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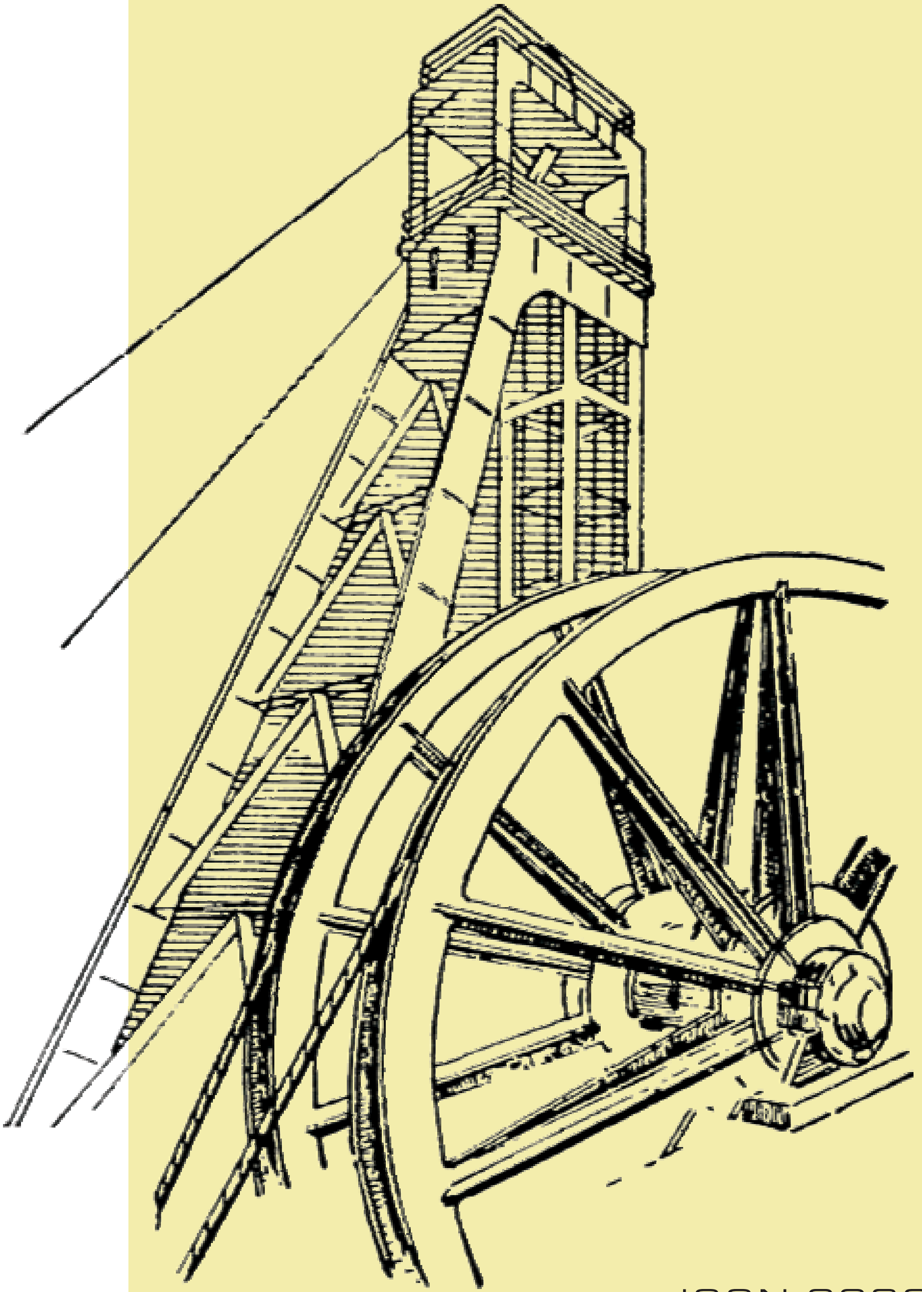

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Povečanje signala nihanja kotalnih ležajev z uporabo prilagodljive krmilne zanke za zmanjševanje šuma

