, Y. Chung (1992) Investigation of the dynamics of the surfaces topography formation during abrasive waterjet machining, *11th International Symposium on Jet Cutting Technology*, pp. 593-603, St. Andrews, Scotland, 8-10 Sept., 1992.

[7] J. Chao, E.S. Geskin (1993) Experimental study of the striation formation and spectral analysis of the abrasive waterjet generated surfaces, *7th American Water Jet Conference*, pp. 27-41, Seattle, Washington, 28-31 August, 1993.

[8] M. Hashish (2004) Waterjet cutting at 600 MPa, *17th International Conference on Water Jetting Technology*, pp. 47-60, Mainz, Germany, 7-9 September 2004.

[9] R. Tunkel (1997) Double action hydraulic intensifier, *9th American Waterjet Conference*, pp. 373-385, Deaborn, Michigan, 23-26 August, 1997.
[10] M.K. Kulekci (2002) Processes and apparatus developments in industrial waterjet applications, *International Journal of Machine Tools & Manufacture*, Volume No 42, pp. 1297-1306.
[11] R. Susan-Resiga (1992) Attenuator's volume influence on high pressure's pulsation in a jet cutting unit, *11th International Symposium on Jet Cutting Technology*, pp. 37-45, St. Andrews, Scotland, 8-10 Sept., 1992.
[12] P.J. Singh (1997) Computer simulation of intensifiers and intensifier systems, *9th American Waterjet Conference*, pp. 397-414, Deaborn, Michigan, 23-26 August, 1997.
[13] G. Yie Gene (1997) A pulsation-free fluid pressure intensifier, *9th American Waterjet Conference*, pp. 365-372, Deaborn, Michigan, 23-26 August, 1997.
[14] P.J. Singh, D. Benson (1992) Development of phased intensifier for waterjet cutting, *11th International Symposium on Jet Cutting Technology*, pp.305-318, St. Andrews, Scotland, 8-10 Sept., 1992.
[15] F. Hu, J. Robertson (1993) Simulation and control of discharge pressure fluctuation of ultra-high pressure waterjet pump, *7th American Water Jet Conference*, pp. 337-349, Seattle, Washington, 28-31 August, 1993.
[16] M. Tremblay, M. Ramulu (1999) Modeling and simulation of pressure fluctuations in high pressure waterjets, *10th American Waterjet Conference*, Paper 12, Houston, Texas, 14-17 August, 1999.
[17] M. Hashish (1984) On the modelling of abrasive-waterjet cutting, *7th International Symposium on Jet Cutting Technology*, pp. 249-265, Ottawa, Canada, 26-28 June, 1984.
[18] M. Hashish (1989) A model for abrasive-waterjet (AWJ) machining, *Transactions of the ASME*, Volume No: 111, pp. 154-162.
[19] D.K.M. Tan (1986) A model for the surface finish in abrasive-waterjet cutting, *8th International Symposium on Jet Cutting Technology*, pp. 309-313, Durham, England, 9-11 Sept., 1986.
[20] W. Koenig, C. Wulf (1984) The influence of the cutting parameters on jet forces and the geometry of the kerf, *7th International Symposium on Jet Cutting Technology*, pp. 179-191, Ottawa, Canada, 26-28 June, 1984.
[21] M. Hashish (1992) On the modelling of surface waviness produced by abrasive-waterjets, *11th International Symposium on Jet Cutting Technology*, pp. 17-34, St. Andrews, Scotland, 8-10 Sept., 1992.
[22] M. Monno, C. Ravasio (2005) The effect of pressure on the surfaces generated by waterjet: preliminary analysis, *7th International Conference on Advanced Manufacturing Systems and Technology*, Udine, Italy, 9-10 June 2005.
[23] M. Monno, C. Ravasio (2005) The effect of cutting head vibrations on the surfaces generated by waterjet cutting, *International Journal of Machine Tools and Manufacture*, Volume No. 45, Issue 3, pp. 355-363.

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Merjenje generacije toplote pri rezanju kosti z abrazivnim vodnim curkom

Heat Generation During Abrasive Water-Jet Osteotomies Measured by Thermocouples

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Abrazivni vodni curek (AVC) je v industriji znan kot hladni rezalni postopek, saj ne opazimo pomembnega toplotnega segrevanja na rezalnih robovih v primeru rezanja kovinskih materialov. Zaradi tega se AVC uporablja predvsem tam, kjer ne dovolimo toplotno prizadete cone v samem rezalnem materialu. Za medicinske uporabe je kritična temperatura dosti nižja kakor pri industrijski rabi, saj so kosti zelo občutljive za toploto. Poškodbe na tkivu so odvisne od same temperature v rezalni coni ter času rezanja. Tkivo se uniči že pri izpostavljanju za 10 sekund temperaturam, višjim od 57°C. Da bi se izognili temu učinku, tako imenovani nekrozi, ki povzroča slabše rasti kosti, je treba upoštevati temperaturo pri samem rezanju z AVC. Prvi koraki so narejeni v tem prispevku. Generacija toplote pri rezanju kosti z AVC je bila izmerjena z uporabo termoelementov, ki so bili vstavljeni v kortično votlino goveje kosti. Vplivi parametrov kakor so: tlak, rezalna hitrost, pretok abraziva, abrazivni material so prikazani v tem prispevku, prav tako tudi vplivi postavitve termoelementov.

(Ključne besede: medicina, rezanje kosti, curek vodni, curek abrazivni, meritve temperature, termočleni)

Water-jet technology is known in industry as a cold-cutting process because no significant thermal effects are observed at the cutting edges of, e.g., metallic workpieces. Thus, water jets are mostly used for applications where no structural changes are allowed. For medical applications the critical temperature is much lower than for industrial use, because bones react very sensitively to heat. The damage to the tissue depends on the temperature and the time of exposure. The tissue is irreversibly destroyed after a period of approximately 10 seconds at 57°C. To avoid this effect, which causes the so-called necrosis formation, and which results in poor bone healing, heat management is required for water-jet osteotomies. The first step is made in this paper. The heat generation during abrasive water-jet osteotomies was measured by thermocouples that were inserted into the cortical hollow bone segments of cattle. The influence of parameters like pressure, traverse rate, abrasive flow rate and abrasive material are shown in this paper together with the influence of the location of thermocouples, which represents an increment of the bone tissue.

(Keywords: medicine, osteotomy, abrasive water jet, temperature measurement, thermocouples)

0 INTRODUCTION

For orthopaedic surgery the standard method for cutting hard biological tissue like bones is still the use of mechanical tools like the oscillating saw [1]. However, bone reacts very sensitively to heat. Thermal damage to living tissue is related to the magnitude of the temperature and the exposure time [2].

Figure 1 shows the critical temperature with respect to the exposure time. When exceeding these limits, irreversible tissue damage occurs. Conventional tools, like saws and medical burs, generate temperatures of up to more than 100°C and cause, as a result, a layer of destroyed cells at the resection edges ([2] to [4]). These temperature traumas are responsible for a lack of bony ingrowths in prosthe-

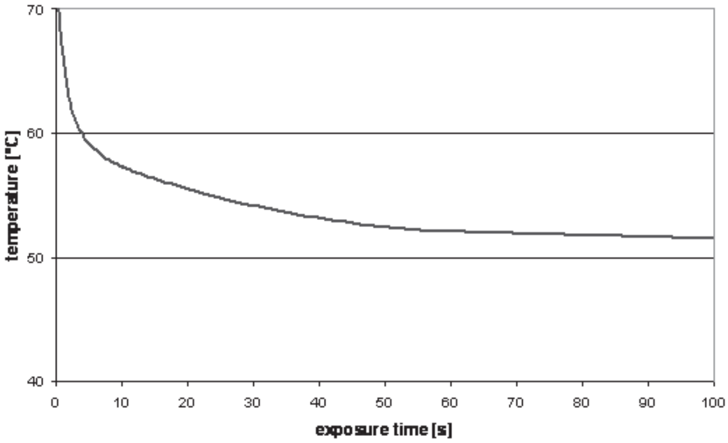

Fig. 1. *Necrosis formation of bone depending on the temperature and exposure time [2] and [3]*

ses and delayed bone-healing times ([3] and [4]).

For the last five years the research group from the Hannover Medical School, the Orthopaedic hospital Annastift, the University of Hannover and the University of Veterinary Medicine Hannover have investigated the possibility of introducing the water jet as a technique for medical applications. The feasibility of the abrasive water injection jet (AWIJ) as a tool for orthopaedic purposes, which can cut freely defined geometries with high accuracy, is already proven. The roughness is adjustable by choosing the parameters, and an average surface roughness of less than 20 µm can be realised [5]. Furthermore, the main focus in recent times has been the investigation of clinically usable abrasive materials. The requirements for abrasives that can be used for medical purposes, like biocompatibility and the biodegradability of the particles as well as the cutting performance obtainable with these abrasives, were examined ([6] and [7]). A major advantage of the AWIJ compared to the conventional bone-cutting tools seems to be that cutting with a water jet is a “cold cutting process”. For pressure levels up to 100 MPa this has already been proven. The maximum temperature rise for this pressure was determined to be 13 K [8]. In-vivo studies of pigs have shown that this pressure is not sufficient when used in combination with a necessary new abrasive feeding system, with which the risk of embolism can be excluded [9]. Therefore, the pressure level for the AWIJ-Osteotomy has to be increased, and this is associated with an increase in the amount of transformed energy. Thus, a rise in temperature during the cut is assumed, which has to be screened.

The aim of this study is to investigate the heat generation during an AWIJ-osteotomy with re-

Fig. 2. *Preparation of the hollow bone segments (specimens)*

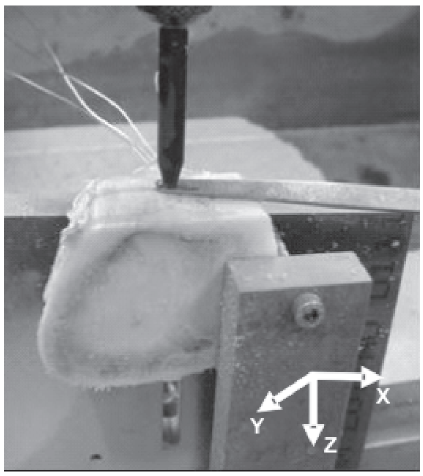

Fig. 3. *Fixation of the bone segments*

spect to parameters like pressure, abrasive flow rate, traverse rate and type of abrasive material.

1 MATERIALS AND METHODS

For this study hollow bones from the lower leg of cattle (bovine tibias) were used. The hollow bones were cut into segments with a band saw of approximately 2-cm thickness and then frozen at –32°C. The cortical thickness of the hollow bone segments varied between 4 and 14.8 mm. Before the AWIJ-cut, the segments were defrosted in saline solution at 37°C. An AWIJ-cut was performed to get a plain area on one side of the bone (see Figure 2). Afterwards, three bores were drilled in each cortical bone with a diameter of 0.6 mm. The depth of the bore was 6 mm ± 0.7 mm (the y-direction, see Figure 3). The distance between the three thermocouples was 1 mm for all measurements (the z-direction, see Figure 3).

Before inserting the thermocouples (type K, measurement range 0–1100°C, diameter 0.5 mm) the hole was filled with heat-conductive paste. Afterwards, the thermocouples were glued onto the bone with a hot sticking pistol to avoid any displacement during the cut. The sampling rate for the temperature was set to 0.1 s and the values were recorded using DasyLab Software.

The water-jet system consisted of an Uhde high-pressure intensifier (maximum pressure 400 MPa, maximum water-flow rate 4 l/min) and a 2-axis cutting table with a positioning accuracy of < 0.1 mm. The z-axis could be manipulated manually to set the stand-off distance. For this purpose the bone segment was fixed with the plain surface facing upwards. To measure the temperature of an AWIJ-cut with regard to the thermocouples' position a preliminary cut (in the x-direction) had to be conducted for each specimen to determine the cutting width. With this knowledge it was possible to cut directly in front of the thermocouples' head. A safety offset was set to 0.5 mm in the y-direction for all tests.

2 RESULTS

2.1 Influence of the thermocouples' location on the temperature

The thermocouples demonstrate an increment of bone tissue. Thus, with the experimental set up it was possible to check the temperatures of three bone increments with respect to a measurement period for each AWIJ-cut regarding their distance to the surface (z-direction) and regarding the distance of the cutting edge (see Figure 4).

The standard parameters were set as followed:

Abrasive material	Garnet
Pressure	300 MPa
Abrasive flow rate	6 g/s
Orifice/focus-diameter	0.25 / 0.8 mm
Traverse rate	100 mm/min

For all tests, the measured temperature is a maximum for the top thermocouple, which is placed directly on the bone surface. This is reasonable because it is a fact that the jet's energy decreases with the increasing depth of the cut. As a result less energy can be caused by friction.

In Figure 5 the measured maximum temperatures versus the distances of the thermocouples from

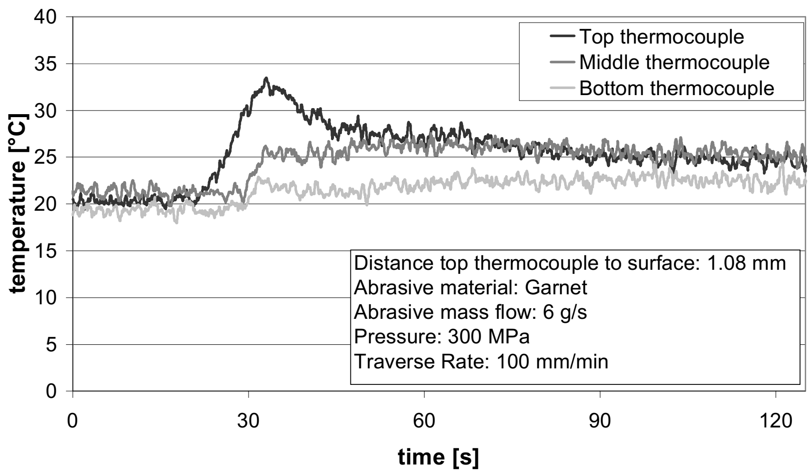

Fig. 4. *Example of a temperature measurement with three thermocouples*

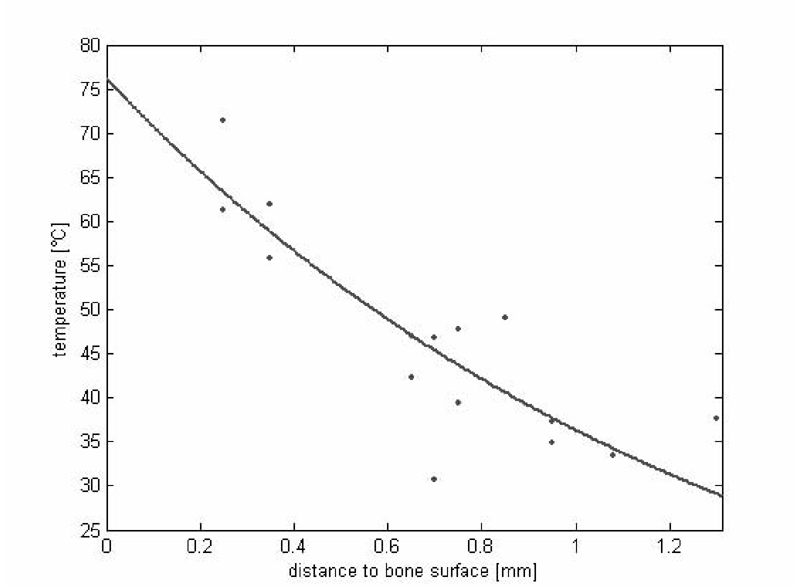

Fig. 5. *Temperature versus the distance of the thermocouples from the surface*

the surface for standard parameters are shown. Furthermore, an extrapolation of the measurement points based on a consideration of the least-squares method has been conducted.

It is obvious that the deeper the bone increment is placed, the less heat affects the cells during an AWIJ-osteotomy. Without a consideration of the exposure time, cell damage for a bony layer of a maximum of 1 mm thickness could occur during an AWJI-osteotomy (standard parameters), when assuming the critical temperature of 37°C.

2.2 Influence of different distances to the cutting edge on the temperature

To investigate the influence of bone increments that are not located directly at the cutting edge on the temperature, another parameter study was carried out. After a first cut at the specimen's border, the cut was shifted parallel in the direction of the thermocouple (the y-direction). Six cuts were performed until a distance of 1 mm between the thermocouple and the cutting edge was reached. The standard cutting parameters were used.

Figure 6 shows a mapping of the results. An association between the distance of the bone surface and the thermocouple and the temperature gradient can be seen. For increments of bone further inwards in the cortical bone, the temperature gradient is smaller than for increments that are directly at the surface. The reason is the influence of heat radiation at the surface.

2.3 Influence of the parameters on the temperature

The main point in this work was to investigate the influence of parameters like pressure, traverse rate and abrasive flow rate. The first step was to obtain general information about the parameters' influence on the temperature and exposure time. Therefore, the standard parameters were used, and each parameter was individually varied.

Figure 7 shows the results of the parameter study measured by a thermocouple that was placed 0.35 mm from the bone surface. It is obvious that the AWIJ with standard parameters does not cause any tissue damage during an AWIJ-osteotomy. The maximum temperature can still be decreased by lowering the pressure or the abrasive flow rate. When decreasing the traverse rate to generate a better surface quality of the cutting edges, a critical temperature and exposure time can be exceeded (e.g., standard parameters, but a traverse rate of 10 mm/min). Consequently, heat management, even for AWIJ-osteotomies, is required to completely avoid irreversible cell damage to the bone tissue.

2.4 Influence of different abrasive materials on the temperature

For medical applications it is not possible to use garnet as an abrasive material, because of a lack of biocompatibility and biodegradability [6, 7]. As a result, biocompatible abrasives were investigated and compared with respect to their impact on heat

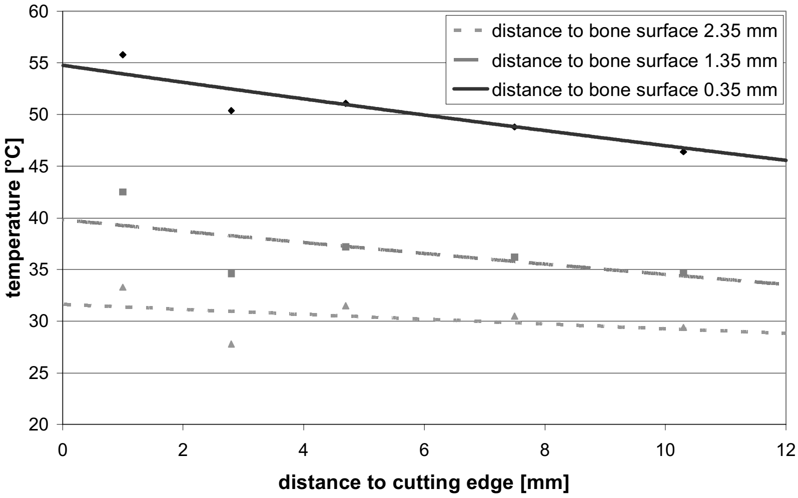

Fig. 6. *Temperature versus distance between the thermocouple and the cutting edge*

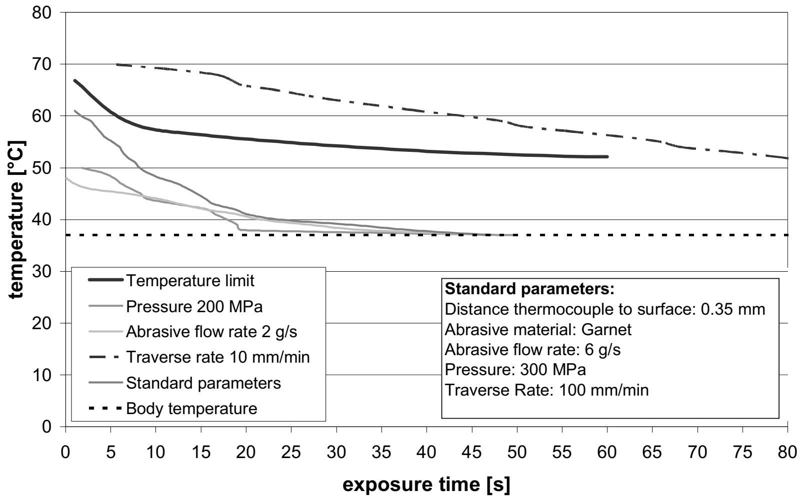

Fig. 7. *Effect of parameters on the temperature and the exposure time*

development during the AWIJ-cut. To secure the comparability of the abrasives' impact, the pressure was set to 350 MPa and the cutting performance of the different abrasives (magnesium, AZ91, sucrose and garnet) had to be similar. For this purpose the volume flow rate for all the abrasives was kept constant at 3.65 ml/s, according to the optimum (mass) flow rate of sucrose. The resulting abrasive (mass) flow rates are shown in Figure 8 (see inset).

To achieve an equal cutting performance of the different abrasives, the cutting depth in PVC depending on changes in the traverse rates was determined. Unfortunately, it was not possible to maintain the grain size distribution of the abrasives, which would also have an influence on the cutting performance. It is obvious that the biocompatible abrasives have a lower cutting performance than garnet for the same traverse rate. However, it is already known that the cutting ability of magnesium is superior to sucrose as an abrasive material [7]. The traverse rate for the influence comparison of the abrasive materials with respect to the temperature and exposure time was set according to the maximum traverse rate by using sucrose as the abrasive material to fully cut through a bovine tibia.

In Figure 9 the results of this abrasives' comparison are shown. It is clear that all of the tested abrasives do not cause cell damage, except for sucrose, using the given parameters. The problem is the bad cutting performance of the sucrose and, as a result, the necessity of a low traverse rate. Finally, it can be said that it is possible to avoid the irreversible damage of cells for all abrasives except sucrose for a bone layer below 0.35 mm.

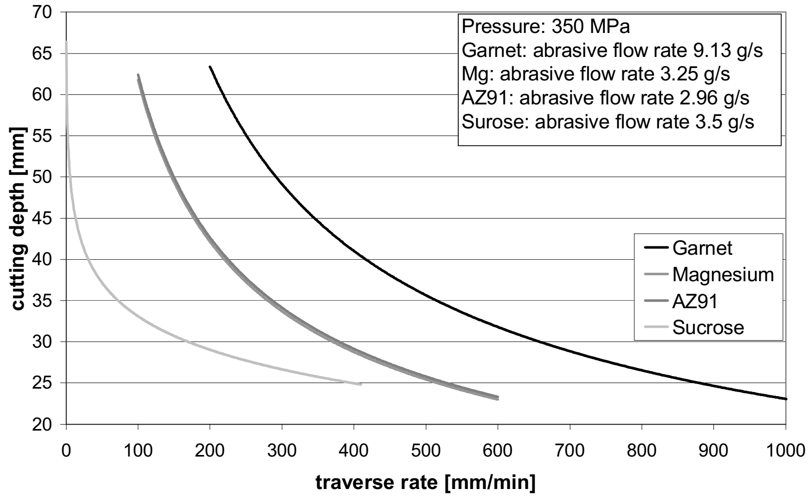

Fig. 8. *Cutting depth versus the traverse rate (specimen material PCV)*

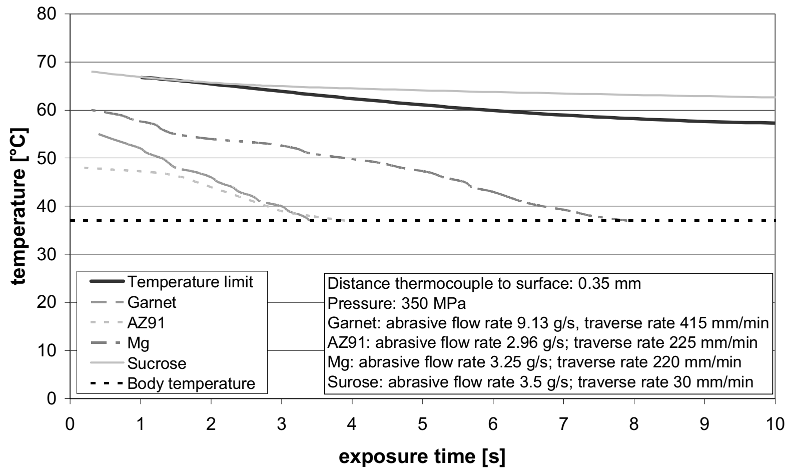

Fig. 9. *Temperature versus exposure time for different abrasive materials*

3 CONCLUSIONS AND OUTLOOK

With this presented study a further step to introduce the abrasive water injection jet for medical application has been made. It can be seen that it is possible to avoid bone-cell damage during osteotomies with the AWIJ by adjusting the parameters. In detail, a decrease in pressure and abrasive flow rate result in a lower temperature increase and a shorter exposure time to the critical temperatures. However, an increase in the traverse rate will have the opposite effect. With respect to an improvement in the surface quality of the cutting edges, by lowering the traverse rate the temperature increase has to be taken into consideration.

In addition, it has to be said that some factors have not been taken into account in this study. For further investigations the starting temperature of the bony specimens has to be increased to 37°C to reach comparable in-vivo conditions. The influence of the cortical bone thickness as well as the hardness, which differ for each bone, should be added into the evaluation of the results.

The aim of future investigations will be the determination of parameter limits to avoid cell damage, especially for biocompatible abrasives with respect to the new abrasive feeding system. This will make temperature management possible, whereby cell damage can be totally avoided by using the AWIJ for medical purposes.

4 REFERENCES

[1] R. Baumgarten, M. Kettler, C. Zeiler, A. Betz, L. Schweiberer (1997) Möglichkeiten der Knochendurchtrennung. *Unfallchirurgie*. Vol. 100, 797/804.

[2] A. Fuchsberger (1985) Untersuchungen der spanenden Bearbeitung von Knochen. PhD-Thesis. *Technical University Munich*.

[3] L. S. Matthews, C. Hirsch (1972) Temperatures measured in human cortical bone when drilling. *The Journal of Bone and Joint Surgery*. Vol. 54-A, No. 2, 297/308.

[4] S. T. Larsen, L. Ryd (1989) Temperature elevation during knee arthoplasty. *Acta Orthop Scand*. Vol. 60, No. 4, 439/442.

[5] F. Pude, S. Schmolke, K. Schwieger, M. Honl, H. Louis (2003) Abrasive waterjets as a new tool for cutting of bone – laboratory tests in the field of knee endoprostheses. *Proceedings of the 6th international conference on management of innovative technologies MIT'2003*. Ljubljana, Slovene Society for Abrasive Water Jet Technology, 63/72.

[6] F. Pude, S. Schmolke, L. Kirsch, K. Schwieger, H. Louis, C. J. Wirth, M. Honl (2002) Investigations on the cutting performance of different biocompatible abrasives in abrasive waterjets for the use in orthopaedic surgery. *IPEM 8th Annual Scientific Meeting.* York, Institute of Physics and Engineering in Medicine, 105/107.

[7] H. Louis, F. Pude, S. Schmolke, L. Kirsch, C. J. Wirth (2002) First investigation on the use of biodegradable magnesium powder as abrasive material for cutting biological hard tissue. *16th International Conference on Water Jetting*. Cranfield, Bedfordshire, BHR Group Limited, The Fluid Engineering Centre, 379/386

[8] S. Schmolke, F. Pude, L. Kirsch, M. Honl, K. Schwieger, S. Krömer (2004) Wärmeentwicklung bei der Wasser-Abrasivstrahl-Osteotomie – Temperature measurement during abrasive water jet osteotomy. *Biomedizinische Technik*. Vol. 49, 18/21.

[9] F. Pude, C. Biskup, A. Schenk, S. Schmolke, C. Kuhlmann, S. Krömer, A. Andreae, L. Kirsch (2005) Erste klinische Überprüfung der Anwendbarkeit des Wasserabrasivstrahls als Osteotomiewerkzeug im Tierversuch. *Biomechanica*, Hamburg, Deutschland.

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Hibridno obstreljevanje s suhim ledom in laserjem

Hybrid Dry-Ice Blasting Laser Processing: Nd-YAG-Laser-assisted Dry-Ice Blasting for De-Coating

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V primeru visoko vrednih surovih materialov ali visokih obratovalnih stroškov se splača reciklirati izdelek, saj tako prihranimo denar in razpoložljiva sredstva. Recikliranje po navadi zahteva čiščenje oziroma odstranjevanje barve. Največkrat se za to uporabljajo običajni čistilni postopki. Obstreljevanje s suhim ledom in lasersko procesiranje sta dve naravno sprejemljivi alternativni tehniki čiščenja. Kljub vsemu imata tudi ti dve svoje tehnološke omejitve.

Obstreljevanje s suhim ledom temelji na mehanskem, toplotnem in sublimacijskem mehanizmu, ki omogoča mehko delaminacijo, čiščenje in predpripravo brez poškodb obdelovanca. Laserski postopek pa ponuja možnost definiranega odstranjevanja prevlek in obdelavo površin samega obdelovanca. Obe tehnologiji ne povečujeta odpadkov. Zelo vezivni in trdi zaščitni sloji se zelo težko odstranijo z uporabo obstreljevanja s suhim ledom. Laserskemu postopku pa delajo preglavice debele prevleke.

Da bi povečali njun učinek, jih združimo in izvedemo hibridni postopek. Odvzem materiala se je pri obstreljevanju s suhim ledom v hibridni kombinaciji z laserskim postopkom izkazal bolj učinkovit kar za 49 odstotkov. Rezultati kažejo, da je treba pazljivo načrtovati obratovalne razmere. Le v takem primeru je hibridna tehnologija konkurenčna običajnim čistilnim tehnologijam.

(Ključne besede: obstreljevanje, suhi led, procesiranje lasersko, čiščenje, postopki hibridni)

In the case of high-value raw materials or high manufacturing costs, the recycling of products is reasonable because it helps to save money and resources. However, recycling usually makes a cleaning or de-coating process necessary. Normally, these processes are based on conventional cleaning and de-coating methods. Dry-ice blasting and laser processing are two environmentally friendly alternatives that have different advantages over the conventional methods. However, both have technological and economic limitations.

The effect of dry-ice blasting is based upon a mechanical, a thermal and a sublimation mechanism that allow a soft de-lamination, cleaning and pre-treatment while the workpiece remains undamaged. Laser processing offers the possibility of a defined removal of the coating/contamination and a treatment of the surface of the workpiece itself. Both technologies do not increase the amount of waste. Strongly adhering or hard contaminations and protective or functional coatings are difficult to remove with dry-ice blasting, while laser processing is unsuitable for removing thick coatings or contaminations. The combination of both technologies offers different strategies for machining. On the one hand the laser can be applied in de-focused mode for heating up the surface of the workpiece, thereby increasing the thermal mechanism of dry-ice blasting. On the other hand a focused laser application makes a defined surface structuring or smoothing possible. In addition, both methods can be applied at the same focal point.

In order to measure the area-related cleaning efficiency a PUR-2 component varnish-substrate combination was chosen as a standard among the multitude of materials, coatings and contaminations available. The material removal rate achievable with dry-ice blasting was increased using the hybrid technology by up to 49%. The results show that an individual optimization of the parameters for the application is a pre-condition. Only then is the hybrid technology competitive in relation to conventional cleaning technologies.

(Keywords: dry ice blasting, laser processing, cleaning, de-coating, hybrid systems)

0 INTRODUCTION

In the case of high-value raw materials or high costs for manufacturing the recycling of products is reasonable. This implies, as well as used products, faulty coatings of products within the manufacturing process. Recycling saves money and resources. Therefore, it is economically and ecologically favourable. Usually for recycling a cleaning or also a de-coating process is necessary, using mechanical, chemical or aqueous methods. But these conventional technologies are often time and energy consuming. Furthermore, they involve high costs for waste disposal and personnel, while offering only low flexibility [1]. Dry-ice blasting and laser processing are two environmentally friendly alternatives to these conventional technologies [2]. With regard to special cases of applications and to the economic point of view, both technologies have their respective limits.

The objective of hybrid dry-ice-blasting laser processing is to increase the area-related cleaning and de-coating ratio. The combination of both technologies will expand their economic and technological limits. An easily replicable substrate-varnish combination was chosen from the variety of materials, coatings and contaminations. With this standard substrate-varnish combination the process parameters of each stand-alone technology have been optimized. Thereafter, the results of these investigations were compared with the results of the hybrid experiments.

1 APPLIED CLEANING TECHNOLOGIES

1.1 Dry-Ice Blasting

Dry-ice blasting is a blasting technology that uses solid carbon dioxide – so-called dry ice – as a one-way blasting medium. The pressurized (57 bar) liquid carbon dioxide is expanded quickly to atmospheric pressure. Because of the Joule-Thomson effect it is cooled down to -78.5° C and solid carbon-dioxide snow is generated. A hydraulic stamp presses the carbon dioxide snow through the conical holes of a mould and finally forms the cylindrical dry-ice pellets. The pellet parameters (density, hardness, shape) are influenced by the conditions during their production (i.e., degree of compaction). For the blasting process the dry-ice pellets are injected into the blasting air stream by a dosing device and are then accelerated.

Dry-ice blasting is based on a mechanical, a thermal and a sublimation mechanism. The temperature of -78.5° C of the dry-ice pellets leads to a local cooling down at the point where the dry-ice particles hit the surface. Due to this, elasticity is lost and the coating embrittles and shrinks. Different thermal expansion coefficients of the substrate and the coating produce cracks in the coating. The kinetic energy of the particles and the air stream contribute to the removal. The sublimation of the dry ice leads to a sudden increase in volume by a factor of 700, which supports the process [3]. When the adhesive energy is exceeded by this combined thermo-mechanical effect the coating chips off [2].

A fundamental advantage of dry-ice blasting is that there are no residues left due to the sublimation of the dry ice. While other cleaning processes require complex processing or increased disposal costs, no media remains in the structure of the workpiece (i.e., boreholes and cavities) [2]. No special cleaning equipment is needed for the exhausted air due to the non-toxic blasting medium, carbon dioxide. Except for the removed coating-particles, which might have to be filtered off. Because of the non-corrosive and non-abrasive behaviour no post-treatment is needed for the workpiece. Dry-ice blasting allows a flexible soft de-lamination and cleaning, even of sensitive or structured surfaces. Contaminations and protective films (i.e., the paint of metal components) can be removed by dry-ice blasting. Strongly adhering or hard contaminations and protective or functional coatings are difficult to remove. The complete removal of rust using dry-ice blasting is, e.g., impossible.

1.2 Laser Processing

Laser processing has become a field of increasing significance in recent years. Surfaces can be cleaned, structured or modified flexibly and precisely by laser processing due to specific parameters. The controlled application of energy allows a melting or sublimating of the surface material, depending on the composition and thickness of the contamination or coating, as well as on the parameters of the laser process. Further fields of application are the removal of paint from metal components (i.e., exchange engines) [4], the removal of scale from welding seams [5], as well as the cleaning of railroads, memorials and pylons.

Cleaning and de-coating with laser processing offers significant advantages. It combines contact- and force-free processing of high precision with a low thermal and mechanical influence that can be applied to sensitive surfaces. By offering a selective cleaning, the depth of removal of consistent material is easy to control. Therefore, a high degree of automation, especially an online control, is possible. The removal of thick contaminations and coatings are the economic, and sometimes even the technological limits of the application. The more abrasive the parameters of laser processing are, the higher is the risk of damaging the surface of the substrate below an inconsistent coating or contamination.

1.3 Hybrid Dry-Ice-Blasting Laser Processing

The combination of both technologies offers different strategies for machining. While the laser can be applied de-focused for heating up the surface, a focused laser application enables a defined processing of the surface. The de-focused laser prevents a cooling down of the workpiece. The higher temperature increases the thermal shock when the dry-ice particles hit the surface and the efficiency is improved. Therefore, the wavelength has to be chosen according to the absorptance of the surface of the substrate. A focused laser application enables a defined surface structuring or smoothing of the workpiece. Thus, a preliminary purification by dry-ice blasting can be followed by a final laser-processing cleaning step. It, furthermore, makes it possible to combine the cleaning process with a potential following pre-treatment process (i.e., to realize a defined roughness). Both technologies can be applied at the same focal point or at different focal points. Two different focal points allows a repeatable quick change of separate processing by each single technology while using the same focal point for both technology is easier to realize.

2 EXPERIMENTAL SETUP

An easy-to-replicate standard was used to analyze the removal of highly adhesive coatings from incorrectly coated workpieces within the manufacturing process or the removal of partly remaining coatings from used products. A coating of PUR-2 component varnish with a thickness of 100 µm and 200 µm was defined as the standard and applied in two layers, one white primer and a black finishing varnish. The plates of hot-dip galvanized steal with dimensions of 150 mm x 50 mm were used as a substrate.

For dry-ice blasting the Artimpex device “Cryonomic Cab 52” was used. This device is based on the injection principle. For laser processing the “Sv10” of Bauer & Mück GmbH, Berlin was used. The Nd:YAG laser has a wavelength of 1064 nm, a cw output of 100 W in multi-mode and 18 W in basic mode. The laser beam was focused by a 1D scanner, which was moved by a robot together with the dry-ice blasting nozzle.

To measure the removal rate the surface profile was detected perpendicular to the movement of the robot. Therefore, the tactile measurement equipment “Talysurf-120L” of Taylor Hobson GmbH, Wiesbaden was used. The cone point of the applied sensing device had a radius of 2 µm and an angle of 60°. The cross-sectional area (CSA) of the removed material was calculated based on the detected profile. For the calculation the software “Talymap Univ. 2.0.10” was used. Compared to a gravimetric measurement the applied method has the advantage of additional information about the material removal perpendicular to the direction of the robot’s movement.

First, the individual technologies were optimized to reach the maximum material removal rate. The blasting pressure, the distance between the blasting nozzle and the surface, the blasting angle and the dry-ice mass flow rate were optimized. For laser processing the focus, the pulse rate, the distance of the single pulses on the surface of the workpiece and the period between the single pulses were varied. A suitable feed rate was chosen by an optical evaluation as well as from the tactile measurement.

3 RESULTS OF EXPERIMENTS

The optimized dry-ice blasting parameters, blasting pressure, blasting angle, dry-ice mass flow rate and blasting distance, were constant. The number of repetitions and the feed rate of the robot were varied for each test. For the shown results the laser pulse rate, the power output of the laser, the distance of the pulses on the surface and the laser feed rate (independent of the dry-ice blasting feed rate) were varied. The applied dry-ice blasting parameters are shown in Table 1; the laser processing parameters are shown in Table 2.

Table 1. *Dry ice blasting parameters*

Dry-Ice Blasting Parameters:	A	B	C	D	E
Number of repetitions of the test	1	2	3	4	6
Feed rate [cm/min.]	3	6	9	12	18
Constant Dry-Ice Blasting Parameters:					
Blasting pressure	12 bar				
Dry-ice mass flow rate	60 kg/h				
Blasting distance	10 mm				
Blasting angle	90°				

Table 2. *Laser processing parameters*

Laser Processing Parameters:	A	B	C	D	E
Pulse rate [kHz]	4	6	5	5	5
Power output [W]	91	91	85	85	85
Pulse distance [µm]	10	20	20	20	20
Feed rate [cm/min.]	20	20	20	50	50

Subsequently, the results for the PUR-2 components varnish standard with a thickness of 200 µm are shown exemplarily. The used standard consisted of a white primer and a black finishing varnish. A comparison of the material removal of single dry-ice blasting and a hybrid-laser-assisted dry-ice blasting is shown in Figure 1. The cross-sectional area (CSA) is used as an indicator.

Figure 1 shows the cross-sectional area (CSA) of the removed material of tests A to E, applying different parameters. The removed material was increased in each test by laser-assisted dry-ice blasting compared to the stand-alone dry-ice blasting. The best improvement of 49 % was obtained in test A, the parameters of test B resulted in the smallest improvement, of 28 %.

4 SUMMARY

Dry-ice blasting and laser processing are ecological alternatives to conventional mechanical, chemical or aqueous cleaning and de-coating methods. However, neither technology is suitable for highly adhesive or hard coatings and contaminations. By combining both technologies the material removal of a defined testing standard was increased up to 49% compared to the optimized stand-alone technology. The optimized parameters of the stand-alone methods are not the ideal parameters of the hybrid combination.

It is planned to optimize the processing strategy of the focused laser application for the hybrid combination of both technologies. Further tests are planned to research the strategy of de-focused laser application to increase the thermal mechanism of dry-ice blasting. Finally, a combination of both strategies will be investigated by applying two lasers of different wavelengths.

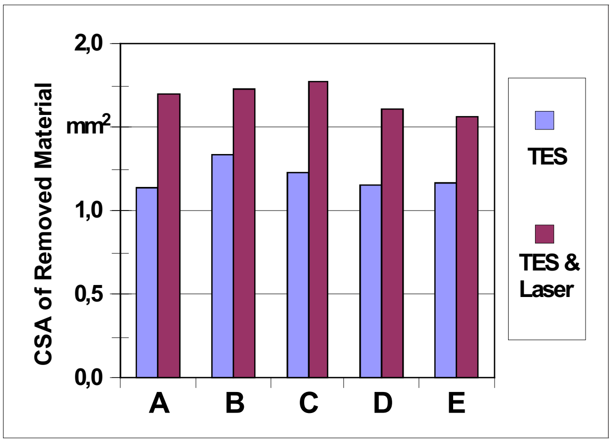

Fig. 1. *Cross-sectional area (CSA) of the removed material by dry-ice blasting and laser-assisted dry-ice blasting*

5 REFERENCES

[1] G. Striegel, E. Hoffmann, G. Kreisel, R. Grün (1999) Verfahren der Teilereinigung ganzheitlich bilanzieren. *Metalloberfläche,* 53 (1999) 4, pp.19-23.

[2] E. Uhlmann, A. El Mernissi, J. Dittberner (2004) Blasting techniques for disassembly and remanufacturing. *Proc. Global Conference on Sustainable Product Development and Life Cycle Engineering*, pp. 217-223.

[3] M. Krieg (2005) Trockeneisstrahlen – mit Schnee oder mit Pellets? *JOT*, pp. 50-55, 06/2005.

[4] E. Uhlmann, A. El Mernissi, J. Dittberner (2004) Dry ice blasting and laser for cleaning, process optimization and application. *Proc. IFAC-MIM Conference on Manufacturing, Modelling, Management and Control*.

[5] E. Büchter (1998) Reinigen und Entschichten mit dem Laser. *Metalloberfläche,* 52 (1998) 12, pp. 944-945.

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Učinkovitost rezanja in dosegljiva kakovost pri uporabi abrazivnega vodnega curka pri tlaku 6000 bar

Cutting Performance and Obtainable Quality when Applying 6000-Bar Abrasive Water-Jets

Holger Werth[1] - Waldemar Hiller[1] - Christoph Luetge[1] - Joerg-Peter Koerner[1] - Frank Pude[1] - Inge Lefevre[2] - Roland Lefevre[2]
([1]Uhde High Pressure Technologies GmbH, Germany; [2]L & D Jet Techniek, Belgium)

UHDE HPT razvija, oblikuje in gradi visokotlačne ojačevalnike že več ko 40 let za različne vrste uporabe. Trenutni tlaki, ki se jih da doseči, dosežejo neverjetne vrednosti do 14.000 bar (203,280 psi).

Za obdelavo z vodnim curkom je UHDE HPT razvil dva osnutka za doseganje 6.000 bar (87,000 psi). Oba osnutka sta se že izkazala v praktični uporabi. Povišanje tlaka pri rezanju z abrazivnim vodnim curkom daje:
- večje rezalne hitrosti
- izboljšano kakovost reza ob enakih rezalnih hitrostih
- globlje reze brez abraziva
- manjše obratovalne stroške

V tem prispevku je predstavljena primerjava pri rezanju z abrazivnim vodnim curkom s 3.500 bar in 6.000 bar.

(Ključne besede: rezanje s curkom, curek vodni, curek abrazivni, učinkovitost rezanja, hrapavost površin)

UHDE HPT has been developing, designing and building high-pressure intensifiers to cover the widest range of applications for more than 40 years. The operating pressure can reach an incredible 14,000 bar (203,280 psi).

For water-jet technologies UHDE HPT has developed two concepts for the 6,000 bar (87,000 psi) pressure range. Both concepts have proven themselves in practical applications. The incremental increase of the working pressure greatly improves the working efficiencies and the economic benefits:
- higher cutting speed,
- improved cutting quality at the same cutting speed,
- deeper cuts without adding abrasives,
- low operating costs.

In this paper the results of comparisons between 3,500- and 6,000-bar abrasive water-jet cutting operations will be presented.

(Keywords: abrasive water jet cutting, cutting performance, surface roughness)

1 HIGH-PRESSURE INTENSIFIER

For industrial applications typical intensifiers are designed for a 3,500 to 3,800 bar design pressure and operate at pressures of 2,500 to 3,800 bar, depending on the required cutting application. Since water-jet cutting is competing with a lot of other cutting processes, like laser-cutting or plasma-cutting, it has to prove to be a superior technology to expand its market share. Therefore, a further development in the direction of higher cutting speeds and better accuracy has to be achieved.

To achieve this goal higher operating pressures for the intensifiers and the nozzle system have to be obtained. Therefore, the development of intensifiers for higher pressures is an important factor to increase the productivity of the process.

The above-described tendency to increase the pressure has already been taken into account by all intensifier manufacturers, and that is why they are now offering pumps for service pressures up to 4,200 bar.

Certainly, this is a step in the right direction, to increase cutting speeds, but the result is limited and has to be paid for with a shorter life for the HP components.

A real step to revolutionise the process is to have a system operating at 6,000 bar. Only by having such pressures available at the cutting nozzle would it be possible to cut metals or other hard materials without abrasives at an acceptable speed.

Therefore, the development of the Uhde intensifiers to pressures of up to 6,000 bar has been undertaken.

This development was based on Uhde's longstanding experience in building autofrettage pumps for 14,000 bar and the experience related to pumps for food pasteurisation systems up to 6,000 bar.

Thus, all the basic data about the fatigue life of high-pressure components under such pressures are available within Uhde and can be used for the further development of reliable intensifiers.

1.1 The flexible two-stage HP intensifier concept

In order to overcome the fatigue problems, a flexible 6 kbar two-stage pump concept was chosen to get practical experiences with such a system in a job shop during day-to-day operation. Furthermore, the investment costs of such a pumping system have to be affordable and the investment risk has to be limited by using standard – or only slightly modified – catalogue HP intensifiers as a developmental basis. One standard water-jet cutting pump (Type HP19/37-S) operates at 3.5 kbar and delivers into a buffer vessel. The pump is pressure controlled and operates in such a way that the buffer vessel is held at a constant pressure. The second-stage pump (Type HP19/45-S) is connected with its suction piping to that buffer vessel and compresses the water to the final discharge pressure of up to 6 kbar.

The flexible system arrangement shown in Figure 1 permits either the independent or joint operation of both HP intensifiers according to the specified basic characteristics of the installed pressure intensifiers for the single mode.

The use of various electrically/pneumatically actuated high-pressure valves permits the easy selection of the relevant modes (single-stage or two-stage) on the control panel of the cutting installation [1].

The advantage of this concept is that the pulsations from 0 to 6,000 bar are distributed in two stages (Figure 2). The dynamic load on the second-stage pumps is reduced to an acceptable level of 2.5 kbar. All the critical components (check-valves, packing, HP cylinder) benefit from that reduction in load.

The cylinder can be designed without problems for an infinite life [2]; this also applies for the check-valve body. The load on the check-valve seat is also greatly reduced, since the closing element is supported by the first-stage pressure and does not experience the full pressure loading from the high pressure.

Another advantage of this flexible two-stage system is that the user can decide to cut, e.g., with three of four abrasive cutting heads under normal pressures or one abrasive cutting head at 6 kbar.

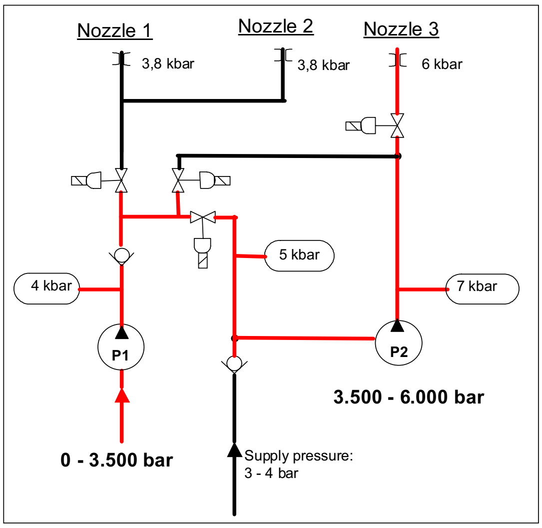

Fig. 1. *Flexible two-stage pump concept*

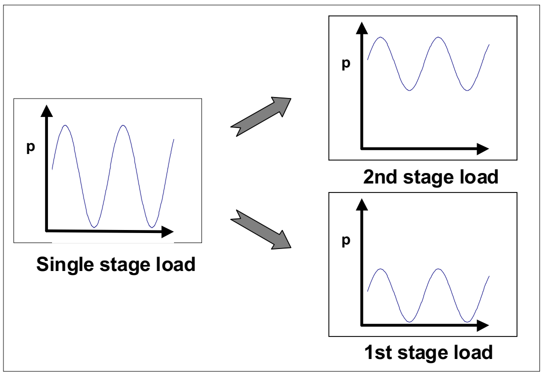

Fig. 2. *The two-stage operation for pressure load*

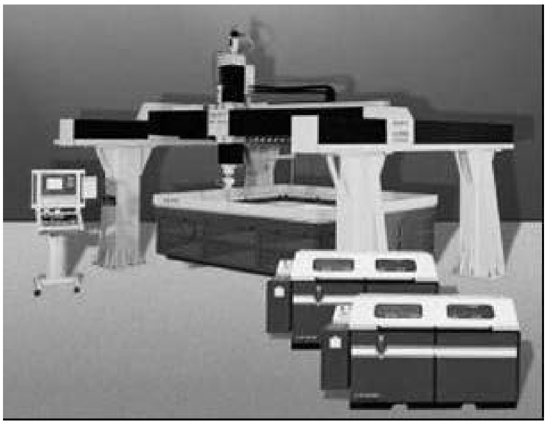

Fig. 3. *Numerically controlled 6 kbar AWIJ portal system*

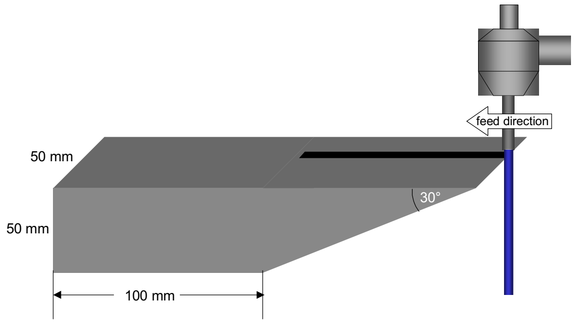

Fig. 4. *Experimental setup (schematic)*

Figure 3 shows the HP pumping system in front of a five-axis portal handling system.

1.2 HP piping

The HP piping used is made of the material HP160, which was subjected to an autofrettage treatment:

Two dimensions were chosen:

· Fixed piping: outer diameter 9.53 / inner diameter 3.21 mm

· Flexible piping: outer diameter 6.35 / inner diameter 2.39 mm

The average water discharge rate (real) through the orifice is represented by the following equation:

$$V_{eff} = c_D \cdot A_{nozzle} \cdot \sqrt{\frac{2(p_1 - p_2)}{\rho}}$$

The resulting flow rate is V_{eff} = 1.4 l/min when using an orifice of d_W = 0.20 mm at an operating pressure of 6,000 bar.

The velocity in the HP pipe, having a nominal width of 2.39 mm and taking into account turbulent flow, is calculated as follows:

$$v = \frac{V_{eff}}{A_{ti}}$$

The resulting velocity for the smallest tube within the HP unit is v = 5.4 m/s.

2 CUTTING PERFORMANCE

The cutting performance of the ultra-high-pressure abrasive water-jet at 6,000 bar was tested in comparison with a state-of-the-art 3,500 bar AWIJ. The cutting tests were performed at L&D JobShop by applying a three-axis CNC handling system. The cutting samples were wedge-shaped aluminium blocks (see Figure 4). The aim of this geometrical selection is the utilisation of the complete jet power by transferring the cutting process to a kerfing process. This also simplifies the evaluation of the test results because of the possibility of using one sample block for various cutting/kerfing trials. The aluminium block is not cut into pieces and the cutting performance for the chosen parameters can easily be read off by measuring the length of the “cutting track” on the bottom side of the sample block and dividing it by two. This works if the angle of the wedge is chosen to be 30°, because of the known angular relation sin30° equals 0.5.

On every specimen up to 10 tracks were placed and afterwards measured by reading off the distance between the tip of the wedge and the first boundary on the bottom side of the block (see Figure 5, right-hand side). This means that a restarted cutting behind a “metal bridge” will not be taken into account for the evaluation.

2.1 Test results

Cutting tests were performed with an Allfi-Centerline cutting head and an Allfi-Typ-VI-Slimline HP valve. The dimensions of the water orifice and the focussing tube were fixed as shown in Table 1.

The abrasive material used for the tests was Garnet Mesh 80.

In the first step the optimal mass flow rate of the abrasive material was investigated. Due to

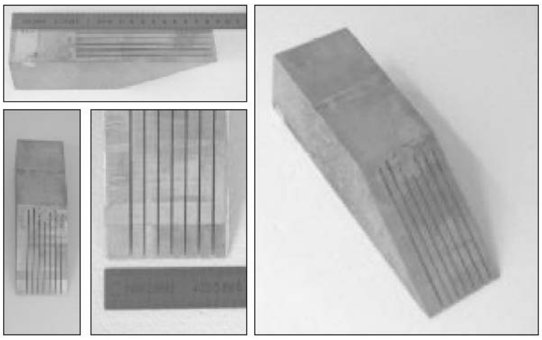

Fig. 5. *Specimen after cutting/kerfing*

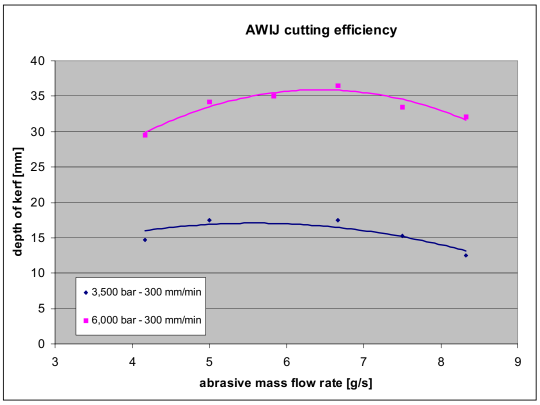

Fig. 6. *Variation of abrasive mass flow rate for finding an optimum*

Table 1. Dimensions of the abrasive cutting head

	water orifice	focussing tube
inner diameter	$d_W = 0.20$ mm	$d_F = 0.76$ mm

Table 2. Optimal abrasive mass flow rate for selected parameters

	3,500 bar	6,000 bar
opt. mass flow rate [g/s]	$m_{opt,\ 3,500} = 5.33$	$m_{opt,\ 6,000} = 6.67$

different volume rates of the water flow through the orifice based on the different pressure levels (3,500 and 6,000 bar) the capacity of the pure jet to be mixed with abrasive grains is not identical.

Therefore, cutting tests with a variation of the abrasive mass flow rate (Figure 6) were performed with the goal to find an optimum for each pressure level.

Figure 6 shows idealized graphs for finding the optimal abrasive mass flow rates, which are listed in Table 2.

In the second step the evaluated optimal mass flow was applied for further tests. Now a comparison of the cutting efficiencies of both the 3,500- and the 6,000-bar abrasive water jet could be undertaken under fair conditions.

Figure 7 shows the results of a cross-over comparison using the optimal mass flow rate for our own and the test partner's parameters (Figure 7). This is to demonstrate that the cutting performance with reduced abrasive consumption is also highly efficient.

The cutting performance, represented by the obtained depth of kerf, is shown in Table 3 for different traverse rates.

Table 3. Obtained depths of kerfs by varying the traverse rate

	3,500 bar 5.33 g/s	6,000 bar 5.33 g/s
200 mm/min	22.5 mm	42.1 mm
250 mm/min	20.0 mm	37.0 mm
300 mm/min	17.3 mm	32.8 mm
350 mm/min	14.8 mm	30.4 mm

(5.33 g/s ≅ 320 g/min)

3 SURFACE ROUGHNESS

One critical point when machining materials with abrasive water jets is the obtainable surface roughness on the cutting edge. Due to the energy loss of the jet on its way through the workpiece the surface roughness becomes worse if the energy level falls below a boundary value.

If the jet parameters are stable the quality of the cut can be influenced by the traverse rate. That means that a disproportional increase of cutting speed will lead to a loss of quality.

3.1 Test results

Tests were performed with different materials (aluminium, stainless steel) with different thicknesses for each particular sample group (20mm, 50 mm, 100 mm).

After cutting the surface roughness of each sample was measured at different positions (see Table 4) with fixed distances to the point of the jet's entrance (top side of the sample). The measurement results were generated by a sensing device working with a small diamond on the tip.

Table 4. Positions for the measurement of surface roughness

material thickness [mm]	measurement positions [mm]
20	7 /15
50	9 / 25 / 41
100	10 / 40 / 60 / 90*

* due to selected parameters the roughness could not be measured (see Figure 8)

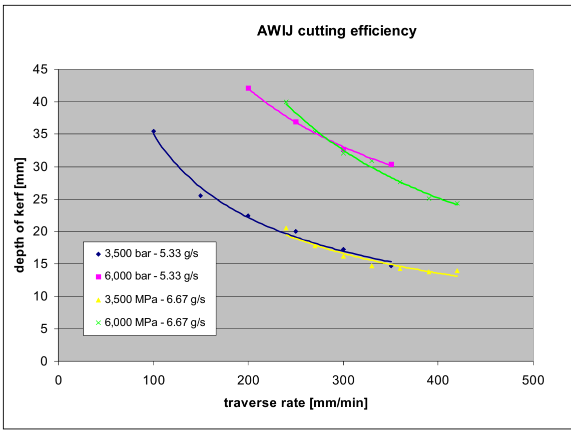

Fig. 7. *Comparison of 3,500 and 6,000 bar AWIJs with used cross-over abrasive mass flow rates*

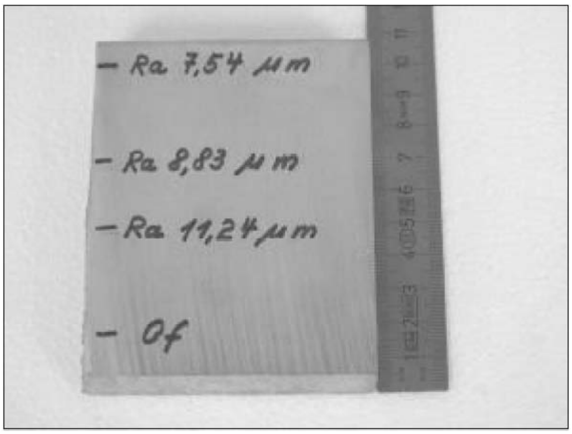

Fig. 8. *100-mm aluminium sample marked with the results of the roughness measurement*

Figure 8 shows a photograph of a 100-mm sample after measuring and marking.

In the bottom position the surface profile is presented by striation marks; the surface is both rough and wavy. The used sensing device is not able to generate data on such a profile ("Of" means "no function").

For a visualization the results from the samples can be transferred to a bar graph (Figure 9).

This shows the general trend of increasing roughness values with both an increasing traverse rate and an increasing distance from the jet's point of entrance.

In Figures 10 and 11 the results from stainless-steel samples are compared. In these graphs the points represent one combination of pressure level and measuring position (e.g., position 25 mm and 3,500 bar) are aligned with an idealized straight line.

For each pressure level these lines intersect at that point where the traverse rate is reached, which leads to similar surface qualities on both the top and

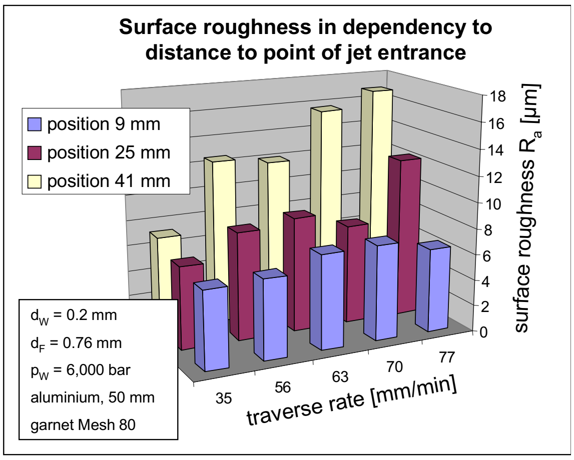

Fig. 9. *Allocation of roughness values on the cutting edge, depending on the cutting speed*

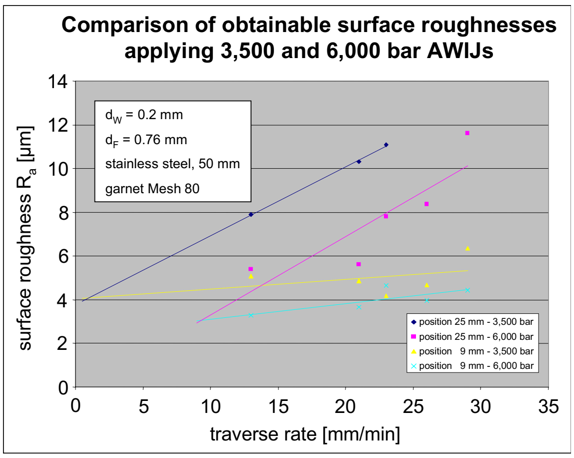

Fig. 10. *Prediction of the maximum tarverse rates for quality cuts (50-mm stainless steel)*

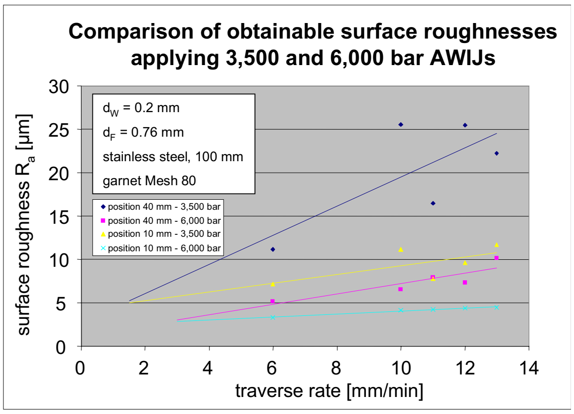

Fig. 11. *Prediction of the maximum tarverse rates for quality cuts (100-mm stainless steel)*

Table 5. *Obtained surfaces qualities on 50-mm samples*

traverse rate [mm/min]		surface roughness R_a [µm]		
		measurement position		
aluminium	st. steel	9 mm	25 mm	41 mm
	13	3.27	5.38	7.86
	21	3.64	5.62	11.90
	23	4.65	7.81	--
	26	3.96	8.35	--
	29	4.42	11.63	--
35		5.97	6.33	7.28
56		6.10	8.27	12.58
63		7.28	8.81	12.08
70		7.36	7.62	15.73
77		6.43	12.28	16.95

the bottom of the cutting edge. This means a quality cut with a constant roughness over the whole surface.

As expected, the cutting speed for quality cuts with a 6,000 bar AWIJ is much higher than that of the compared 3,500 bar AWIJ.

Table 5 shows the results of trials with 50-mm samples.

4 CONCLUSIONS AND OUTLOOK

The tests made at L & D JobShop show an increase in the machinable material thickness at a proportion of about 87%. This result is reached by an increase in the pressure of 71%. To find reliable data for the particular top cutting speed of each selectable parameter field the number of trials must be increased enormously.

The increase of cutting performance with a constant abrasive mass flow rate gives an extra economic benefit for the application of this ultra-high-pressure technology. By doubling the cutting speed compared to the 3,500 bar systems a 6,000 bar AWIJ consumes only half of the abrasive material for the same cutting application. Being aware of the large proportion of cutting cost that results from the consumption of abrasive material, the increase of pressure leads to an effective opportunity to save money.

The cutting efficiency of 6,000 bar abrasive water injection jets brings further progress for this technology, being in continuous competition with other unconventional cutting technologies, like laser beam, flame, or plasma-arc cutting. The increase of the cutting speed at stable qualities of the cutting edge in comparison with 3,500 bar systems allows us to offer JobShop activities where in the past no economic success was achievable.

Also, the enhancement of possible material thickness that can be machined opens new application fields for this innovative technology.

The ongoing development with the goal to increase the lifetime of wear parts in, e.g., the pump units will lead to further acceptance for what is still referred to as an unconventional tool.

5 REFERENCES

[1] I. Lefevre, R. Lefevre, T. Stinckens, P. Koerner, C. Luetge, H. Werth (2004) Experiences of a job shop with 6 kbar abrasive water-jet cutting technology during day to day operation. Gee C., editor, *Proc. of 17th Int. Conf. on Water Jetting*, pp. 449-462, Mainz, Germany, 7-19 Sep., 2004.

[2] P. Koerner, W. Hiller, H. Werth (2002) Design of reliable pressure intensifiers for water-jet cutting at 4 to 7 kbar. Lake P., editor, *Proc. of 16th Int. Conf. on Water Jetting*, pp. 123-132, Aix-en-Provence, France, 16-18 Oct., 2002.

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Preučevanje in razvoj stekleno-vlaknenega vibrometra primernega za popolno vsadne slušne pripomočke

Investigation and Development of a Fiber-Optic Vibrometer for Use in Totally Implantable Hearing Aids

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([1]Vienna University of Technology, Austria; [2] Institut bezbednosti, Serbia; [3] Schwerpunktkrankenhaus, Austria; [4] Integrated Microsystems Austria)

V tem prispevku prikazujemo rezultate raziskave in razvoja stekleno-vlaknenega vibrometra, primernega za popolno vsadne slušne aparate (TIHA). Najpomembnejši del te raziskave so: opto-elektronična metoda za obdelavo signalov, opto-mehanično postavljanje zaznavnega vlakna, kirurško vsajanje ter biozdružljivost materialov. Izvedli smo in vitro in in vivo meritve tarče, ki je v našem primeru vibracija nakovala s podnanometrsko ločljivostjo na vsem slišnem zvočnem spektru in z uporabo nizkih in visokih koherenčnih tehnik. Velik preboj je narejen pri zmanjšanju porabe električne energije opto-elektronične in postopkovne enote na 2 mA@2,2 VDC z uporabo digitalne obdelave signalov imenovane tehnika DSP.

(Ključne besede: vibrometrija, vlakna optična, pripomočki slušni, vsadki, DSP)

In this paper we present the results of the research and development of a fiber-optic-based vibrometer for use in totally implantable hearing aids (TIHAs). We addressed the most important issues regarding the projected vibrometer: the optoelectronic measurement technique and signal processing, the optomechanical positioning of the sensing fiber, the surgical implantation technique and the material's biocompatibility. We performed in-vitro and in-vivo measurements of the target (e.g., incus) vibrations with a sub-nanometer resolution over the whole audio range, using low and/or high coherence techniques. A breakthrough is made by a dramatic reduction of the power consumption of the optoelectronic and signal-processing unit to about 2 mA at 2.2 VDC by introducing a digital signal processing (DSP) technique.

(Keywords: vibrometry, fiberoptics, hearing aids, implants, DSP)

0 INTRODUCTION

Hearing loss occurs to most people regardless of their age. There are some 31.5 million people in the USA (as of 2005) with hearing loss. Hearing loss is the single most common birth "defect" in America. There is a similar situation in Europe. Approximately one third of all seniors aged 75 years and older have significant hearing loss. About 14 percent of all people aged 45 to 64 years have demonstrable hearing loss. Hearing loss negatively impacts quality of life, personal relationships and of course, the ability to communicate. Some 90 to 95 percent of all cases of hearing loss can be corrected with hearing aids.

There are many types of conventional hearing aids (CHAs). They are electric, battery-operated devices that amplify and change sound to allow improved communication. Hearing aids receive sound through a microphone, which then converts the sound waves to electrical signals. The amplifier increases the loudness of the signals and then sends the sound to the ear through a speaker. However, they have a number of disadvantages, e.g., acoustic feedback, poor sound fidelity and the stigma of aging [1].

For these reasons there is a continuous effort in the scientific community to improve current hearing devices or even to develop new types of device. The most interesting approach is the development of partially or totally implanted hearing aids (TIHAs) ([2] and [3]). Basically, these devices are also composed of a microphone and actuators, just like conventional hearing aids. The largest problem still existing in implantable hearing aids is the lack of a reliable microphone to provide a long-lasting sensing functionality.

This paper is devoted to the research and development of a novel implantable microphone based on fiber-optic low- and high-coherence interferometry [4, 5]. The main properties outlined in the projected microphone are the ability for contact-less measurement of the middle-ear ossicles vibrations with sub-nanometer resolution across the full audio-frequency range. During this project we have had to investigate, in a parallel way, the optoelectronic sensing unit and signal processing, the optomechanical miniature stage for holding, adjusting and fixing the sensing fiber, and the surgical implantation and biocompatibility of the materials.

One of the prime goals of the project was to achieve a low-power vibrometer to be considered as a serious candidate for all kinds of currently used implantable hearing aids, including cochlear implants (CIs). Finally, a great breakthrough was made by dramatically reducing the power consumption from 70mA at 12 VDC to about 2 mA at 2.2 VDC of the entire sensing system. It was reached by introducing digital signal processing and a vertical cavity surface-emitting laser diode (VCSEL) as a light source.

1 METHODOLOGY

1.1 Principle of operation

The sensing principle is based on low- or high-coherence interferometry ([4] and [5]) performed by a fiber-optic interrogation set up, depicted in Fig.1. The core of the sensing system is a 3×3 single mode (4/125 μm) fiber-optic coupler [6], which provides two interferometric signals mutually shifted in phase by $2\pi/3$. The benefit of such an approach is the overcoming of signal fading, which usually occurs in classical interferometric schemes based on just a single 2×2 coupler.

Three input arms of the 3x3 coupler are connected with two receiving photodiodes and one light source, e.g., a laser diode or a superluminiscente diode. One outlet arm is immersed in index-matching gel to suppress the back-reflection from the fiber end. The second outlet arm is directed to the referencing mirror and the third arm, called the sensing arm, is directed toward the vibrating target, e.g., the incus in the middle ear. Beams reflected from the vibrating target, and beams reflected from the reference mirror are combined in the coupler generating the quadrature interferometric signal.

We stimulated the incus vibrations by generating sound pressure from a loudspeaker. We applied a sinusoidal pure tone with a frequency varying between 500 Hz and 5 kHz at a sound level between 70 and 90 dBA SPL. The sound was measured continuously by a Digital Sound Level

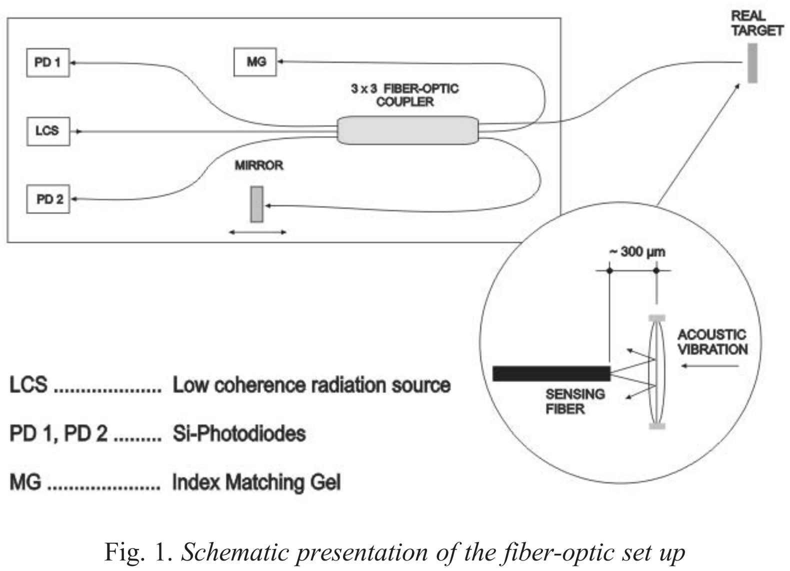

Fig. 1. *Schematic presentation of the fiber-optic set up*

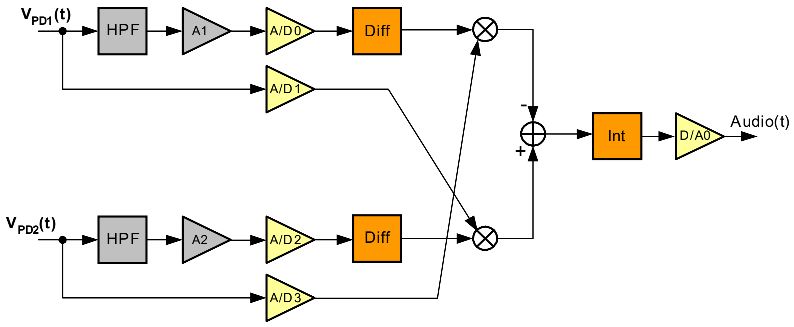

Fig. 2. *Block diagram of the DSP realization of the cross-multiply technique*

Meter RO-350 at about 10 cm distances from the rabbit ear.

1.2 Signal processing

Signal processing of the first model of the fiber-optic vibrometer was realized entirely by analog SMD technology [7]. The primary goal of the first model was to develop and to adopt an appropriate algorithm for signal processing, taking into account the mathematical description of the sensing principle [8]. Therefore, we did not take care so much about the power consumption and the overall dimensions of the model. However, in the last phase of the project we approached the requirements governed by the final usage of the microphone, low-power consumption and small overall dimensions of approximately 20x20x4 mm. The only way to fulfill these technical demands was the development of DSP.

Fig. 2 shows the DSP realization of the cross-multiply technique, which was previously realized in analog technology. Subtraction, addition and multiplication are supported in the MSP430 core by generic instruction or by a special on-chip hardware module. There are two DSP algorithms used in microphone design that are critical in time: discrete time differentiation and integration. The implementation of these functions mainly determines the sound quality and the low-power performance. However, quality and power are opposite requirements. Higher sound quality consumes more power, and lowering the power leads to decreasing sound quality.

1.3 Optomechanical stage

The main requirements for a miniature mechanical system aimed at holding, adjusting and final fixing of the sensing fiber are: fast and easy positioning of the sensing fiber toward the vibrating target and firm fixation of the fiber in the optimum position in terms of the maximum back-reflected signal. Additionally, all the materials as well as the sensing fiber must be biocompatible.

In order to fulfill the above requirements we developed several different miniature mechanical stages, starting with the simple one depicted in Fig. 3.

Fig. 3. *The first version of the titanium holder*

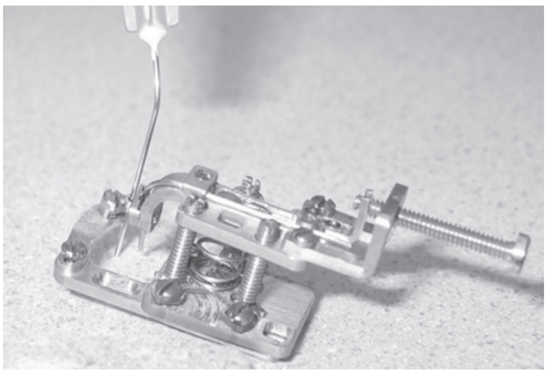

Fig. 4 *A prototype of the holder with the possibility for fine positioning*

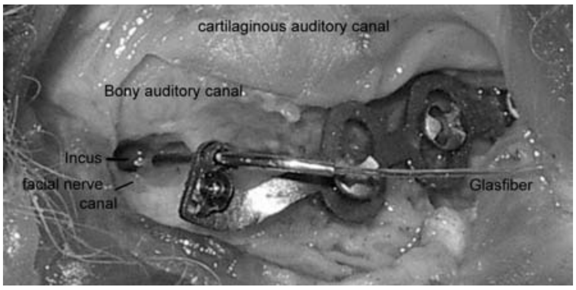

Fig. 5. *An implanted sensing fiber and Ti holder*

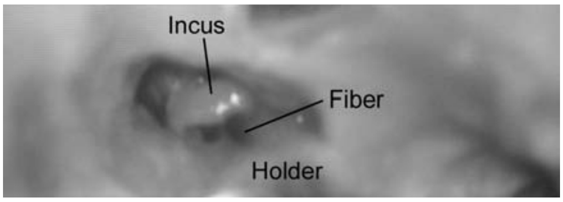

Fig. 6. *A close up of the real target, i.e., the rabbit incus*

This model, made of titanium (Ti), could not provide stable fixation of the sensing fiber after the adjusting procedure, so we developed the model depicted in Fig. 4. This model has the possibility to adjust the fiber in the x-y-z directions as well as angular adjusting. The special feature of the model is an ability to lock the optimum fiber position and to keep it for a long period of time after the implantation. The model is made of brass.

1.4 Surgical technique

For *in-vivo* experiments the sensing fiber was implanted surgically and firmly fixed onto the rabbit scull using the first model of the titanium holder. Fig. 5 presents an implanted sensing fiber fixed by a titanium holder. Fig 6 is a close up of the same situation, showing how the real target looks, i.e., the rabbit incus.

For this purpose the middle ear was opened using a retro-auricular transmastoid recess approach. Care was taken to leave the ear channel and tympanic membrane intact as well as the original state of the whole auditory chain [9].

1.5 Biocompatibility issue

The biocompatibility of the applied materials, the titanium and the glass optical fibers, were investigated by the preparation of histological specimens of the implanted fibers. We implanted the sensing fiber in two rabbits. They carried the implanted fibers and titanium holders for approximately two months. After this time we killed the rabbits and extracted the implants for the histological investigation. The main goals of the *in-vivo* experiments and the histological research were to determine whether the implanted devices can provoke an inflammation and to see if scar-tissue cells grow over the wall and the tip of the fiber.

2 RESULTS

In Fig. 7 we present the morphology of a relatively fresh human incus taken by a fringe projection profilometer. The roughness of the incus surface is about 15 μm peak-to-peak. A similar result was obtained from the investigation of the rabbit

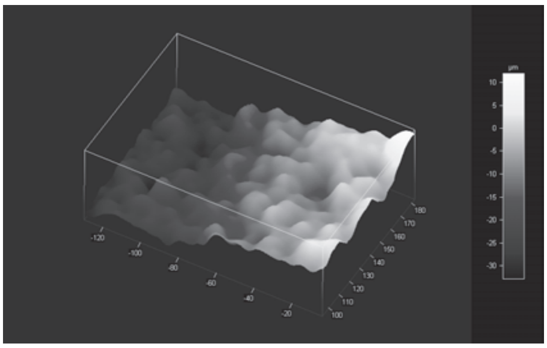

Fig. 7. *Roughness of a human incus bone taken by a fringe projection profilometer*

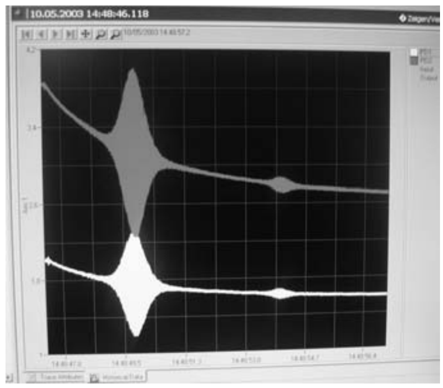

Fig. 8. *Coupling curves between the end of the sensing fiber and the incus surface captured by the two photodiodes PD1 and PD2 y-axis: signal, V; x-axis: time, sec*

incus. In both cases the incus surface behaves as a pure diffusive target with a relatively small reflectivity of about 2%.

Fig. 8 presents coupling curves between the sensing fiber and the incus obtained by simultaneously capture of the signals on PD1 and PD2. There are two typical low-coherence interferograms, the larger one coming from the end of the sensing fiber and smaller one coming from the incus surface.

After signal processing, made by the analogue electronic circuit, we obtained quadrature signals in the shape of the Lissajous figure presented in Fig. 9. The useful signal appeared as a moving part of a full ellipse. The length of the trace represents the amplitude of the incus vibration, approximately 7 nm peak-to-peak at 2 kHz and 70 dB SPL. The width of the trace roughly shows the noise level.

Fig. 10 presents the frequency response of the rabbit incus. The obtained frequency response has a typical shape characteristic for other animals as well as for human beings. We can see the occurrence of the resonant frequency somewhere around 2 kHz. Similar results regarding the amplitude of the vibrations of the ossicles in a human middle ear were obtained by Vlaming et al. [10].

In Fig. 11 we present the frequency response of the DSP based low-power fiber-optic vibrometer obtained by measuring the amplitude of the vibrating of an aluminum mirror. The mirror was stimulated to vibrate by a piezo transducer, previously calibrated with a Polytec laser vibrometer.

Fig. 12 presents a histological specimen of part of the middle ear containing the sensing fiber and the incus. The fiber-tip–incus separation in this case was no more than 50 μm. The overall incus dimensions are 1.5 × 2 mm.

3 DISCUSSION

The morphology of the incus, Fig. 7, originating either from the rabbit or human beings, is very developed with a lot of hills and valleys. For this reason we had a lot of troubles to find an appropriate facet that would be able to reflect the impinged light beam backward into the sensing fiber. The problem was even larger because of the very small reflection of about 2%. We found that the average overall dimensions of such a facet were about 15×15 μm. The beam coming out from the tip of the sensing fiber forms a dot of about 15 μm in diameter if the target-to-fiber tip separation is approximately 100 μm. This means we had to have a very fine adjusting system to meet the appropriate facet of the incus. It was achieved with the mechanical stage presented in Fig. 4.

The aiming of the sensing fiber toward the incus was followed up by monitoring the intensity of the back-reflected signals, captured by photodiodes PD1 and PD2, depicted in Fig. 8. The moment of the occurrence of the second interferogram meant that we obtained the back-reflected signal from the target. The separation between the first and second interferogram is equal to the separation between the sensing fiber tip and the incus surface. It is a very good method for adjusting the sensing fiber position to be sufficiently far away from the incus. It is of primary importance

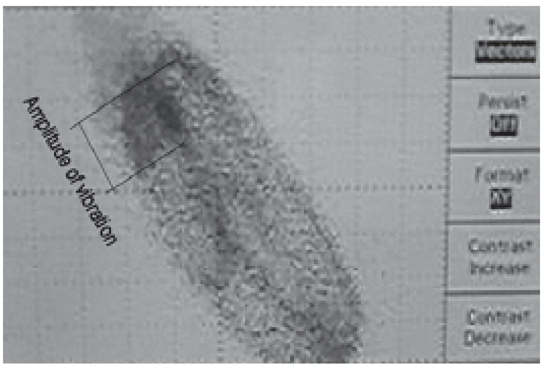

Fig. 9. *Quadrature signals presented as the Lissajous figure of the rabbit incus. The amplitude of vibration was about 7 nm peak-to-peak at 2 kHz and 70 dB SPL*

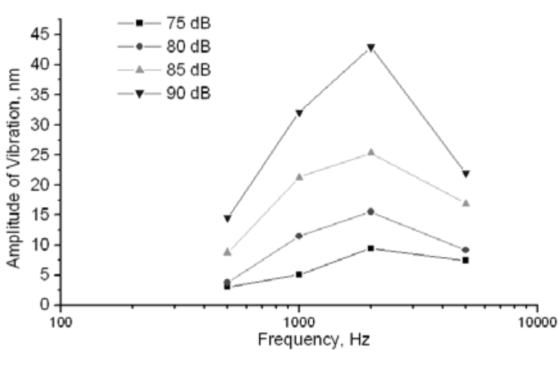

Fig. 10. *Experimentally obtained frequency response of the analog based fiber-optic vibrometer*

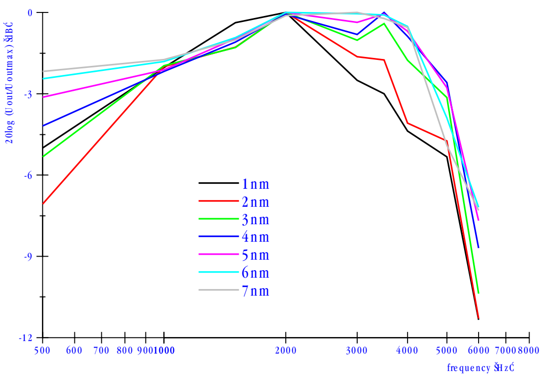

Fig. 11. *Experimentally obtained frequency response of the DSP based fiber-optic vibrometer*

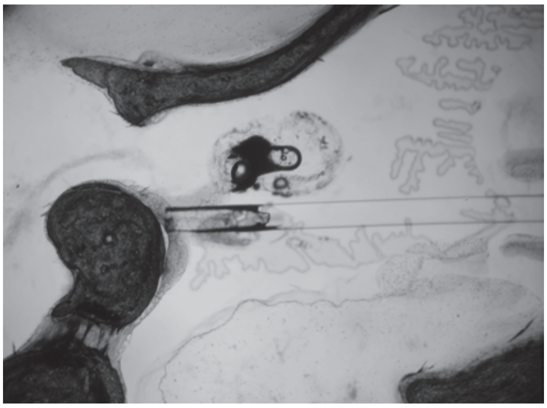

Fig. 12. *Histological cross-section of the middle ear containing an implanted sensing fiber vs incus*

to provide the sensing function of the microphone, even in the case of relatively large DC shifting of the auditory ossicles due to a change of atmospheric pressure. We set up the fiber-incus separation to be between 200 and 300 µm.

Fine adjustment of the mechanical stage was used to optimize the outlet signal, graphically presented as a Lissaojus figure, Fig. 9. The only small waking part of the full ellipse corresponds to the real amplitude of the incus vibration. There is a method [5] to reconstruct the amplitude of the vibrations using data presented in the Lissaojus figure.

Applying the above-mentioned procedure we obtained the frequency response of the fiber-optic vibrometer either for the analog or DSP-based version. However, the first one was made by low-coherence interferometry, and second one by high-coherence interfereometry. Both of them have some advantages and disadvantages. The first one provides high optical power, offers a more comfortable method for adjusting the fiber and the definition of the fiber-to-incus separation. However, the electrical power consumption is too high. For example, a laser diode polarized just below the threshold in order to work as LCS consumed approximately 70 mA without an electrical analog circuit. The final implantable microphone cannot tolerate such a high power consumption.

On the other hand, the high-interferometry based vibrometer provides a remarkably reduced power consumption of less than 2 mA at 2.2 VDC. This was achieved by introducing VCSEL as a light source, which consumed about 0.5 mA. The rest of the current was consumed by the digital signal processing. However, the price for this progress was a remarkable decrease in the optical power. For example, we measured just about 2 µW of the optical radiation emitted from the third (middle) outlet arm, later immersed in index-matching gel, Fig. 1. If we know that the incus reflection is about 2% it means that, in the best case, we had an incus-reflected light intensity of below 40 nW. However, even with such a modest optical power we got very good results. This was possible with a specially developed software package for signal processing based on the algorithm depicted in Fig. 2. The introduction of DSP into the optoelectronic interface of the vibrometer gave a great opportunity to miniaturize the whole device.

Finally, *in-vivo* experiments were performed on two rabbits for 2 months, and showed there were no inflammation effects onto the surrounding tissue of the animals. Histological investigation of the implanted sensing fibers showed there was no scar-tissue cell growth over the wall of the glass fiber. However, in one case, depicted in Fig. 12, we noted there was cell growth over the tip of the sensing fiber. It was caused by touching the incus surface with the end of the sensing fiber and creating a wound over the incus. During the healing phase the scar tissue covered the wound and even established a new connection with the not-so-distant fiber tip.

4 CONCLUSION

We can conclude that we established low- and high-interferometry techniques as a platform for the realization of one contact-less fiber-optic vibrometer suitable for application in TIHAs. We addressed the most important issues regarding the final implantable microphone: the optoelectronic circuit and signal processing, the optomechanical adjustment, and the surgical and biocompatibility problems. Because of that we performed an *in-vivo* investigation of the implanted sensing fiber and the mechanical holder.

We pointed out the most important result that we recently obtained by dramatically decreasing the power consumption (approximately 2 mA at 2.2VDC) of the whole sensing system introducing DSP and VCSEL as a light source.

The next steps in the investigation will be as follows: miniaturization and optimization of the optoelectronic unit, optimization of the optomechanical assembly for the fiber adjustment, and biocompatibility and encapsulation of the whole system ready to be implanted.

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5 REFERENCES

[1] J. M. Kartush, M. Tos (1995) Electromagnetic ossicular augmentation device, *Middle and inner ear electronic implantable devices for partial hearing loss*, vol. 28, pp. 155-172, 1995.

[2] E. Dalhoff, R. Gartner, U. Hofbauer, H. Tiziani, H. P. Zenner and A. W. Gummer (1998) Low-coherence fibre heterodyne interferometer for both dc and high-frequency vibration measurements in the inner ear, *J. Mod. Optics*, vol. 45, pp. 765-775, 1998.

[3] E. Fischer, R. Link, E. Dalhoff, S. Heim, H. Tiziani, H. P. Zenner and A. W. Gummer (1995) Infrared fiber interferometer for microvibration measurements in the inner ear, *SPIE*, vol. 2395, pp. 248-257, 1995.

[4] D. Goodman (1995) General principles of geometric optics, in Handbook of Optics, (M. Bass, eds.), pp. 1.3-1.109, *McGraw-Hill. Inc.*, New York.