Enhancing the Vibration Signal from Rolling Contact Bearing Using an Adaptive Closed-Loop Feedback Control for Wavelet De-Noising

Jorge P. Arenas

Predstavljenih je bilo že več metod s področij časa in frekvence za nadzorovanje razmer in ugotavljanje napak na opremi oz. postopkih. Nadzorovanje in ugotavljanje izvajamo z analizami in tolmačenjem signalov, pridobljenih z zaznavali in pretvorniki. Vendar pa vsako notranje nihanje, ki se prenaša preko sosednjih teles, v ozadju povzroči nihanje, v katerem se signal, ki ga potrebujemo za analize, pogosto izgubi, še posebej v zgodnejši fazi nastanka napake. Če je šumnost nihanja v ozadju prevelika oz. je signal nihanja ležajev premajhen, so lahko običajne metode, kot npr. analiza zmanjševanja šuma valovanja, neučinkovite pri izničenju šuma takih signalov.

V prispevku smo predstavili kombinacijo povečanja prilagodljivega signala in spremembo valovanja za zmanjšanje šuma signala nihanja, izmerjenega na kotalnih ležajih. Kot postopek prilagodljivega utežnega krmiljenja smo uporabili algoritma normaliziranega najmanjšega srednjega kvadrata in rekurzivnih najmanjših kvadratov. Končni namen prilagodljivega filtra je bil zmanjšanje srednje kvadratične vrednosti signala napake, kar pomeni povečanje razmerja izstopnega signala in šuma sistema. Rezultati so pokazali, da povečanje prilagodljivega signala nihanja in sprememba valovanja povzročita najboljše razmerje signala in šuma. Kar pomeni, da lahko rezultat odkrije skrite sestave signala, ki so povezane neposredno z notranjimi okvarami v ležajih.

(Ključne besede: ležaji kotalni, signali nihanja, analize šuma, zanke krmilne)

Several techniques in both the time and frequency domains have been reported for the condition monitoring and fault diagnosis of equipment and processes. The monitoring and diagnosis is accomplished through the analysis and interpretation of signals acquired from sensors and transducers. However, any structure-borne vibration propagated through the neighbouring structures will produce a background vibration in which the required vibration signals for the diagnosis are often submerged, in particular during the early stage of failure development. If the background-noise level is too high or when the bearing vibration signature level is too low, traditional techniques such as wavelet de-noising analysis can be ineffective in cancelling the noise of such signals.

In this paper the combination of an adaptive signal enhancement and the wavelet transform for de-noising a vibration signal measured on a rolling contact bearing is presented. The normalized least mean-square and recursive least-square algorithms were used as the adaptive weight-control mechanism. The final aim of the adaptive filter was to minimize the mean-square value of the error signal, which implies the maximization of the output signal-to-noise ratio of the system. The results showed that a combination of the adaptive vibration signal enhancement and the wavelet transform yielded the best signal-to-noise ratio. This means that the result can reveal hidden signal structures that are directly associated with a bearing's internal defect.

(Keywords: rolling contact bearings, vibration signals, noise analysis, feedback control)

0 INTRODUCTION

The condition monitoring and fault diagnosis of equipment and processes are of great practical concern. Several techniques in both the time and frequency domains have been reported for this purpose [1]. Mechanical condition monitoring is concerned with the evaluation of the operating conditions of a machinery system or its components. The main purpose of the condition monitoring is to detect the presence of faults and damage in machinery during operation. It encompasses both diagnosis and prognosis in order to determine the remaining safe operating life of a machine before a breakdown or failure occurs [2].

Any operation of machinery involves the generation of forces that produce vibrations. Even a machine in good running order produces its own characteristic vibration, caused by the various dynamic forces associated with its operation.