[5] M. C. Tomic, J. M. Elazar, and Z. V. Djinovic (2002) Low-coherence interferometric method for measurement of displacement based on a 3x3 fiber-optic directional coupler, *J. Opt. A: Pure Appl. Opt.*, vol 4, pp. 381-386, 2002.

[6] K. Koo, A. Tveten, and A. Dandrige (1982) Passive stabilization scheme for fiber interferometers using (3x3) fiber directional couplers, *App.Phys. Lett.*, , vol. 41, pp.616, 1982.

[7] Z. Djinovic, S. Mitic, R. Pavelka, D. Vujanic, A. Vujanic, Ch. Kment (2004) Contactless technique for in-vivo measurement of amplitude vibrations of the auditory ossicles, *Proc. 24th International Conference on Microelectronics (MIEL 2004)*, Vol. 1, Nis, Serbia and Montenegro, May 16-19, pp. 201-204.

[8] M. C. Tomic (2004) Fiber-optic sensors based on low coherence interferometry , PhD, Belgrade.

[9] R. Pavelka, A. Vujanic, Z. Djinovic, S. Mitic, D. Vujanic, Ch. Kment, M. Tomic (2003) Animal experiments with a fiber-optic vibrometer to be used as a microphone for totally implantable cochlear and middle ear implants, *Proceedings of the 4 th International Symposium on Electronic Implants in Otology & Conventional Hearing Aids*, 5-7 June, Toulouse, France.

[10] M. Vlaming, and L. Feenstra (1986) Studies on the mechanics of the normal human middle ear, *Clin. Otolarryngol.,* vol. 11, pp. 353-363, 1986.

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Uvajanje informacijskih tehnologij z namenom izboljšanja sistema za upravljanje s kakovostjo

Implementation of Information Technology for the Purpose of Quality Management System Improvement

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V tem prispevku je predstavljena programska oprema za nadzor neusklajenosti sistema za upravljanje s kakovostjo z namenom uskladiti jih s standardom JUS ISO 9001:2001. Prav tako je treba ugotoviti in izpostaviti področje, na katerem pride do največ neusklajenosti. Podane so tudi natančne analize za vsako individualno področje in definirani predlogi za popravna oziroma preventivna dejanja, ki izboljšujejo sistem za upravljanje s kakovostjo, glede na pridobljene rezultate in opravljene raziskave na tem področju.

(Ključne besede: oprema programska, zagotavljanje kakovosti, neusklajenosti)

In this paper software for the macro-control of Quality management system (QMS) nonconformities, with the aim to classify them according to the JUS ISO 9001:2001 standard's areas and to mark those areas in which the major part of the nonconformities has emerged, is described. Detailed analyses for each respective area and the defined proposals for corrective and preventive actions for improving the QMS, based on the obtained results and on the inspection of the identified area, are given.

(Keywords: software, quality assurance, nonconformity)

0 INTRODUCTION

Market requirements in the 21st century will be characterized by a large variety and a relatively small demand for products. Effort that is more active is necessary for the development and the application of standards, and this conditions producers to adjust their products and processes by defined norms. The customer is in a privileged position and has a large assortment of products and services that should meet a customer's specific requirements.

Such conditions for operations require additional and permanent efforts, both on the part of the management and on the part of the employees in organizations, in order to improve processes and products as well. For such purposes, it is necessary to know how to manage processes in organizations along with the aim to meet the target defined in advance, which is confirmed by the following quotation:

What is necessary to learn (which is not easy) is the skill to "manage" the process that leads to the solution of problem – instead to manage people that work to solve such problem. (Alan Bloch).

The area for improvements within organizations is the control of nonconformities and, within that framework, the process to discover or to anticipate the possibilities for the emergence of nonconformities, as well as the application of corrective and preventive actions. In addition, the JUS ISO 9001:2001 standard imposes on organizations a requirement that relates to the control of nonconforming products. Consultants, certification and accreditation authorities have the need to manage QMS nonconformities in addition to the control of nonconforming products in organizations. That is why this paper is oriented toward the software that will support the macro-control of QMS nonconformities.

1 THE NEED FOR NONCONFORMITIES MACRO-CONTROL

The emergence of nonconformities in the quality management system and in the very business system in general represents a permanent danger for an organization, its operations, its image within the marketplace and its financial performance. These are the conditions that have encouraged the authors of this paper to begin research into the control of nonconformities as the basis for the model for improving the quality management system as the most advanced form of business management. The research has its aim to develop a model for improving QMS, based on **real** nonconformities' control. Such nonconformities have been identified, based on the **objective findings provided by external auditors** of both the quality system and the quality management system, which resulted from their working visits to organizations within the country and within the neighboring countries. Based on 1150 nonconformities, which were found in more than 350 organizations, the analysis was performed and the preventative actions were defined with the aim of decreasing the number of corrective actions and with the aim to create a system based on the "ZERO defect" principle.

As a support to data analysis and to the development of the model for improving QMS, applicable software has been developed. In line with the principles of software engineering [1], on the one hand, and with the necessities this work imposes, on the other hand, the process of software development was conducted, having full respect for Deming's P-D-C-A philosophy (P-Plan, D-Do, C-Check, A-Action), through the phases presented in Figure 1.

Identifying future customers and defining their requirements were the starting points for the development of such software, and all with the aim of anticipating the emergence of nonconformities, to define corrective and preventive actions and to improve QMS. The appearance of nonconformities within the quality management system is in relation to:

- system auditors, who aim to detect nonconformities while performing checks, to evaluate the process capacity and the harmony of the system with the standard requirements;
- consultants, who give advice with the aim to harmonize operations with the principles presented in the standards;
- employees in organizations, who maintain, re-evaluate and improve the quality management system via the process of nonconformity control.

2 APPLICABLE SOFTWARE WORKING OUT FOR QMS IMPROVEMENT

From the point of view of the software application, the above stated three groups were observed as future users. By observing the identified customer, on the one hand, and the elements for nonconformities control, on the other hand, while defining the project task, the following requirements, which the software has to meet, have been presented:

- to enable real-time inspection of standards, as the basis for the control and the harmonization of the quality management system;
- to enable the acquisition of nonconformities;
- to present nonconformities, depending on the specified standard requirement;
- to present nonconformities depending on the size and the activity of a company and on the standard requirement as well;
- to point to the most burdened points with respect to the frequency of nonconformities the emergence of particular points of the standard, and to the size of the company according to which such nonconformities are presented;

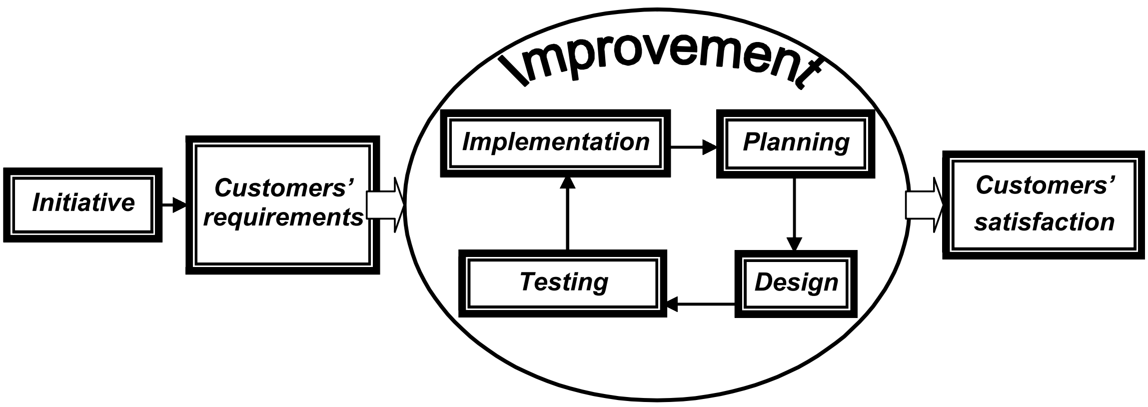


Fig. 1. *Software development activities*

- to generate a sequence of numerous corrective actions for the elimination of nonconformities, based on findings resulting from controls in certain areas of the standard;
- to suggest preventive actions intended for particular areas of the standard;
- to be cheap;
- to be compatible with the most frequently used hardware and software configurations;
- to be appropriate for broad usage and to be adapted for users that are not familiar with a computer.

The software is based on a database, the structure of which is shown in Figure 2.

The concept "to learn via mistakes" was the starting point for a thorough consideration of the structural database and the application design.

The causes for such mistakes, which result in knowledge, have been identified, based on the nonconformities defined by the performed analysis.

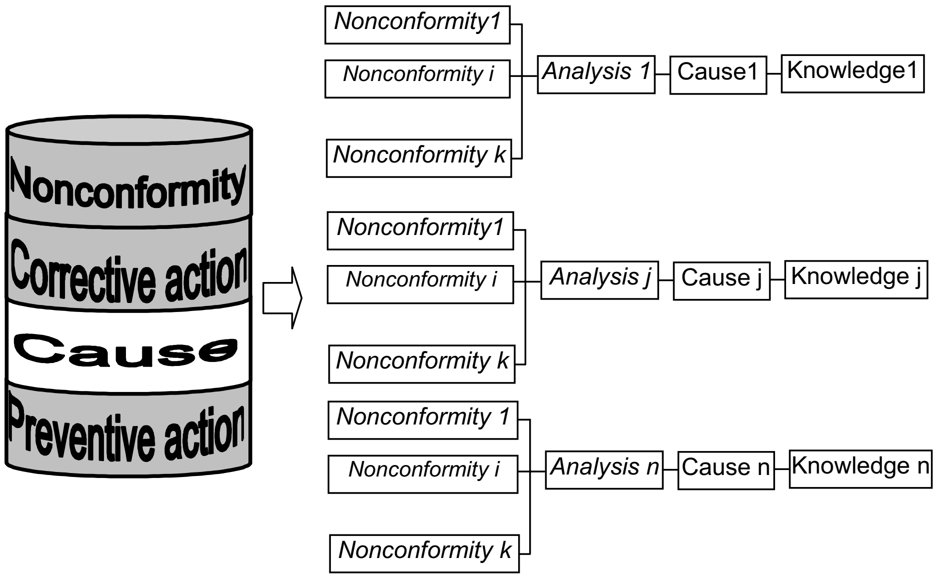


Fig. 2. *DB structure and approach data treatment*

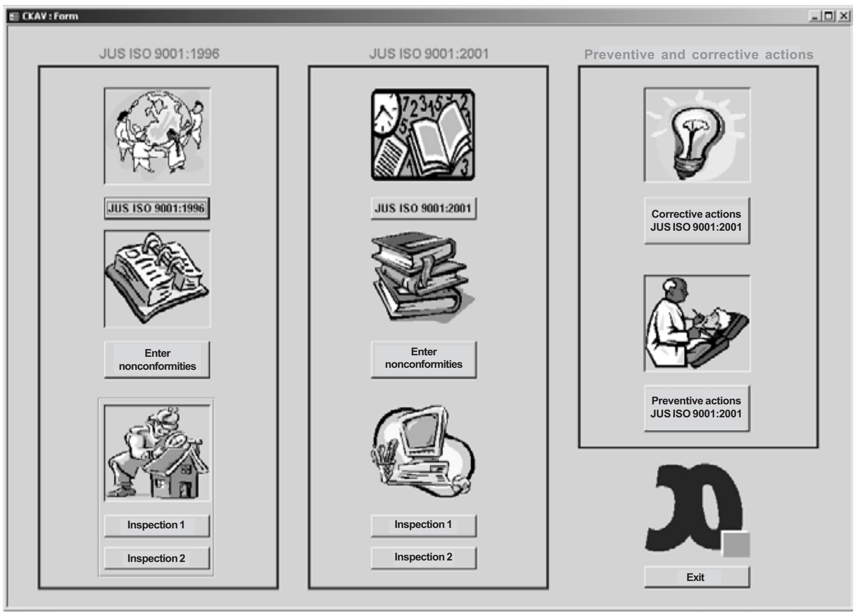


Fig. 3. *Appearance of the starting form*

All the nonconformities were divided into groups, depending on the standard requirements, i.e., on the area of such a standard in which the requirements have been specified. In addition, the grouping was carried out in relation to the activities and the size of the respective organization.

Gathered and grouped data were then analyzed so as to give a clear picture of the specificities of the nonconformities' emergence, depending on the standard requirements and on the type of company, and in order to create the basis for defining corrective and preventive actions, i.e., to generate knowledge.

The starting display form of the software is presented in Figure 3 [3].

For the purposes of this work the following analyses were carried out for each standard:

- The analysis of nonconformity frequency in relation to the standard requirement,
- The analysis of nonconformity frequency in relation to the standard requirement and to the activity and the size of the company.

The analyses carried out in such a manner gives the results that enable the inspection of nonconformity sequence of the order per defined criteria, i.e., the points which are most burdened from the point of view of nonconformities' emergence are identified.

This is indicated by numerical data, and the numerical data is the number of nonconformities per stated separation criteria. Such critical points represent the elements to be improved, and their priorities are defined with the number of identified nonconformities.

In addition, this analysis also results in alphabetical data that can be used for knowledge generation. It is a clearly presented sequence of original textual presentations of nonconformities and corrective actions, wherein the program users can find them or can use them as the support for the completion of their activities

In addition to the analysis relating to the new version of the standard, the analysis of the previous version was performed, based on the same criteria. The results obtained were used for knowledge generation, i.e., for defining preventative actions based on the correlation table in JUS ISO 9001:2001. Figure 3 shows the application has been divided into three parts. The first part relates to the quality system JUS ISO 9001:1996 standards and the second part relates to the quality management system JUS ISO 9001:2001 standard. The third part relates to the review and the usage of the proposed corrective and preventive actions for the new version of the JUS ISO 9001 standard.

3 SOFTWARE APPLICATION RESULTS

Based on the results obtained from the presented software, which are given in Figure 4, the identification of the five most burdened areas of the standard was done from the point of view of the nonconformities' emergence

The picture reflects the areas in which detailed analyses will be carried out, and for JUS ISO 9001:2001 they are as follows:

- Requirement 4.2 - the requirement that relates to the documentation;

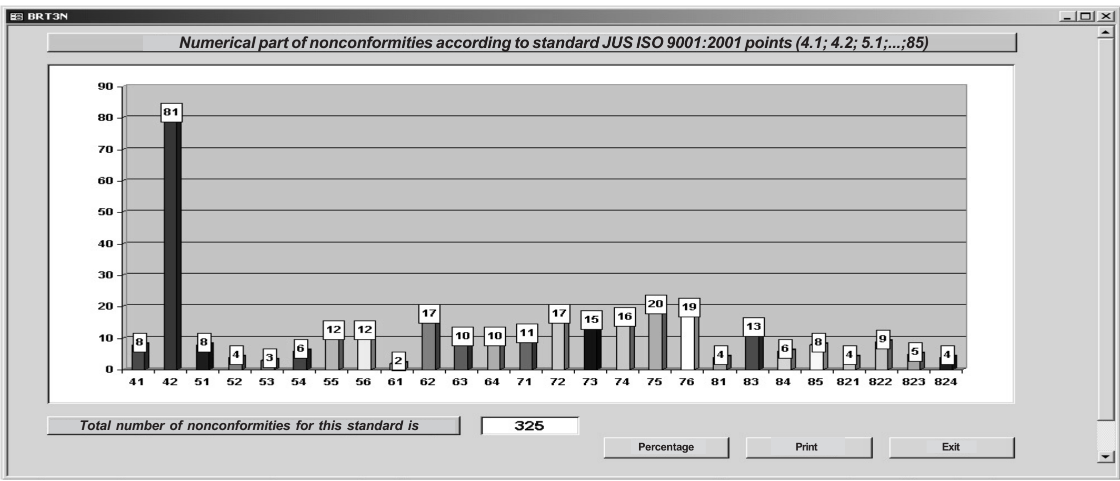
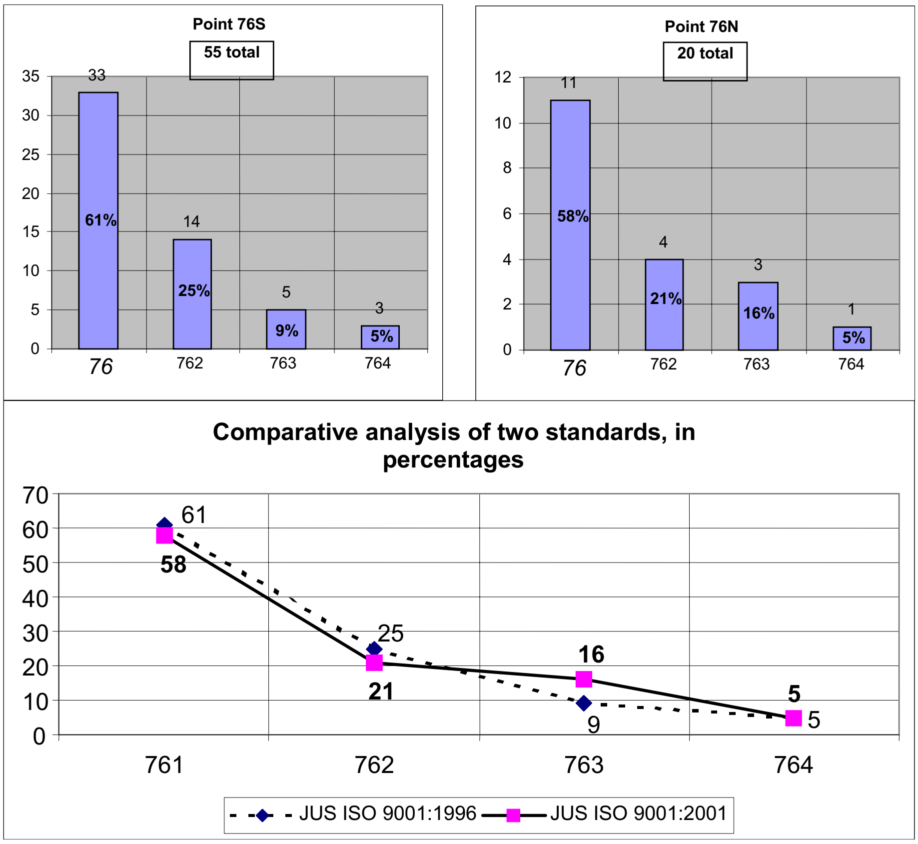


Fig. 4. *Histogram*

- Requirement 6.2 - the requirement that relates to the human resources;
- Requirement 7.2 - the requirement that relates to the customer;
- Requirement 7.5 - the requirement that relates to the production and servicing,
- Requirement 7.6 - the requirement that relates to the control of the surveillance and measurement devices.

The JUS ISO 9001:2001 standard has been used as the basis or the starting point for the analysis and the requirements that have been identified as the most critical and of highest priority from the point of view of the nonconformities' emergence in support of the improvement. An accurate picture of the weaknesses in organizations, i.e., of places where the advancement should be done for the purpose of improving the overall quality management system's performance is acquired in such a manner and through the current standard. As the support in the course to reach improvement within the actual and priority places, the experiences with nonconformities resulting from the old standard are added to the basis in order to create as real a picture as possible and to define the history and the tendencies in the emergence of the nonconformities, i.e., in the system's weak points, and to define as good a preventive actions as possible. For the purpose of the previously mentioned, the nonconformities derived from the previous version of the JUS ISO 9001:2001 standard were identified and presented in parallel diagrams, and all for the needs of the defined critical requirements of the mentioned standard. This paper presents only the completed analysis for point 7.5 (Figure 5).

The picture reflects that the emergence of the new standard has brought aggravations in the



Legend:
761 *– etaloning or verifying, and the records thereof*
762 *– identifying measuring equipment, for the purpose of etaloning status designating*
763 *– adjustment protection*
764 *– protection against damage or malfunction*

Fig. 5. *Analysis of requirement 7.6*

parts of the production and servicing processes management. At the same time, the improvement can be noticed in the part of the validation process in production and servicing. The reasons for the worse production and servicing processes management can be found in the chaotic organizational structures within our companies and in the disorientation during the ownership transformation processes, which again influences the quality of the mentioned processes as well. In addition, the improvement in the part of the validation is the consequence of increased competitiveness within the market place that forces organizations to improve their validation processes for the purpose of survival and regardless of the obvious problems inside those organizations. Other elements that relate to the identification, consistency, the property of customers and the maintenance of products, keep the same trend, as was the one in the previous standard.

Therefore, we have two elements in this case (751 and 752), that supplement each other by their nature and that are completely unlike as regards our circumstances. That is why it is necessary to act by preventive actions that have been proposed for this case and for the purpose of improving the situation, and especially for the case of production and servicing processes management.

The proposals of preventive actions are as follows:

- Absolute respect for the process approach in the part of the quality management system with the aim to overcome organizational and ownership transformations and to create a sense of private ownership for employees, both at the level of processes and activities, independently of current organizational and ownership structures within organizations;
- Introduction of information technologies based on modern and, at the same time, cheap and easily available database models, for the purposes of identifying and the consistency of products;
- Permanent analyzing of reports on rejects and customers' complaints, as well as re-evaluating and presenting the given results, along with adequate incentives for, or with assigning responsibilities to, the employees in such sectors.

The analysis and other points of the standard can be found in corresponding literature [3].

5 CONCLUSION

The basis for software functioning aimed at the support to QMS is composed of a database that contains 1150 nonconformities originating from more than 350 organizations. The nonconformities were provided, based on the available reports in two certified authorities that have the biggest number of certificates issued.

Query-based data selection and their analysis point out that the emergence of new versions of the JUS ISO 9001 standard did not significantly change the statuses within the systems.

The software enables the review of nonconformities and the review of corrective and preventive actions that are the result of analyses being carried out within the identified areas. The results indicate a particularly disturbing situation in the area of documents management and of the records of the quality management system. In addition, the significant number of nonconformities within the management of processes relating to the customers contributes to the previous thesis, regardless of the very core of new standard and of the approach it requires being exactly the respect for demands and the satisfaction of customers. On the other hand, if a part of the findings resulted from an evaluation of the quality management system is taken into consideration, it can be concluded that the evaluators do not often point out the essential nonconformities. Namely, the very evaluations speak more of deviations that should not be equated with nonconformities, whereas the nonconformities represent a higher category that should primarily reflect the dissatisfaction of customers or the poor quality of products.

6 REFERENCES

[1] JUS ISO 12207:1997 (1997) Information technology – Software life cycle processes, *Federal Standardization Agency*, Belgrade (in Serbian).
[2] JUS ISO 9001-2001 (2001) Quality management system – Requirements, *Federal Standardization Agency*, Belgrade (in Serbian).
[3] Vujoviæ A. (2004) Nonconformities macro control as the basis for QMS improvement model, Master's Thesis, *Faculty of Mechanical Engineering*, Podgorica (in Serbian).

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Mehanska mikroobdelava s frezanjem, žično erozijo, potopno erozijo in diamantnim struženjem

Mechanical Micro-Machining Using Milling, Wire EDM, Die-Sinking EDM and Diamond Turning

Alberto Herrero[1] - Igor Goenaga[1] - Sabino Azcarate[1] - Luis Uriarte[1] - Atanas Ivanov[2] - Andrew Rees[2] - Christian Wenzel[3] - Claas Müller[4]
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Med vsemi različnimi mikroobdelavami se ta prispevek osredotoča na tehnike, ki se lahko štejejo kot običajni obdelovalni postopki. Obravnavani so naslednji obdelovalni postopki: zelo natančno rezkanje, obdelava s tanko žično erozijo, potopna erozija ter diamantno struženje. Kljub splošnosti postopkov ima vsaka izmed njih posebno lastnost, ki izboljša njihove zmožnosti obdelave. Postopki so v tem prispevku analizirani, prikazane pa so tudi njihove razlike s splošnimi obdelovalnimi postopki nato pa so prikazane še njihove omejitve. Predstavljene so tudi najnovejše uporabe in potencialni trgi. Čisto na koncu je prikazana še primerjava teh postopkov z drugimi izdelovalnimi postopki, kakor je litografija z namenom poudariti mogoče pristojnosti in dopolnila.

(Ključne besede: obdelave zelo natančne, mikroobdelave, rezkanje, struženje diamantno, obdelave elektroerozijske)

From among all the different techniques currently applied for micro-manufacturing, this paper focuses on those techniques that can be considered as conventional techniques because of their direct relationship with standard machine tools. The following processes are discussed: ultra-precision milling, thin-wire EDM, die-sinking micro-EDM and diamond turning. Despite the mentioned relationship with conventional machine tools, they all have special characteristics that enhance the capability of the machining principle. The processes are analysed, showing the differences with respect to the corresponding conventional processes and stating their current limitations. A review of the state of the art, applications and potential markets is presented. Finally, the capabilities of these technologies and the other micro-manufacturing techniques (lithographic processes) are compared in order to highlight the possible competences and complementariness that they present.

(Keywords: ultra-precision machining, micromachining, milling, diamond turning, EDM)

0 INTRODUCTION

During recent years, the so-called “micro-technologies” have invaded the production of different components in some strategic sectors like automotive, electronics are medical ([1] and [2]). The name has been used during the past 5 years, and brings together all those technologies that are capable of producing small parts. In any case, even today, it has an ambiguous meaning due to the lack of clearly defined dimensions. The discussion about the meaning of “micro-technologies” is not new ([3] and [4]), and the dimensional limits are still fuzzy. The reasonably accepted limits are shown below:

· Micro-technologies: from 0.5 to 499 μm in 2D/3D.
· Nano-technologies: from 0.5 to 499 nm in 2D/3D.

In order to keep these dimensions in perspective: 1 micrometer is 0.001 millimetres, and 1 nanometre is 10^{-6} millimetres (1 nm = 10^{-9} m) or 10 angstroms. An illustrative example is the dimension of a human hair (Fig. 1), with a usual diameter of 80 to 100 μm.

Micro-technologies are capable of achieving tolerances smaller than 0.5 μm and an average sur-

Fig. 1. *A hair machined by a femto-second laser (image captured by x20 confocal microscope)*

face roughness of less than 50 nm. The corresponding conventional processes achieve 1 to 10-μm tolerances (if CNCs are used, 10 to 100 for manual machines) and a 50 to 100-nm average roughness. Micro-technologies are usually divided into two groups:

1) *Lithographic processes:* they have evolved from the 2D technologies applied in the production of circuit boards. They can produce stair-by-stair (referred as 2.5D) structures with very high resolution in XYZ. Most of these technologies must be applied in a clean-room environment. They can machine a limited range of materials (silicon being the most documented material) with a maximum aspect ratio close to 1:100 (which can be improved for some techniques, like LIGA).
2) *Ultra-precision processes:* they are the evolution of the usual industrial production technologies for precision components. They were initially applied by watchmakers, but now other sectors like surgical equipment, aerospace or nuclear vessels make use of them. The applied machinery is adapted for micro-machining: smaller tools, higher resolution, environmental isolation, etc.

Some technologies belonging to the second group are analysed below: micro-milling, diamond turning and EDM.

1 LITHOGRAPHIC VS ULTRA-PRECISION PROCESSES

From searching the available information about micro-technologies, it seems like lithographic and ultra-precision processes are competitors in the production of microsystems. Nevertheless, if a deeper analysis is performed, these technologies are found to be complementary, and only compete in some particular cases; just as happens between different machining technologies.

Analysing the geometry of the obtainable features, ultra-precision technologies can produce complex free-form 3D profiles that cannot be obtained with lithographic processes.

Considering the maximum dimensions of the part, the lithographic processes can only machine parts on very flat wafers and cannot take an accurate reference with respect to other features of the part. The ultra-precision technologies have an important market in the machining of small accurate features or textures of bigger parts (moulds, dies, punches, etc.) obtained by conventional machining methods.

Considering the machinable range of materials, the clean-room processes can machine silicon, Pyrex, glass, chrome, nickel, gold, etc., with some of them being brittle and difficult to machine using ultra-precision techniques. On the other hand, ultra-precision techniques can machine most plastics, metals and ceramics. The material of a micro-part is an important specification when choosing the right machining process.

Concerning the part's accuracy, generally speaking, the clean-room processes obtain a better accuracy (one order of magnitude better: ±0.1 μm vs ±1 μm) than the mechanical processes, which are limited by the tolerances of the part-to-tool stiffness loop. On the other hand, this consideration must be carefully analysed, because, despite the high precision of lithographic processes when projecting a mask, the mask accuracy itself should be considered as an error in the process. This error can be very small (<50 nm when using an ion beam, but it is a very expensive process) but sometimes the mask is produced by ultra-precision techniques like laser or milling. Considering the production yield, lithographic processes are easier to apply for high-yield production, but they are very expensive for low-yield production; the ultra-precision processes being more suitable for the production of small series.

The integration of all these technologies in industry is very slow. They are mainly applied by universities and research centres due to the high cost of the required equipment and their low productivity, added to the required skills for the process application, which leads to the important cost of manpower.

Those countries that have an active industry based on microelectronics are more active in the research of lithographic processes; however, those countries with a tradition in the metal-processing industry are more active in the research of ultra-precision technologies.

2 DIAMOND TURNING

Diamond turning is a cutting process capable of producing an absolute accuracy of better than 1 µm, and a 0.002 to 0.005 µm average roughness in some metals, plastics and ceramics [6]. Its application is the production of mirror surfaces in optical-quality components, moulds or reference parts.

The machine must be able to provide high stiffness, thermal and kinematic stability (lack of straightness errors, angular errors or vibrations, hydrostatic bearings are usual for this purpose) and high resolution [7] (~0.01 µm). The tool geometry must be accurate, the control of the edge radius and the tool tip radius being the key parameters to obtaining a mirror finish. The control must be performed with an accuracy of 3 to 75 nm.

2.1 Diamond for Turning

Diamond presents some special features that make it ideal for cutting: high stiffness (E = 700 to 1200 GPa; G = 300 GPa), high thermal conductivity at room temperature (2000 W/mK), easy to work and easy to obtain flat surfaces and sharp edges in its crystallographic directions. Diamond can machine for long periods, keeping the tool geometry and providing both high precision and low roughness (depending on the tool radius and the process parameters). On the other hand, diamond is a brittle material and the tool can break easily if it receives an impact (tool higher than the part's axis, excessive feeds, important variations in the depth of cut, etc.), with this being catastrophic.

As a cutting tool diamond can be found as:

- *Natural Mono-crystalline Diamond:* presents different properties in different crystallographic directions and can have some impurities that reduce the tool's service life.
- *Poly-crystalline Diamond (PCD)*: is a cermet composed of cobalt as a binder and small diamond grains.
- *Synthetic Diamonds*: are obtained using pure graphite that is pressurised (55000 bar) and heated (1500ºC). The obtained diamond has a perfect crystallographic structure with almost no impurities.

In the diamond-turning process, natural and synthetic diamond tools are usually applied, with the latter ones being more expensive (no imperfections). In other processes, like grinding or cutting tools, PCD and synthetic diamond are applied as hard coatings.

2.2 Diamond Machinable Materials

Diamond has a low reactivity with many other materials. At high temperature it reacts with those metals that have an affinity for the carbon in its structure, forming carbides that contaminate the tool, which loses its properties and wears ([8] to [10]).

Favourable materials are:

- *Metals:* aluminium alloys, brass, bronze, copper, gold, silver, zinc, beryllium, lead, tin, indium, plutonium, magnesium
- *Plastics:* metacrylate (PMMA), polycarbonate, Teflon, PVC, polypropylene, polyester
- *Glass:* silicon, germanium

Glass machining produces a higher tool wear [11]. The machining of plastics can introduce some internal tensions that cause the subsequent deformation of the plastics. In all these materials an average surface roughness of 3 to 6 nm and an absolute accuracy of 1to 2 µm can be obtained.

With regard to the materials that have an affinity for carbon, these include: steel, nickel, titanium, molybdenum, cobalt, chrome, vanadium, rhodium and tungsten.

2.3 Diamond Turning Process

The machine configuration and the process concept are similar to a conventional lathe, but the process parameters are different [7]. The part must be pre-machined in another lathe, with an excess of material of around 0.3 to 0.5 mm.

The tool-tip radius must be controlled with a very high precision [12], the other parameters of the tool are as follows (Fig. 2): the rake angle is close to 0º (slightly positive for plastics ~5º) and the clearance angle is close to 6 to 10º. Diamond makes it possible to obtain an edge radius close to 20 n be-

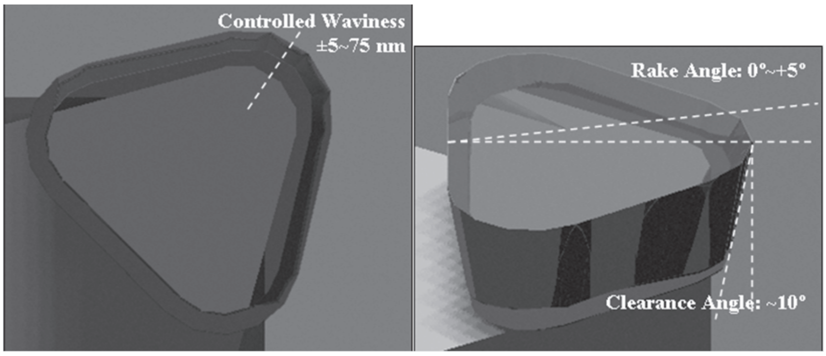


Fig. 2. *Typical tool geometry (solid rendering)*

tween the clearance and the rake planes. Such a small value makes it possible to cut with a very small depth of cut. Rough machining for diamond turning implies a depth of cut of 40 to 50 µm, in finishing it can be 1 to 2 µm. The usual feeds are 5 to 40 mm/rev, and the spindle speed range is 1500 to 2000 rev/min.

The coolant is an air-oil mixture targeted at the tool tip. It will remove the chips, lubricate the cutting area, and cool the tool. The chips must be removed because otherwise they would cause marks if they stayed stuck to the tool edge. Special care must be taken when orienting the coolant nozzles.

2.4 Diamond Turning Applications

The process can be applied for two different purposes:

1) The machines are stiff, stable and can move with very high precision. These specifications make it suitable for micro-machining (Fig. 3, right).
2) Using the correct tools, mirror finishing can be obtained, avoiding several operations (turning-grinding-polishing) (Fig. 3, left).

For micro-machining the process is suitable for producing small diameter shafts (0.2 to 0.02 mm) and small slots (using small tailor-made tools). Part cutting becomes an important issue. Mirror finishing is currently its main market, and some applications are as follows: laser-driving optics, wavelength-filtering surfaces, moulds for components of optical quality, etc.

3 MILLING

The ultra-precision milling process is very similar to conventional milling, being an intuitive process that can easily be assimilated by any operator. Despite cutting chip widths of just a few nanometres, the effect of inter-atomic forces, sometimes considered by other authors, is negligible.

The milling machine has some special characteristics. At present, there are a few commercial solutions ([14] and [15]). Knowledge about the machine is linked to the process knowledge, and it is important to understand what happens at the tip of the tool. Just as with diamond turning, the process parameters, the tools and the cutting process itself have some differences with respect to conventional milling.

3.1 Tools and Auxiliary Systems

Micro-milling depends a lot on the auxiliary components needed for the process, which is why the entire group (machine, components, tools, etc.) must

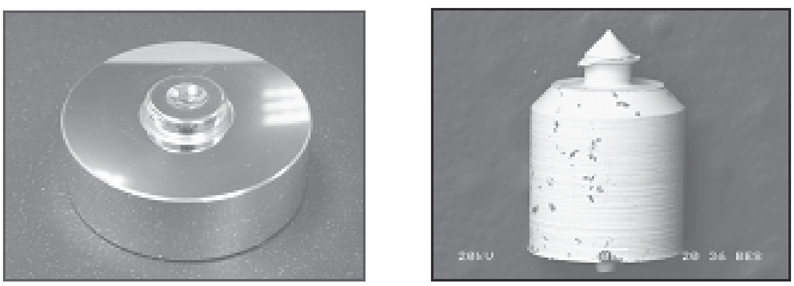


Fig. 3. *Mirror surface machined in aluminium (shape error <0.08 µm in spherical zone, <0.05 µm in flat zone); Miniature Ø0.75 mm brass part.*

be analysed as a whole. Apart from the machine, this includes the tools, the spindle, the collet and the referencing system.

Tools

The tool market is very active in the development of new tools (drills, mills) for micro-machining. In the past several years the minimum diameter of mills has decreased from 0.25 mm to 0.1 mm, the range includes spherical and straight 2-flute mills made of carbide with different coatings (TiAl, TiAlN, CBN, CBD, etc.). In any case, the range is limited and there are no different geometries for different materials. This is an important problem because most of the tools are designed for steel machining. It is important to point out that grain size has a large influence on the tool's performance.

Commercial tools have a well-defined geometry with small tolerances. The tolerances indicated in the catalogues for the sum of the geometrical error plus the run-out error are de ±10 μm. (The tolerance-to-size ratio is poor when compared to conventional high-speed machining mills.) The real errors are usually smaller (±5 μm). A second option is to use tailor-made tools. These tools are provided by specialised companies at a higher cost. These mills can present one (engraving tool) or two flutes with a custom geometry (face angle, helix angle, rake angle) and the diameters can be as small as 0.01 mm. The geometry of the tools has a high dispersion, which is an important issue when changing the tool to continue a machining process.

Spindle and collets

Because of the use of such small tools, the spindle must rotate at high revolutions (120000 to 160000 rev/min) to achieve an appropriate cutting speed for most materials. Apart from the speed, the spindle must be stiff (>25 N/μm) and it must have a small run-out (<1 μm) in order to ensure the high precision of the cutting process. To reach such high speeds, the spindles have ceramic ball bearings that are continuously cooled and lubricated. They are usually low-power electro-spindles (200 to 500 W) or aerostatic spindles.

Usually, the tool is clamped manually using special collets to reduce the run-out. The most common form of collets are the precision ER type collets (clamp a small range of diameters close to a nominal value) and the super-precision ER type collets (only clamp the nominal diameter). The precision collets can present big run-out errors that depend on the clamped diameter, the super-precision collets have run-out errors smaller than 2 μm.

Tool wear during micro-milling is relatively high, and that is the reason why it is usual to use two or more mills per operation (one for rough machining, the other for finishing). Tool change is a critical operation because the tool run-out, tool height and collet run-out are modified, thus it must be performed carefully, cleaning the cone, collet, tool and nut and applying controlled torques.

Referencing system

In many cases the micro-milling operations must be referenced to other operations, surfaces or part features that have previously been machined. Part referencing is performed in the same way as in conventional milling: the tool is moved until it is "touching" the part in different axes. Commercial touch triggers have errors close to 5 to 10 μm, but this error is very big for micro-machining.

Alternatively, the trigger is done optically. The machine resolution being much better than in conventional systems (approaching micron-by-micron), it is more difficult to identify the first chip that is cut in the part. In order to assist this action, the micro-milling machines are equipped with high magnification (x100 to 200) vision systems that are used for referencing and also to inspect the machining process. Depending on the applied magnification, both the field of view and the depth of view get very reduced, and the working distance must be fixed with higher precision. It is typical to use zoom systems capable of augmenting the image from x60 to x200: the highest magnification is only used for referencing, while the lower magnification provides a greater depth of view that is adequate for process inspection.

3.2 Materials for Milling

The application of different coatings for the tools and different cutting speeds makes it possible to machine metals, plastics and ceramics ([14] and [15]).

The greater limitations of the process are the lack of tool geometries adapted to machine different materials and the high wear produced at the tool tip (specially for hardened steels and ceramics).

3.3 Micro-milling Process

As was mentioned for diamond turning, the machine configuration and the geometrical concept are similar to the corresponding macro-process, although there are some important differences in the machine components and the process parameters ([16] and [17]).

Considering the process parameters, the depth of cut is very reduced for roughing (<10 μm, depending on the part material and the tool diameter) and finishing (2 to 3 μm). These values would cause part sticking and wrong cutting during normal machining. The feeds are reduced (<40 mm/min) and the spindle rotates at high speed (>40000 rev/min). The cutting speeds are close to 25 m/min for steels, and the chip thickness is small (<0.5 μm).

Tool geometry has a large influence on the cutting performance. An important effect that is not usually considered in milling is the edge radius between the rake face and the clearance face. This radius can be the source of important errors during the milling process, because the tool instead of the cutting ploughs the surface material when the depth of cut is very small. The edge radius must be smaller than the chip thickness in order to cut (~0.1 μm, Fig. 4).

Analysing the distribution of the cutting forces acting on the flute of the tool (Fig. 4) it can be appreciated that when cutting a 2-μm depth of cut, the mean rake angle will be different to the nominal value. The mean rake angle will depend on the rake face, the tool edge radius [18], tending to be negative and so plough the material.

The forces acting on the tool will be relatively larger than during normal milling: the specific cutting pressure (p_s) increases as the depth of cut decreases (it is experimentally tested for normal machining). Unfortunately, the values for micro-milling are still unknown. If the values are extrapolated assuming an exponential relation, the cutting forces are close to 5 to 10 mN when milling hardened steels. Considering the tool diameter, these forces cause important deflections that produce higher tool wear and tool breakage.

Micro-milling can obtain an average surface roughness, R_a, close to 0.1 to 0.05 μm, burr formation being a key issue for this technology. Burrs tend to appear on the edges when machining boxes, they are small chips that could not be evacuated and were stuck to the piece walls by the next flute. Deburring is a complex task that can be minimised with optimised tool paths and using a new tool for finishing.

3.4 Micro-milling applications

Comparing micro-milling to other micro-machining technologies, this process is capable of machining freeform 3D shapes (Fig. 5 left) that cannot be obtained with most of the other processes (2D or 2.5D).

In the other processes the machinable range of the materials is limited (electrically conductive

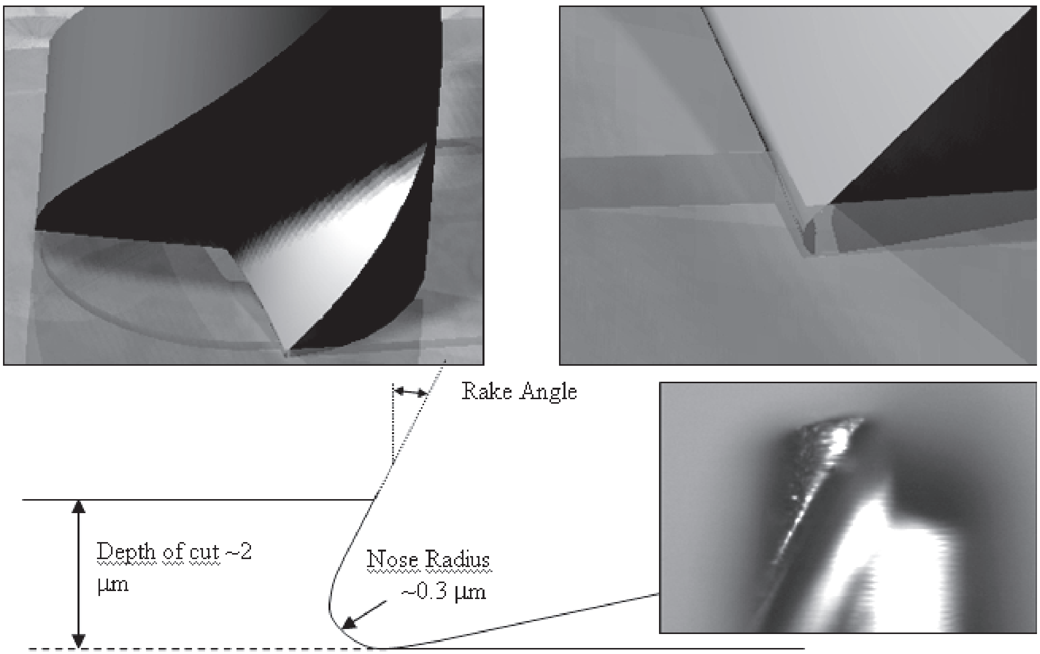


Fig. 4. *Geometry of a 2-flute straight mill, detail of the edge radius. Ø 0.2 mill captured by confocal microscope (x100)*

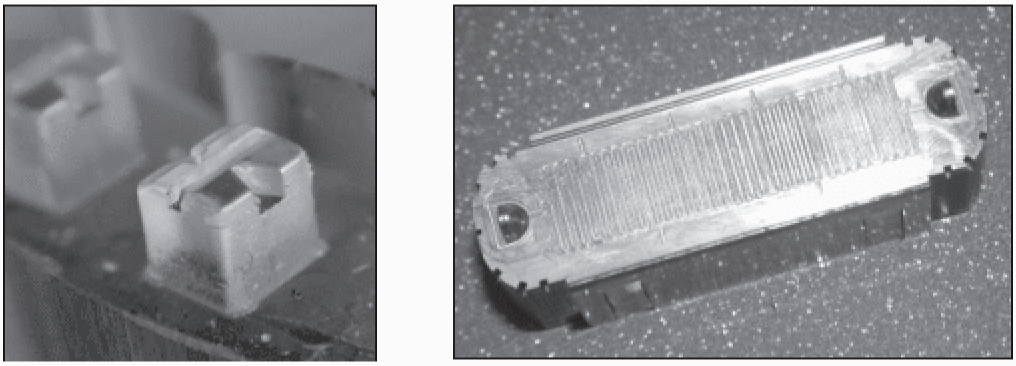


Fig. 5. *Bracket made of polysulfone (3x3x2 mm); mould for a drug-delivery system (channel height 0.1 mm; channel width 0.3 mm; wall thickness 0.2 mm; accuracy ±2 µm; roughness 0.15 µm Ra).*

materials for EDM, diamond-compatible materials for diamond turning, etc.), but micro-milling can be applied to a wider range of materials by using mills with different coatings. This is also important because it can process not only miniaturised parts, but also precision features in big parts.