Some of the most important components in rotating machinery are the bearings, of which the rolling-contact type are the most commonly used. Rolling element bearings have some unique concerns, which are not found in journal bearings. They are a result of the rolling elements being contained between the inner and outer raceways. The rolling elements are normally kept from touching each other by a cage. Because of the metal-to-metal contact, this bearing provides very little vibration damping. Therefore, rolling element bearings, as a result of their design and installation, provide a very good signal transmission path from the vibration source to the outer bearing housing. Although these bearings are very precisely machined parts some defects reduce their service life severely and can cause the breakdown of rotating machinery. Each component of the bearing will generate specific frequencies as the defects initiate and become more prevalent.

Bearing-element rotations generate vibrational excitation at a series of discrete frequencies that are a function of the bearing geometry – roller diameter, pitch diameter of the bearing, contact angle between the rolling element and the raceway, number of rolling elements – and the shaft's rotational speed. In addition to these discrete frequencies their harmonics will also be excited. However, there are three major frequencies that are commonly identified and associated with defective bearings: 1) the rolling-element pass frequency on the outer race, which is associated with an outer race defect, 2) the rolling-element pass frequency on the inner race, which is associated with inner-race defects, and 3) the rolling-element spin frequency, which is associated with ball or ball-cage defects. Given the geometry of the bearing, the values for the discrete frequencies have been summarized by Shahan and Kamperman [3].

Localized defects such as a surface crack are a typical failure form in rolling-element bearings. The vibration generated in a normal bearing is usually dominated by the components caused by shaft rotation, stiffness variation, load fluctuation, etc. When a localized defect is induced, repeated impacts will be generated due to the passing of the rolling elements over the defect.

The condition monitoring and fault diagnosis in the machinery is accomplished through the analysis and interpretation of the signals acquired from sensors and transducers. The impacts have a wide-band energy that often sets off some modes of resonance with the bearing elements. This process adds additional impulsive components to the vibration and results in vibration signals of a non-stationary nature. Wavelet analysis has been shown to be a promising tool to overcome this problem. Several wavelet-based techniques have been presented for the feature enhancement and feature extraction of transient signals [4]. These techniques are much more effective than traditional techniques and have been successfully used in the condition monitoring and fault diagnosis of mechanical systems [5].

However, any structure-borne vibration propagated through neighbouring structures will produce a background vibration in which the required vibration components for diagnosis are often submerged, in particular during the early stage of failure development. If the background noise level is too high or when the bearing vibration signature level is too low, traditional techniques such as wavelet de-noising analysis are often ineffective in cancelling the noise of such signals. Therefore, enhancing the signals before de-noising to extract the frequency components is a very important task in detecting the defect.

Moreover, for model-based identification methods in the frequency domain it has been established that its performance can be affected by errors and the results might not be accurate. Recently, Vania and Pennacchi [6] have mentioned the random/bias errors in the vibration data as a source of inaccuracy. This means that a source of error for the identification methods can be the presence of noise in the vibration signals or errors in the order analysis. In this work, an adaptive closed-loop feedback control was applied to a bearing vibration signal buried in a background vibration noise in order to enhance this signal before applying a wavelet de-noising method to identify the frequency components of the rolling contact bearing.

1 THEORY OF ADAPTIVE FILTERING

If accurate information about the signals to be processed is available, the designer can easily choose the most appropriate algorithm to process the signal. When dealing with signals whose statistical properties are unknown, fixed algorithms do not process these signals efficiently. The solution is to use an adaptive filter that automatically changes its characteristics by optimising the internal parameters. These adaptive filtering algorithms are essential in many statistical signal-processing applications. The complete specification of an adaptive system consists of three items [7]: 1) the application, defined by the choice of the signals acquired from the environment to be the input and desired output signals, 2) the adaptive filter structure (FIR, IIR), and 3) the algorithm.

The most widely used adaptive FIR filter structure is the transversal filter, also called the tapped delay line, that implements an all-zero transfer function. For this realization, the output of the filter $y[n]$ is a linear combination of the filter coefficients, which yields a quadratic mean error ($MSE=E\{|e[n]|^2\}$, where $E\{\}$ denotes the statistical expectation operator) function with a unique optimal solution.

Typical impulse responses of ideal filters approach amplitudes of zero exponentially over time. Approximate realizations are thus possible with finite-length FIR filters. Of course, non-causal filters are not physically realizable in real-time systems. However, in many cases they can be realized approximately in delayed form, providing an acceptable, delayed real-time response. In practical circumstances, excellent performance can be obtained with two-sided filter impulse responses, even when they are truncated in time to the left and right. Using the delay, the truncated response can be made causal and physically realizable [8].

The usual method of estimating a signal corrupted by additive noise is to pass the composite signal through a filter that tends to suppress the noise, while leaving the signal relatively unchanged. The design of such filters is the domain of optimal filtering, which originated with the pioneering work of Wiener [9].

Noise cancelling is a variation of optimal filtering that is highly advantageous in many applications. It uses an auxiliary or reference input derived from one or more sensors located at points in the noise field where the signal is weak or undetectable. This input is filtered and subtracted from a primary input containing both signal and noise. As a result, the primary noise is attenuated or eliminated by cancellation.

If filtering and subtraction are controlled by an appropriate adaptive process, noise reduction can, in many cases, be accomplished with little risk of distorting the signal or increasing the output noise level. In circumstances where adaptive noise cancelling is applicable, it is often possible to achieve a degree of noise rejection that would be difficult or impossible to achieve by direct filtering [10].

In the signal-enhancement application the reference signal consists of a desired signal $x[n]$ that is corrupted by an additive noise $N_1[n]$. The input signal of the adaptive filter is a noise signal $N_2[n]$ that is correlated with the interference signal $N_1[n]$, but uncorrelated with x[n].

1.1 Normalized Least-Mean-Square

The least-mean-square (LMS) algorithm is a search algorithm in which a simplification of the gradient-vector computation is made possible by appropriately modifying the objective function. This algorithm is widely used in various applications due to its computational simplicity. The convergence characteristics of the LMS can be shown for a stationary environment and the convergence speed is dependent on the eigenvalue spread of the input-signal correlation matrix [11]. Other features of the LMS are an unbiased convergence in the mean to the Wiener solution and stable behaviour when implemented with finite-precision arithmetic.

The normalized least-mean-square (NLMS) algorithm uses a variable convergence factor that minimizes the instantaneous error. Such a convergence factor usually reduces the convergence time but increases the misadjustment. The NLMS algorithm usually converges faster than the LMS algorithm, due to the variable convergence. It is interesting to note that the faster convergence of the NLMS algorithm has been noticed by many researchers in computer simulations, but never theoretically proven. It appears that Bitmead and Anderson [12] coined the name of the NLMS algorithm in 1980. The NLMS algorithm can be summarized by the following two equations:

$$e[n] = d[n] - \mathbf{w}^H[n]\,\mathbf{u}[n] \tag{1}$$

and

$$\mathbf{w}[n+1] = \mathbf{w}[n] + \frac{\mu}{\alpha + \| \mathbf{u}[n] \|^2}\mathbf{u}[n]\,e^*[n] \quad (2),$$

where n=1, 2, …, $e[n]$ is the error, $d[n]$ is the desired signal, $\mathbf{w}[n]$ is the vector of the filter coefficients (taps), $\mathbf{u}[n]$ is the vector of the input signal, α and μ are positive constants, the superscript H denotes the Hermitian transposition, the asterisk denotes a complex conjugation, and the norm in Eq. (2) corresponds to the Euclidean norm. It is clear that the NLMS algorithm alters the magnitude of the correction term without a change in its direction. Accordingly, it bypasses the problem of noise amplification that is experienced in the LMS algorithm when $\mathbf{u}[n]$ is large. However, in so doing it introduces a problem of its own, which is experienced for small $\mathbf{u}[n]$. This problem is overcome by using the positive constant α. Also, a sufficient condition for the NLMS algorithm to be convergent in mean square is that $0 < \mu < 2$ [13]. If no previous information for the values of $\mathbf{w}$ is available, then it is usual to initialise the algorithm with $\mathbf{w}[0]=\mathbf{0}$.