Another advantage of micro-milling is its similarity with the conventional process. This makes the process easier to introduce in industry. Many applications of micro-milling involve the machining of medical parts (Fig. 5, right) and surgical tools (the sector in which this technology has opened new opportunities), moulds and dies, scientific research, etc.

5 DIE-SINK EDM AND MICRO-EDM

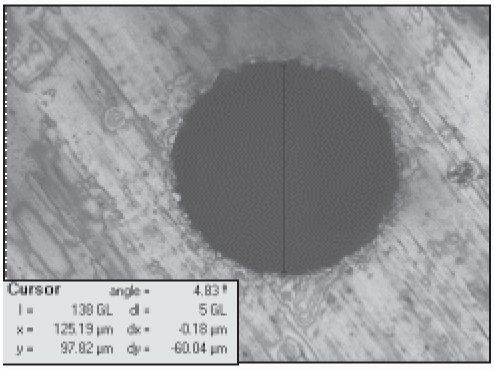
The lack of cutting forces and the capability of removing small portions of material per spark makes EDM a perfect process for micro-machining. The die-sinking EDM process was studied by many companies and institutes, with new machines and auxiliary systems capable of machining smaller features appearing. Comparing the process to conventional EDM, the main differences are the electrode dimensions, the higher resolution of the machine and the capability to produce less energetic pulses (~100 nJ). As T. Masuzawa explained [19], the pulse energy is proportional to the voltage, the intensity and the spark duration. The process is also different in terms of sludge removal, process parameters and electrode wear.

The current and voltage must have some minimum values to overcome the resistance of the cables and connections and produce the spark. Thus, to reduce the pulse energy, the time must be controlled. Transistorised generators can reduce the pulse interval to 0.5 ms, while the relaxation circuits (RC circuits) can produce pulses of some microseconds. Most of micro-EDM machines use RC generators with small condensers (<10 pF), reducing pulse time and energy.

One of the most important applications for micro-EDM is micro-drilling with small electrodes (Ø0.1 mm, with an aspect ratio 50:1) made of tungsten. These can be used for fuel injectors, air injectors, precision dispensers, ink-jet printing, filters, etc. Smaller holes can be made by electrode-dressing techniques (Fig. 6 left). Among these techniques are the following: slab milling and wire electro-discharge grinding (WEDG – Wire Electro Discharge Grinding, developed in 1985, by T. Masuzawa of Tokyo University). WEDG is a technique that incorporates a wire electro-discharge unit horizontally in the sinking EDM working area. Changing the electrode polarity, it can be dressed against the wire electrode, decreasing its diameter to 10 to 20 µm. Controlling the Z axis rotation, it is possible to produce form electrodes [22].

A second research field in the sinking EDM process has started to use the electrode to sculpt complex 3D shapes, controlling its position in space (similar to the milling process) (Fig. 6, right). This process is named EDM-milling. In EDM-milling the tip of the electrode wears and loses its initial shape. Adjusting the process parameters, the modified shape is maintained within the process and only the tool height must be compensated. The compensation depends on process parameters and part material; electrode wear characterisation and trajectory planning being the key issues ([23] and [24]). It is a slow process (depth of cut ~20 µm in roughing, 3 µm in finishing) that obtains an accuracy of ±2 µm.

The difference with respect to conventional EDM machines, apart from the machine precision, is



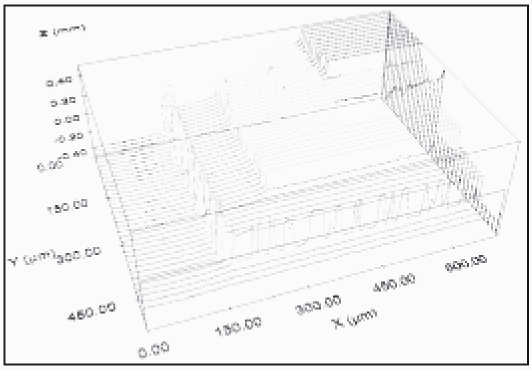


Fig. 6. *Ø0.060 mm hole by s-EDM (Ø0.2 mm tungsten electrode dressed to Ø0.036 mm). 1x1 mm EDM-milled pyramid with 0.2 mm stairs (captured by confocal microscopy x20).*

that micromachining systems can interpolate in 3D and erode in any spatial direction, controlling the gap width. Commercially the range of such systems is limited [25], and only two companies offer products focused on micro-EDM.

The process limitations are that vertical walls and sharp edges cannot be produced (unless special shaped electrodes are used for finishing) and the electrode wear/part wear ratio is higher than in conventional EDM because finishing parameters are applied during the whole process (positive polarity, high frequency and low energy).

The combination of electrode dressing and EDM-milling makes it possible to machine very small freeform surfaces in conductive materials. The electrode can be dressed to diameters not obtainable with cutting tools, making it possible to machine smaller features.

4.1 Electrodes and Auxiliary Tools

The applied electrodes are made of different materials and the machine is equipped with some special systems that are different from normal EDM.

The most used material for micro-EDM electrodes is tungsten, due to its high stiffness and fusion temperature. On the market there are cylindrical electrodes down to Ø0.06 mm and tube electrodes (holed) down to Ø0.1 mm. Handling electrodes below Ø0.1 mm is almost impossible, but there are feeding systems for this purpose.

The manual collets are specially designed to clamp small diameters and have fine-regulation systems to reduce the rotation run-out. Apart from the collets, it is common to use ceramic guides that make it possible to work with longer electrodes that minimise the need for manual feeding. Optical microscopes are another usual accessory for micro-EDM machines, apart from being used to reduce the electrode run-out, they are also used to align the collet and the ceramic guide.

The machines have rotary spindles to ensure the highest circularity when drilling (<2 µm for Ø0.2 mm electrodes). In some cases the spindle rotation can be controlled (C axis) to produce shaped electrodes. The dielectric is usually oil, but some machines apply de-ionised water to drill higher aspect ratios in steel.

4.2 Micro Die-sinking EDM Applications

The main application for this process is the machining of high-aspect-ratio small holes (>Ø0.15 mm) for injection. A second important application is performing drills for subsequent wire threading in the WEDM process. Concerning the EDM-milling process, the application is mould machining in hard-to-machine materials.

5 THIN-WIRE EDM

The thin-wire EDM process (sometimes call micro-WEDM) is very similar to the conventional WEDM process. The wire electrodes that are used have smaller diameters (<0.050 µm) making it possible to machine miniaturised complex ruled surfaces with an aspect ratio greater than 10:1, and micrometric accuracy [26]. The machining systems are an evolution of conventional WEDM machines that achieve higher accuracy (1–3 µm, depending on the part height) in small travels and fine adjustable wire traction [27]. All those wires with a diameter smaller than 0.05 mm are considered thin wires. The spark generator is usually an RC type generator that can provide high-frequency and low-energy pulses.

The applied dielectric fluid is oil because it has a higher resistivity than water, reducing both the energy of the spark reaching the part and the gap width. Thus, it is possible to reach a higher precision and a smaller surface roughness. A disadvantage is that by using oil the productivity is 10 times lower.

The thin wires, due to their small section and mass, cannot be tensioned with high forces to reduce the effect of the process forces. All these forces cause wire vibration and deformation levels that are larger than in conventional WEDM. Process optimisation can be done choosing the right cutting strategies, parameters, dielectric flow and wire tension for each kind of material and each part height.

5.1 Wire Electrodes and Auxiliary Tools

The minimum machinable feature depends on wire diameter, wire tension, wire guiding and the skills of the operator to thread it correctly. Usually, the wire electrode is made of tungsten (Fig. 7, left), although there are wires made of molybdenum or brass-coated steel. The minimum market-available wire diameter was 0.030 mm (±1 μm), until last year, when two smaller dimensions entered the market: Ø0.025 and Ø0.020 mm. The limit is not in the wire manufacturing (Bedra presented some demonstrators of Ø0.015 mm wire in ISEM XIV) but in the machine's capability to work with such small wires (guides and tension). It is important to point out that the dimensional tolerances are similar to conventional wires (±2 μm for Ø0.25 mm wires), the tolerance/diameter ratio being worse for thin wires.

Wire guides are another important issue; most machines are designed to work with Ø0.030 mm, there are no existing consumables to use thinner wires. The wire guides are machined by laser and cannot be controlled better than conventional ones, the diameter and roundness errors being 1 to 2 μm. This makes the process less accurate than expected. Finally, wire threading is difficult to perform. In most commercial machines the automatic threading is only reliable up to Ø0.05 mm (some companies like Agie or Makino have a threading system for Ø0.020 mm), making manual threading a complex task that can last for ±10 minutes; this limits the industrialization of the process.

5.2 Thin-Wire EDM Applications

In thin-WEDM, the wire is continuously renewed and the process achieves high accuracy. It can machine any ruled surface but, when the machining is performed inside a part, a threading hole must be machined previously. The process can machine hardened materials and is used in the machining of precision features of moulds, dies and punches. It can also machine mechanical components (Figs.7 and 8), small connectors, etc.

6 CONCLUSIONS

All these technologies present important capabilities that can be applied mainly to the development of precision miniaturised moulds, punches and dies. Most of them keep a strong relationship with the corresponding conventional technologies, and this makes it easier for them to be assimilated by the metal-processing industry.

The limits of these technologies are not in their positioning accuracy, but in the development of improved tools and referencing systems. At present, all these processes are being actively researched and their introduction in some industrial sectors (surgical tools, car sector, etc.) has started the initiation of a strong market around them.

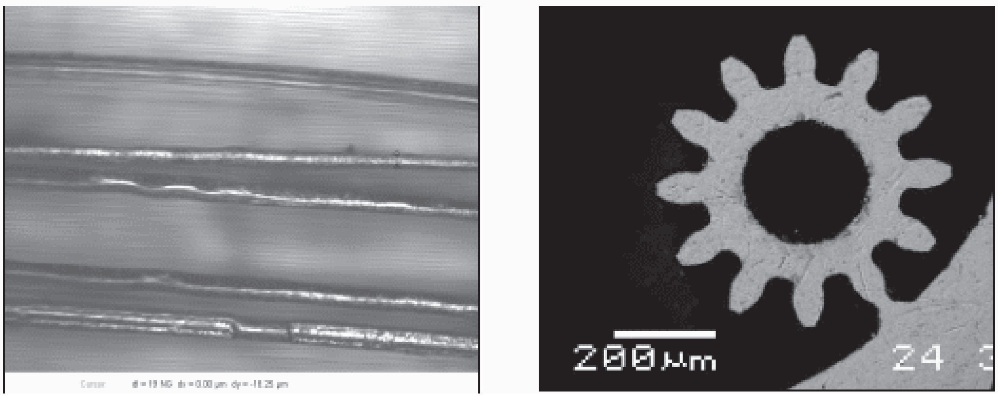


Fig. 7. *Used and new Ø0.030 mm tungsten wire; Ø0.5 mm nominal diameter gear cut by Ø0.030 mm WEDM.*

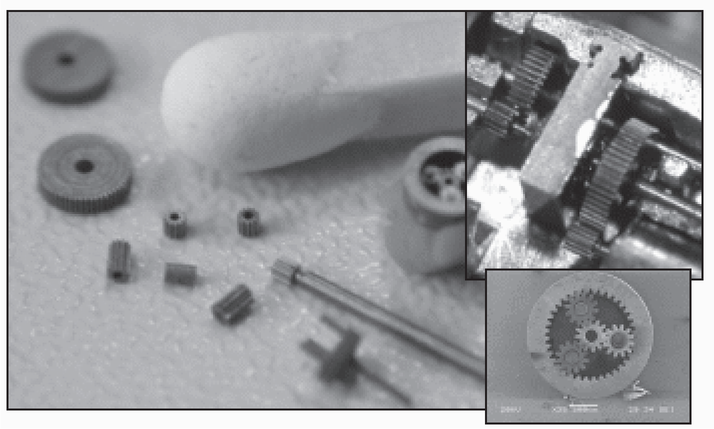


Fig. 8. *Thin-Wire EDM-ed components for a micro-car transmission*

7 REFERENCES

[1] Wechsung R. et al. (1998) Market analysis for microsystems, 1996-2002, A NEXUS Task Force Report. *Nexus Office* (eds). Grenoble.

[2] Wechsung R. et al. (2002) Market analysis for microsystems II, 2000-2005, A NEXUS Task Force Report. *Nexus Office* (eds). Grenoble.

[3] Bueno R., Corta, R., Herrero, A. (1999) Microtechnologies in Spain. *Semaine Nationale des Nano et Micro Technologies*. Menrt, París. Noviembre 1999.

[4] Bueno R., Corta R, Herrero A. (1999) MICROMACHINE: Perspectivas en torno a las máquinas, microfabricación y fabricación de precisión, *Fundación Tekniker*. Eibar.

[5] Masuzawa T. (2000) State of the art micromachining. Colibri A.G. (eds) *Annals of the CIRP 49-2*. Uitendorf, Switzerland, pp 473–488.

[6] Benjamin, R. J. (1983) Diamond machining applications and capabilities. *SPIE* Vol. 433, pp. 24-31, 1983.

[7] Weck M. et al. (1988) Performance assessment in ultraprecision micro-machining.*Annals of the CIRP*, 37/1/1988, p. 499.

[8] Moriwaki T. et al. (1990) Effect of cutting heat on machining accuracy in ultra precision diamond turning. *Annals of the CIRP*, 39/1/1990, p. 81.

[9] Evans C., Bryan J.B. (1991) Cryogenic diamond turning of stainless steel. *Annals of the CIRP* 40/1/1991, p. 571.

[10] Shimada S. et al. (2000) Suppression of tool wear in diamond turning of copper under reduced oxygen atmosphere. *Annals of the CIRP*, 49/1/2000, p. 21.

[11] Nakasuji T. et al. (1990) Diamond turning of brittle materials for optical components. *Annals of the CIRP*, 39/1/1990, p. 89.

[12] S. Asai S. et al. (1990) Measuring the very small cutting edge radius for a diamond tool using a new type of SEM having two detectors. *Annals of the CIRP*, 39/1/1990, p. 85.

[13] Herrero A., Bueno R. (2001) Development of a three axes travelling column ultra-precision milling machine, *Proceedings of the 10th ICPE*. Yokohama. Japan. 18-20 July, 2001.

[14] Spath D. et al. (2000) Micro-milling of steel for mould manufacturing - influences of material, tools and process parameters. *EUSPEN 2000*.

[15] Takeuchi Y. et al. (1996) Ultraprecision 3D machining of glass. *Annals of the CIRP*, Vol. 45/2/1996.

[16] L. Uriarte, A. Herrero, R. Oñate (2004) Fresadora de ultraprecisión de 3 ejes de columna móvil. XV Congreso de Maquinas-Herramienta y Tecnologias de Fabricacion. ISBN 931828-7-7. San Sebastian, October 2004.

[17] Weck M., y Fischer, S. (1997) Development of an ultraprecision milling machine. P*roceedings of the 9th IPES/4th UME*. Braunschweig. Alemania. 26-30 Mayo, 1997.

[18] Lucca D.A., Seo Y.W., Komanduri R. (1993) Effect of tool edge geometry on energy dissipation in

ultraprecision machining. *Annals of the CIRP*, 42/1/1993, p. 83.
[19] Masuzawa, T. (2001) Micro EDM, *Proceedings of the ISEM XIII* Vol I., p.3-19
[20] Masuzawa T., Tsukamoto J., Fujino M. (1989) Drilling of deep microholes by EDM. *Annals of the CIRP*, 38/1/1989, p. 195.
[21] Masuzawa T., Fujino M. Et al. (1985) Wire electro-discharge grinding for micro-machining. *Annals of the CIRP*, 34/1/1985, p. 431.
[22] S Piltz S., Uhlmann E. (2004) Micro machining of cylindrical parts by electrical discharge grinding. *ISEM XIV*.
[23] Zhao W., Yang Y. et al. (2004) A CAD/CAM system for micro ED-Milling of Small 3D Freeform Cavity. *ISEM XIV*.
[24] Bleys P., Kruth JP., Lauwers B. (2004) Sensing & compensation of tool wear in milling EDM. *ISEM XIV*.
[25] Beltrami I. (2004) Micro and nano electride-discharge machining. *ISEM XIV*.
[26] Klocke F., Lung D., Antonoglou G.. (2004) Using ultra thin electrodes to produce micro-parts with wire-EDM. *ISEM XIV*.
[27] Mu-Tian Y., Huang CW. Et al. (2004) Development of a prototype micro wire-EDM machine. *ISEM XIV*.

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Mikropreoblikovanje – Trenutno stanje in prihodnje zahteve

Microforming – Current Status and Future Demands

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Kovinskopreoblikovalno skupnost začenja zelo zanimati mikropreoblikovanje. To lahko razložimo z velikim številom novih uporab in izdelkov, ki so prišli na trg v zadnjih letih. Le-ti vsebujejo vse manjše geometrijske izmere, njihove serije pa so vedno večje. Do sedaj je bila večina teh izdelkov izdelanih s tehnologijami, ki so primerne za maloserijske izdelke. Analiza trga kaže na enakomerno rast potrebe po majhnih izdelkih in zato potrebo po novih tehnologijah, ki so primerne za velikoserijske proizvodnje. Preoblikovanje ustreza tem zahtevam, saj lahko dosega velike natančnosti in ima visoko produktivnost.

Namen tega prispevka je podati pregled trenutnih raziskav mikropreoblikovanja in prikaz zmožnosti te tehnologije. Analiza trenutnega stanja bo dala vpogled na področja, kjer so še vedno luknje v znanju in bi jih bilo treba zapolniti.

(Ključne besede: mikropreoblikovanje, stanja trenutna, zahteve razvoja)

Microforming technology is gaining increasing interest from the metal-forming community. This can be explained by the large number of new applications and products delivered to market in the past, yielding smaller and smaller geometrical dimensions of the final products and thus demanding the smallest specimens to be manufactured in large quantities. Up to now, most of these parts were being manufactured by machining technology, well suited to the production of small series. The analysis of the current market situation shows that the steadily increasing trend towards the smallest products is continuing in the future and thus requires new manufacturing technologies for large-quantity production. Forming technology seems to be well suited due to its high production output and high accuracy.

The aim of this paper is to give an overview of the current research activities related to microforming technology, showing microforming technology's capabilities and problems. The analysis of the current status will give a hint to existing gaps in knowledge and finally describe the future demands.

(Keywords: microforming, current status, future demands)

0 INTRODUCTION

The current production processing for the smallest metallic parts is mainly done using machining or electrochemical technologies, both well suited if small quantity, non-silicon production at a high level of precision level is required. Considering the trend of the past years, leading to smaller and smaller product dimensions and a rapid increase in the production numbers of micro-technical products - from a marked volume of 15 up to an estimated $35 billion in 2002 [1] - the main focus of the manufacturing industry is to be set to other production technologies, like metal forming, which is well-suited to mass production. In order to satisfy these demands, research activities in microforming technologies are being encouraged by a still growing number of research institutes in bulk and sheet/foil metal forming.

1 GENERAL

As mentioned by various authors ([2] and [3]), the forming of specimens with at least two dimensions at the sub-millimetre scale is subject to so-called size effects. They appear when scaling down the process and process dimensions from a conventional length scale to the micro-scale. Although it is required to scale down the process according to similarity theory [4], it is nearly impossible to apply this to all parameters. This can be explained by having a look at two key parameters: the grain size and the surface topography. If an upsetting test is scaled down from the macro-scale (e.g., billet diameter 4 mm, height 6 mm, mean grain size 4 μm, R_a = 1.2 μm) to the micro-scale (e.g., billet diameter 0.5 mm, height 0.75 mm) it is required by similarity theory to reach a mean grain size of 65 nm and a surface roughness of R_a = 0.15 μm. Due to the specimen production process and the material being unchanged, these values are hardly achievable. In addition to the described geometrical sources of the size effects there are, of course, effects due to physical sources [5]. A reduction of the part volume is subject to a reduction of the microstructural features (the number of defects, the number of grains) leading to a change in the failure probability distribution and finally to different plastic behaviour. Other influences are the change in the ratio between the surface and the volume as well as the increasing influence of other forces (Van der Waals and gravity). Depending on the forming process, the fraction of the influence of the parameters on the forming process is different, as will be shown in detail below.

2 BULK METAL FORMING

For investigations on the above-described size effects, various processes (e.g., can backward extrusion, full forward extrusion, double cup extrusion) concerning bulk metal forming have been investigated with respect to forming behaviour, shape building and scaling effects.

2.1 Cold forging

Since the most relevant parameters in forming processes describing the material behaviour are the flow stress and the flow curve, it is necessary to perform scaled standard tests to obtain these parameters that are valid at the micro-scale. Carrying out tensile tests using CuZn15, CuNi18Zn20 [6], copper [7] and aluminium [8] as well as upsetting tests using copper, CuZn15 and CuSn6 ([9] and [10]) two significant effects have been shown: a reduction of the flow stress when increasing the surface-to-volume ratio as well as an increasing process scatter (Fig. 1).

The first approach to describing the decreasing stresses was made by [11], introducing the so-called surface-layer model. Based on the assumption that grains positioned on a free surface have fewer constraints to fulfil than grains within the material, the local forming behaviour of the surface grains must be different. Dislocations induced by a deformation process are able to pile up at grain boundaries, but not at a free surface. Thus, lower hardening occurs in the region of the free surface. Decreasing the specimen size leads to an increasing share of surface grains and thus a lower integral flow curve.

In the case of the full forward extrusion process, scaled from an initial specimen diameter of 4 mm down to 0.5 mm, an increase in the relative punch force was detected, as shown in Fig. 2. A possible explanation for this effect could be the increasing friction with decreasing specimen dimensions. Fur-

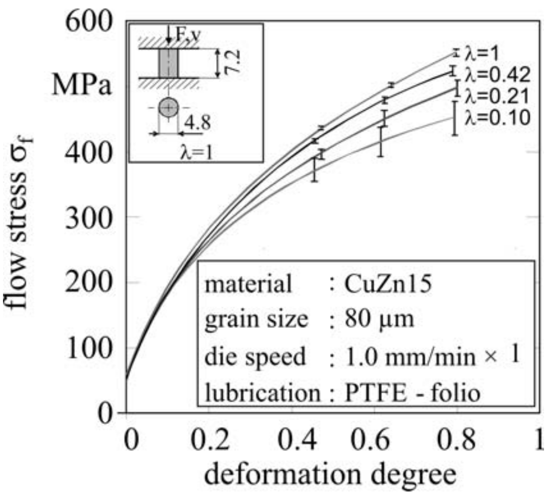

Fig. 1. *Size dependency of the material properties*

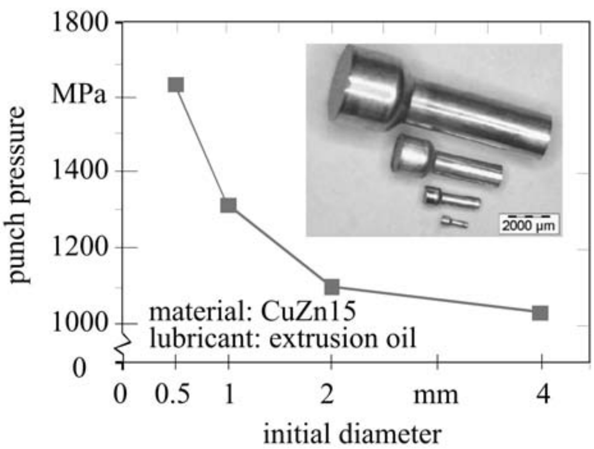

Fig. 2. *Full Forward extrusion*

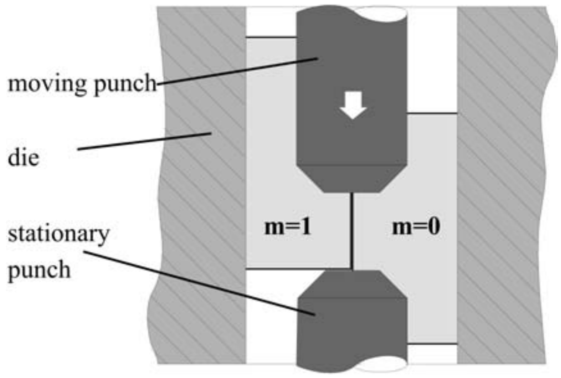

Fig. 3. *Setup of the DCE te*st

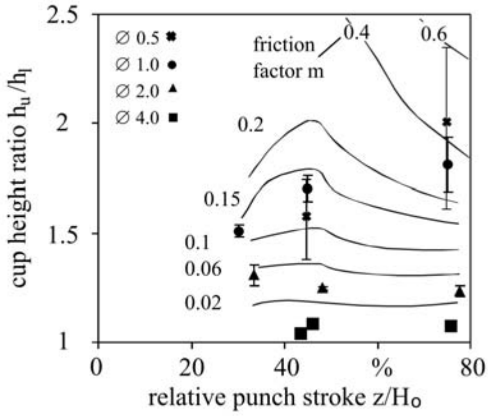

Fig. 4. *Results of the DCE test and the curves of constant friction determined by numerical identification using a FE simulation*

ther tests to study the effects of miniaturization on friction were made by Messner, using the ring compression test [12]. The increase of friction when decreasing the specimen size was analyzed in a more detailed way by [13] using the double cup extrusion (DCE) test, which was first proposed by [14] and applied by [15].

In this test – due to the large plastic deformation being well suited for demonstrating the metal forming processes – a cylindrical billet is positioned between a stationary and a moving punch. Theoretically, in the case of zero friction (m = 0), both cups are supposed to have the same height, but the higher the friction gets, the greater is the height of the upper cup (Fig. 3). Thus, the change in the ratio between the upper and the lower cup is able to characterize the change in the friction conditions. If absolute values of the friction factors are requested, the method of numerical identification can be used (see Fig. 4).

Experimental investigations on frictional size effects have been performed by [13], scaling down specimens that are geometrically similar from a diameter of 4 to 0.5 mm with a ratio of diameter to height $D_0/H_0 = 1$. As can be seen in Fig. 4, the friction increases with decreasing specimen size from a friction factor of about m = 0.02 for the largest specimen up to m = 0.4 for the smallest specimen.

An attempt to describe the frictional behaviour on a topographical level is given by a mechanical-rheological model [13], considering the theory of open and closed lubricant pockets. If a forming load is applied to a specimen surface, the roughness peaks start to deform plastically. From this point on the lubricant is either trapped and pressurized within closed areas, α_{CL}, or squeezed out if a connection to the edge of the surface exists. The forming load can be transmitted into the specimen either by the pressurized lubricant or the flattened asperities.

Due to the scale-invariant production process of a specimen and thus an assumed scale-independent surface topography, the area width where open lubricant pockets appear is constant when scaling down the geometry. Additionally, the area of closed lubricant pockets is reduced and thus the real contact area, α_{RC}, is decreased. This leads to an increase in the friction factor. Further independent investigations have confirmed these results [16].

Based on the mechanical-rheological model, further investigations were performed in order to describe the size-dependent friction factor analytically [17]. Using Wanheim/Bay's [18] friction law and the geometrical boundary conditions, it can be shown that the dependency of the surface topography on the friction factor changes, as it is in good agreement with the experimentally obtained results (see Fig. 5 a-c).

Investigations on micro-extrusion processes with high aspect ratios and large strains have shown a significant dependency of the forming results on the material structure ([2] and [3]). In the case of the backward can extrusion process, the cup geometry was chosen with a cup-wall thickness of about 8 microns. An SEM analysis of the shape building reveals a strong influence of the material structure on the shape building, demonstrated in Fig. 6 by an uneven cup height.

Further investigations using micro-hardness measurements to evaluate the local material flow also confirmed the above-described results. This effect

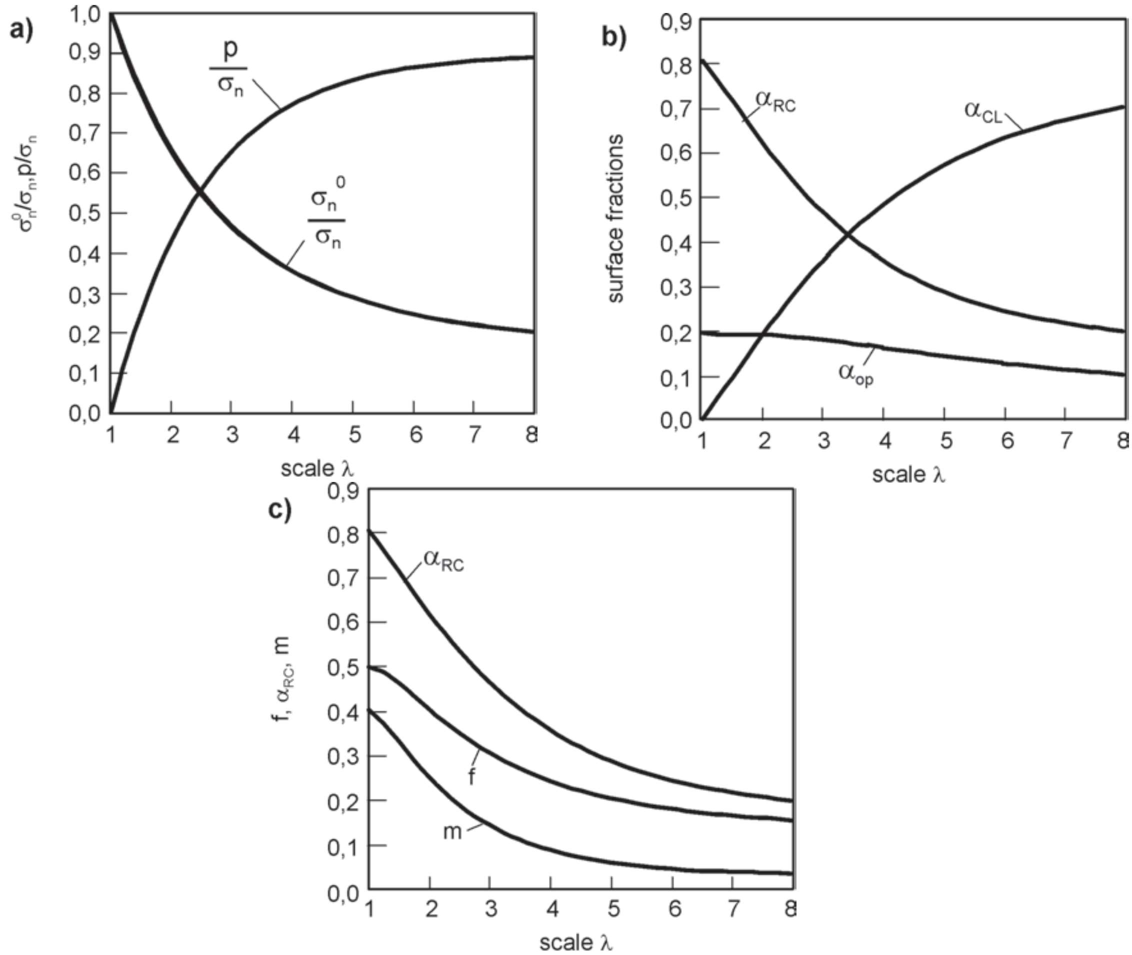

Fig. 5. *Effect of scaling factor λ on p and σ_n^0 normalized to σ_n (a), on α_{RC}, α_{CL} and α_{OP} (b), and on m, f and α_{RC} (c)*

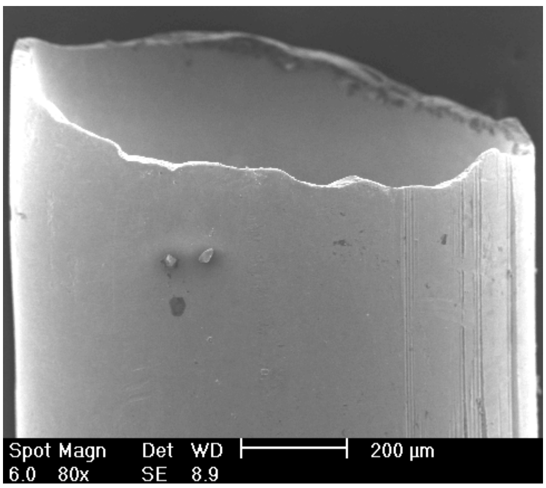

Fig. 6. *Combined full forward cup backward extrusion: effect of specimen size and microstructure on the shape of the extruded parts*

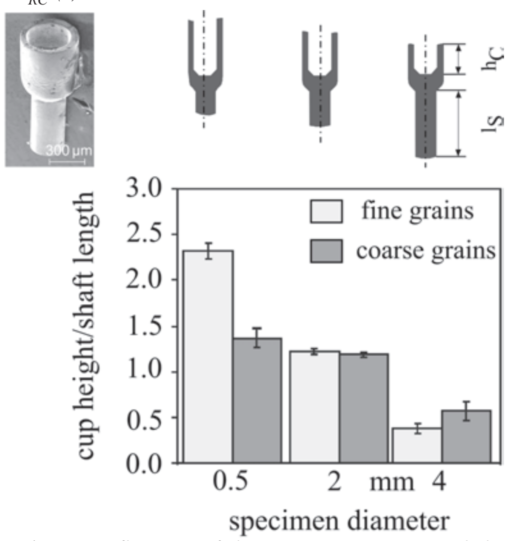

Fig. 7. *Influence of the microstructure and the friction on the shape building using a combined extrusion process*

is less distinct in the case of fine-grained material than in the case of coarse-grained material. In the case of grains being larger than the feature size, they are forced to flow into the smaller features and thus the dependency of the size and orientation causes an uneven cup height.

As expected from the DCE test results, the increase of the friction factor when scaling down leads to an increase of the ratio between the cup height and the shaft length for both cases: coarse-grained and fine-grained material.

The minor increase in the case of coarse grains, shown in Fig. 7, can be explained by the fact that the grain size is in the same range as the feature size. Thus, the material behaviour cannot be considered as polycrystalline; it is easier for the material to flow in the shaft than into the cup.

2.2 Warm forging

An important size-effect at the micro-scale is the large scatter of the process results in the case of cold forging, preventing any application in serial manufacturing processes.

As is known from forming at the conventional length scale, an increase in the forming temperature leads to the activation of additional sliding systems in the material, and thus a decreasing flow stress and a better formability.

To quantify the influence of the elevated temperature on the flow stress at the micro-scale, upsetting tests at different temperatures (20°C, 100°C, 200°C and 300°C) were performed [19]. The material for the tests was CuZn15 and X4CrNi1810 steel. As can be seen in Fig. 8, a significant decrease of the flow curve is achieved, as well as a decrease in the process scatter.

Further investigations on the backward can extrusion process [20] have confirmed these findings. A detailed analysis of material hardening was performed using a micro-hardness measurement system. This enables a strain measurement indirectly on a deformed specimen at high resolution (see Fig. 9). Therefore, the measurement load is set to 20 mN, yielding a minimum distance between two measurement points of 40 microns. The analysis of the local hardening shows clearly that, in contrast to the forming process performed at room temperature, the plasticized area at elevated temperatures is smaller and more concentrated around the punch. Thus, it can be stated that the forming behaviour of the material at elevated temperatures is closer to the one obtained in the macro-case, reducing the characteristics at the micro-scale.

2.3 Coining

Studies concerning the coining of aluminium sheet metal have been performed by Ike and Plancak [21]. Using dies with hole diameters from 0.05 to 1.6 mm, half hard commercially pure aluminium of 2-mm thickness and 30-mm diameter, the coining re-

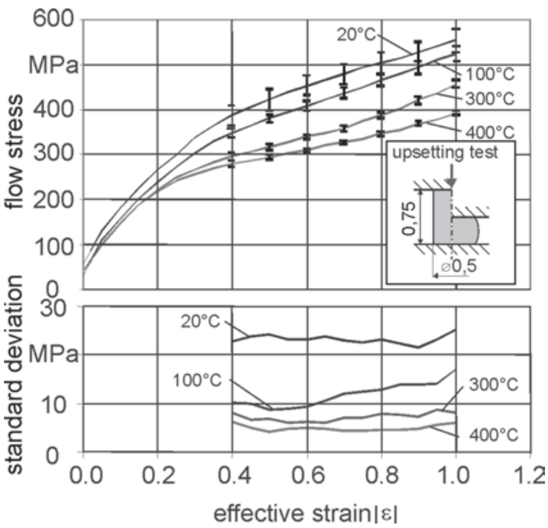

Fig. 8. *Dependency of the flow curve on temperature using CuZn15*

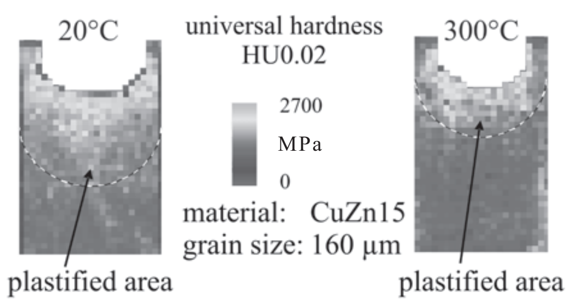

Fig. 9. *Hardness measurement of a formed specimen at elevated temperature*

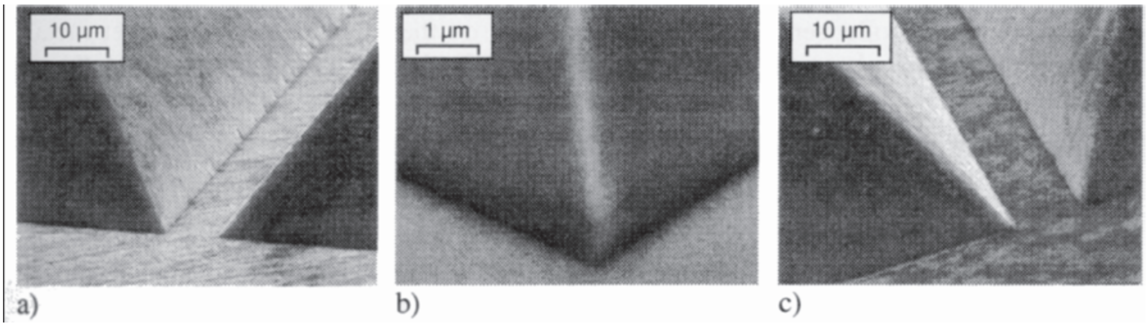

Fig. 10. *Micro-geometry after cold embossing a) aluminium, b) brass, c) stainless steel (IWU)*

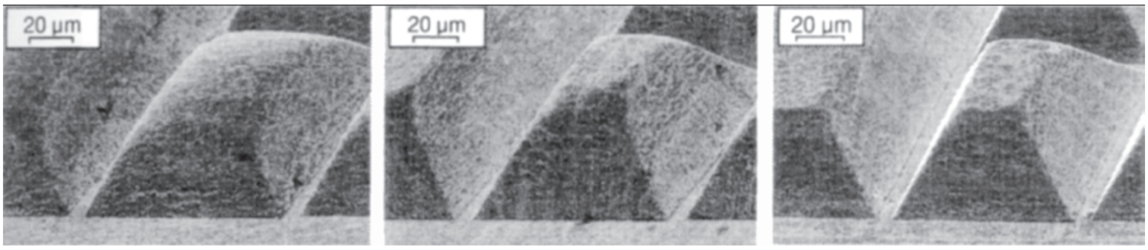

Fig. 11. *Micro-geometry in ZnAl after superplastic coining (IWU)*

sults were evaluated in terms of aspect ratio, the radial position of the hole and the die and the emerging forming load. It was shown that the beginning of plastic flow is independent of the radial position of the hole, but the height of the pins is clearly bound to the position of the holes and its diameter.

At LWP Saarbrücken, Germany [22], the coining of the smallest cavities with a thickness of about 400 microns has been investigated. The results show that in the case of micro-coining the influence of the tool geometry and the tool deflection on the forming results must be considered. This is due to the relatively high nominal stresses (a minimum of three times the flow stress of the coined material) leading to a large influence on the tool system: tool deformation, tool deflection and tool damage.

The aim of the investigations on coining technologies at IWU Chemnitz was to establish this technology for the production of geometrically defined micro-structures for applications in the fields of micro-fluidics, micro-optics and information technology ([23] and [24]). In a first set of experiments the tools were made out of single crystal silicon with an almost smooth surface (Fig. 10). Thus, it was possible to create structures of 100 microns with radii of some 100 nm in aluminium, copper, brass and steel.

The analysis of the coined material shows that the shape of the rim strongly depends on the material. While aluminium shows a maximum bulging of 30% of the coining depth, steel shows a maximum of only 5%. Using a fine-grained ZnAl alloy in a superplastic state at 250°C (Fig. 11), high precision and good surface quality are achieved at low compressive stresses of 25 MPa.

3 SHEET METAL FORMING

Besides bulk metal forming, micro-sheet metal forming plays an increasingly important role, especially in the electronics industry. The smallest lead frames, characterized by lead widths of about 150 microns, or the smallest connectors made by punching, blanking and bending, are some examples.

3.1 Cutting

Basic investigations on the effects of miniaturization on the blanking process were first performed by Kals [6]. It has been shown that the normalized forming force is constant while scaling down the sheet thickness due to a lack of free surface. When the sheet thickness is below a certain value, the forming force and the ultimate shear strength increases. This effect is explained in detail in Section 3.2.

Other investigations have shown that there is a dependency between the tool and process parameters and the accuracy of the produced lead frames. The deflection of the leads in the plane of the sheet increases with the decreasing width of the lead. The deflection is also influenced by the different clearances between the tool and the die in a progressive tool. They also showed that increasing the strip-holder pressure has a positive effect on the accuracy in most cases. Also, the dynamic behaviour of the tool affects the accuracy [25], e.g., increasing the blanking speed results in a reduced accuracy. The performed experiments have additionally shown that increasing the strip-holder force clearly improves the quality of the product. Other investigations on the deflection of a punch during the blanking process [26] have shown an increase when the punch is eccentric, relative to the die.

A particular blanking process, the so-called dam-bar cutting, was investigated in [27] and [28]. This is a mechanical trimming process, removing the dam-bar between the leads after the IC package is encapsulated. Due to the special shape of the specimen, which is rectangular around the IC, investigations have to be performed considering the anisotropic behaviour of the material in the shearing line. Further investigations of different materials have shown that an increase in the angle α reduces the maximum cutting forces, but leads to an increasing burr height.

An important aspect for industrial production is the life of the tool. Therefore, investigations in [28] were performed to show the dependency of the punch forces and thus the tool stresses on the clearance between the punch and the die and the hardness of the used sheet material. While tools made of tungsten carbide (WC) have the longest life time, the tools made of bare HSS show the highest wear. An improvement can be reached by using coatings like TiN or plasma-nitriding. In this case, tools made of steel and WC were compared according to their tool life in an industrial production process for the blades of shavers. While the first only reaches a quantity of 50,000 parts, the latter exceeds 1.15 billion parts. Thus, it is obvious that the use of the more expensive WC as tool material (a factor of 1.8 compared to steel) is more economical than the use of steel.

3.2 Bending

In industrial applications, micro-bending processes are frequently used in the case of spring, clamp or lead frame production. Considering the characteristics of this process, i.e., that the part dimension is close to the sheet thickness, conventional FE simulation programs, which assume plain-strain conditions in the deformed area, are not applicable. In order to overcome this, a first model was developed that makes possible a calculation under plane-stress conditions [29], and there is an improved version that considers the anisotropy of the material [30].

Basic investigations on the relationship between miniaturization and the bending process were first made in [6]. The analysis of the experimental results has shown that the process forces relative to the size decrease with miniaturization in the case of small grains. In the case of large grains (only a few grains over the sheet thickness), the force increases again.

This effect has been confirmed by investigations in [35], performing scaled bending experiments on metallic foils. It was shown that depending on the thickness of the sheet (scaled from 200 microns down to 25 microns) and on the material structure, the bending moment and thus the spring-back angle increases when scaling down. This confirms the previously described theory of strain-gradient plasticity ([31] to [34]).

When scaling down the foil thickness, two contrasting effects appear: the effect of the reduction of the flow stress due to an increasing share of surface grains on the overall volume, and the effect of an increasing flow stress caused by the increasing density of geometrically necessary dislocations. When the foil thickness gets smaller, the latter effect gains a larger influence, resulting in both a higher normalized bending moment (see Fig. 12) and a higher spring-back angle.

3.3 Deep drawing

Deep drawing processes on the conventional length scale are frequently used to produce cups, housings, etc. Basic investigations at the micro-scale were performed by [35]. It was shown that varying the drawing clearance has an influence on both the shape building (see Fig. 13) and the maximum drawing ratio. Independent investigations by Hirt [36] have confirmed these findings.

Further investigations made by Vollertsen [37] evaluated the friction conditions during micro-cup deep drawing. For this approach, the rather complex deep drawing process has been simplified us-

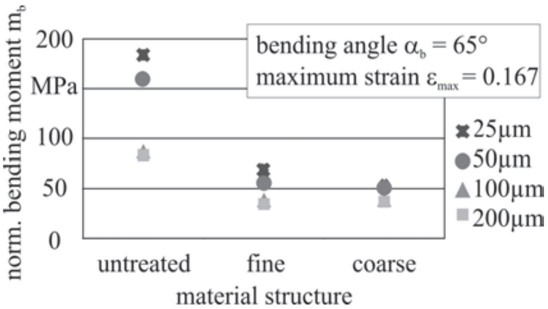

Fig. 12. *The dependence of the bending moment on the sheet thickness and the material structure (LFT)*

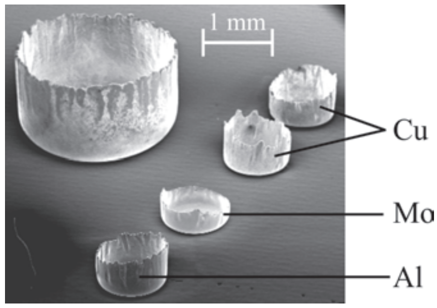

Fig. 13. *Shape of deep drawn cups using different materials (pure copper, molybdenum, aluminium)*

ing a strip deep drawing process with a two-dimensional stress state. The friction coefficients are calculated analytically from the experimental data.

4 SIMULATION

The simulation of the forming processes gains increasing interest even at the micro-scale. Whilst at the conventional length scale, simulation methods are commonly used for the process design. At the micro-scale the simulation programs do not seem to be applicable because of their inability to consider scaling effects.

Sarma et al. [38] carried out FE simulations discretizing the material in different grains, whose forming behaviour depends on the orientation of the crystal lattice associated with each grain and on the critical resolving shear stress parameter of the slip systems. The plastic deformation of the grains is described by modelling grains with different slip plains. Based on Schmid´s law, slip starts when the resulting shear stress reaches a critical value. The material parameters are obtained by fitting the crystal plasticity model to experimentally verified data. Ku et al. [39] did not model the real shape of each grain, but they also discretized the material in grain elements, which are represented by six node elements each consisting of two quadrilaterals. Each quadrilateral is built up of two four-node elements. They also introduced a new so-called grain-boundary element, which is used for the investigation of the sliding and extension between grains. An alternative approach to studying the influence of miniaturization on micro-forming processes by means of a numerical simulation is shown by Engel et al. [40], introducing the so-called surface-layer model. The geometry of the workpiece is divided into two areas: the surface area and the inner area. Within the simulation model two different flow curves are assigned to the two areas. Due to the slight grain-boundary influence on the grains near the surface, the behaviour of these grains resembles that of single crystals, while the behaviour of grains within the material is equal to polycrystals. The transition between the flow stress, $k_{f,I}$, of the inner area and the free surface area, $k_{f,FS}$, is described in a discontinuous way. This approach explains the reduction of the integral flow stress with the decreasing size of the workpieces, but it is not able to show the influence of the grain structure on the scatter of the forming factors. Another disadvantage is the result of the unsteadiness of the flow stress at the transition from the inner material area to the surface area [41]. Based on the above-described surface-layer model, another approach has been realized by considering the material structure in a simulation programme [42] (see Fig. 14). Several techniques for the computational generation of grain structures have been developed. Among these, Monte-Carlo-Potts models, vertex tracking, front tracking, Voroni tessellation, phase field approaches and cellular automata are examples for different grain-generation technologies. Cellular automata are algorithms to describe the evolution of complex systems by using transformation rules. They are specified by a set of deterministic or stochastic transformation rules that are applied to the sites of a lattice. The lattice is typically regular and defined by a number of points that carry the actual values of the state variables, e.g., particle density. Probabilistic cellular automata also allow a statistical description of grain growth [43]. It has been shown that the so-called mesoscopic model is able to consider scaling effects like the decrease of the flow stress when scaling down the process as well as the increase of the process scatter.

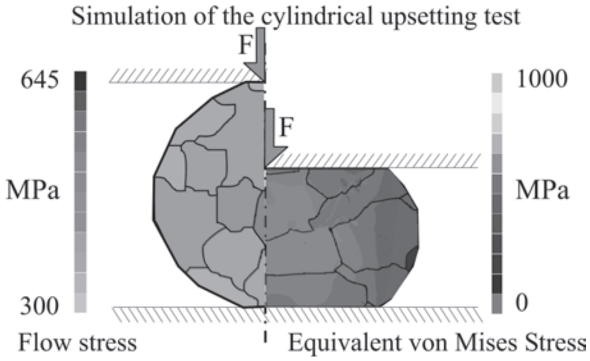

Fig. 14. *Mesoscopic model*

5 CONCLUSIONS

As can be seen from the large amount of research activities in the field of microforming, some aspects are already identified and described, but several problems are still unsolved. Thus, only a few applications in this relatively wide field are already industrially applicable (especially in the field of microelectronics), other applications are close to a breakthrough. In most research areas great effort has been made to identify the size effects, now these effects must be described and solutions must be proposed to solve the problems that occur. This can be done purely academically, but considering the great advantage of the forming process for serial manufacturing, it will also be reasonable to start future research activities together with industry, not only to enhance process knowledge but also its usability and stability.

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6 REFERENCES

[1] R. Wechsun et al. (2002) Nexus market analysis for microsystems, 2000-2005. Nexus Task Force Market Analysis. *Wicht Technologie Consulting*. München.

[2] Engel, U., Tiesler, N., Eckstein, R. (2001) Microparts - a challenge for forming technology. Kuzman, K. (edtr): *ICIT 2001 3rd Int. Conf. on Industrial Tools*, Celje, Slovenia, 31-39.

[3] Engel, U., Eckstein, R. (2002) Microforming - from basic research to its realization. *J. Mater. Process. Techn.* 125-126(2002) 35-44.

[4] Pawelski, O. (1992) Ways and limits of the theory of similarity in application to problems of physics and metal forming. *J. Mater. Process. Technolog.* 34 (1992) 19 - 30.

[5] Vollertsen, F., Schulze-Niehoff H., Hu, Z. (2004) State of the art in micro forming. *Proceedings of the 1st International Conference on New Forming Technology*, Harbin, China, pp. 17 - 28.

[6] Kals, R.T.A. (1999) Fundamentals on the miniaturization of sheet metal working processes. *Meisenbach*.

[7] Kocanda A., Prejs, T. (2000) The effect of miniaturization on the final geometry of the bent products. Pietrzyk et al. (Eds.): *Metall Forming 2000, Proceedings of th 8th International Conference on Metal Forming*, Rotterdam, A.A.Balkema, 375-378.

[8] Raulea, L.V., Govaert, L.E., Baaijens, F.P.T. (1999) Grain and specimen size effects in processing metal sheets. Geiger, M. (Ed.): A*dvanced Technology of Plasticity 1999. Proceedings of the 6th International Conference on Technology of Plasticity Nuremberg*, September 19-24, 1999, Berlin, Springer, Vol. II, 939-944.

[9] Picard, P.; Michel, J.F. (1999) Characterization of the constitutive behaviour for very small components in sheet metal forming. *Proceedings of the 2nd ESAFORM Conference on Material Forming*, Guimarães, Portugal, 1999, 169-170.

[10] Geiger, M., Engel, U., Vollertsen, F., Kals, R., Meßner, A. (1994) Metal forming of microparts for electronics. *Production Engineering* 2 (1994) 1, 15-18.
[11] Engel, U., Meßner, A., Geiger, M. (1996) Advanced concept for the FE-simulation of metal forming processes for the production of microparts. *Advanced Technology of Plasticity 1996. Proceedings of the 5th International Conference on Techn. of Plasticity Ohio*, Vol. II, 903-907.
[12] Engel, U., Messner, A., Tiesler, N.: Cold forming of microparts – Effect of miniturization on friction. Chenot, J.L. et al (Eds.): *Proceedings of the 1st ESAFORM Conf. on Materials Forming*, Sophia Antipolis, France, 77-80.
[13] Tiesler, N., Engel, U., Geiger, M. (1999) Forming of microparts – Effects of miniaturization on friction. Geiger, M. (Ed.): *Advanced Technol. of Plasticity, Proc. Of the 6th Int. Conf. on Technology of Plasticity ICTP 1999*, 19-24 Sep 1999, Nuremberg, Germany, Berlin, Springer, Vol. II, 889- 894.
[14] Geiger, R. (1976) Der Stofffluß beim kombinierten Napffließpressen. Berichte aus dem Institut für Umformtechnik der Universität Stuttgart Nr. 36, *Verlag Girardet Essen*.
[15] Buschhausen, A., Weinmann, K., Lee, J.Y., Altan, T. (1992) Evaluation of lubrication and friction in cold forging using a double backward-extrusion process. *Journal of Materials Proc. Techn.*, 33 (1992), 95-108.
[16] Tiesler, N., Engel, U. (2000) Microforming - effects of miniaturization. Pitrzyk, M. et al. (Eds.) *Proceedings of the 8th International Conference on Metal Forming*, Rotterdam, A.A. Balkema, 355-360.
[17] Engel, U. (2004) Tribology in microforming. *Proc. 2nd Int. Conf. On Tribology in Manufacturing Processes ICTMP*. Nyborg, Denmark, June 15-18, 2004. Vol. 2, 549-60, to appear in Wear (2005).
[18] Bay, N. (1987) Friction stress and normal stress in bulk metal forming processes. *J. Mech. Work. Technol.* 14(1987)2, 203.
[19] Process characterization and material flow in microforming at elevated temperatures (2004) *J. Manuf. Processes*, 5 (2004) 1.
[20] Egerer, E., Engel, U. (2004) Process characterization and material flow in microforming at elevated temperatures. *J. of Manuf. Proc.* 5(2004)1, 11-16.
[21] Ike, H., Plancak, M. (1999) Controlling metal flow of surface microgeometry in coining process. Geiger, M. (Ed.): *Advanced Technol. of Plasticity, Proc. Of the 6th Int. Conf. on Technology of Plasticity ICTP 1999*, Nuremberg, Germany. Berlin, Springer, Vol. II, 907- 912.
[22] Thome, M., Hirt, G., Ellert, J. (2005) Metal flow and die filling in coining of microstructures with and without flash, *Proc. of the International Conference on Sheet Metal 05*, pp. 631 - 639.
[23] Schubert, A., Burkhardt, T., Kadner, J., Neugebauer, R. (1999) High precision embossing of metallic parts with microstructure. McKeown, P. et al (Eds.): *Precision engineering – nanotechnology. Proceedings of the 1st International Euspen Conference*, Aachen, Shaker, Vol. I, 530-533.
[24] Schubert, A., Böhm, J., Burkhardt, T. (2000) Mikroprägen - Herstellen metallischer Mikrostukturbauteile durch Kaltprägen. *wt* 90 (2000) H. 11/12, 479-483.
[25] Jimma, T., Sekine, F., Sato, A. (1990) Effects of dynamic behavior of tools on blanking of electronic machine parts. *Advanced Techn. of Plast.*, Vol. 3, 1990, 1459-1464.
[26] Doege, E. (1996) Optimierung von Mikroschneidverfahren zur Herstellung von Kontakten für die Halbleitertechnik. *Report, DO 190 / 96-1, DFG*, Hannover.
[27] Lee, W.B., Cheung, C.F., Chan, L.K., Chiu, W.M. (1997) An investigation of process parameters in the dambar cutting of integrated circuit packages. *J. of Materials Processing Technology* 66 (1997), 63-72.
[28] Cheung, C.F., Lee, W.B., Chiu, W.M. (2000) An investigation of tool wear in the dam-bar cutting of integrated circuit packages. *Wear* 237 (2000), 274- 282.
[29] Chan, K.C., Wang, S.H. (1999) Theoretical analysis of springback in bending of integrated circuit leadframes. *J. of Materials Proc. Technology* 91 (1999), 111-115.
[30] Chan, K.C., Wang, S.H. (1999) The grain shape dependence of springback of integrated circuit leadframes. *Materials Science and Engineering* A 270 (1999), 323-329.
[31] Ashby M.F. (1970) The deformation of plastically non-homogeneous materials. *Phil. Mag.* 21 (1970) 399-424.
[32] Fleck N.A. and Hutchinson J.W. (1997) Strain gradient plasticity. *Adv. Appl. Mech.* 33 (1997) 295-361.
[33] Fleck N.A. and Hutchinson J.W. (2001) A reformulation of strain gradient plasticity. *J. Mech. Phys. Sol*. 49 (2001) 2245-2271.

[34] Michel J.-F. and Picart P. (2002) Modelling the constitutive behaviour of thin metal sheet using strain gradient theory. *J. Mater. Proc. Technol.* 125-126 (2002) 164-169.
[35] Geiger, M., Engel, U., Eckstein, R., Tiesler, N. (2004) Umformtechnische Herstellung metallischer Kleinstteile. Feldmann, K., Geiger, M. (Hrsg.): *SFB 356 Produktionssysteme in der Elektronik.* Bamberg, Meisenbach, S. 33-72.
[36] Justinger, N., Witulski, H., Hirt, G.. (2004) Experimental and numerical investigation of miniaturisation in deep drawing, *Proc. of the 10th International Conference on Metal Forming*, Krakow, pp. 693 - 699.
[37] Hu, Z., Vollertsen, F. (2004) Friction test for deep drawing with respect to size-effects, P*roc. of the 1st International Conf. on New Forming Techn.*, Harbin, pp. 153 - 159.
[38] Sarma, G., Radhakrishnan, B., Dawson, P. (2002) Mesoscale modeling of microstructure and texture evolution during deformation processing of materials. *Advanced Eng. Materials* 4 (2002) 7, 509-514.
[39] Ku, T.W., Kim, D.J., Kang, B.S. (2002) Finite element analysis and experiments of milli-part forming of trip bending using grain element. *Journal of Materials Processing Technology*, 125-126 (2002), 512-517.
[40] Engel, U., Messner, A., Geiger, M. (1996) Advanced concept for the FE-simulation of metal forming processes for the production of microparts. Altan T. (Edtr.): *Advanced Techn. of Plasticity 1996*, Vol. II, 903-906.
[41] Raabe, D. (1998) Computational materials science: The simulation of materials microstructure and properties. *Wiley-VCH*, Weinheim, Germany, 201-204.
[42] Geißdörfer, S. Engel, U. (2004) Mesoscopic model - Simulation of size effects in microforming. Jan Kusiak et al (Edtrs): *Proceedings of the 10th International Conference on Metal Forming 2004*, Krakow, 19.-23.09.2004, GRIPS' Sparkling World of Steel Vol. 1: Proceedings, No. 3, GRIPS media GmbH, 2004 pp 699-703.
[43] Mehnert, K., Klimanek, P. (1997) Grain growth in metals with strong textures: Three-dimensional Monte-Carlo simulations. *Computational Materials Science* 9 (1997), 261-266.

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Integrirano oblikovanje izdelkov s področja drobnih elektromehanskih izdelkov

Integrated Design of Mycro-Electro-Mechanical Systems

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Ta prispevek želi najprej opredeliti postopek oblikovanja s področja izdelkov drobnih elektromehanskih sistemov. V tem delu želimo prikazati, kako nasloviti izdelovalnost. Le-to vsebuje znanje izdelovalnih postopkov, ki vodijo do izvedbe teh izdelkov (osredotočili se bomo na izdelke predvsem iz elektronske industrije). Nato si bomo ogledali glavne vrste metodologij oblikovanja, da bi razumeli, kako lahko upoštevamo izdelovalne tehnologije obenem pa so predstavljena še računalniško podprta orodja za te metodologije. Končujemo pri potrebah specifikacij za metodologije oblikovanja, ki bi ponudile oblikovalcem večjo neodvisnost od proizvodnih omejitev.

(Ključne besede: MEMS, DFM, omejitve proizvodne, metodologije oblikovanja)

This paper is a first attempt to qualify the design process in the field of micro-electro-mechanical systems products. Through this study we try to analyse how the issue of manufacturability is addressed. This requires an understanding of the specificities of the manufacturing process involved in the realization of these products (we focus on a process derived from the electronics industry). Then we look at the main design methodologies to understand how the manufacturing can be taken into account. Computer-aided tools associated to these methodologies are presented at the same time. Finally, we conclude on the need for specifications for the design methodology that would provide designers with greater independence from manufacturing constraints.

(Keywords: MEMS, DFM, manufacturing constraints, design methodology)

0 INTRODUCTION

MEMS (micro-electro-mechanical systems) are small components built of both electronic and mechanical parts. Their sizes (whole or part) range from a few micrometers to millimetres. A detailed taxonomy of microproducts can be found in [1]. A few MEMS are already integrated in mass-market products (automotive, cellular phones, ink-jet printers, PDA, etc.) but major potential applications are still to come.

MEMS are fundamentally multidisciplinary devices, and so are the design teams. Hence, designers from different disciplines need to communicate efficiently, but also have to collaborate with manufacturing experts. This last point is all the more important since micro-manufacturing processes are often unfamiliar to the designer in charge of the mechanical part. This lack of knowledge combined with the R&D context involves, most of the time, a traditional design approach for new products, based on "top-down" methodologies. This approach does not support collaborative design and implies many "build and test" iterations, which increase the time to market and product costs. In this paper we will try to describe design methodologies that are advocated to deal efficiently with the problem of manufacturability.

The next section is dedicated to a brief overview of the most representative manufacturing processes in order to have a better knowledge of what kind of constraints the designers have to deal with.

1 MEMS MANUFACTURING PROCESSES

The main manufacturing processes used in the micromachining of MEMS are derived from the silicon industry, with all electronic and mechanical parts being realized at the same time. Indeed, processes must be compatible with Very Large Scale Integration (VLSI) technologies: for instance, during the manufacturing sequence, the temperature should not exceed a certain value to avoid any alteration of the electronic parts. In general, a multiphysics aspect with strong coupling at this scale level will greatly influence the design process [2].

MEMS are built from silicon wafers by a sequential process consisting of stacking up layers of materials with appropriate geometries. Thus, the third dimension is not achieved in one step, but results from the whole sequence. The manufacturing operations are based on whether chemical or physical principles applied to the wafers. They can be broadly divided into three main processes, which are: additive processes, selective processes and etching processes. Patterns are created on the surface, or in the bulk, of the silicon wafer by selecting thin films previously deposed, and then etching processes remove material that has been selected. The organization of these three processes constitutes a step of the global manufacturing process, and one of the difficulties in MEMS manufacturing is to organize these steps in a manufacturing sequence. Indeed, processes used in a step should not deteriorate the material previously that is deposed, selected and etched.

1.1 Additive processes

The first building block in MEMS processing is the addition of thin films of material with a thickness between a few nanometres and about 100 micrometers. Additive technologies can be classified into two groups: addition that happen because of a chemical reaction or addition that happen because of a physical reaction.

1.1.1 Chemical Reaction

These processes exploit the creation of solid materials directly from chemical reactions in gas and/or liquid compositions or with the substrate material. The main processes are chemical vapour deposition, electrodeposition, epitaxy and thermal oxidation.

Chemical Vapour Deposition (CVD) The substrate is placed inside a reactor to which a number of gases are supplied. A chemical reaction takes place between the source gases and produces a solid material with condenses on all surfaces inside the reactor, including the substrate. The two most important CVD technologies in MEMS are:

Low-Pressure CVD produces layers with excellent uniformity of thickness and material characteristics and deposits films on both sides of at least 25 wafers at a time, but the deposition temperature is higher than 600°C.

Plasma-Enhanced CVD can operate at lower temperatures (down to 300°C), but the quality of the films tends to be inferior to LPCVD processes. Moreover, most PECVD processes can only deposit the material on one side of the wafers, at 1 to 4 wafers at a time.

A variety of materials can be deposited with CVD technologies; however, some of them are less popular with fabs because of hazardous the by products formed during the chemical reaction (Figure 1)

Example : Thick and smooth amorphous Si film of 2 μm without hillocks was obtained at a low temperature of 300°C by PECVD technology [3]. Fabrication of a suspended MEMS microstructure is thus possible (Figure 2)

Electrodeposition. The substrate is placed in a liquid solution (electrolyte) and requires an electrical potential to provide a chemical redox resulting in the formation of a layer of material on the substrate. This process is typically restricted to electrically conductive materials and it is well suited for making films of metal, such as gold, copper and nickel. The films can be made in any thickness from ~1μm to >100μm.

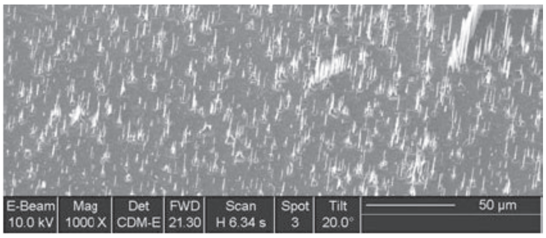


Fig. 1. *Example of bi-product "grass" formed by CVD process*

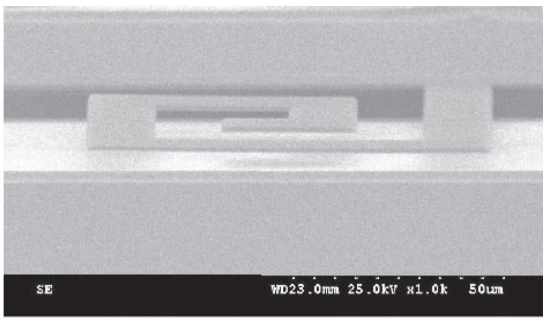


Fig. 2. *Suspended Si microstructure*

Epitaxy. If the substrate is an ordered semiconductor crystal (i.e., silicon, gallium, arsenide), it is possible with this process to continue building on the substrate with the same crystallographic orientation with the substrate acting as a seed for the deposition. An advantage of this process is the high growth of material, which allows the formation of films with a thickness of ~1μm up to 100μm. However, the temperature of the substrate must typically be at least 50% of the melting point of the material to be added. This technology is widely used for producing silicon on insulator (SOI) substrates.

Thermal oxidation. This most basic additive process simply involves oxidation of the substrate in an oxygen-rich atmosphere. This process is naturally limited to materials that can be oxidized and can only form films that are oxides of that material. The temperature is raised to 800–1100°C to speed up the oxidation.

1.1.2 Physical reaction

A common feature of all these processes is that the deposited material is physically moved on to the substrate. In other words, there is no chemical reaction that forms the material on the substrate. The main processes are physical vapour deposition and casting.

Physical Vapour Deposition. PVD covers a number of technologies in which the material is released from a source and transferred onto the substrate. The major physical principle called on is evaporation: the source material is heated to the point where it starts to boil and evaporate before deposing on the substrate. Many materials are restricted in terms of which evaporation method can be used. This typically relates to the phase-transition properties of that material.

Casting. In this process the material previously dissolved in liquid form in a solvent can be deposited on to the substrate by spraying or spinning. Once the solvent is evaporated, a thin film of the material remains. This is particularly useful for polymer materials (i.e., photo-resist), which may be easily dissolved in organic solvents, The thicknesses that can be cast on a substrate range all the way from a single monolayer of molecules (adhesion promotion) to tens of micrometers. The control of the film's thickness depends on the exact conditions, but can be sustained within ±10% in a wide range.

1.2 Selective Process

In the MEMS context the basic selective process is lithography, i.e., the transfer of a pattern to a photosensitive material (mainly photo-resist) by selective exposure to a radiation source such as light using a set of masks. The photo-resist can be either positive or negative; it then reproduces the pattern or its complementary image. Once the photo-resist is exposed it is developed, the pattern appears on the wafer, and the steps of the deposition or the

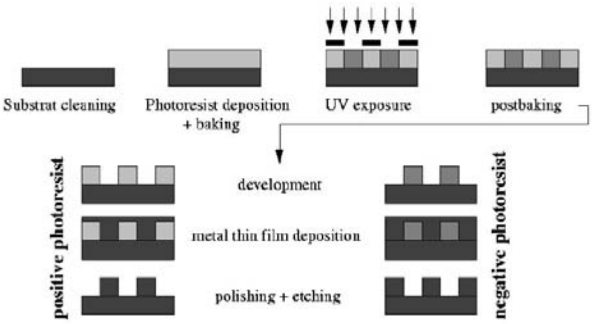


Fig. 3. *Photolithography and metal-deposition process steps*

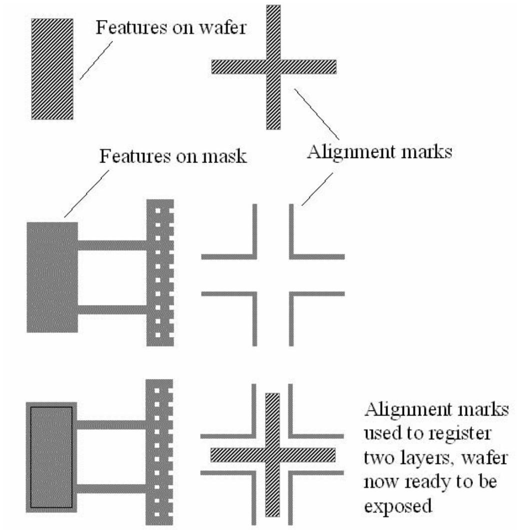


Fig. 4. *Use of alignment marks to register the subsequent layers*

etching then occur. A description of positive and negative lithography, metal deposition and etching is shown in Figure 3.

The main problem during this step is masks' alignment: the patterns for different lithography steps that belong to a single structure must be aligned with each other. The first patterns transferred to a wafer usually includes a set of alignment marks (Figure 4), which are high precision features. They stand as a reference for positioning subsequent patterns with respect to the first pattern.

Other problems, like the exposure parameters required to transfer an accurate pattern on to the photo-resist or the adhesion of the photo-resist on the substrate may occur.

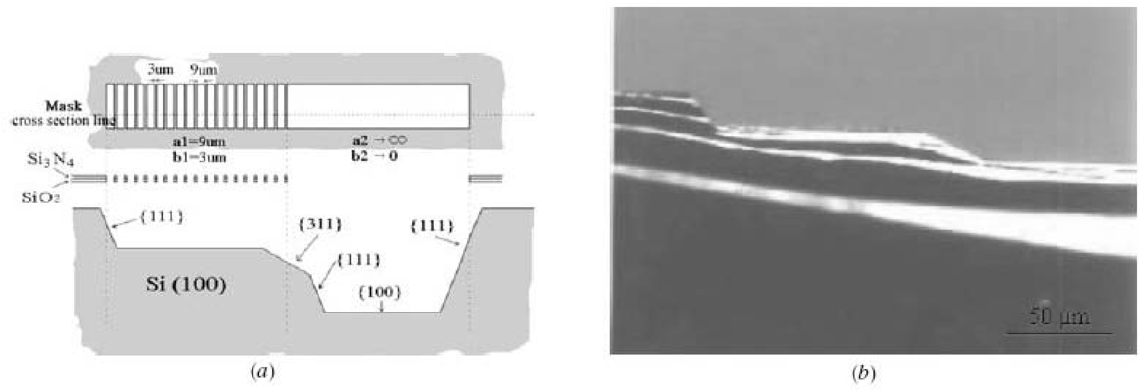
1.3 Etching processes

Etching is the basic manufacturing step to remove material that has been selected during lithography in order to form a functional MEMS structure on the substrate. In general, there are four classes of etching processes. Wet etching, where the material is dissolved when immersed in a chemical solution; dry etching, where the material is sputtered or dissolved using reactive ions or vapour-phase etchant. These two etching processes being either isotropic or anisotropic. Anisotropic etching, in contrast to isotropic etching, means different etching rates in different directions in the material.

Wet etching. This is the simplest technology because all it requires is a container with a liquid solution that will dissolve the material to be removed. But a mask is desired to selectively etch the material, and one must find a mask that will not dissolve, or dissolve much more slowly than the material to be patterned. Etching a hole in a <100> silicon wafer in a chemical (such as potassium hydroxide, KOH) is an anisotropic etching process: the <111> crystal plane appear and the result is a pyramid-shaped hole.

Example: modelling and fabrication of the step-height control of a multilevel Si <100> structure in a KOH solution, using one photo-mask. Conventional multilevel structures are fabricated by lithography, deposition and etching technologies. Multi-masks are required for the multilevel structure formation: m masks can form (m+1) to 2^m level terraced structures. The plurality of masks and process cycles for film deposition, lithography and etching not only make the fabrication of a multilevel structure a long process with a high cost, but it also means that the misalignment problem of the masks cannot be avoided, as we have seen before. In [4] the authors propose a novel model for the step-height control of the Si <100> multilevel structure using one photo-mask and the KOH wet-etching process. The relationship between the step height and the widths and intervals of the masked areas was derived and experimentally verified. Figure 5 shows the mask pattern and cross-sectional diagram of a three-level terraced structure (a) and the micrograph after KOH etching (b).

Dry etching. These technologies can be split into several separate classes, one of which is reactive ion etching (RIE). In RIE the substrate is placed inside a reactor in which several gases are introduced. A plasma is struck in the gas mixture using an RF power source, breaking the gas molecules into ions. The ions are accelerated towards, and reacts at, the surface of the material being etched, forming another gaseous material by chemical reaction. If the ions have high enough energy, they can knock atoms out of the material to be etched without a chemical reaction. By



(a) (b)

Fig. 5. *A three-level terraced structure with different step heights*

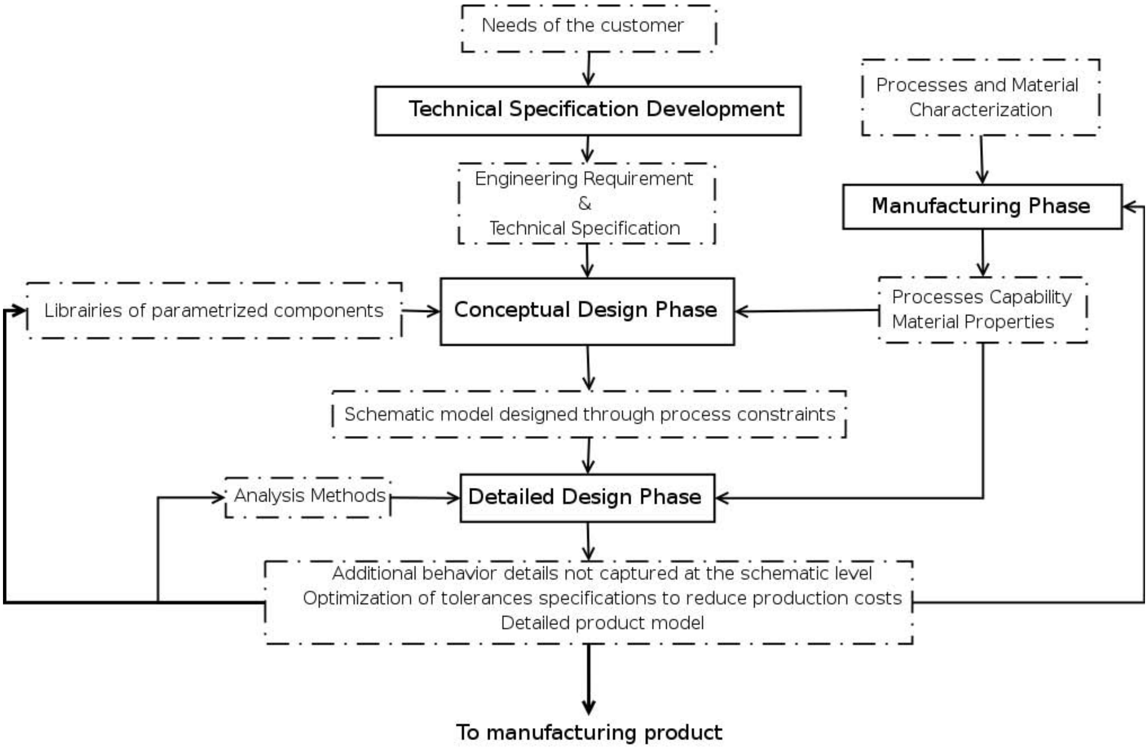


Fig. 6. *Schematic of DFM methodology implementation*

changing the balance between the chemical and physical reactions it is possible to influence the anisotropy of the etching, since the chemical part is isotropic and the physical part highly anisotropic the combination can form sidewalls that have shapes from rounded to vertical. A special popular subclass of RIE processes is Deep RIE (DRIE). This process can achieve depths of hundreds of microns with almost vertical sidewalls and an etching aspect ratio of 50:1. It can also be used to etch completely through a silicon substrate, and the etch rates are 3-4 times higher than wet etching. However, the cost per wafer, for a silicon wafer, will be 1-2 orders of magnitude higher than the wet etching. We have seen that it is possible to identify some process constraints and capability. Thus, the shape and the quality of the product depend on the selected process, since it influences: the quality (thickness and uniformity) of the deposited materials, the deposition rate, the formation of bi-products, the etched shape of the product, the electrical isolation of the wafer, the product costs, etc. We can also see that some parameters are few or less relevant in the choice of process. For example, the batch size is not as sensitive as in traditional macro-manufacturing because of the natural manufacturing organization in the batch and the lots.

Of course, this list is not exhaustive. We simply wanted to show that it was possible, for various processes, to identify the constraints influencing the manufactured product. However, we must keep in mind that there is a wide variety of constraints depending on the physical principle involved in the operation. Thus, it is impossible to give either a generic or a definite classification to guide the process selection. So, there is a stronger need to make all this information available during the design process. This requires identifying what kind of information is necessary for the designers, and at which time during the design process. Moreover, it is necessary to hold account of the constant evolution of the processes and to integrate it into the design tools so that designers do not design according to obsolete processes.

2 MEMS DESIGN TOOLS AND METHODOLOGIES

In order to be able to integrate process constraints in the design process, we were interested in the MEMS design methodologies and especially the way process constraints and capabilities can be integrated. Two types of methods seem to emerge: the first is design for manufacturability, a methodology that considers manufacturability during the design process in order to design manufacturable MEMS. These methods already exist in the fields of electronics or traditional mechanics, and [5] proposes to adapt it to the design of manufacturable MEMS. DFM is an alternative to the traditional MEMS-product development cycle in which in particular "build and test" approach increases the design process and product costs. This method is also proclaimed by one of the renowned integrated specific MEMS design tools, CoventorWare, composed of four main products, which include ARCHITECT, ANALYSER and INTEGRATOR. We will be interested in the applications of the methods in those products, like those presented in [6].

The second method is based on the share of manufacturing knowledge using distributed web tools (that cannot be put in the category of integrated design tools) to help designers select the manufacturing processes and the material combinations.

2.1 Design For Manufacturability

DFM is well known as a design methodology that aims to reduce manufacturing times and costs [7]. In contrast, we will try to value the assistance provided by such a method in the crucial problem of process selection. Fundamental activities of MEMS development may be broadly divided into four overlapping phases, organized as shown in Figure 6.

Technical Specification Development. This is the phase where the needs of the customer are converted into engineering requirements and technical specifications, the starting points of the following phase. It is important that the customer requirements' document maintains the original intent of the customer and is not overly influenced by the perceptions of the engineering teams.

Conceptual Design Phase. This is the phase where designers develop and evaluate many design concepts simultaneously so as to offer enough choices for a successful product. For that, they create then use libraries of standard parametrized component elements that they can piece together to create more complex designs. Each element of the library is essentially an analytical or semi-analytical model that captures the behaviour of the element accurately over all possible displacements of the element. All the parameters of the element model are available to the designers as a variable to be defined and set. For instance, the non-linear beam-element model is the model of an Euler beam, where parameters such as length, thickness, width, as well as material properties such as the Young's modulus, Poisson's ratio, residual stress are all available as variables. As MEMS can sustain mechanical deformations in 3D space, each component model necessarily has 6 degrees of freedom. A schematic model assembled from parametrized library components immediately enables very rapid and accurate characterization of the behaviour of a specific conceptual design. One of the advantages of these phases is the ability of designers to design through process constraints. Indeed, parameters may be well defined within the tolerances of the specific manufacturing unit, and this influences the product-development

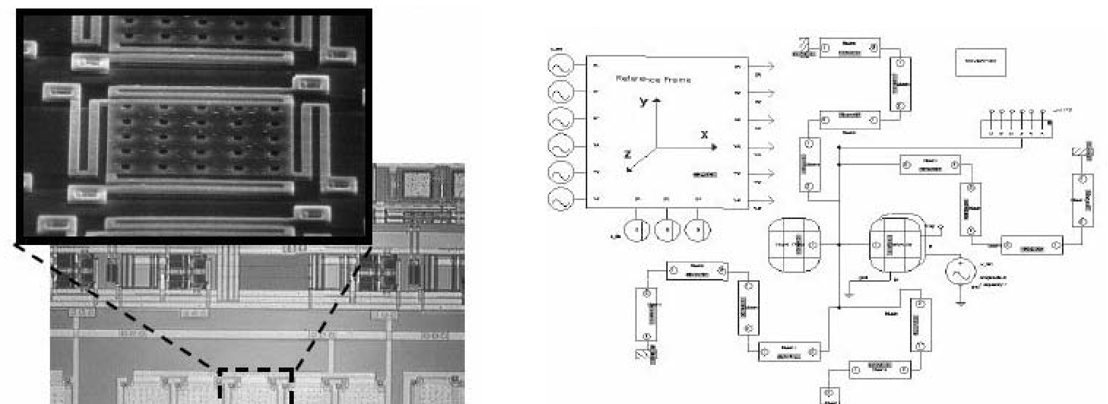


Fig. 7. *CMOS variable capacitor (left) and its schematic model*

process substantially, as only those designs that can be manufactured within the process are considered. Figure 7 shows an example of the conceptual design phase of a variable capacitor designed using ARCHITECT. We can see an image of the CMOS fabricated device (left) and the schematic model (bottom). Each "component" in the schematic model corresponds to a part of the CMOS fabricated device: for instance, the four folded suspension arms are each modelled with four connected parametrized beams.

Detailed Design Phase. During this phase a detailed engineering analysis of the selected design concepts is performed in order to provide additional details of the behaviour of the design or to study the effects not captured at the schematic level during the conceptual design phase. CoventorWare has an analysis tool, ANALYSER, composed of different bundles, which include for instance: finite-element methods (FEMs), for mechanics and general fluidics, boundary element methods (BEMs), for electrostatics and inductance, etc. All the ANALYSER bundles include, moreover, a MEMS-specific mesh generation. These details make it possible for the designers to optimize the product shape and to assess tolerance specifications in order to reduce the production costs. For instance, for a variable capacitor, an analysis performed in the detailed design phase allowed designers to calculate the distribution of the pull-in voltage in the function of the tolerances of the material properties (thickness, stress gradients, etc.) Then, INTEGRATOR reduces the detailed 3D analysis produced in ANALYZER to a reduced-order model that can supplement Coventor's extensive ARCHITECT library of parametrized MEMS components.

Manufacturing Phase. The manufacturing phase begins concurrently with the initiation of the design group's activities, with the aim of:
- identifying critical process characteristics, such as verticality or surface roughness
- identifying and evaluating existing processes, in order to chose between a standard process, a slightly modified standard process or a newly developed process.

This necessarily requires characterization of the processes' capability and the materials' properties: for instance, experiments are initiated so as to determine what kind of shape can be made, and with which processes and materials. Processes' capability and materials' properties information is integrated into the parametrized models used in the design phases.

It should be pointed out that some traditional guidelines of DFM (in the mechanical engineering field) clearly arise in the MEMS context:
- use of standard components,
- develop a modular design,
- design for ease of fabrication,
- avoid separate fasteners.

But some are completely out of scope:
- minimize assembly directions,
- design parts for multi-use.

This only tends to prove that the DFM method cannot be a simple mix of methodology available in both the mechanical and electronic worlds.

After all, we can concentrate on information and distinguish which information should be useful for designers at the conceptual and detailed design phases.

Conceptual Design Phase. At this level the designer needs
- geometrical information, in order to know if he is designing a manufacturable product, and if so, with which process.
- material information, to know which material can be deposited, selected, etched, etc.
- economic information, to help him to choose between two processes having the same performance.
- thermal information, to know if the manufacturing temperature of one schematic element will damage others.

One needs, moreover, to take into account the maximum of information simultaneously because independently this information has only little interest. For instance, it is possible to obtain a rounded wall using a wet etching process, but not in silicon, because of the anisotropic etching properties of this material (taking into account simultaneously the geometrical and material information).

Detailed design Phase. During this phase the designer needs information on the limits of the capabilities of the processes, because in this phase one optimizes the geometrical product characteristics to obtain the required behaviour while assessing the tolerance specifications in order to reduce the production costs. The designer needs, for instance, the minimum thickness or temperature of a deposited material, the best roughness obtained after etching, etc.

2.2 Sharing knowledge using web tools.

The following approach is a more oriented "process selection". Due to the typically unstable context of R&D, designers currently tend to conceive MEMS in terms of processes and materials in which they are familiar and may not consider a process and material combination that may have proven to be more economic. To solve this problem some tools have been developed to help designers select the "best" manufacturing processes and material combinations, based on the sharing of knowledge using the internet and web databases ([8] and [9]).

Processes and materials characteristics are stored in web databases. For instance, on the website www.mems-exchange.org for the silicon nitride PECVD process, one can find information like thickness (the amount of material added to a wafer), atmosphere (to which the substrate is exposed during processing), material (which can be deposited), microstructure, uniformity, wafer geometry, wafer material, wafer thickness, etc. (see Figure 8).

Designers build a manufacturing sequence using this information, and submit it to a specialized team that validate the project or propose the best sequence.

The WebMems-Mass tool also contains manufacturing and materials data, but proposes an algorithm to select processes and material combinations against econo-technical criteria. While running, WebMems-Mass generates a dialogue with the designer to inquire and acquire information about batch size, typical tolerances size, overall shape, cost requirements, etc. Then, the user is given real-time feedback regarding a plausible fabrication sequence. At each step of the design process the user is presented with an updated, ranked list of manufacturing and material possibilities.

Of course, those tools are not integrated MEMS design tools and only help designers select the right manufacturing process and material combination. But these tools shared on the internet are well adapted to a concurrent collaborative design by making it easier for designers from different disciplinary and manufacturing teams to communicate. Using libraries of standard components for the design of new products certainly restricts, a little more, the design state space, but increases the guarantee of designing a manufacturable product. Another advantage of shared web tools is their facility with being updated in order to be aware of manufacturing processes evolution. This seems to be the most efficient answer to the lack of availability with the boundary limits of the manufacturing process.

3 CONCLUSION

MEMS products are getting increasingly popular everyday. Though the industrial context is still research-and-development oriented, efforts are being made to move to a mass-production era.

To achieve this conversion, the concept of manufacturability must be considered. At the present time, manufacturability roughly seems to rely on a good

Silicon nitride PECVD	
Fab site	Commercial
Process characteristics:	
Thickness Amount of material added to a wafer	2.0 µm
Ambient Ambient to which substrate is exposed during processing	nitrogen, silane, ammonia
Material	silicon nitride
Microstructure	amorphous
Sides processed	either
Uniformity	-0.03 .. 0.03
Wafer diameter	150 mm
Equipment	Oxford Plasmalab PECVD System
Equipment characteristics:	
Batch sizes	150 mm: 1

Fig. 8. *Example of typical information available to the designer*

process choice. So we have had a special interest in presenting a sample of manufacturing processes derived from VLSI technologies that our community (mechanical manufacturing) is not familiar with. This has allowed us to propose some rough qualifiers to the information that designers can integrate.

We now have to concentrate on building the manufacturing sequence. Indeed, process selection is only part of the manufacturing issue, and manufacturability is also concerned with process compatibility.

Another aspect of the problem is that the manufacturing process can be based on various physical principles and the knowledge attached to them, even expressed under a constraint form this does not prove easy to understand. Consequently, further studies have to be made concerning the cognitive aspect of the knowledge sharing, as very different communities of experts are involved in such projects.

Finally, VLSI technologies are pushed to their limits to let the designers be more innovative (by introducing non-silicon materials, for example) but we must already think about the integration of innovative technologies in the current design process. This means the introduction of additional, different physical principles (micro-cutting, abrasives, etc.). This will increase the need for a unified classification of manufacturing constraints that would overcome the limits of disciplinary expertise.

4 REFERENCES

[1] A. De Grave(2004) Conception intégrée de micro-systèmes électro-mécaniques. PhD Thesis, *University Joseph Fourier*, 3S Laboratory, Grenoble.

[2] A. De Grave, C. Masclet and D. Brissaud (2004) Integrated design of MEMS, *Proceedings of MIT'04, Constanta*, pp 67-72 , October 4-5th 2004.

[3] C-K Chung, M-Q Tsai, P-H Tsai, C Lee (2004) Fabrication and characterization of amorphous Si films by PECVD for MEMS. *Journal of Micromechanics and. Microengineering*, vol 15, pp.136-142 IOP Publishing, September 2004.

[4] C-K Chung (2003) Modelling and fabrication of step height control of a multilevel Si(100) structure in KOH solution. *Journal of Micromechanics and. Microengineering*, vol 14, pp.341-346, IOP publishing, 2003.

[5] M. G. da Silva, R. Giasolli, S Cunningham, D. DeRoo (2002) MEMS design for manufacturability (DFM). *Sensor Expo & Conference*, Boston, Fall 2002

[6] G. Schröpfer, M. McNie, M. G. da Silva, R. Davies, A. Rickard, F-X Musalem (2004) Designing manufacturable MEMS in CMOS compatible processes – methodology and case studies. S*PIE's Photonic conference, MEMS, MOEMS and Micromachining proceedings*, Strasbourg, 26-30th april 2004.

[7] D. M. Anderson (2004) Design for manufacturing and concurrent engineering, *CIM Press*.

[8] X. F. Zha, H. Du (2003) Manufacturing process and material selection in concurrent collaborative design of MEMS devices. *Journal of Micromechanics and. Microengineering*, vol 13, n. 5, pp.509-52, IOP Publishing Ltd, May 2003.

[9] Mems and technology exchange, available at http://www.mems-exchange.org. last accessed July 05.

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Dvanajst “znakov umiranja” rastočega proizvodnega podjetja

The Twelve “Death Signs” for a Growing Manufacturing Company

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Na podlagi obsežnega dela z malimi in srednje velikimi podjetji (MSVP-SMES) v tem prispevku predstavljamo zgodnje opozorilne znake v proizvodnih MSVP, ki lahko vodijo podjetje v poslovni zaton. V obdobju enega do treh let poslovanja propade največ podjetij, veliko podjetij pa propade tudi v prvih desetih letih. Ključni dejavniki so nezmožnost inovacij, vodenja poslovnih postopkov, proizvodov in storitev. Prispevek predstavlja tipologijo znakov umiranja, ki daje osnovo za dejaven inovacijski program. Zasnova “preventivnega zdravljena” se osredotoča na inovacijo izdelkov in postopkov z navedbo primerov podjetij, ki so uporabila tovrstne preventivne ukrepe. Z upoštevanjem literature in izkušenj s področja tehnologije in menedžmenta inovacij se v tem prispevku osredotočamo na specifične metode inovacije, ki lahko malim in srednje velikim podjetjem omogoči uspeh. Vpeljali bomo tudi zasnove zavarovanja pred upadom na področju inovacije pri MSVP.

(Ključne besede: propadanje podjetij, znaki opozorilni, menedžment inovacij, upadanje rasti, zavarovanje)

Based on extensive work with small and medium-sized enterprises (SMEs), this paper describes the early-warning signs for SMEs in manufacturing, which, if ignored, later result in business decline and even failure. There is a high failure rate for SMEs during the start-up phase of 1 to 3 years, but also a significant failure rate in companies that are less than ten years old. Failure to innovate, the business process, and products and services are the key elements. This paper presents a typology of the “death signs” that can form the basis of a proactive innovation agenda. The concept of “preventive healthcare” is applied to product and process innovation, and cases are cited of companies taking such preventive steps. Drawing on literature and experience from the fields of technology and innovation management the paper focuses on specific methods of innovation that can help a small-to-medium-sized manufacturing firm thrive over the longer term. The concept of “recession-proofing” is also introduced and applied to innovation in SMEs.

(Keywords: company failures, early-warning signs, innovation management, recession-proofing)

0 UVOD

V Združenem kraljestvu približno ena tretjina podjetij ne preživi prvih dveh let. Vzroki so ponavadi slaba poslovna sposobnost, slabe poslovne zasnove, slabo upravljanje s financami in neučinkovito trženje.

Te pomankljivosti, ki od samega začetka poslovanja povzročajo propad podjetij. Druga tretjina malih podjetij ne preživi desetih let. Ta prispevek podpira mnenje, da je nezmožnost za učinkovito inoviranje vzrok za dolgoročen neuspeh. Prav tako navaja številne “simptome”, ki lahko vodijo v poslovni neuspeh. Ti “znaki umiranja” predstavljajo osnovo inovacijskega programa za mala in srednje velika podjetja.

0 INTRODUCTION

In the United Kingdom approximately a third of small businesses do not survive the first two years. This is often down to a lack of business capability, a poor concept, poor financial management, or ineffective marketing.

The “basics” are often not right from the start, and business failure is the result. Another third of small businesses do not survive beyond ten years. This paper supports the view that failure to innovate effectively is a cause of longer-term failure. It also outlines a number of “symptoms” that can lead to a business’s demise. These “death signs” form the basis of an innovation agenda for small-to-medium-sized firms.

1 ZASNOVA ZNAKOV UMIRANJA

Znaki skupinskega umiranja so prvi simptomi, ki opozarjajo na potrebo po inovacijah. Po uspešnem pričetku poslovanja grozi nevarnost usihanja. Brez nenehne poslovne dinamike podjetje izgublja sposobnost prilagajanja spreminjajočim se razmeram, da bi se odzvalo na to kar Levy in ostali [3] imenujejo »okoljski opozorilni znaki«. Francis in ostali [2] opozarjajo, da je lahko inovacijska potreba spremenljiva, saj se podjetje odziva tako na organizacijski kot tudi proizvodni in procesni ravni. Caffyn in Grantham [1] prav tako poudarjata pomen postopno rastočih inovacij izdelkov in postopkov v obdobju razvoja podjetja.

Če se podjetje med 18 mesci in dvema letoma starosti ne uspe inovacijsko odzvati obstaja velika verjetnost, da bo začelo doživljati »znake umiranja«. Ta zasnova je bila razvita v Združenem kraljestvu v delavnicah, ki so potekale z malimi in srednje velikimi podjetji (MSVP) med leti 2003 do 2005. Z več kot 50 podjetji smo preverjali ta nastajajoči model in tipologijo, ki jo predstavljamo v prispevku.

Potreba po preventivnih ukrepih po merilih dejavnega »zdravljenja« je temelj učinkovitega premagovanja znakov umiranja in zagotavljanja dolgoročnega poslovnega preživetja.

Odkrili smo tudi vzporedne znake tako imenovanega »propadanja in odlašanja«, ki povspešijo poslovno umiranje.

Z »umiranjem« označujemo finančni ali poslovni propad podjetja, ki vodi do zaprtja podjetja. Tako lahko poslovna smrt nastane zaradi finančnega neuspeha oz. bankrota, ki vodi podjetje v likvidacijo, ali pa zaradi odločitve lastnika podjetja oz. direktorja, da zapre podjetje.

2 DVANAJST ZNAKOV UMIRANJA RASTOČEGA PODJETJA

Znaki umiranja so predstavljeni kot preglednica zdravstvenega stanja, ki lahko služi kot orodje za samoocenjevanje, razkrivanje priložnosti in za dejavno ukrepanje pri odpravljanju simptomov. Inovacija tako postane orodje za preživetje in rast podjetja. Predstavljeni so kot način zavarovanja podjetja pred upadanjem s spodbujanjem izboljševanja poslovne učinkovitosti in organizacije med obdobji rasti – »zavarovanje pred obdobjem upada«.

1. *Obseg prodaje/povpraševanja narašča počasneje – upadanje rasti je brez ustreznih*

1 THE CONCEPT OF DEATH SIGNS

The signs of corporate death are essentially symptoms giving early warning of the need to innovate. Having survived start-up, the firm is in danger of atrophying. Without an ongoing dynamism the firm loses the impetus to adapt to changing circumstances, to respond to what Levy et al [3] call environmental signals. Francis et al [2] point out that this innovation may need to be transformational as the firm responds to organizational, product and process-innovation perspectives. Caffyn and Grantham [1] also highlight the importance of incremental innovation to product and process as the firm develops.

Without an innovation response at about 18 months to 2 years in the business biography, the firm may experience the onset of what we call the " death signs". This concept arose from workshops in the UK with small to medium-sized enterprises (SMEs) during 2003 to 2005. We worked with over 50 companies, testing out this emerging proposition and forming the typology that is presented in this paper.

The need for preventive measures in the spirit of proactive "healthcare" lies at the heart of effectively managing the death signs and ensuring longer-term business survival.

We also uncovered what might be termed signs of "decay and delay" which overlap with and contribute to the signs of business death.

By "death" we refer to the financial or operational collapse of a business, resulting in closure. Some events of business death will arise from financial failure and bankruptcy, sending the firm into liquidation. Other events arise from the owners or directors of the business deciding to close the business down.

2 THE TWELVE SIGNS OF DEATH IN A GROWING BUSINESS

The death signs can be presented as a health checklist and can provide a useful tool for self-analysis, identifying opportunities for taking proactive steps towards eliminating the symptoms. Innovation therefore becomes the tool of business survival and expansion. They are also presented as a way of recession-proofing a firm by encouraging the strengthening of performance and organisation during times of growth – a "proofing" against leaner times.

1. *The rate of sales/demand acceleration has begun to decline - even though the curve still in-*

izračunov težko zaznati, saj krivulja še vedno narašča;
2. *Izrazi "dobro, zelo ugodno" in podobni kažejo na nevarnost sprijaznjenosti s povprečjem;*
3. *Rahlo naraščanje pritožb in nezadovoljstva – bodisi med zaposlenimi ali zunanjimi javnostmi;*
4. *Opazno je povečanje lojalnosti obstoječih kupcev, hkrati pa rahlo upadanje števila novih kupcev ali strank;*
5. *Zaposleni ne prihajajo na delo tako zgodaj kot prej, vse pogosteje pa odhajajo točno ob uradnem zaključku delovnega časa;*
6. *Povečanje zalog – različnih gradiv, proizvodov, zamisli se ne uresničujejo*
7. *Občutek "izpraznjenosti" – težje se je navdušiti, pričeti z delom, imeti nove zamisli;*
8. *Ena ali več dobrih zamisli iz prejšnjega obdobja je obležalo na delovni mizi;*
9. *Podjetje je na področju inovacij ujeto v preveliko odvisnost od tehnologije ali v odvisnost od ene/dveh oseb ali majhnih skupin;*
10. *Rahlo, vendar opazno naraščanje pritožb glede proizvodov, storitev ali odnosov. Eden ali dva od najpomembnejših kupcev sta prenehala sodelovati s podjetjem;*
11. *Stroški iz meseca v mesec poberejo del dobička zaradi pomanjkanja tekočih virov;*
12. *Občutek vsakdanjosti in dolgočasja kljub navidezno stimulativnemu in dinamičnem okolju. Pomanjkanje pravega "naboja"*

creases, the rate of increase is declining, and this not easy to see unless you do the calculation.
2. *Things are described as "nice", as "very comfortable" - here there is a danger of a collusion of mediocrity.*
3. *A small increase in complaints or dissatisfaction, either internally or externally*
4. *There is an increase in loyalty from existing customers, but a tiny decline in the number of new customers or clients.*
5. *People do not get in as early as they used to; they arrive and leave on time more often.*
6. *An increase in the level of inventory/safety stock - either materials, products, ideas not yet put into action.*
7. *A feeling of "drag" - harder to get enthused, to get going, to be inspired.*
8. *One or several ideas/practices from the "early days" are still in place, and really should not be.*
9. *The organisation is stifled in terms of innovation through over dependence on technology or one or two people/small groups.*
10. *A small but perceptible rise in the number of complaints about the product, service or the relationship. One or two important "first" customers have moved on.*
11. *Costs are eating a little more each month into profitability as a result of a "slackness" with resources.*
12. *There is a hint of "sameness", of boredom even, in an apparently exciting and changing environment. A lack of real "buzz".*

3 RAZPRAVA O POSAMEZNIH ZNAKIH UMIRANJA

1. Obseg prodaje/povpraševanja narašča počasneje – upadanje rasti je brez ustreznih izračunov težko zaznati, saj krivulja še vedno narašča

Ta prvi znak umiranja je slabo zaznaven, saj ne kaže na padanje v prodaji, temveč upadanje stopnje rasti prodaje. Na potrebo po inoviranju opozarja že veliko prej kot običajni opozorilni znak upada rasti prodaje ali celo upada v prodaji.

Pomembno je poudariti, da je to zelo nežen znak. Prodaja namreč še vedno narašča v pozitivnem smislu toda stopnja rasti upada. Potrebno je dejavno ukrepanje, za zaustavitev upadanja, ali za pridobitev vzporednega dotoka dohodkov.

3 A DISCUSSION OF EACH OF THE DEATH SIGNS

1. The rate of sales/demand acceleration has begun to decline - even though the curve still increases, the rate of increase is declining, and this is not easy to see unless you do the calculation

This first death sign is a subtle sign where the early signal of possible decline reveals itself not at first in falling sales, but in a decline in the rate of acceleration of sales growth. It suggests a signal to innovate at a much earlier stage than the usual warning sign of declining sales growth or even a fall in sales.

It is a subtle sign. Sales are still accelerating in a positive sense, but the rate of acceleration is declining. It requires a proactive response to reverse the decline in acceleration or to look for parallel revenue streams.

Tu je delovanje osredotočeno na inovacijo izdelka in storitev. Analiza mora biti opravljena glede na vzroke upada stopnje rasti. Lahko je le del naravne dobe trajanja izdelka. Lahko pa so prisotni tudi drugi dejavniki, ki zajemajo tudi spremembe zahtev kupcev ali njihove povratne informacije o nekaterih lastnostih izdelka ali storitve.

2. Izrazi "dobro, zelo ugodno" in podobni kažejo na nevarnost sprijaznjenosti s povprečjem

Ko podjetje raste in se razvija lahko pride do udobja, neke vrste sprijaznjenosti. Nihče si ne želi sprememb ko barka pluje s polnimi jadri. Razvije se kultura udobja, ki lahko zakrije nekatere izmed znakov umiranja. Ta sprijaznjenost s povprečjem nastane na več področjih in jo je zelo težko odpraviti. Posledice ne-odpravljanja tovrstne sprijaznjenosti – kulturne norme »navidezne prijaznosti«, ki preprečuje izzive in odkritost – je, da postanejo priložnosti za inovacijo prepovedane teme, zato jih podjetje zamudi, kar lahko vodi do izgube poslovnih priložnosti in uspešnosti.

4 STOPNJE SPRIJAZNJENOSTI

4.1 Stopnja sprijaznjenosti 1

Na tej prvi stopnji želja po udobju izpodrine potrebo po odkritosti in s tem tveganje neudobja. Tako nastane površinska (navzven) »prijaznost«, ki ne dovoljuje nikakršnih sprememb v čustvih, mišljenju ali dejanjih. Ta *"status quo"* varnosti pa terja svojo ceno. Potencialno neudobne stvari so opuščene in neizrečene. Nastajajo problemi prikrivanja. Tako, kot če v restavraciji, kjer smo nezadovoljni odgovorimo na natakarjevo vprašanje da je "dobro". Ne želimo motiti ustaljenega reda. Tako si ponavadi dopovedujemo da problemi niso tako veliki, da "ne bo viharja v kozarcu vode". Prav tako se nikoli preveč ne navdušimo nad dobrim izidom. Prava odličnost in sreča sta pomanjšani v prijetni "v redu" ali "vljudnost"

4.2 Stopnja sprijaznjenosti 2

Na drugi stopnji premagamo sprijaznjenost prve stopnje in se končno soočimo z resničnim dogajanjem, čeprav s tem tvegamo neudobje. Navdušeno hvalimo kar je vredno pohvale! Soočimo

Here, action is focused on product or service innovation. An analysis needs to be carried out as to the causes of the reduced rate of acceleration. It may be part of a natural product lifecycle; however, there may be other factors including changing customer requirements or customer feedback about certain aspects of the product or service.

2. Things are described as "nice", as "very comfortable" - here there is a danger of a collusion of mediocrity

As the business grows and develops, a certain comfort can set in, which is actually a form of complacency. No one wants to "rock the boat" of success, and so a culture of comfort develops that can hide some of the death signs. This "collusion of mediocrity" is a many-levelled thing and can be hard to break. The consequences of not challenging such a collusion – a cultural norm of "superficial niceness" that avoids challenge and honesty – is that innovation opportunities become taboo subjects and are missed, with a resulting loss of potential and even effectiveness.

4 LEVELS OF COLLUSION

4.1 Collusion Level 1

At this first level, comfort is sought at the expense of honesty and a risk of discomfort. A superficial "niceness" exists, and it is not the norm to show any extremes of emotion, thought or deed. The status quo of safety is secured at a price. Potentially uncomfortable things are left unsaid. Problems are "papered over". In the restaurant where we might be dissatisfied we tell the waiter, when asked, that the meal is "fine". We do not wish to "rock the boat" or to "muddy the waters". We tend to dilute problems - real problems - down to a "storm in a tea cup". We never get too positive either, too excited over a good outcome. Excellence and joy are diluted down to pleasant "okayness" or "niceness".

4.2 Level 2 Collusion

At level 2 we break the collusion of level one and surface what is really going on, even at the risk of discomfort. We go wild with praise, where such wild praise is due. We call things by their real name, where se s stvarmi, ki povzročajo težave. Pogosto pride do očiščenja in vse pride na dan. Toda tu se pogosto ustavimo in zavzdihnemo: "No to pa je bilo zares dobro. Vse smo privlekli na dan" in upamo da je tovrstna izrečenost dovolj. Ničesar pa ne naredimo. Obred odkritosti razumemo kot skrajno točko, izvedba pa je preveč oddaljena, da bi se je lotili. Spet se vse ustali in ponovno se pojavijo enake težave. Na nek način je ta nenadna odprtost tako pretresljiva, da nas paralizira v popolno nedelovanje!

4.3 Stopnja sprijaznjenosti 3

Na tretji stopnji stojimo pred pragom sprememb. Stvari so dobile prava imena – vemo kaj je treba storiti. Izpovedali smo resnično stanje. Vsa vprašanja so bila izpostavljena. Nato pride do vdaje. Zadamo si le najmanjše in najlažje spremembe, pogosto z izgovorom, da je spremembe treba izvajati postopoma. Pogosto bi bil pravilni odziv začetek izvajanja učinkovitih sprememb, ne pa zgolj taktika sprenevedanja ali sprijaznjenje. Ne le metoda izogibanja! Namesto, da bi spremenili sistem se le poigramo s sedanjim. Tako naredimo majhen korak kjer bi bil potreben velik preskok. Rezultat je, da je spremembo prepoznamo kot iskrenost, očiščenje, ob prvi oviri pa se umaknemo. Nastopi prva stopnja sprijaznjenosti in rečemo si – »Dobro smo opravili, da smo prišli tako daleč«. Toda naboj je bil veliko večji.

4.4 Stopnja sprijaznjenosti 4

Tu začnemo s spremembami pa naj bodo še tako težavne. Vendar sprememb ne izpeljemo do konca in stvari se vrnejo v prvotno stanje. Pomanjkanje vztrajnosti in nedoslednost vodita k pomanjkanju zagona. Prvotni naboj je izgubljen. Vdaja onemogoči vsako možnost zmage.

3. *Rahlo naraščanje pritožb in nezadovoljstva – bodisi med zaposlenimi ali zunanjimi javnostmi*

V povezavi z (2) lahko pride do manjšega povečanja nezadovoljstva v podjetju ali njegovem okolju. Toda te težnje morda ne zabeležimo v formalni obliki, saj se prepogosto zatrjuje, da je rast edini kazalnik uspeha! Toda, rasteči krivulji lahko že

such things are causing problems which need to be honestly named. A catharsis often occurs, as things come out into the open. But then we stop there, often with a big sigh. We say: "Well now that was a fine thing. We got everything out in the open." In the hope that saying it will be enough. However, nothing is done as a result. The ritual of honesty is seen as the end point, more than enough for us to bear. Soon, everything settles again and the same problems occur or the good and bad practice is neither built nor improved upon. In some ways the sudden openness is so traumatic that it paralyses us into inaction.

4.3 Level 3 Collusion

At Level 3 we stand on the threshold of change. Things have been truly named - we know what needs to be done. We have named the state of affairs and all is out in the open. The issues have been surfaced. And then, we falter. We embark instead only on the smallest, easiest change, often under the guise of "taking little steps". Often incremental change is the right course, but not as a collusion or a delaying tactic. Not as an avoidance method. Instead of changing the system that needs to change, we simply tinker with the current one. We take a small jump when a large leap is required. The result: the change identified with honesty, the catharsis experienced, falls at the first hurdle. Collusion level 1 kicks in and we say - "Well, we have done well to come so far". Yet the potential was so much greater.

4.4 Level 4 Collusion

Here we begin to make the change we need to make, no matter how daunting. However, there is no follow through and soon things revert back to their former state. Even honest, dramatic change requires perseverance, and here the lack of follow up leads to things running out of steam. Momentum is lost and no one challenges this. Defeat is snatched from the jaws of victory.

3. A small increase in complaints or dissatisfaction, either internally or externally

Linked to (2) there may be a small increase in dissatisfaction, either internally or externally, but this information may not even be collected formally, as growth seems to be the only performance indicator. However, within the upward growth curve may be zasledimo majhna opozorilna znamenja, ki kažejo na pomanjkljivosti ponudbe izdelka ali storitve.

Brez dejanskih in izčrpnih povratnih informacij – in delovanja v skladu z njimi – se lahko krivulja kaj kmalu obrne navzdol!

Dolgoročno uspešna podjetja te povratne informacije vidijo kot priložnost za odkrivanje novih inovacijskih področij. »Dobro« je sovražnik »boljšega« in ključni element za ohranjanje poslovne rasti iz leta v leto je prav nenehno inoviranje.

Uporaba inovacij in reševanje problemov je potrebno uporabiti in opraviti analizo temeljnih vzrokov, ki jih razkrivajo povratne informacije, saj prav te kažejo potencialne šibkosti in izboljšave izdelkov in storitev, ki sedaj sicer še dobro delujejo.

4. Opazno je povečanje zvestobe obstoječih kupcev, hkrati pa rahlo upadanje števila novih kupcev ali strank

Ta opozorilni znak kaže na pomakanje ustanavljanja novih področij poslovanja, čeprav zvesti kupci še vedno omogočajo poslovno rast. Vprašati pa se je treba: Zakaj zgolj ohranjamo zveste kupce ne pridobivamo pa novih?

Neprestano tržno raziskovanje bi pokazalo zakaj ne pridobivamo novih kupcev. Morda gre za neučinkovito ciljno trženje. Morda pa bi bilo treba preveriti izdelek ali storitve. Tu se lahko izkažejo strategije različnosti izdelkov in masovnega prilagajanja kot učinkovit način inovacije.

5. Zaposleni ne prihajajo na delo tako zgodaj kot prej, vse pogosteje pa odhajajo točno ob uradnem zaključku delovnega časa

Ta opozorilni znak kaže na probleme pri nastajanju in širjenju izurjenosti, ki povzroča zdolgočasenost in celo samozadovoljnost. Izurjenost ustvarja »mehanične« navade, ljudje postanejo zdolgočaseni in izgubijo občutek za izzive. Podjetje je v svojem delovanju preveč avtomatizirano.

Spodbuditi je treba možnosti za ponovno vzbujanje zanimanja za izdelek, ponovno povezovanje s poslanstvom in vrednotami. Obogatitev dela, usposobljenost za več veščin in menjava zadolžitev, izpopolnjevanje in razvoj ter skupinsko delo so možne organizacijske inovacije.

warning signs pointing to small “cracks” in the product or service offer.

Without real and comprehensive feedback – and action on that feedback – the curve may soon head downwards.

Successful firms in the long term see such feedback as a welcome opportunity to identify innovation areas. “Best” is the enemy of “better”, and continuous innovation is seen as a key factor in sustaining year-on-year business growth.

The use of innovation and problem-solving techniques needs to be applied and the root cause analysis carried out as feedback identifies potential weaknesses and improvements to products and services that are already performing well.

4. There is an increase in loyalty from existing customers, but a tiny decline in the number of new customers or clients

This warning symptom points to the lack of new business generated, even though the historical customer base may still be generating growth for the company. One would need to ask: Why are our older customers staying and why are we not attracting new business?

Market research on an ongoing basis should identify what is keeping new customers away. It may be through ineffectively targeted marketing. Or it may point to aspects of the product or service offer that may need to be looked at. Here, strategies of product differentiation and mass customization may be effective styles of innovation.

5. People do not get in as early as they used to; they arrive and leave on time more often

This warning sign points to the problem of growth developing into a routine that creates boredom and even complacency. Routines create “mechanical” habits of working; people become bored and the sense of challenge is lost. The company feels too automated in its processes.

Here, there is potential to look at ways of re-generating interest in the product, connecting again with the business purpose and the values that led to the creation of the enterprise in the first place: job enrichment, multi-skilling, and job rotation. Training and development, and team working are all possible organizational innovations.

6. Povečanje zalog – različnih gradiv, izdelkov, zamisli se ne uresničujejo

Tu so »zaloge« opredeljene zelo široko. V želji, da bi vzdrževali rast se vzdržuje visoko raven storitev za kupce s kopičenjem zalog. To sicer lahko zagotovi kratkoročno zadovoljenost kupcev. Dolgoročno pa investicija v kopičenje zalog zakriva težave in tudi nastajajoče potrebe po organizacijski in poslovni prilagodljivosti, ki ne temelji na »varnostni zalogi«.

Tudi prekomerno zaposlovanje je lahko ena izmed zvrsti kopičenja zalog, še posebej v storitvenih dejavnostih. Preveč investiramo v človeške vire, ki sicer prispevajo k rasti prihodka, vendar zmanjšujejo donosnost.

Prav tako lahko obstaja »zaloga idej«, pripravljeno za uporabo. Ta pa hitro zastari, ker nimamo časa, da bi vse te ideje pregledali, med tem ko se trudimo da tečemo na mestu. Zgodnja rast je neke vrste umetni vrhunec, ki ga doživi podjetje, toda v prihodnosti ga čaka tudi velik padec.

Zato mora podjetje tudi v času rasti pregledati svoje zaloge in prepoznati organizacijske inovacije, ki bi te zaloge zmanjšale ter vzpostavile novo dejavnost in prožnost, ki ne bi temeljila na umetnem kopičenju zalog.

7. Občutek "izpraznjenosti" – težje se je navdušiti, pričeti z delom, imeti nove zamisli

Podobno kot pri (5) ta znak kaže na pomanjkanje zanimanja prvotnih ustanoviteljev podjetja, ki bi si morali ogledati vzroke za izgubo vzpodbude v podjetju. Morda gre zares zgolj za izgubo zanimanja. Veliko poslovnežev je bolj navdušenih nad postavljanjem podjetja in so bolj uspešni pri ustvarjanju novih podjetij kot njihovem vzdrževanju. Morda bi bilo koristno razmisliti o različnih oblikah lastništva, ali pa bi morali prvotni ustanovitelji oditi novim izzivom nasproti.

Med zaposlenimi je lahko že rast sama po sebi vir napetosti in pritiska. Morda bi bilo koristno razmisliti o različnih načinih nagrajevanja, in podeljevanja priznavanj. Pridobivanje virov ne bi smelo biti zgolj del izurjene rasti, ki povzročajo velike pritiske pri delu in vodi do zgodnjega izgorevanja zaposlenih.

8. Ena ali več dobrih zamisli iz prejšnjega obdobja je obležalo na delovni mizi

6. An increase in the level of inventory/safety stock - either materials, products, ideas not yet put into action

We are defining "inventory" broadly here. In a wish to continue growth, customer service levels are kept high by the holding of inventory. This can create short-term customer satisfaction as demand is met across the board. However, investment in inventory is not sustainable in the long run and hides problems as well as the need for organizational and operational flexibility that is not based on "safety stock".

Overstaffing can also be a kind of inventory, especially in service industries. We over invest in human resources, which creates growth in turnover but eats into profitability.

Also, there can be a "stock of good ideas", sitting on the shelf, waiting to be implemented, going out of date, which we simply do not have time to look at, as we "run to stand still". In a way the early growth can be seen as a kind of "artificial high" for the business, with a big fall waiting to happen in the future.

So, even during times of growth, the firm needs to look at its inventory levels and identify organizational innovations to reduce inventories of all kinds and create an agility, a flexibility, not based on high inventory.

7. A feeling of "drag" - harder to get enthused, to get going, to be inspired

Similar to (5), this sign underlines the loss of interest of the original pioneers in the business, who need to look at the causes of their loss of motivation in the enterprise. It can simply be a loss of interest. Many entrepreneurs are excited by entrepreneurship itself, and are better at setting up businesses than sustaining them. It may be that different forms of ownership need to be looked at, or that the original pioneer needs to move on to new challenges.

Among staff, growth itself can be a source of stress and pressure. It may be that different models and types of reward, recognition, and resourcing need to be looked at as routinised growth combined with high-pressure working leads to early burn out.

8. One or several ideas/practices from the "early days" are still in place, and really should not be

V zgodnjem obdobju po ustanovitvi delo v podjetjih temelji na improvizaciji, neformalnih oblikah dela in »gašenju«. Uspeh temelji na igrivosti in veliki meri kreativnosti. Ni toge razmejitve med funkcijami in poslovanje raste na osnovi dobre zamisli in velike mere navdušenja. V obdobju rasti pa se pojavi potreba po bolj sistematičnem pristopu in večji konsistenci delovanja. Možna postane tako imenovana ekonomija rasti. Potrebno je opustiti nekatere zamisli in prakse, ki so nam dobro služile v času zagona, ki pa dolgoročno zavirajo uspeh. Tako lahko na primer določena metoda obdelave naročil, programski paket, ali določen »ekspert«, ki postanejo neustrezni zaradi zahteve po bolj zapleteni in celostni storitvi. Tu je inovacija sposobnost opustiti preteklost, prepoznavanje anahronističnega vedenja in sistemov in odkrivanje novih metod, proizvodnih oblik in delovnih praks.

9. Podjetje je na področju inovacij ujeto v preveliko odvisnost od tehnologije ali v odvisnost od ene/dveh oseb ali majhnih skupin

To je lahko resen problem majhnih podjetij, ki temeljijo na »osebnostih«. Družinska podjetja najbolj ovira prav ta problem. Najboljši primer tega je »računalniški genij« ali »izumitelj«, ki je tudi direktor ali pa vsaj vplivna osebnost v podjetju. Rast prinese tudi potrebo po hitrejšem odločanju, in poseganju po širšem spektru znanj, »eksperti« v podjetju pa temu preprosto niso kos. Običajno so potrebni ukrepi kot je delegiranje pristojnosti, spopolnjevanje in prilagajanje novim poslovnim okoliščinam.

Pojavi se lahko tudi potreba po opustitvi določenih praks, ki so prej vodile v zgodnjo rast vendar so sedaj postale predrage in neučinkovite. Primer tega so velike ugodnosti za določene kupce, ki se preprosto premočno zažrejo v donosnost podjetja in tako z ekonomskega vidika niso upravičljive.

Največji izziv v tem primeru je najti ustrezne poslovne pristope, ki ustrezajo naši definiciji usluge kupcem, a hkrati ne zmanjšujejo rasti.

10. Rahlo, vendar opazno naraščanje pritožb glede izdelkov, storitev ali odnosov. Eden ali dva od najpomembnejših kupcev sta prenehala sodelovati s podjetjem

V povezavi s (3) in (4) vidimo upad prvotne skupine kupcev. V tako dogajanje se moramo

The early days of a start-up are often based more on improvisation, informal working and "fire-fighting". Success is based on a kind of playfulness and a lot of creativity. Boundaries between functions are not always clear and the business grows on the back of a good product idea and much enthusiasm. As growth takes place, there will be a need for a more systematic approach, for more consistency in working. Economies of scale become possible. It becomes necessary to drop ideas and practices that served the company during start-up, but may actually inhibit success in the long term. For example, a particular method of processing orders, a software package, or a particular "expert" who simply is no longer an expert in a bigger company requiring a more complex and comprehensive service. Here, innovation is about letting go of the past, of identifying anachronistic behaviours and systems and finding new methods, product designs and working practices.

9. The organisation is stifled in terms of innovation through over dependence on technology or one or two people/small groups

This can be a real problem for small firms that are built around "personalities". Family businesses suffer most from this situation because sensitivities are involved. The best examples of this are the "Computer Whiz-Kid" or the "Inventor" who is also a director or, at least, a highly influential player in the firm. Growth begins to demand quicker decisions, drawing on a broader knowledge base and our "experts" are simply not up to the task. Standing aside, up-skilling, and reorientation to the new business reality, may all be required steps.

There may also be a need to drop certain practices that led to early growth but are now too costly or inefficient. One example is the practice of making high-cost promises to certain customers, which simply eat too much into profitability to be justifiable.

Here, the challenge is to find new working methods that also align with the company's definition of customer service and do not eat into growth.

10. A small but perceptible rise in the number of complaints about the product, service or the relationship. One or two important "first" customers have moved on

Linked to (3) and (4), we see the loss of our original customer base. We need to look into this temeljito poglobiti. Morda je neizbežno, da bodo kupci, katere smo v neformalnih »zgodnjih dnevih« zelo privlačili, sedaj postali predragi kupci v našem bolj učinkovitem in rastočem modelu poslovanja. Toda inovacijski izziv leži v tem, da ohranimo vse kupce in hkrati gojimo tudi uspešnost in učinkovitost v času rasti.

Zgodnji kupci imajo lahko dragocen vpogled v kakovost našega izdelka ali storitve, ki smo jo morda izgubili v prizadevanju za rast. Obstaja nevarnost, da je podjetje v času rasti izgubilo svojo prvotno edinstvenost. Standardizacija izdelkov in poslovnih postopkov je lahko z nekaterih vidikov dobra, lahko pa povzroča tudi izgubo »enkratne prodajne zamisli«. Včasih se to zgodi, ko prvotni lastnik podjetje proda večjemu podjetju, ki pa enostavno nima enakega sklopa vrednot, ki so privlačile prvotne kupce.

11. Stroški iz meseca v mesec poberejo del dobička zaradi pomanjkanja virov

Samozadovoljnost z viri lahko nastopi v času rasti podjetja. O tem smo že razpravljali s primerom kopičenja zalog. Vendar ima večja zaloga vsaj cilj ohranjanja uslug kupcu na visoki ravni, ohlapen odnos do upravljanja z viri pa je neke vrste oblika organizacijske lenobe. Ključno je, da poleg prodajne rasti in tržnega deleža, kot indikator uspeha štejemo tudi donosnost. Eden izmed običajnih inovacijskih pomoči je upravljanje s stroški v Dobičkovnem centru in Stroškovnem centru, pomaga lahko tudi »Vitko mišljenje«.

12. Občutek vsakdanjosti in dolgočasja kljub navidezno stimulativnemu in dinamičnem okolju. Pomanjkanje pravega "naboja"

Občutek »dolgočasja«, kot je smo ga opisali zgoraj, se lahko kaže na zelo različne načine. Pomanjkanje »naboja« lahko vodi do pomanjkanja dejavnosti v podjetju. Zaposleni ne predlagajo novih zamisli za inovacijo, nastopi pomanjkanje kreativne energije in »naboja«, ki se kaže že v telesni govorici in komunikacijskih veščinah zaposlenih v odnosu s kupci. Primer tega so lahko gostinske storitve v hotelu, ki je »izgubil svoj prvotni čar«. V proizvodnem podjetju se lahko kaže v zmanjšanju predlogov zaposlenih in nezmožnosti, da bi s skupinskim delom dosegalo prave rezultate

carefully. It may be inevitable that customers who were attracted to the informal "early days" are actually now high-cost customers in our more efficient, growing set-up. However, the innovation challenge is to keep all of our customers, while finding efficiency and effectiveness as the business grows.

Early customers may have valuable insights to impart about the qualities of our product and service that we have lost in the quest for growth. There is a danger that the very uniqueness at start-up is lost as the business grows. Standardisation of products and business processes may look good on the bottom line, but might actually cause the business to lose its "unique selling proposition". Sometimes this happens when the original owners sell the business and move on, and a larger takeover firm simply does not have the same set of values that brought customers to the company in the first place.

11. Costs are eating a little more each month into profitability through a "slackness" with resources

A complacency with resources can set-in as a company grows. We already discussed this using the example of inventory. However, whereas higher inventory at least has the goal of keeping customer-service levels high, slackness with resources is a kind of organizational laziness. It is vital here to look at profitability, not just sales growth or market share as performance indicators. Profit-centre and cost-centre cost management is a usual aid to innovation here, as is "lean thinking".

12. There is a hint of "sameness", of boredom even, in an apparently exciting and changing environment. A lack of real "buzz"

Finally, the particular aspect of "boredom" mentioned earlier can manifest itself in very particular ways. The lack of "buzz" can result in a lack of proactivity in the business. People do not come forward with new ideas for innovation; there is a lack of creative energy and "buzz", which even shows itself in the body language and communication skills of customer-facing staff. An example of this can be in hotels and catering, where customers feel the place has "lost its original charm". Yet even in a manufacturing company it manifests itself in a reduction in suggestions from employees and a failure of team projects to deliver real results.

Tu je inovacijski izziv vzpodbuda in izboljševanje delovnega okolja. Zelo pomembno je uvajanje novih proizvodov na trg, nove tržne dejavnosti in ponovno vzpostavljanje stika s poslovno vizijo.

5 SKLEP

Vsak izmed navedenih znakov umiranja lahko pripomore k dolgoročnemu neuspehu podjetja. Tudi v času rasti smo našli sledi teh znakov umiranja na področjih grafičnega oblikovanja, proizvodnje, finančnih storitev, umetnosti, prevozništva in gostinstva.

Tipologija znakov umiranja lahko služi kot koristno orodje za razpravo med člani uprave ali na timskih sestankih – je orodje za inovacijo.

MSVP z visoko rastjo morajo spoznati, da zahteva po inovaciji nastopi že v najzgodnejših fazah njihovega delovanja. Inovacije izdelkov, storitev in poslovne organizacije so pomembni in celo ključni elementi v času zagona in po njem.

Ko smo vprašali udeležence naših delavnic, med letoma 2004/05, zakaj ne ukrepajo ustrezno ob znakih umiranja smo zasledili številna znamenja »propadanja in odlašanja«. Presenetljivo je, da za nedelovanje niso navajali zgolj izgovora, da so prezaposleni z upravljanjem rasti!

5.1 Znaki propadanja in zavlačevanja za podjetja v zagonu in preživeli

1. Nikoli niste zares ustanovili pravega podjetja – pravna oblika ni popolna niti ni vaše zaveze k njej.
2. Poigravate se s spletno stranjo, s katero niste zadovoljni. Spletna stran skorajda nima obiskovalcev in ni nikoli zares dokončana
3. Kar naprej se ponovno izumljate. Ni jasne notranje ali zunanje istovetnosti.
4. Imate »dobro« zasnovo ali ideologijo, toda kupcev niste prepričali v nakup
5. Imate alternativen model trženja, ki se vam zdi smiseln, toda ne deluje kot bi moral.
6. Prevzamejo vas obdobja truda in motivacije, toda ti niso dovolj za uspešen zagon.
7. Niste povsem izdelali poslovnega načrta, ki bi bil uporaben.
8. Kar naprej se poigravate z izdelkom.
9. Oglaševanje je zakrpano, nekonsistentno nenačrtovano ter ne izhaja iz poslovnega načrta.

Here, the innovation challenge is one of motivation and improving the working environment. The launching of new products, new marketing campaigns and reconnecting with the business vision are important.

5 CONCLUSION

Each of the death signs can contribute to a failure over the long term for the enterprise. Even during high growth we have found evidence of these death signs in sectors including graphic design, manufacturing, financial services, the arts, transport and hospitality.

The typology of death signs is in itself a useful tool for discussion at board and team meetings. It is a tool for innovation.

High-growth SMEs need to recognize the need for innovation at the earliest stages of development. Innovation with respect to product, service and business organization is all relevant and even critical during and beyond start-up.

When we asked participants at our workshop during 2004/05 why they were not acting on these death signs (and many were not and were shocked by the list), we identified a number of signs of “decay and delay”, not all of which are concerned with simply being “too busy” with coping with growth.

5.1 Signs of Decay and Delay for Start-ups and Start-up Survivors

1. You have never really properly set up – the legal form is not appropriate, clear nor fully committed to.
2. Tinkering with a website you are not really satisfied with. The website is not getting hits, and is never satisfactorily completed.
3. You keep re-inventing yourself. There is no clear internal or external identity.
4. You have a “fine” concept and ideology but have not persuaded customers to buy.
5. You have an alterative model of marketing that makes sense to you, but is not quite working.
6. You have bursts of effort and motivation but it is not enough so far to effect a successful launch.
7. You have not genuinely developed a business plan that you find authentically useful.
8. You keep tinkering with the product.
9. Advertising is patchy, inconsistent and not planned nor derived from the business plan.

10. Kar naprej napačno usmerjate energijo.
11. Preganja vas dvom – bo delovalo? Je vredno?
12. Vaša zamisel je preveč zapletena in zahteva preveč razlag in upravičevanja.
13. Izčrpavate se z lastno administracijo.
14. Prisiljeni ste služiti denar za preživetje iz drugih virov, ki pa črpa vašo energijo potrebno za zagon podjetja.

Ta seznam tvori osnovni program inovacije za soočanje z znaki umiranja. V nadaljnjih raziskavah nameravamo raziskati in preveriti te anekdotične ugotovitve in povezati znamenja propada in zavlačevanja s specifičnimi znamenji umiranja, da bi tako lahko zasnovali bolj natančen program inovacije. Vzdolžna raziskava bo potem služila za pregled najbolj uspešnih inovacijskih strategij.

10. You keep engaging in displacement spending and effort.
11. You are plagued by self-doubt. Will it work? Is it worth it?
12. Your concept is too complicated and requires too much justification and explanation.
13. You are burning out doing your own administration.
14. You are stuck having to earn money from other sources to survive, which saps the energy required to really launch.

This list actually forms the basis of an agenda of innovation for dealing with the death signs. In our future research we intend to explore and validate these anecdotal findings and attempt to map the signs of decay and delay onto the specific death signs in order to arrive at a more focused innovation agenda. Longitudinal research will then help to examine the most successful innovation strategies.

6 LITERATURA
6 REFERENCES

[1] Caffyn, S., A. Grantham (2003) Fostering continuous improvement within new product development processes. *International Journal of Technology Management* 26(8): 843-856.

[2] Francis, D., J. Bessant, et al. (2003). Managing radical organisational transformation. *Management Decision* 41(1): 18-31.

[3] Levy, P., D. Knowles (2003) Product and process innovation in small and medium sized firms using action learning. *Management of Innovative Technologies MIT 2003*, Piran, Slovenia.

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Naloga navideznih omrežij v navideznem podjetju

The Role of Virtual Networks in a Virtual Enterprise

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Napredki pri razvoju izdelkov so pokazali usmeritev k integraciji različnih razvojnih faz skozi integracijski podatkovni model in sodelovalne tehnologije. Razvojna faza prihodnosti bo vsebovala vse faze izdelovalnega kroga izdelka. Obenem pa bodo interakcijske in komunikacijske tehnologije omogočile ljudem z različnim znanjem sodelovanje in s tem doseganje najboljše oblike izdelka. Ta prispevek orisuje futuristično različico proizvodnega kroga s poudarkom ustvarjalne oblike. Mi ga imenujemo neposredna digitalna oblika. Prav tako ta prispevek predstavlja vizijo podjetja naslednje generacije in opisuje jedro informacijske tehnologije, na katerem bi lahko bil zgrajen sistem prihodnosti. Predstavljene so tudi zamisli navideznih podjetij in navideznih oseb, opremljenih z novimi spletnimi tehnologijami, to so: internet, intranet in extranet. Le tako bodo lahko podjetja ostala konkurenčna in rasla na današnjih turbulentnih trgih.

(Ključne besede: podjetja navidezna, skupine navidezne, mreže navidezne, tehnologije spletne)

Advances in product development concepts have demonstrated the trend for integrating different development phases through the integrated product data model and collaboration technologies. Future product-development processes will take all aspects of the whole product lifecycle into account. At the same time, interaction and communication technologies will allow people with different knowledge backgrounds and dealing with different aspects of a product work together to achieve the best product design. This paper sketches a future vision of product development with an emphasis on the support of creative design. We call it direct digital design. This paper presents a vision of next-generation enterprise working environments and describes a core information technology that future systems can be built on. The concepts of a virtual enterprise (VE) and of virtual teams, enabled by a new generation of internet/intranet/extranet-based services are discussed here, as a means to stay competitive and to thrive in a turbulent market.

(Keywords: virtual enterprises, virtual teams, virtual networks, internet technologies)

0 INTRODUCTION

The internet is a world-wide conglomerate of different networks that communicate with each other via a common protocol, independent of the type of hardware used. Various network services can be used by everyone, either supplying or demanding them. The large range of distribution, the platform independence, the large number of user-friendly services that are easily accessible through the world wide web as well as the open standards used and the free or budget-priced products (such as browsers, html editors, software updates) have led to a widespread and continuously growing proliferation of the internet [1].

The advantages offered by the internet for covering the information needs are held to be the following [2]:

- Reduction of local barriers by means of world-wide information offers;
- Reduction of time barriers by means of permanently available information;
- Reduction of (transaction) costs by way of the automation of information processing on the supply and/or the demand side;
- Improved coordination and cooperation with

external partners using an integrated information and communication platform (e.g., platform independence, information exchange without media ruptures).

However, the application-to-application communication problem still exists. Businesses need a standardized way for applications to communicate with one another over networks, no matter how those applications were originally implemented [3]. Web Services, the latest evolutionary step in distributed computing, represent exactly this solution, by providing a standardized method of communication by means of which different applications can be integrated together in ways not possible before. Different applications can be made to call on each other's resources easily and reliably, and the different resources that applications already provide can be linked together to provide new sorts of resources and functionality [4]. Moreover, the application integration becomes much more flexible because web services provide a form of communication that is not tied to any particular platform or programming language [5]. At the core, web services represent a unit of business, application, or system functionality that can be accessed over the internet. Web services are applicable to any type of web environment, internet, intranet, or extranet, and be focused on business-to-consumer, business-to-business, department-to-department, or peer-to-peer communication (see Figure 1).

We present in figure 1 a general architecture for the virtual enterprise environment implemented in the CESICED platform.

A web service consumer could be a human user accessing the service through a desktop or a wireless browser; it could also be an application program or even another web service [6].

1 COLLABORATION AND COMMUNICATION IN THE CESICED PLATFORM

A central point of future product development is therefore collaboration and communication. This is based on consistent, integrated data sets and on tools that support the collaboration (see figure 2).

Traditionally, only data about the designed product are stored, and made available for the product development team and archived for later product-development projects [7]. With product lifecycle management, information coming from all product lifecycle phases is to be integrated, including sales, operation and service data about sold/installed products. Product-data management technologies are extended to manage more complex and more dimensional data. With this data management, tools used by different people throughout the product lifecycle are integrated, including requirement analysis, reverse engineering, production planning, resource planning, logistics and traditional design and simulation systems [8].

An environment supporting collaborative design would comprise the following components:
- Integrated data sets, including a description of the product and all the related processes, and

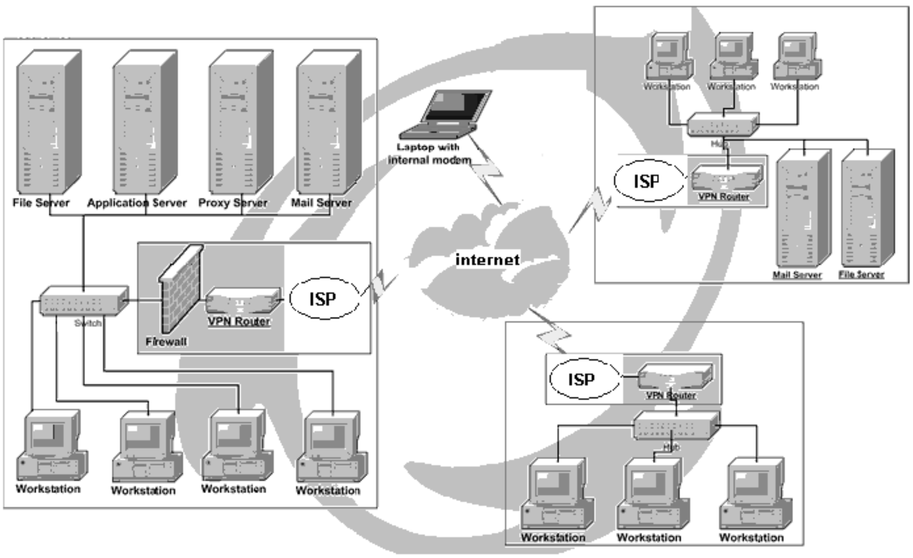

Fig. 1. *Internet/intranet/extranet-based tools in the CESICED platform*

including data collected from the lifecycle of this and other related products;
- Interface to detailed planning, analysis and simulation systems, as some of the product and process features need to be derived from the collected data;
- Simulation and visualization engines, to obtain an virtual environment containing easy and understandable representations of product features and scenarios;
- Multi-modal, intuitive user interfaces, which allow people to easily view and manipulate the product features.

The collaborative design is based on the simulation of scenarios [9].

The key elements of a scenario are the desired product, the targeted environment, the lifecycle processes and the people involved in the processes ([10] and [11]).

2 THE NETWORK SUPPORT FOR VE

A hierarchical network design model breaks the complex problem of network design into smaller, more manageable problems. Each level, or tier, in the hierarchy addresses a different set of problems, so that network hardware and software can be optimized to perform specific roles. Devices at the lowest tier of the hierarchy are designed to accept traffic into a network and then pass traffic up to the higher layers [2].

The core of the network has one purpose: to provide an optimized and reliable transport structure by forwarding traffic at very high speeds. In other words, the core layer should switch packets as fast as possible. Devices at this layer should not be burdened with access-list checking, data encryption, address translation, or any other process that stands in the way of switching packets at maximum speed [12].

The distribution layer sits between the access and core layers and helps differentiate the core from the rest of the network. The purpose of this layer is to provide boundary definition by using access lists and other filters to limit what gets into the core. Therefore, this layer defines the policy for the network. A policy is an approach to handling certain kinds of traffic, including routing updates, route summaries, virtual local area network (VLAN) traffic, and address aggregation. You can use policies to secure networks.

The access layer feeds traffic into the network and performs network entry control. End users access the network via the access layer. As a network's "front door," the access layer employs access lists designed to prevent unauthorized users from gaining entry. The access layer can also give remote sites access to the network via a wide-area technology, such as Frame Relay, ISDN, or leased lines.

A reliable and available network provides users with 24-hours-a-day access.

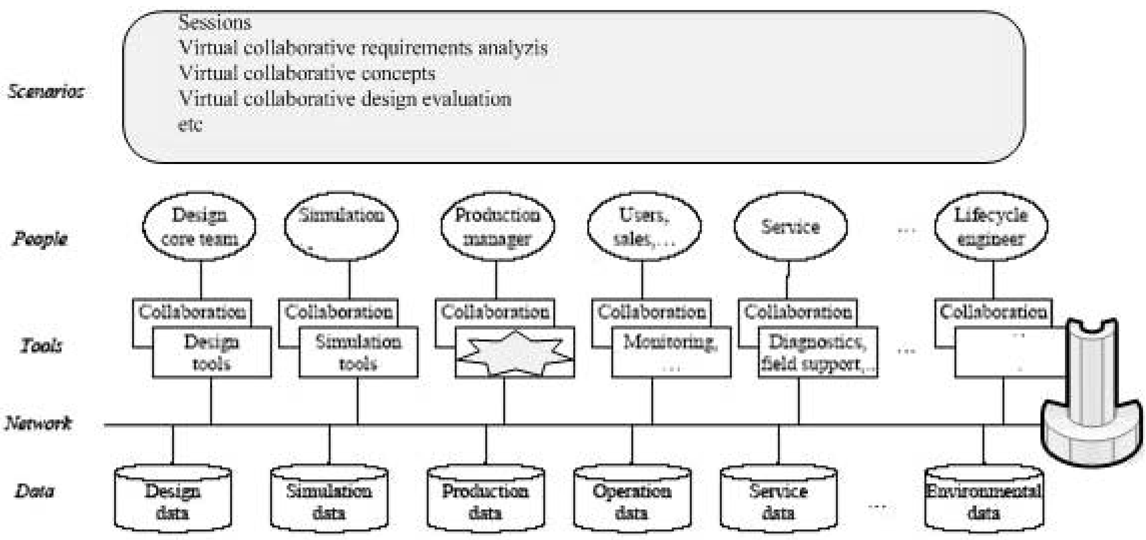

Fig. 2. *The key elements of collaboration and communication in the CESICED platform*

In a highly reliable and available network, fault tolerance and redundancy make outages and failures invisible to the end user. However, the high-end devices and telecommunications links that ensure this kind of performance come with a large price tag. Network designers constantly have to balance the needs of users with the resources at hand.

Multicast traffic can also consume a large amount of bandwidth. Multicast traffic is propagated to a specific group of users. Depending on the number of users in a multicast group or the type of application data contained in the multicast packet, this type of broadcast can consume most, if not all, of the network resources. As networks grow, so does the amount of broadcast traffic on the network. Excessive broadcasts reduce the bandwidth available to the end users and force end-user nodes to waste CPU cycles on unnecessary processes. In a worst-case scenario, broadcast storms can effectively shut down the network by monopolizing the available bandwidth.

Two methods can address the broadcast issue for large switched LAN sites.

The first option is to use routers to create many subnets and logically segment the traffic. However, this scenario can create a bottleneck in the network.

A second option would be to implement virtual local area networks (VLANs) within the switched network. A VLAN is a group of end devices that populate multiple physical LAN segments and switch ports; they communicate as if they were on a single LAN segment.

One of the primary benefits of VLANs is that LAN switches (by creating VLANs) can be used to effectively contain broadcast traffic and manage traffic flows.

The VLAN is the best support for the virtual design offices or the virtual teams [3]. The interconnection of VLANs is realized on level two (ELAN – Emulation Local Area Network), and on level three (MultiProtocol Over AT – MPOA).

MPOA Client (MPC) and MPOA Server (MPS) are given their configuration by LECS (LAN Emulation Configuration Server). The virtual networks MPOA is named IASG (Internet Address Summarization Groups).

In this case a design team is formed with members located at different geographic locations [2]. A virtual local area network is created for the project (see figure 3).

In addition to the team's full-time members, the team also includes contributing members who are recruited for specific components of the project. As such, a core group is responsible for leading the project and a sub-group is involved in specific components of the project [12].

While the full-time employees form the central core of the team, experts in the different problems of the project (control systems, mechanical systems, electronic systems, programmers etc.) are also team members.

Virtual teams for engineering design are becoming more commonly used in industry and the engineering education community must prepare graduates to be employed in such working environments. It is inevitable that multidisciplinary teams for product design, with members located in different geographic locations, will become more commonplace in the future. It is widely understood that successful design is often a highly collaborative team-based activity [3]. To be effective, a virtual team must be able to communicate, collaborate and coordinate, all at distance. Though some corporations are practicing a form of distributed design, a documented procedure for conducting distributed design and product development has yet to be created, tested and distributed. However, the same set of skills that guide design teamwork for a team where all members are in one location is different from that set of skills needed to lead a virtual team.

The term "virtual team" is a misnomer as although it makes reference to virtual reality and the concept of creating a virtual space that can be experienced it also suggests that the virtual team is not actually a team, and as such can lead to a loss of performance. In the initial stages it became clear that whilst a distributed computer-based platform could support distributed teams it could not completely replace face-to-face contact [3]. The reasons behind this are complex but lie largely in the operational cultures of the organizations and individual apprehension about the process of decision making and conflict resolution in a distributed environment. In particular it is recognized that face-to-face contact at the beginning of a project leads to significant advantages in the areas of building trust, establishing the team working methods and communications protocols, and defining a common vision of the product. This presented an opportunity to explore how collaborative tools and technologies can be used to support the gathering of distributed teams within a co-located environment for key decision-making sessions [12]. To illustrate the infancy of distributed virtual design, the method of

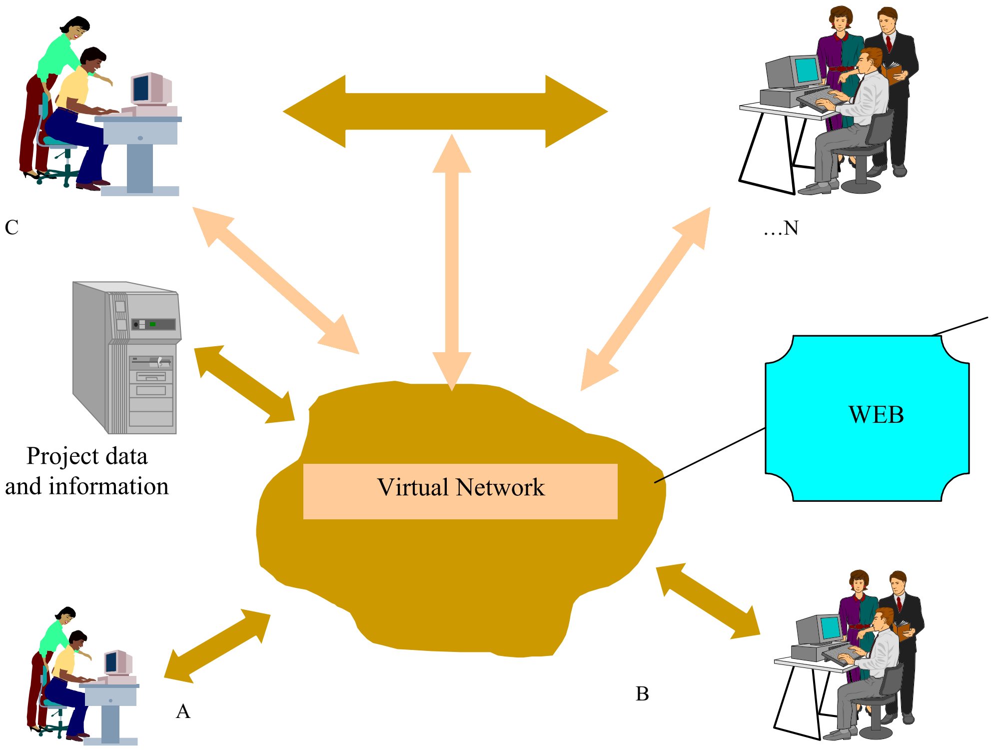

Fig. 3. *Virtual teams in collaborative processes within a virtual organization*

distributed team members working on any project currently lacks a universal name [2]. Terms such as virtual teams, collaborative learning groups, geographically and temporally dispersed teams, globally distributed teams, distributed design, e-design and e-teams, are all used to describe various internet-based design activities [12].

3 CONCLUSIONS

In this paper we discussed different related issues and proposed a concept for supporting creative design in an interdisciplinary team, considering all the phases of the product lifecycle. This is a vision for the future of product development. We know that developments in all of the sub-areas are necessary to achieve this vision. We do not expect full implementation in the short term. With this paper we want to stimulate discussions and further R&D, and to encourage colleagues both from academic institutes and from the industries to stepwise, incrementally, but continuously develop and deploy emerging technologies and concepts. In this way we will be stepwise closer to our vision.

The concept of the CESICED platform, enabled by a new generation of internet/intranet/extranet-based services is discussed here, as a means to stay competitive and to thrive in a turbulent market. The new internet technologies, the latest evolutionary step in distributed computing, has been proposed as the platform for realizing the CESICED infrastructure. This platform for research, training, consulting in the new digital economy is developed at the University "POLTEHNICA" of Bucharest in the PREMINV research laboratory.

4 REFERENCES

[1] S. Szykman, S.J. Fenves, W.Keirouz, S.B. Shooter. (2001) A foundation for interoperability in next-generation product development systems in Computer-Aided Design 33; *Elsevier Science*, pp. 545-559.

[2] G. Dragoi (2003) Intreprinderea integrata: metode, modele, tehnici si instrumente moderne de dezvoltare si realizare a produselor. ISBN 973-8449-25-1, *Politehnica Press,* Bucharest, Romania.

[3] G. Drăgoi, M. Guran, C. Cotet: The PREMINV platform for training in management and engineering for virtual enterprise, in Collaborative Business Ecosystems and Virtual Enterprises, edited by Luis M. Camarinha - Matos, *Kluwer Academic Publisher* pp. 571-579, ISBN 1-4020-7020-9.
[4] G. Drăgoi, Cotet, C., Roşu, L., Roşu, S. (2004) Virtual teams in collaborative systems in networks and corporations, *Proceedings of the 7th Conference on Management of Innovative Technologies (MIT'2004)*, 4th - 5th October 2004, pp. 119-124, ISBN 973-700-028-5, Constanta, Romania.
[5] G. Drăgoi, Cotet, C. (2004) Virtual laboratories for the collaborative design to improve product development, *International Journal of Simulation Modelling-IISJMM*, vol. 3, number 1, pp.29-40, march 2004.
[6] G. Drăgoi, G.L. Roşu, S. Roşu (2003) Supporting global design teams through virtual design offices, *Proceedings of the 6th Conference on Management of Innovative Technologies (MIT'2003)*, 13th -14th October 2003, pp. 237-242, Fiesa - Piran, Slovenia, ISBN 961-6238-81-7.
[7] Khoshafian, Setrag (2002) Web services and virtual enterprises, *Tect*. Chicago, USA.
[8] K. Furst, T. Schmidt, G. Wippel (2002) E-service based business information systems, *Proceedings of the 8th International Conference on Concurrent Enterprising – ICE2002*, Centre for Concurrent Enterprising, University of Nottingham; Nottingham, UK, pp. 381-38.
[9] IBM Software Development Platform: IBM rational software solutions (2005) *IBM Corporation*, Bucharest, Romania.
[10] G. Dragoi, D. Brissaud (2003) An internet based quality tool for customers to improve product development, Recent Advances in Integrated Design and Manufacturing in Mechanical Engineering, *Kluwer Academic Publisher*, pp.503-512, ISBN 1-4020-1163-6.
[11] G. Dragoi, B. Radulescu, S. Tichkiewitch (2004) A cooperative system for the design of the mechatronic products with the multidisciplinary optimization, Methods and tools for co-operative and integrated design pp. 281-290, *Kluwer Academic Publisher*, Netherlands, ISBN 1-4020-1889-4.
[12] G. Drăgoi, G.C.E. Cotet, L. Roşu, S. Roşu (2004) Virtual teams in collaborative systems in networks and corporations, *Proceedings of the 7th Conference on Management of Innovative Technologies (MIT'2004)*, 4th - 5th October 2004, pp. 119-124, ISBN 973-700-028-5, Constanta, Romania.

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Uvod v diagnostiko postopka razslojevanja kompozitnih materialov pri rezanju z visokotlačnim abrazivnim vodnim curkom

An Introduction to the Diagnosis of the Delamination Process for Glass/Epoxy Composites During High-Pressure Abrasive Water-Jet Cutting

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(Institute of Advanced Manufacturing Technology, Cracow, Poland)

Razslojevanje je glavna težava pri rezanju z vlakni ojačanih kompozitnih materialov z abrazivnim vodnim curkom. Je specifični pojav pri obdelavi kompozitnih materialov in je neodvisna od metode obdelave. V prispevku je predstavljen zamisel diagnostičnega sistema, ki temelji na digitalni časovni in frekvenčni analizi zajetih signalov za sprotno spremljanje razslojevanja kompozitnih materialov, ojačanih s steklenimi vlakni. Opisana je uporabljena merilna oprema ter prikazani so rezultati raziskave.

(Ključne besede: diagnostični sistemi, materiali kompozitni, rezanje s curkom, curek vodni, curek abrazivni)

The main problem during the abrasive water-jet cutting of fibre-reinforced composites is delamination. This delamination is a phenomenon specific to composite materials, which is independent of the machining method used. In this paper the concept of a diagnostic system is presented, based on a digital time and frequency signal analysis, for the online detection of the delamination in glass-fibre-reinforced composites. The applied measurement equipment is described and the research results are presented.

(Keywords: diagnostic systems, composites materials, abrasive water jet cutting)

0 INTRODUCTION

The advanced development of the electrical and machine-building industries as well as other branches of technology have created the rapid growth of the applications of new generations of construction materials, including composites fulfilling the requirements for high mechanical strength, the exploitation of which may replace commonly used traditional materials. One of the obstacles to the application of composite materials based on glass and carbon fibre is their mechanical workability, limiting the desired parameters of the technological quality, efficiency and purity of the end-product. The classical methods of cutting and machining that are used have many disadvantages, such as fast glazing of the cutting edge ([1] to [5]) overheating of both the material and of the tool ([3] and [6]), dusting of the reinforcing fibres ([2], [3] and [5]), and limitations on the shapes of the forms produced. These problems stimulated a search for new methods to work the material. Among them, the technology of high-pressure abrasive water-jets is of the highest importance. Recent developments in this technology make it possible to form composite elements with highly complex shapes in 2D and 3D [7].

1 DELAMINATION PHENOMENON OF THE COMPOSITE MATERIAL

The delamination of the material is a new and not completely understood phenomenon accompanying the cutting of composite materials with an abrasive water-jet under high pressure. The material damage is caused by the loss of coherence of the individual adjoining layers of the composite [8]. When cutting with an abrasive water-jet, delamination occurs in the external layers at the water outlet alongside the cutting edge (see Figure 1).

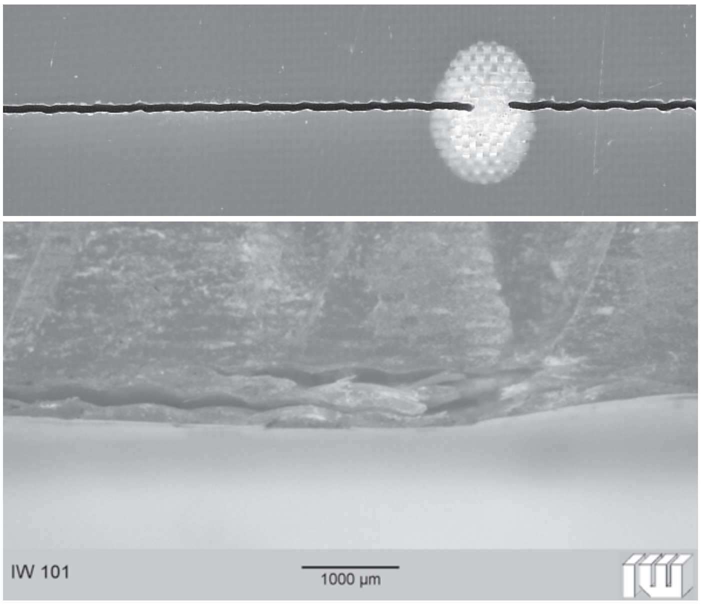

Fig. 1. *Macro- and microscopic views of the delamination on the glass fibre/epoxy-resin composite surface*

It may cause variable but serious damage to a material, usually containing several to several tens of square millimetres of area, including one or more layers of laminate. Further propagation of the delamination does not proceed spontaneously. However, when the material is subjected to a loading under working conditions the properties of the material may deteriorate and the structure in which it is used may fail (for instance, the buckling of a construction [8]). In the worst case the element may be completely destroyed. For this reason the degree of delamination of a material should be considered as a critical criterion determining the technological quality of the production of elements from a fibrous composite material. It can be assumed that there are two main reasons for the delamination during the cutting of laminar fibrous composite materials when using the abrasive water-jet:

1) those due to the properties of a material, which are the consequences of inhomogeneity, caused by incorrect or uncontrolled manufacturing processes or damage to the fibrous mat during its production (knots, fluff),
2) those caused by the cutting process itself, due to the inherent instability of the abrasive water-jet, being a liquid.

This may also be connected to instantaneous irregularities in the amount of abrasive material supplied. The supply of abrasives is mainly reliant on the systems feeding the abrasive material to the cutting head and on the inhomogeneity of the abrasive material (its density, shape and grain size).

Taking into account the serious technical and financial consequences of damaging composite materials by delamination, the introduction of systems monitoring its occurrence, its extent and the identification of damaged areas along the cutting line should be considered at an initial stage of the machining. In the rather meagre literature on this subject the problem of delamination by water-jet cutting or the possibility of monitoring the phenomenon do not appear to have been addressed.

2 CONCEPT OF THE MONITORING SYSTEM OF THE GLASS/EPOXY COMPOSITE DELAMINATION PROCESS

The published results of experimental studies on abrasive water-jet cutting, obtained with the use of various types of measuring sensors, have not dealt with the question of delamination and have focused mainly on two areas of investigation:

– diagnosis of the rate of wear of the cutting nozzles, using microphones or hydrophones ([9] to [11]),
– recognition of the state of complete or incomplete cutting or boring the material, using microphones, hydrophones, vibration sensors or acoustic emission sensors ([11] to [14]).

These studies have shown that this type of diagnostic methodology can be highly effective in

selected applications. This is important where direct control of the process is not possible, for example when working underwater. The literature describes attempts to diagnose cutting with an abrasive water-jet based on physical processes during:
– the formation of the abrasive water-jet,
– the removal of material during cutting.

These are:
– the level of the sound generated in the cutting head and during the interaction of the abrasive water-jet with the surrounding air and the material being machined,
– vibrations within the workpiece, caused by the impact of water droplets and abrasive particles, the pulsation of the water supply, the varying quantities of the supplied abrasive material and the cyclic character of the material removal process,
– the emission of an acoustic wave, due to the micro-cutting, material erosion, formation of micro-fractures and splitting within the worked material.

The process of cutting composite materials is accompanied by analogous physical processes. Additionally, the literature describes measurements of acoustic emissions carried out during the tests of the mechanical strength of the composite materials being considered, which have led to the conclusion that the processes of fracturing of the fibres and their being pulled out of the woven mat, as well as the tearing off of adjacent layers of a laminate during delamination, may also be a useful investigation source in the form of acoustic emission signals [15]. Therefore, a monitoring system based on vibration sensors, acoustic-emission detectors and microphones should be considered. To analyse the usefulness of particular sensors it is proposed that an analysis of collected signals be made in the time and frequency domains.

3 EXPERIMENTAL RESEARCH

3.1 Experimental setup

Preliminary studies had been carried out on glass-fibre/epoxy-resin laminated plates, containing 63% fibres. The investigations were carried out under the following conditions:
– water pressure: 300 MPa,
– abrasive mass-flow rate: 6 g/s,
– type and size of the abrasive: garnet 80 mesh,
– diameter combination of the water nozzle and the mixing nozzle: 0.3/0.8 mm,
– cutting without immersion of the element,
– thickness of samples: 10 mm, 20 mm.

The signals from two sensor groups were studied during this phase to evaluate the usefulness of the signal:
– contact sensors:
a) vibration sensor (accelerometer) Brüel&Kjær 8309,
b) acoustic emission sensor Brüel&Kjær 8313,
– non-contact sensor:
a) hydrophone Brüel&Kjær 8103.

The sample was cut towards the mounted sensors so the measuring distance diminished over time. A diagram of the test setup is shown in Figure 2.

One of the reasons for the delamination of the composite material being cut with the abrasive water-jet was assumed to be a lack of uniformity in the feed rate of the abrasive material. Therefore, to simulate a realistic situation for the delamination of samples and to evaluate the effectiveness of delamination recording by individual sensors during the studies, disturbances or irregularities in the supply of the abrasive material were introduced. This was achieved by modifying the abrasive supply system so that the supply of abrasives to the cutting head could be interrupted for programmed intervals.

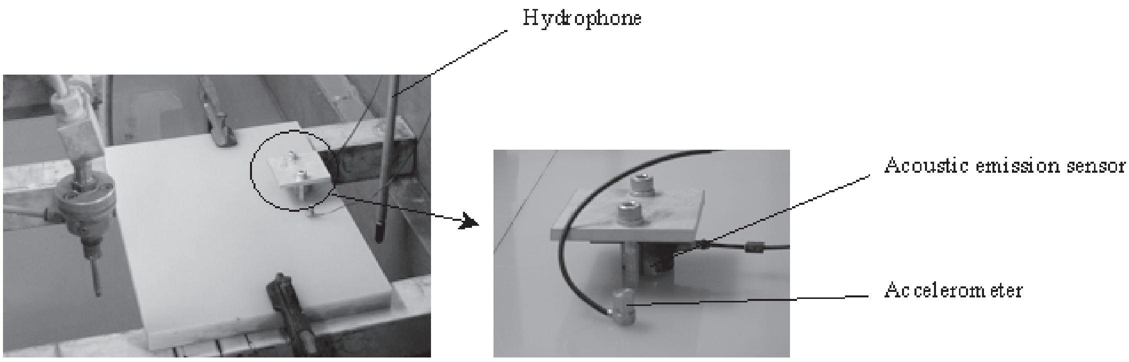

Fig. 2. *Experimental setup for the diagnosis of the delamination process*

The signals generated by the sensors were collected, translated and sampled by the data-acquisition plate, and afterwards analysed using specialised software. The acoustic-emission signal was sampled at 700 kHz, and the signals of the vibrations and the sound level were analysed at 200 kHz. The signal analysis was carried out on the basis of time and frequency. The following characteristic parameters were chosen to describe a signal:

- in the time domain: the signal amplitude, variance and kurtosis,
- in the frequency domain: the time-frequency spectrum (STFT spectrogram).

Variance contains information about the average divergence of a signal from its average value and it is a measure of the dynamics of signal energy [16]. Kurtosis shows the shape of the curve of the density of probability and is used for showing the

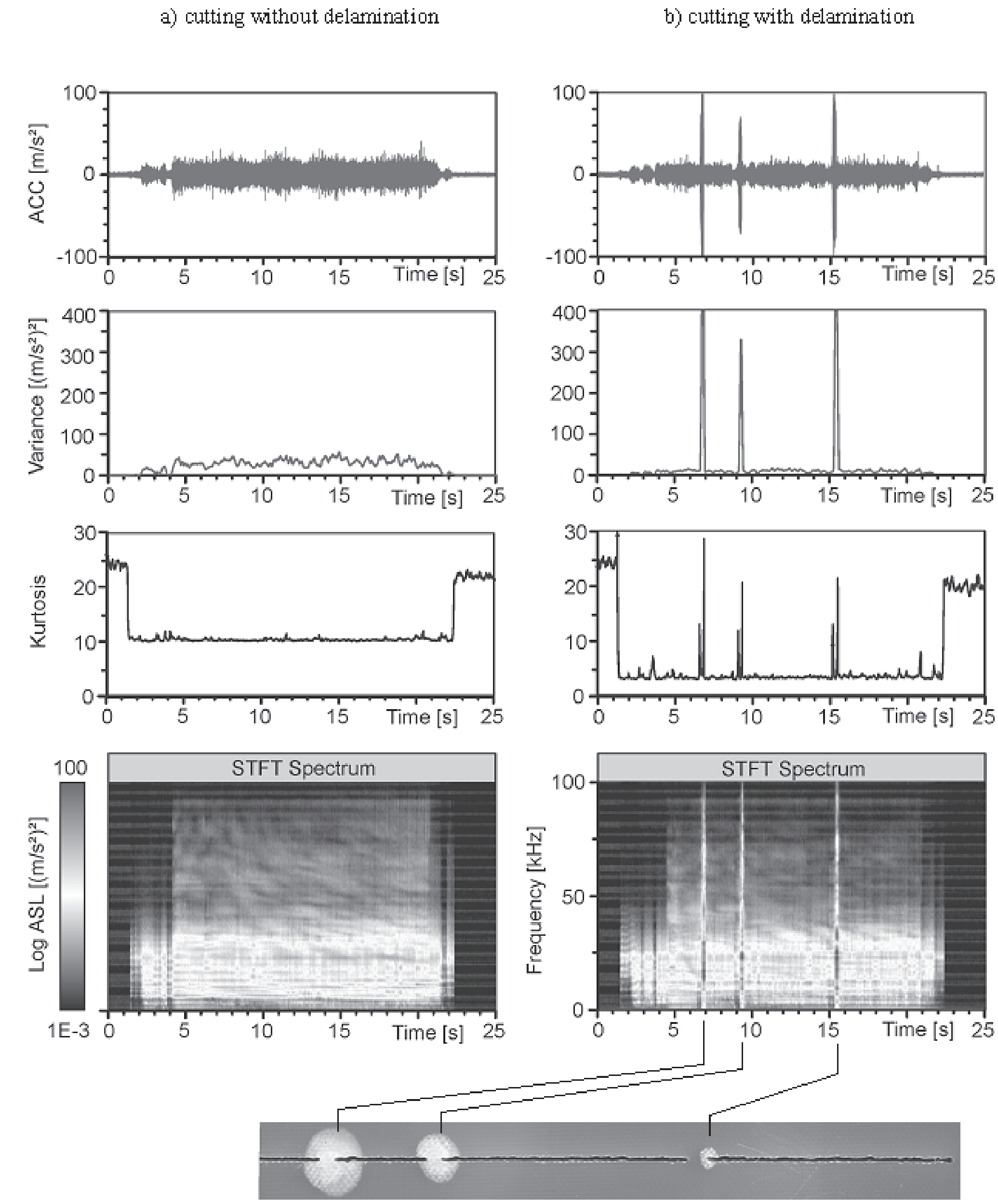

Fig. 3. *Characteristic quantities of the signal recorded on the vibration sensor for the abrasive water-jet cutting: a) cutting without delaminations b) cutting with delaminations. Composite material thickness – 20 mm, v = 500 mm/min.*

shortwave components of a signal, the so-called "peaks". The STFT spectrogram shows, on the other hand, which part of a signal is contained in a chosen frequency band within a selected time interval [17].

3.2 Results

During the investigation, interruptions in the supply of abrasive material longer than 1 second were introduced. The aim of these tests was to find whether the selected sensors could differentiate a stable cutting from a disturbed state, causing the extensive delamination. Figure 3 shows a sample set of time-based emissions, statistical indices and the time-frequency spectra for both states, for the signal registered by the sensor of vibrations. In a stable mode the time signal contains no high-amplitude disturbances and the kurtosis and variance are free from peaks (see Figure 3a). In the time-frequency spectrum there are also no peaks, except in the broad band corresponding to the stable process of removal of the material. On the other hand, in the time signal with introduced disturbances the sections of signal corresponding to the delamination of the composite are easy to identify, due to the very high amplitude values (see Figure 3b). Similarly, the characteristic symptoms of delamination can be observed via changes in the acoustic emission signal (Figure 4b). Using STFT spectra of the vibration sig-

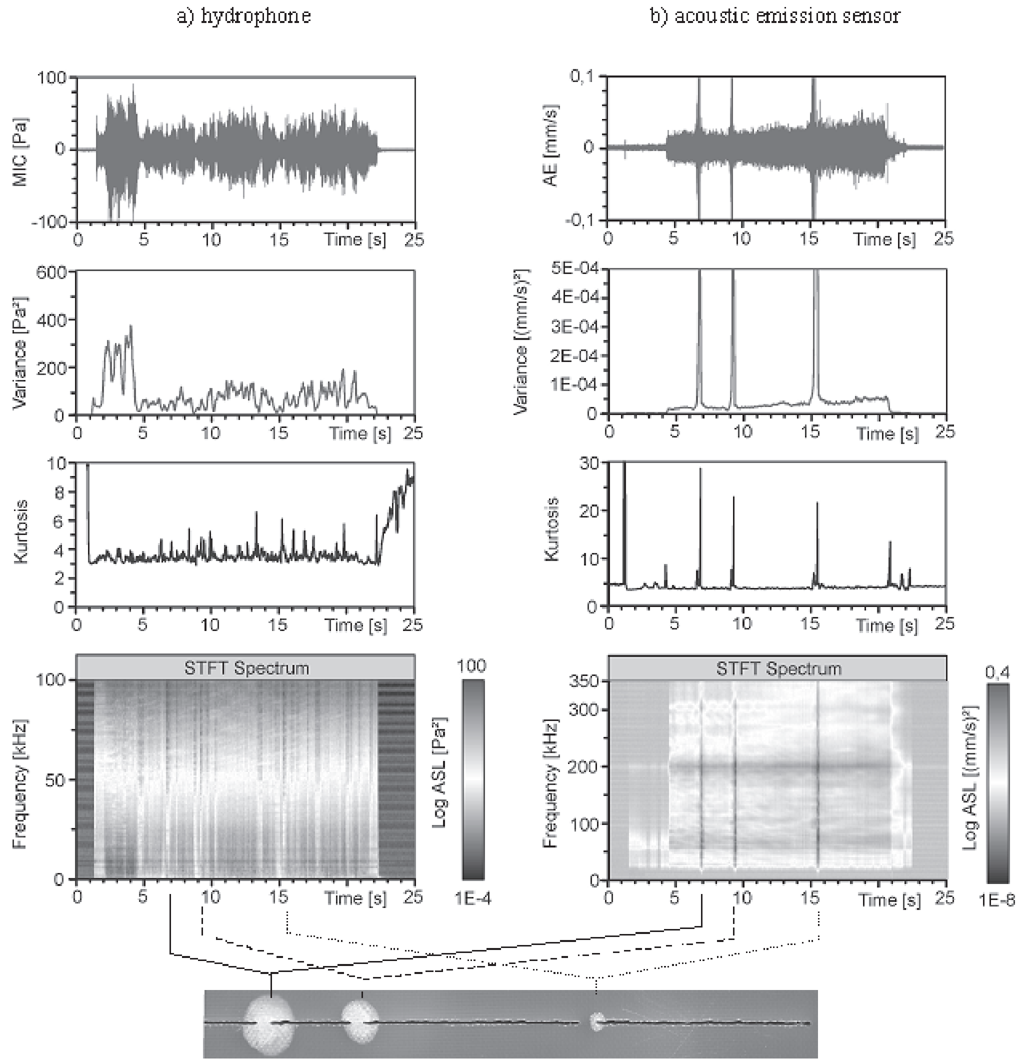

Fig. 4. *Characteristic quantities of the signal recorded for the abrasive water-jet cutting with delaminations: a) signal from the hydrophone b) signal from the acoustic emission sensor. Composite material thickness – 20 mm, v = 500 mm/min.*

nals of the acoustic emissions it would appear that the process of the loss of the coherence of inter-laminate layers cannot be ascribed only to one frequency or a defined frequency band. During delamination the sensors registered signals in the form of short, very intense peaks over the whole measured frequency range. The applied methods of signal analysis did not appear to be very effective for getting useful information from a hydrophone signal (see Figure 4a). This may be ascribed to the high level of background noise, particularly the high level of acoustic pressure generated by the friction of the sound generated by the abrasive water-jet passing through the successive air layers impinging on the hydrophone signal.

4 CONCLUSIONS

The obtained results prove that it is possible to monitor the delamination process for a composite thickness in the range 10 to 20 mm as it is cut with an abrasive water-jet. The purpose of this test is to detect delamination and its position along the line of the cut. During the tests it was found that hydrophones were not particularly useful in signal analysis. Conversely, very good identification of the delaminations of composites using vibration and acoustic-emission sensors was obtained. The presented analysis of the signals shows that delamination is a sudden process that cannot be predicted early enough to prevent it from happening. However, the obtained results create the basis for the automation of diagnostic procedures.

5 REFERENCES

[1] V. Hohensee (1987) Konturbearbeitung von Bauteilen aus faserverstärkten Kunststoffen. *Kunststoffberater*, Nr. 12, pp. 32-36.

[2] D.C. Davis (1989) Robotic abrasive waterjet cutting of aerostructure components. SME Technical Paper MS(89-912), *Conference: Nontraditional Machining*, Orlando, Florida.

[3] R. Komanduri (1993) Machining rfiber-reinforced composites. *Mechanical Engineering*, pp. 58-64, April 1993.

[4] W. König, C. Wulf (1983) Ein sauberes Trennverfahren für Faserverbundkunststoffe. *Industrie Anzeiger*, Nr. 56/57 v. 20.7., pp. 32-33, 1983/105.

[5] C.W. Wern, M. Ramulu (1995) Machining mechanics in fiber reinforced plastics. *Machining of Advanced Materials, ASME*, AMD-Vol. 208/MD-Vol. 59, pp. 1-27, 1995.

[6] V. Hohensee (1992) Umrißbearbeitung faserverstärkter Kunststoffe durch Fräsen und Laserschneiden. *Fortschritt-Berichte VDI*, Reihe 2: Fertigungstechnik, Nr. 251, VDI-Verlag.

[7] A. Karpiński, H. Louis (2003) Abrasive water jet, a multifunctional tool for 3-dimensional machining. *Proc. of 3rd International Conference on Machining and Measurements of Sculptured Surfaces: MMSS'2003*, pp. 423-434, Cracow.

[8] A. Muc (2003) Mechanika kompozytów włóknistych. Kraków.

[9] B. Jurišević, M. Junkar (2001) Adaptive control constraint (ACC) of abrasive water jet (AWJ) cutting. *Proc. of 2nd Int. Conference on Water Jet Machining WJM 2001*, pp. 71–76, Cracow.

[10] R. Kovacevic, L. Wang, Y.M. Zhang (1993) Detection of abrasive waterjet nozzle wear using accoustic signature analysis. *Proc. of 7th American Waterjet Conference*, Seattle, pp. 217–231.

[11] H. Louis, G. Meier (1991) Methods of process control for abrasive water jets. *Proc. of 6th American Waterjet Conference*, Houston, pp. 427–437.

[12] H. Kwak, R. Kovacevic, R. Mohan (1996) Monitoring of AWJ drilling of ceramics using AE sensing technique. *Proc. of 13th Int. Conference on Jetting Technology*, Sardinia, pp. 137–152.

[13] R. Mohan, A. Momber, R. Kovacevic (1994) On-line monitoring of depth of AWJ penetration using acoustic emission technique. *Proc. of 12th Int. Conference on Jetting Technology*, Rouen, pp. 649–665.

[14] U. Südmersen (2003) Akustische und schwingungsbasierte Überwachungsmethoden. *26. Sitzung Arbeitskreis Wasserstrahltechnologie*, Hannover.

[15] I. Malecki, J. Ranachowski (1994) Emisja akustyczna. Źródła, metody, *Zastosowania*. Warszawa.

[16] O. Pietsch, Ch. Scheer, U. Südmersen (2003) Schwingungsanalysen als Hilfsmittel zustandsorientierter Wartung und zur Qualitätssicherung in Produktionanlagen. *Hannover University*.

[17] J. Moczko, L. Kramer (2001) Cyfrowe metody przetwarzania sygnałów biomedycznych. *Wydawnictwo Naukowe UAM*, Poznań.

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Karakterizacije postopka čiščenja z vodnim curkom – simulacija postopka

Characterization of a Pure Water-Jet Cleaning Process – Process Simulation

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Čiščenje z vodnim curkom je zelo uporabljana tehnologija za odstranjevanje površinskih slojev. Uporabe segajo od grobega čiščenja sten ladij pa vse do čiščenja turbinskih delov med vzdrževanjem. Kljub temu je načrtovanje takih postopkov zelo odvisno od sposobnosti operaterja ter v večini primerov zahteva predhodno testiranje za zagotovitev ponovljivosti in stabilnosti postopka.

Predstavljena raziskava opisuje postopke, tehnike in orodja za obravnavo opisanega problema ter predstavlja integrirano orodje in model postopka odstranjevanja površinskih slojev. To okolje omogoča uporabniku načrtovanje in simulacijo celotnega postopka čiščenja, vključno z obnašanjem orodja ter reakcijo površine, kar definira optimalne postopkovne parametre in strategijo čiščenja še pred zagonom črpalke. Simulacija temelji na posebej standardiziranem eksperimentalnem postopku, ki normira obnašanje šobe in odziv materiala.

Druga uporaba predstavljenega sistema je načrtovanje in optimizacija samega orodja, npr. geometrijska postavitev šobe, ki zagotavlja enakomerno obremenitev na površini, kar bistveno zmanjša stroške in čas izdelave novega sistema za čiščenje površin z vodnim curkom.

(Ključne besede: čiščenje, curek vodni, odstranjevanje slojev, modeli, simuliranje)

Water-jet cleaning is a widely used technology for decoating surfaces. Its applications range from rough ship-wall cleaning jobs to the surface processing of turbine parts as part of maintenance operations. However, the jetting task layout and planning is very dependent on the particular user's skill and often requires preliminary tests in order to ensure a reliable and reproducible surface condition.

The presented work describes procedures, techniques and tools for dealing with this problem and introduces an integrated tool and decoating process model. This environment enables the user to design and simulate a complete cleaning task, including tool behaviour and surface reaction and thereby to determine the optimum parameters and machine setups before even switching on the pump for the first time. To put the simulation on solid ground, it is based on a special standardized experiment to normalize the nozzle behaviour and the material's response.

Another application of the package is the design and optimisation of the jetting tool itself, e.g., the geometrical arrangement of its nozzles to ensure a homogenous surface load. This can drastically reduce the costs as well as the time-to-market of a new water-jet cleaning device.

(Keywords: cleaning, de-coating, water-jet, models, simulations)

0 INTRODUCTION

Using a high-pressure water jet for cleaning and material-removal purposes is a well-known technology. As a result of increasingly restrictive environmental regulations, water-jetting has become even more popular than, e.g., chemical methods because no side products are produced during the process.

Applications range from the relatively insensitive cleaning of hull plankings to the delicate task of combustion-chamber and turbine-blade restoration.

In order to maximize the water-jet cleaning tool's efficiency, several single nozzles are usually integrated into one rotating head. With this, combined with a linear motion, a planar surface treatment can be achieved.

There are three main goals:

- complete coating removal without gaps due to insufficient trace overlapping,
- minimisation of the required energy for the cleaning process,
- the protection of the substrate material from damage by excessive water-jet loading.

However, creating a homogenous distribution of water-jet energy with this setup is not a trivial problem. With a rotating tool, the load at the small side regions of the treated area is normally loaded several times higher (depending on the process parameters) than at the relatively wide inner regions. This is, in the best case, a waste of energy, and in the worst case, means unwanted substrate degradation at the more heavily loaded side areas.

The design, prototype production and optimization of an optimised cleaning head is a very time-and-money-consuming process. Therefore, an appropriate tool for simulating the behaviour of a user-defined multi-nozzle water-jet tool can significantly reduce the costs and the time-to-market period. This paper describes such a set of simulation tools, developed at the Institute of Materials Science, University of Hannover, and is the second part of the paper "Pure WJ cleaning process characterization: approach and technologies" which was presented at the MIT conference 2003 in Piran [1].

1 MODELLING APPROACH

The aim of the simulation tool is to predict the cleaning and material-removal performance of a given multi-nozzle water-jet tool based on a set of input parameters. These parameters are schematically listed in Figure 1.

The **geometrical setup data set** defines the design and the kinematics of the cleaning tool to be simulated. These parameters are later on subject to an optimization in order to achieve a homogenous planar treatment.

The **nozzle characteristics data set** is generated by using a standardized experiment. In this experiment the specimen is loaded under controlled conditions with a single nozzle. The specimen can be a bulk material, but it can also be a coating/substrate system.

Afterwards, the specimen's properties are analyzed in terms of changes caused by the jet. This data is then combined to produce a virtual image of the single nozzle's behaviour, and later on fed into the simulation package.

Afterwards, the simulator processes this data and produces a matrix of the virtual workpiece's surface, corresponding to the type of nozzle characteristics' input. This matrix is then available for numerous kinds of visualisation or post-processing algorithms, and some of them are presented in the following.

2 SIMULATION SPECIFICATIONS

2.1 Input

2.1.1 Geometrical and kinematic data

The simulation tool requires the following geometrical input data:

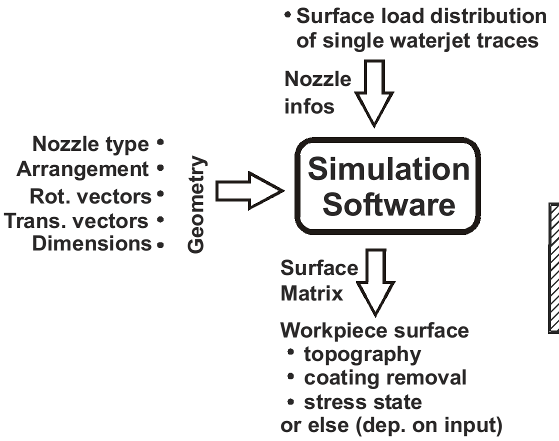


Fig. 1. *Simulator Input / Output*

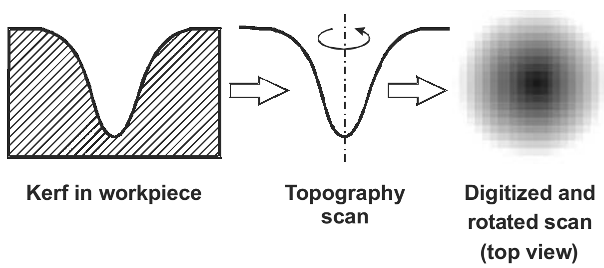


Fig. 2. *Generation of a nozzle-characteristics matrix in terms of material removal*

- Nozzle position relative to the rotational axis and two spatial angles, in the case of an axially symmetrical profile, and three spatial angles in the case of, for example, a flat spray nozzle.
- Rotational and linear traverse rates.
- Characteristics of a possible superimposed movement of the head itself, for example, a rotational movement.

The model's background, as it is described above, is based on experimental data, i.e., the erosive potential of a water-jet nozzle. The reason why this approach was chosen is that the mechanical or structural data of technical coating systems, which is required for a physically based model (see [3] and [4]), is in most cases not accessible due to inhomogeneities in the coating layer, deterioration, mechanical load, and many other factors influencing the condition of the covering.

2.1.2 Nozzle characteristics

In order to acquire characteristic data to describe the nozzles' behaviour in the simulation, a standardized experiment is carried out:

A specimen is loaded with a single water jet generated by the nozzle that is to be analyzed. The stand-off distance, the angle of impact and the linear traverse rate is varied. Then, the specimen is analyzed to determine the change that resulted from the water-jet treatment. This may include changes of:

- topography, e. g., material ablation (kerfing),
- coating removal, e. g., if and how far a coating has been removed,
- any other scalar material property that is of interest for the subsequent simulation. This can be, e.g., the inner stress state, the hardness, and the roughness.

The measured property is then compiled into a matrix determining the specific alteration capabilities of the respective nozzle. For example, regarding material removal for a cylindrical nozzle, this matrix represents the kerf geometry axially rotated (Figure 2).

2.2 Simulation process, output matrix

Using the geometrical, kinematical and nozzle data, the simulation software computes the matrix of the results on the basis of user-definable discrete time increments.

The data generated by the simulator consists of a matrix representing the altered surface of the virtual workpiece and the droplet flow intensity. The resolution, e. g., the matrix size, can be adapted to the user's requirements. Every algorithm is performed with double-precision floating-point variables, so that a sufficient accuracy is guaranteed.

2.3 Post-processing

For post-processing and visualisation of the result matrix, several integrated tools are available, for example, the later-described threshold analysis. In addition, the results matrix can be exported in standard formats for it to be imported into mathematical analysis software tools, like MathCad® or MatLab®.

3 EXAMPLES

In the following, results of the performed multi-nozzle cleaning-head simulations are presented. For visualisation purposes, the result matrices are normalized to a maximum level of 256, and every level corresponds to a shade of grey between white (no alteration by the virtual water jet) and black (maximum alteration).

3.1 Software features

In the following a simulation of a cleaning tool with a single nozzle is visualized for demonstrative purposes. The used parameters are given in Table 1.

These parameters generate a profile with an insufficient overlapping of traces, so that the underlying kinematics of the simulation become visible. Two different types of visualisation are presented: Figure 3 shows a 2D grey-code plot, while Figure 4 shows a 3D profile plot.

Both Figure 3 and Figure 4 show an area of approximately 200 x 200 mm. The used nozzle characteristic data was the experimentally determined kerf depth in aluminium (AlMgSi1) at a water-jet pressure of 300 MPa. The maximum achieved kerf depth in the simulation was near to 200 μm.

Figure 5 demonstrates a threshold analysis filter method of the results matrix. This can be used to determine those parts of the workpiece that have reached a certain condition, for example, a sufficient coating removal or beginning substrate degradation. Here, the minimum kerf depths in the aluminium specimen of 75, 100 and 150 μm have been used as criteria. All the areas in which these conditions have

Table 1. *Simulation parameters*

Rotational speed	1500 min-1
Swivel frequency	0.5 Hz
Traversal speed	0.1 m/min
Stand-off distance	50 mm
Nozzle diameter	0.2 mm
Nozzle angle	10°
Nozzle's distance from rot. axis	50 mm

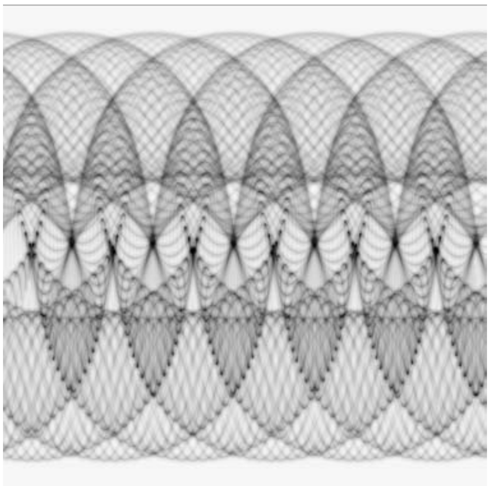


Fig. 3. *2D grey-code plot, rotating head with swivelling*

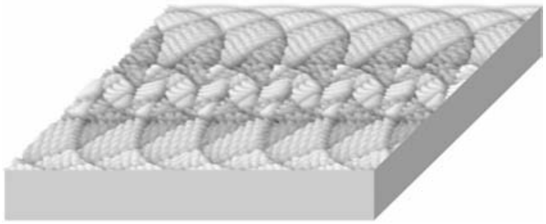


Fig. 4. *3D profile plot, rotating head with swivelling*

been achieved are marked black; all the other areas are white.

3.2 Preliminary optimisation results

In order to qualify the simulation's accuracy, a standard industrial multi-nozzle water-jet tool for general cleaning purposes was modelled, and a simulation at common parameters was performed (Table 2). The result is shown in Figure 6: it shows a deviation between the maximum and inner region load of approximately 65%. This setup was verified experimentally (specimen material PMMA). The experiment showed a close correlation between the actual material removal and the simulation results (deviations were found at higher peripheral speeds, see Section 4).

Next, the geometrical arrangement of the nozzles was slightly altered, and the simulation was rerun with otherwise identical parameters. Here, the deviation between the maximum load and the inner-region load was reduced to 49%. As a third step, a swivelling movement, as described before, with a frequency of 5 Hz was superimposed, which further reduced the deviation down to 29%.

Subsequently, a threshold filter was applied (Figure 7). This filter discriminates areas with a hypothetical maximum value and marks them black; areas with less than this value are left white. A graphical analysis of the generated filter plots shows a mean pixel density of 25% for the industrial head's results, of 34% for the optimized head and of 54% for the optimized head with swivelling motion.

However, the potential for the optimisation of the cleaning tools has not been exploited yet. The presented software package now allows for a systematic and automated investigation of geometrical and nozzle-based variations of cleaning-tool setups, and may therefore be a helpful tool for the cost-effective design of custom-made rotational water-jet cleaning heads.

Further research in this area at the Institute of Materials Science, as well as at the Department of Materials Mechanics, are already in progress.

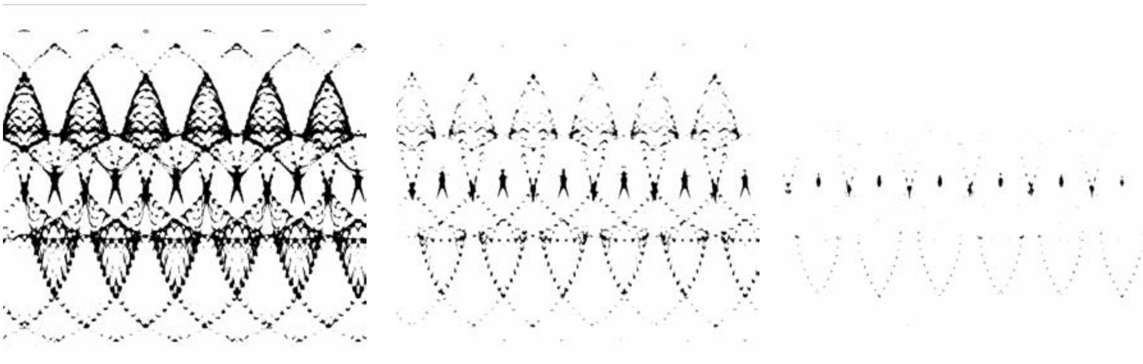


Fig. 5. *Threshold filter, rotating head with swivelling*

Table 2. *Simulation parameters*

Rotational speed	1000 min-1
Traversal speed	0.1 m/min
Stand-off distance	300 mm
Number of nozzles	5
Nozzles' diameter	0.3 mm
Nozzles' angles	4 to 7.5°
Nozzles' distance from rot. axis	3 to 17 mm

4 MODEL EXTENSION: JET DISINTEGRATION DUE TO EXTERNAL EFFECTS

During the verification phase of the model, slight deviations of the theoretic results from the real ones appeared when simulating the ablation potential of rapidly rotating jetting heads. These deviations proved to be statistically significant.

Due to the fact that this effect was becoming clearly observable when using higher rotational speeds, an influence of this movement on the water jet's structure itself was assumed.

Two main differences exist between the reference setup (one nozzle, static) as the empirical basis of the model, on the one hand, and the industrial cleaning tool (several nozzles, rotating) on the other hand: Firstly the complex fluid-flow conditions within the rotating head, and secondly, the inertial and wind forces that the jet is subjected to after having left the nozzle.

In order to quantify these influences, which obviously led to an enhanced disintegration of the water jet into droplets, several experiments were designed and carried out as described in the following.

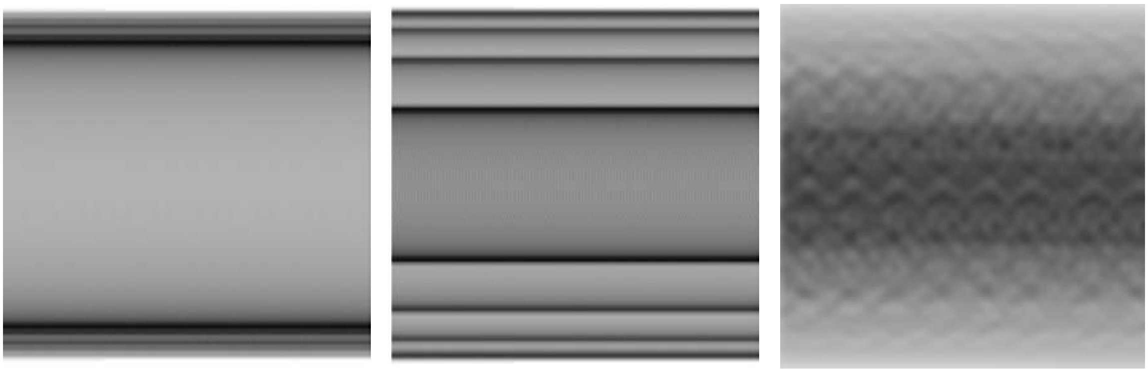
4.1 Target impact point relocation

With increasing angular velocity and distance from the rotational axis, the centrifugal force on the water jet increases as well. As a consequence, the water droplets are radially accelerated, and the impact point moves outwards accordingly.

To investigate the dimension of this effect, the already-described industrial jetting head was modified by replacing four of the five nozzles with dummy plugs.

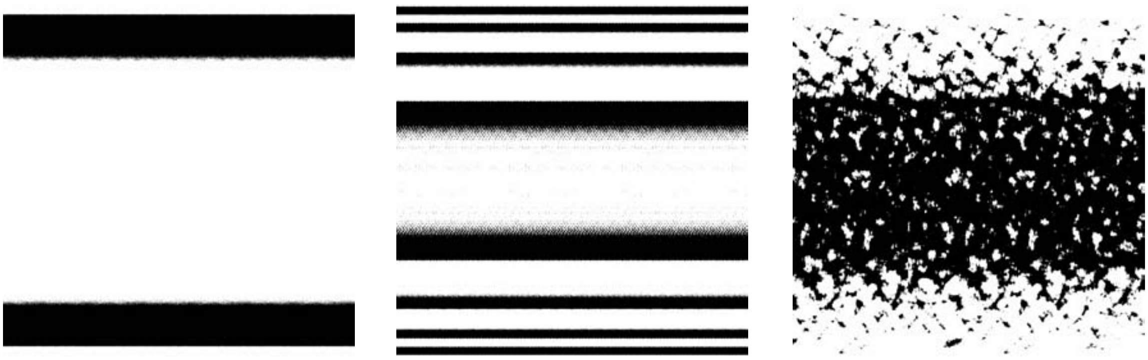
Then, kerfing experiments with this single nozzle were carried out whilst varying the rotational speed. The linear feed was set to zero, so that circular overlapping paths were retraced by the jet. Afterwards, the circular kerf's geometry was measured by means of a laser auto-focus system. This showed that the target impact-point relocation due to high peripheral speeds was in the range of 4% for a median circumference of a kerf of 50 mm.

Apart from inertial forces, the simple backlash effect of the jet can also move the impact point (anyone who has ever used a garden hose is familiar with this). However, the relation between the jet's



Grey-code plot
Original configuration, optimised configuration, and optimised configuration with swivelling at 5 Hz

Fig. 6 *Preliminary optimisation results*



Threshold filter
Original configuration, optimised configuration, and optimised configuration with swivelling at 5 Hz

Fig. 7. *Preliminary optimisation results*

velocity and the circumferential speed of the nozzle is so high that this effect is below 0.5%, and will be neglected in what follows. In addition, this backlash is solely a time-based lag, so that the above-described continuous model is not directly influenced unless the investigated time step is not chosen to be too small (in the range of ms).

4.2 Alteration of the jet structure

The most significant factor for an accurate virtual reproduction of a water-jetting process is a detailed knowledge of the jet's disintegration behaviour.

For most materials, the character of the water-jet loading has a substantial influence on the particular erosion rate. The quality of the impinging jet may range from purely static in direct proximity to the nozzle to fully dynamical at wider stand-off distances. In particular, ductile materials react very sensitively in terms of ablation rates (see [2] and [5]) in a way that a distinct maximum material removal rate is to be found when using a water jet with a certain ratio of dynamic and static quotients. Variation of the stand-off distance is a very powerful lever in this respect: a distance modification of 10% can lead to a change in the erosion rate of more than 25% ([2] and [5]).

Thus, the potential influence of the cleaning tool's parameters (inlet conditions, revolutions per minute) is to be thoroughly investigated in order to determine a corrective factor. This factor represents the accumulated effects of the specific cleaning tool on the jet structure and is a function of the angular velocity. It includes the complex inlet conditions within the tool that generate a higher rate of turbulence in the fluid flow before the nozzle, as well as the increased jet disintegration due to wind and inertial forces after the nozzle.

As part of the model described here, this corrective tool factor adjusts the input parameter of the stand-off distance and has therefore a direct impact on the scalar magnitude of the resulting matrix.

For the examined cleaning tool, the described factor ranges from 1.012 to 1.04. The corrected stand-off distance causes a change in the result-matrix magnitude of up to approximately 10%.

5 CONCLUSIONS AND OUTLOOK

The results that were generated with the presented software package show the close analogy of the simulation environment with the actual rotating multi-nozzle cleaning tool. The first optimisation efforts proved the strong potential for improving the overall homogeneity of the water-jet loading by rotating heads, by correction of the geometric nozzle arrangement, and by superposing additional movements of the head itself.

Referring to the software package, further investigations include the implementation of complex nozzle designs (for example, flat-spray nozzles), and the development of an improved user interface leading to a multifunctional expert system. Additionally, automated optimisation algorithms will be introduced that generate optimised head configurations based on given specific constraints and parameter limits. During the verification of the model, it was found that the rate of jet disintegration is a function of the rotational velocity of the cleaning tool. This effect was examined and experimentally quantified by means of a tool factor as a corrective scalar for the stand-off distance as an input variable of the model.

Acknowledgement

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6 REFERENCES

[1] Louis, H., Polak, H., Schenk, A., and Pude, F. (2003) Pure WJ cleaning process characterization: approach and technologies. *Proceedings of the 6th international conference on management of innovative technologies MIT'2003*, Piran, Slovene Society for Abrasive Water Jet Technology: Laboratory for Alternative Technologies, 111/118.

[2] Louis, H., von Rad, Ch., and Schenk, A. (2002) Decoating with water jets. *2nd International Conference on the Problems of the Rational Nature Management*. pp. 249/254.

[3] Milchers, Wolfgang (2001) Abtrag von Polymeren mit dem reinen Wasserstrahl. Diss., *VDI-Verlag* Düsseldorf.

[4] Louis, H., Milchers, W., and Pude, F. (2000) Study on the removal of brittle polymers with pure waterjets. *15th International Conference on Jetting Technology*, pp. 335/352.

[5] Louis, H., Mohamed, M., Pude, F. (2003) Cutting mechanism and cutting efficiency for water pressures above 600 MPa. *2003 American Waterjet Conference*, August 14-17, Houston, Texas (released on CD).

[6] Louis, H., Pude, F., Schenk, A., Stavrov, V.V., Stavrov, V.P. (2004) Simulation of multi-nozzle rotational cleaning tools. 1*7th International Conference on Jetting Technology*. 2004 Bedford, UK, pp. 327/336.

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Konstrukcijska in geometrijska optimizacija spojev, narejenih iz laminiranih kompozitnih materialov

The Constructive and Geometrical Optimization of the Junctions in Structures Made from Laminated Composite Materials

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(University Politehnica of Bucharest, Romania)

Porušni mehanizmi so za kompozitne materiale, še posebej za laminirane kompozitne materiale, dosti težji in zahtevnejši od porušnih mehanizmov pri homogenih in izotropnih materialih. Zaradi tega se trudimo, da bi imeli pri modeliranju in analizi le-teh krajevna napetostna stanja v conah, kjer nastajajo veliki napetostni gradienti. Predvsem v podpornih točkah, geometričnih prekinitvah, spojih itn. V primeru spojev je treba izboljšati konstrukcijsko in tehnološko rešitev, ki zagotavlja največjo mehansko trdnost, upoštevajoč interpretacijo med plastmi. Naslednji korak je v optimizaciji geometrijskih in konstrukcijskih konfiguracij samih spojev. Avtorji predlagamo metodologijo za geometrijsko in konstrukcijsko optimizacijo spojev in struktur narejenih iz laminiranih kompozitnih materialov. V tem prispevku je prikazanih nekaj primerov modeliranja z metodo končnih elementov za spoje v industrijskih primerih.

(Ključne besede: kompoziti laminarni, optimiranje, spoji, metode končnih elementov)

Failure mechanisms for composite materials and especially for laminated composites are different and more complex than for homogeneous and isotropic materials. This is why the modeling and analysis of such structures are done with the main aim being to determine the local stress states in the zones where high stress gradients occur, e.g., supports, points where loads are applied, geometric discontinuities, and junctions. In the case of junctions, one should elaborate constructive and technological solutions that ensure the maximum mechanical strength, taking into account the interpenetration between the layers. The next step is the optimization of the geometric and constructive configurations for the junctions. Here we propose a methodology for the geometrical and constructive optimization of the junctions in structures made from laminated composite materials. Some examples of modeling for junctions in industrial structures, using the finite-element method, are presented.

(Keywords: laminated composites, optimization, junctions, finite-element methods)

0 INTRODUCTION

Failure mechanisms for composite materials and especially for laminated composites are different and more complex than the ones for homogeneous and isotropic materials. That is why the modeling and analysis of these materials should be made with the main aim being to determine the local stress states in the areas with high stress concentrations, for example, supports, points where loads are applied, geometrical discontinuities, and junctions.

In the case of junctions, one should produce constructive and technological solutions about the interpenetration of the layers so as to ensure a better mechanical strength for the given loads. The next step is the optimization of the geometrical and constructive configurations of the considered junctions. Here we propose a methodology for constructive and geometrical optimization for junctions made from laminated composite materials. Some examples of finite-element modeling and analysis are presented for junctions belonging to process equipment.

1 EXAMPLES OF JUNCTIONS FOR STRUCTURES MADE FROM LAMINATED COMPOSITES

Some simple and frequently encountered junctions are presented in different constructive variants. For each one, depending on the functional, technological and economic factors, the optimum variant is chosen. In Fig. 1, four variants of a simple junction (variation of the external diameter from $2R_1$ to $2R_2$, with the internal diameter r) are presented for a tube manufactured from a composite material with six laminae (layers).

The following observations should be noted:
- the continuity of the laminae is not ensured for variant *a*;
- partial continuity exists for variant *b*;
- all laminae have continuity in variant *c*;
- the junction of the composite material with a homogeneous one is shown in variant *d*.

Different variants of a junction between a tube and a flange are depicted in Fig. 2. The tube has an external diameter $2R_1$, an internal diameter 2r, and the flange has a thickness h and an external diameter 2R. The composite material is made of three laminae for the tube and seven for the flange. One can see that in variant a where there is no interpenetration between the layers of the composite belonging to the flange and the tube (the flange is outside the tube and is glued with an adhesive), the mechanical strength of the structure is small. Delamination can occur for the external layer of the tube.

In Fig. 2, e and f, variants of the junction with one of the components made from a homogeneous material are shown.

For each of the above-mentioned variants, homogeneous elements for reinforcement may be introduced. For example, for an aluminum–resin composite material, a steel reinforcement is shown in black in Fig. 2, b–f.

For a more complicated junction, like the one between the cylindrical shell of a tank (with diameters $2R_1$ and $2R_2$) and a lateral nozzle (with diameters $2r_1$ and $2r_2$), five variants are presented in Fig. 3. Similar observations to those in the previous cases can be made. It is important to note variant c, in which a ring is used.

2 MODELING AND ANALYSIS OF JUNCTIONS

In the case of junctions, modeling and analysis have as the main goal a determination of the stresses in the layers and at the interface between the layers. If one uses the finite-element method,

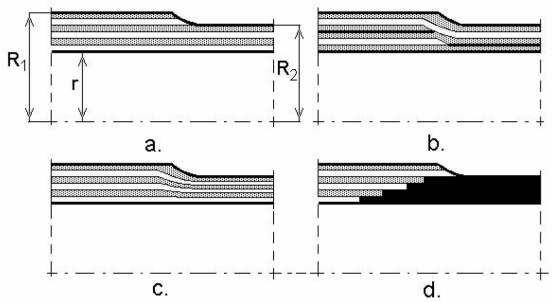

Fig. 1. *Variation of the external diameter of a tube*

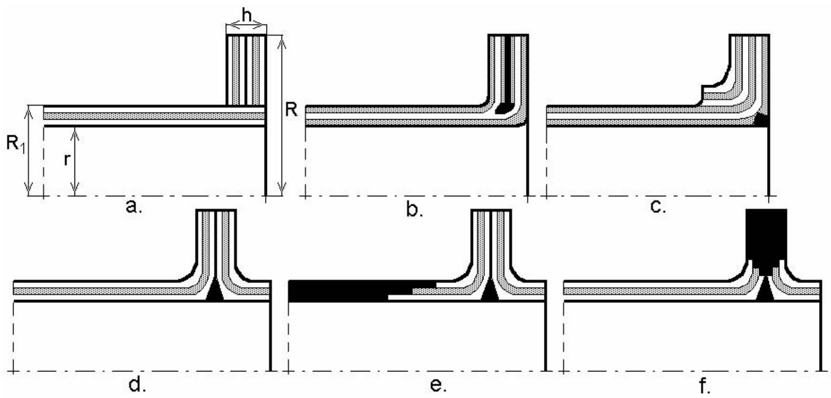

Fig. 2. *Junction between a tube and a flange*

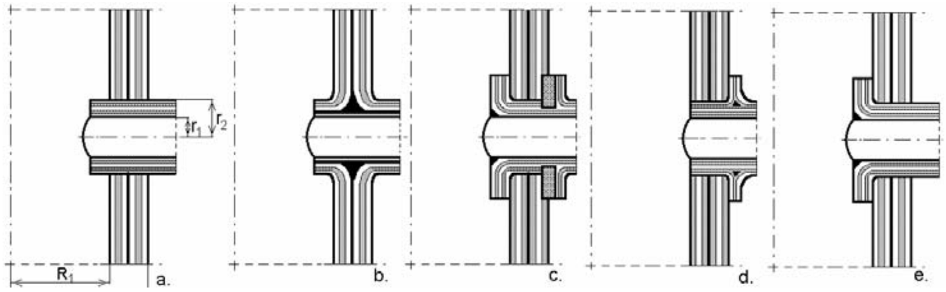

Fig. 3. *Junctions between a tank and a nozzle*

special elements for different types of composites are used.

A specific modeling, like for local problems, is necessary. This means that one should use a refined mesh in order to take into account the geometry and properties of each layer. In this way, information regarding the values of the interface stresses can be obtained, in order to assess any possible failure or delamination.

An example of finite-element modeling and analysis for the structure in Fig. 2,c is further presented in order to illustrate the previous assessments. The following dimensions were considered: $R_1 = 65$ mm, $r = 50$ mm, $R = 120$ mm, $h = 30$ mm, for an aluminum–epoxy-resin composite material. All the layers have a thickness of 5 mm. A steel ring was inserted (drawn in black in Fig. 4) in order to increase the strength and stiffness of the flange. The elastic constants are:

- $E = 70000$ N/mm^2, $G = 25000$ N/mm^2, $\upsilon = 0.35$ for aluminum
- $E = 2440$ N/mm^2, $G = 1200$ N/mm^2, $\upsilon = 0.46$ for resin
- $E = 2.1 \cdot 10^5$ N/mm^2, $G = 8.1 \cdot 10^4$ N/mm^2, $\upsilon = 0.3$ for steel.

An internal, uniform pressure of 5 N/mm^2 was applied to the tube. Constraints were applied on the frontal surface of the flange.

An axially symmetrical model was considered, using triangular elements. Each layer was separately modeled in order to introduce different elastic constants. The model has 243 nodes and 388 elements, and is shown in Fig. 5.

Some results of practical interest are shown in Fig. 6. The values of the von Mises equivalent stress σ_{eq}, the normal stress σ_y and the shear stress τ_{xy} were calculated in the nodes lying on the interface between two layers (drawn with a thick line).

The stresses were defined with respect to the global system of axes (Fig. 4). Using the values of these stresses, it is possible to assess whether the junction resists, or not, the applied loads, based on the specific criteria for composite materials [1].

3 METHODOLOGY FOR THE OPTIMIZATION OF THE JUNCTIONS IN STRUCTURES MADE OF LAMINATED COMPOSITES

In order to successfully optimize a junction in a structure made of a laminated composite material, some aspects should be taken into account:

1. The local character of the analysis is the fundamental problem in the case of junctions. That is why a sub-model or a sub-structure of the junc-

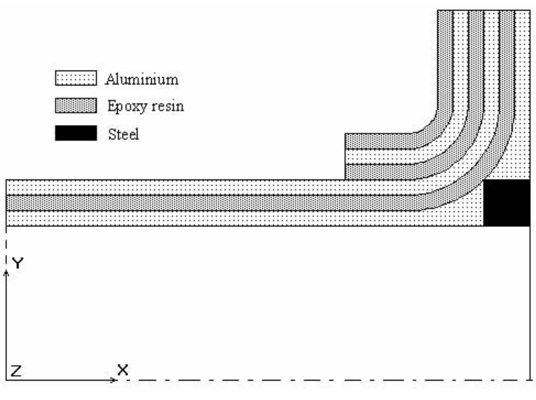

Fig. 4. *The studied junction*

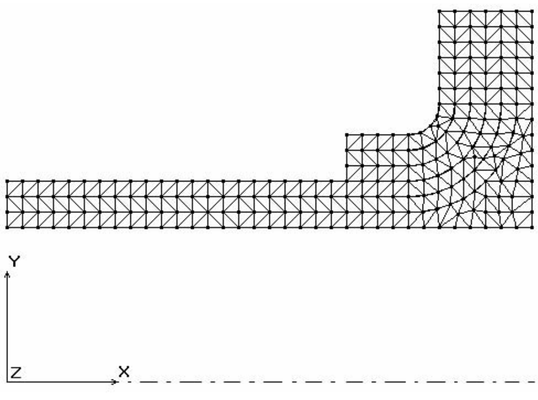

Fig. 5. *The finite-element mesh*

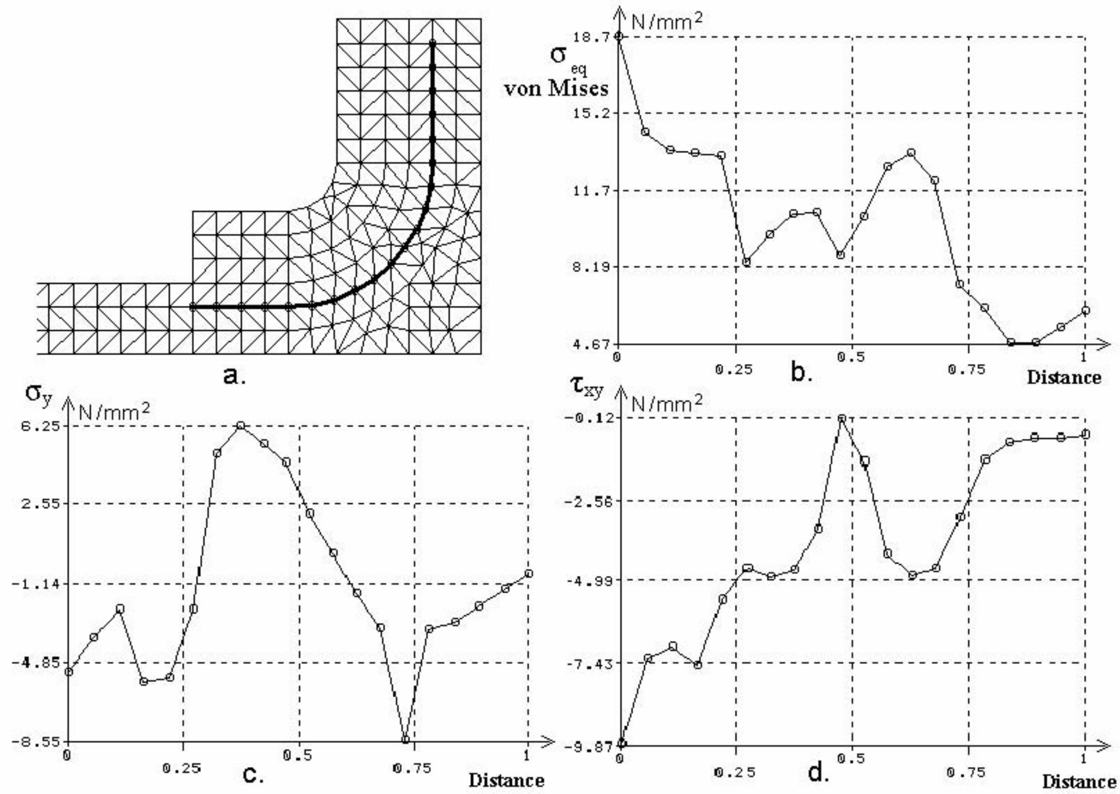

Fig. 6. *Results for the junction in Fig. 4*

tion is to be analyzed. This approach ensures the efficiency of the process;

2. A parametric mode is used, i.e., all dimensions will be denoted with letters. Some parameters will have constant values, others will be declared as *design variables*;
3. The constant values of the parameters must be established with discrimination in order to avoid a geometrical configuration with superposition, voids, distortions, etc;
4. The definition of the geometry (points, lines, surfaces, volumes) must be done so as to emphasize the different layers, because these layers are made from different materials. The results obtained following a finite-element analysis must give information regarding the *interface* stresses and strains;
5. The mesh must be obtained by generating the nodes and elements along each layer as distinctive groups of elements with different physical, mechanical and elastic properties.

All other aspects of the modeling, analysis and optimization are the usual ones for a finite-element analysis.

4 EXAMPLE OF THE OPTIMIZATION OF A JUNCTION

The variant of a junction between a tube and a cylindrical flange (Fig. 2, c and Fig. 4) was chosen in order to illustrate the above-mentioned optimization methodology. This junction is presented in Fig. 7, were three design variables were considered: H1, H2 and R1.

The composite material is aluminum–epoxy-resin, having the same elastic constants as in the previous example. The thickness of the layers were denoted as H1 and H2.

A constant internal pressure p = 0.1 N/mm^2 was applied to the tube.

An axially symmetrical model was considered, using triangular elements. Each layer was separately modeled in order to introduce different mechanical characteristics. The model has 1202 nodes and 2140 elements (Fig. 8).

The optimization function was the weight of the junction and the restriction was an imposed value for the equivalent von Mises nodal stress. Also, constant values were chosen

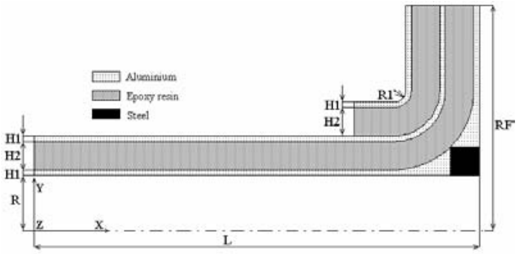

Fig. 7. *Constructive scheme of a tube-flange junction*

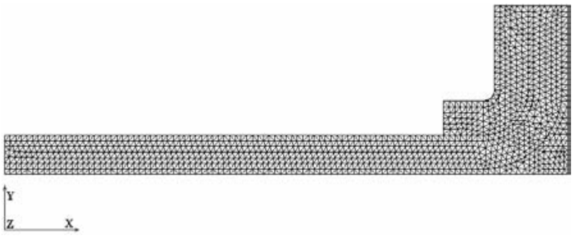

Fig. 8. *The finite-element mesh for the model in Fig. 7*

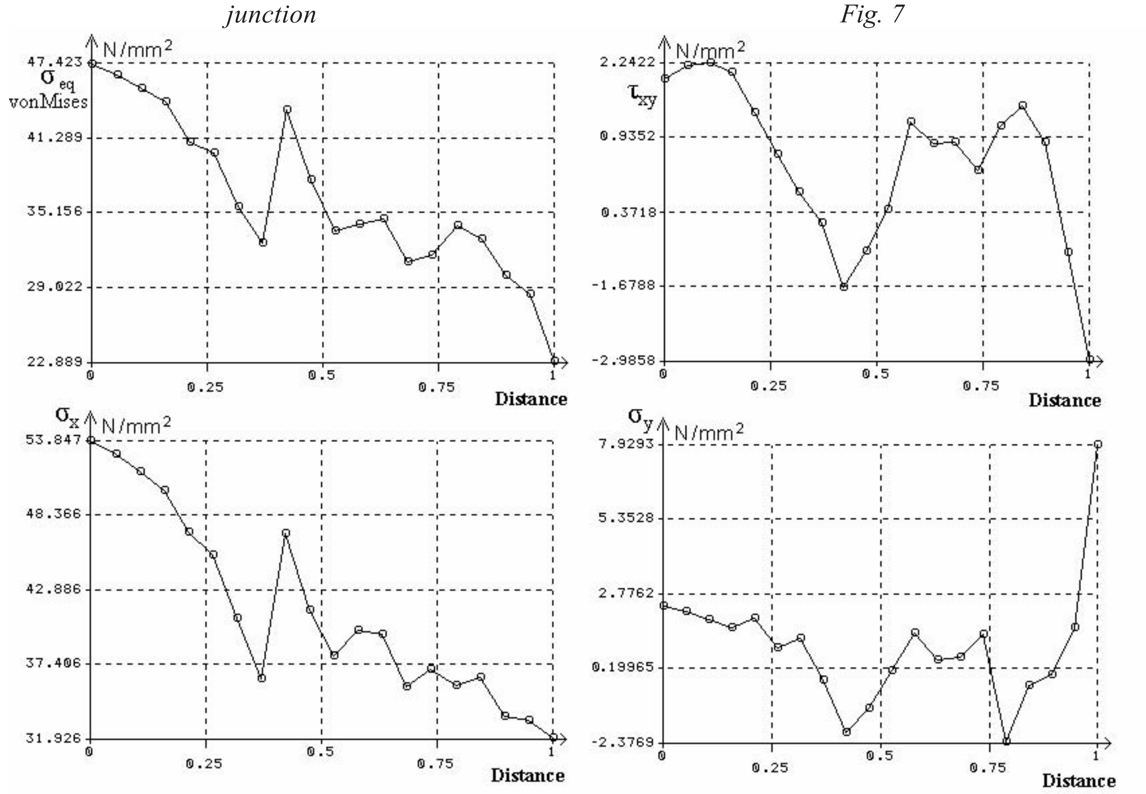

Fig. 9. *Results obtained for the junction from Figure 7*

for some parameters, i.e., R =50 mm, L = 4R, RF = 10R.

The following values for the design variables were obtained: H1 = 4.5 mm, H2 = 26.6 mm and R1 = 8.4 mm. The maximum value of the equivalent stress was 47.4 N/mm^2 and the weight of the junction was 156 N.

Some of the results are graphically presented in Fig. 9. In this figure the results were plotted for a part of a longitudinal line on the internal surface of the tube (starting from the middle to the flange surface).

The variations of the equivalent von Mises stress σ_{eq}, the normal stresses σ_x and σ_y and the shear stress τ_{xy} are plotted with respect to the global system of axes from Fig. 7.

5 CONCLUSIONS

A methodology for the optimization of junctions in structures made from a layered composite material is presented. Different types of junctions are presented, and the methodology is illustrated for one of these examples. Using this methodology one can obtain design variables with values that minimize an optimization function, for example, the weight of the structure, by imposing restrictions on the values of parameters such as the maximum equivalent stress.

The procedure can be successfully used in the design process, where all the aspects (constructive, technological, economic, etc.) must be taken into account.

6 REFERENCES

[1] Şt. Sorohan, I.N. Constantinescu (2003) The practice of finite element modeling and analysis, *Politehnica Press Publishing House*, Bucureşti (in Romanian).
[2] A. Hadăr, I.N. Constantinescu, A. Motomancea (2004) About the theoretical and practical analysis of the junctions of layered composite structures, *1st International Conference "From Scientific Computing to Computational Engineering"*, pp. 230-2338-10 September 2004, Athens.
[3] A. Hadăr, G. Jiga (2004) Numerical modelling of fiber reinforced composites including interlaminar effects and local deterioration, *HELLAS-COMP 2001, 2nd National Conference on Composite Materials*, p. 21-31, Patras, Greece.

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Obzornik za matematiko in fiziko, Ljubljana
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Varilna tehnika, Ljubljana
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Gorkič A., Bračun D., Možina J., Diaci J.: Minimizacija oblikovnih nepravilnosti laserskih zvarov z uporabo Taguchijevih metod
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Unapređenje ventilacionih sistema sa promenljivim protokom vazduha

Magdeburger Wissenschaftsjournal, Magdeburg
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Vse okrajšave naj bodo, ko se prvič pojavijo, napisane v celoti v **slovenskem jeziku**, npr. časovno spremenljiva geometrija (ČSG).

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[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.

[3] Muhs, D. et al. (2003) Roloff/Matek Maschinenelemente – Tabellen, 16. Auflage. *Vieweg Verlag*, Wiesbaden.

Podatki o avtorjih

Članku priložite tudi podatke o avtorjih: imena, nazive, popolne poštne naslove in naslove elektronske pošte.

SPREJEM ČLANKOV IN AVTORSKE PRAVICE

Uredništvo Strojniškega vestnika si pridržuje pravico do odločanja o sprejemu članka za objavo, strokovno oceno recenzentov in morebitnem predlogu za krajšanje ali izpopolnitev ter terminološke in jezikovne korekture.

Avtor mora predložiti pisno izjavo, da je besedilo njegovo izvirno delo in ni bilo v dani obliki še nikjer objavljeno. Z objavo preidejo avtorske pravice na Strojniški vestnik. Pri morebitnih kasnejših objavah mora biti SV naveden kot vir.

Units and abbreviations

Only standard SI symbols and abbreviations should be used in the text, tables and figures. Symbols for physical quantities in the text should be written in italics (e.g. *v, T, n,* etc.). Symbols for units that consist of letters should be in plain text (e.g. ms^{-1}, K, min, mm, etc.).

All abbreviations should be spelt out in full on first appearance, e.g., variable time geometry (VTG).

Figures

Figures must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Fig. 1, Fig. 2, etc. Pictures may be saved in resolution good enough for printing in any common format, e.g. BMP, GIF, JPG. However, graphs and line drawings sholud be prepared as vector images.

When labelling axes, physical quantities, e.g. *t, v, m,* etc. should be used whenever possible to minimise the need to label the axes in two languages. Multi-curve graphs should have individual curves marked with a symbol, the meaning of the symbol should be explained in the figure caption.

All figure captions must be bilingual.

Tables

Tables must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Table 1, Table 2, etc. The use of names for quantities in tables should be avoided if possible: corresponding symbols are preferred to minimise the need to use both Slovenian and English names. In addition to the physical quantity, e.g. *t* (in italics), units (normal text), should be added in new line without brackets.

All table captions must be bilingual.

The list of references

References should be collected at the end of the paper in the following styles for journals, proceedings and books, respectively:

[1] A. Wagner, I. Bajsić, M. Fajdiga (2004) Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors, *Stroj. vestn.* 2(2004), pp. 72-79.

[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.

[3] Muhs, D. et al. (2003) Roloff/Matek Maschinenelemente – Tabellen, 16. Auflage. *Vieweg Verlag*, Wiesbaden.

Author information

The information about the authors should be enclosed with the paper: names, complete postal and e-mail addresses.

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