1.2 Recursive Least-Squares

Least-squares algorithms aim at the minimization of the sum of the squares of the difference between the desired signal and the model filter output. When new samples of the incoming signals are received at every iteration, the solution for the least-squares problem can be computed in recursive form resulting in the recursive least-squares (RLS) algorithm. The RLS algorithm is known to pursue a fast convergence, even when the eigenvalue spread of the input-signal correlation matrix is large. Of course, this algorithm has excellent performance when working in time-varying environments. All these advantages come at the cost of increased computational complexity and some stability problems, which are not as critical in the LMS-based algorithms. Some references mention that although the RLS does not attempt to minimize the mean-square error (in the ensemble-averaged sense), nevertheless, the mean-square value of the true estimation error converges within less than $2M$ iterations, where M is the number of taps coefficients in the tapped-delay-line filter [13]. The RLS algorithm, for n=1,2,…, can be summarized by the following equations:

$$\mathbf{K}[n] = \frac{\mathbf{P}[n-1]\,\mathbf{u}[n]}{\lambda + \mathbf{u}^H[n]\,\mathbf{P}[n-1]\,\mathbf{u}[n]} \tag{3}$$

$$\xi[n] = d[n] - \mathbf{w}^H[n-1]\,\mathbf{u}[n] \tag{4}$$

$$\mathbf{w}[n] = \mathbf{w}[n-1] + \mathbf{K}[n]\xi^*[n] \tag{5}$$

$$\mathbf{P}[n] = \frac{\lambda}{\mathbf{P}[n-1] - \mathbf{K}[n]\,\mathbf{u}^H[n]\,\mathbf{P}[n-1]} \quad (6),$$

where λ is a constant, called the forgetting factor, which is close to but less than 1 and $\xi[n]$ is called the *a posteriori* error. The initialisation for the algorithm is $\mathbf{w}[0]=\mathbf{0}$ and for the matrix $\mathbf{P}[0]=\delta^{-1}\mathbf{I}$, where $\mathbf{I}$ is the identity matrix and $\delta \ll 1$.

1.3 Wavelet de-noising

In several research fields, a common problem consists of recovering a true signal from incomplete, indirect or noisy data. The development of fast computers has allowed the practical implementation of wavelets that help in solving this problem, through a technique called wavelet shrinkage and thresholding methods [14]. The theory of wavelets can be found in several modern textbooks (for example, see [15]).

Decomposing a data set using a discrete wavelet transform (DWT) is analogous to using filters that act as averaging filters and others that produce details. Some details in the data set correspond to the resulting wavelet coefficients. These coefficients can be used later in an inverse wavelet transformation to reconstruct the data set. If the details in the data set are small, they can be omitted without substantially affecting the main features of the data set. Therefore, thresholding means to set to zero all the coefficients that are less than a particular threshold. This process generally gives a low-pass and smoother version of the original noisy signal. The objective of wavelet de-noising is to suppress the additive noise $N_1[n]$ from a signal $s[n]$, where $s[n]=x[n]+N_1[n]$. The signal $s[n]$ is first decomposed into the L-level of the wavelet transform. Then, for noise suppression, the thresholding of the resultant wavelet coefficients is performed. The thresholding is based on a value δ that is used to compare with all the detailed coefficients. Two types of thresholding are more popular:

1) Hard thresholding, which is the usual process of setting to zero the coefficients whose absolute values are lower than the threshold,
2) Soft thresholding, which is an extension of hard thresholding by first setting to zero the coefficients whose absolute values are lower than the threshold and then shrinking the non-zero coefficients toward zero.

Then, in summary, the technique of wavelet de-noising consists of transforming, thresholding and inverse-transforming the signal. This technique has been very useful in handling noisy data because the de-noising is carried out without smoothing out the sharp structures. The result is a cleaned-up signal that still shows important details [16].

2 RESULTS

An experiment was conducted to acquire real signals for testing an adaptive rolling-contact-bearing vibration-signal enhancement system. The experimental scheme is shown in Fig. 1, where some of the blocks indicate the filtering process. The ball bearing used for the test was a single-row radial ball bearing having 20 balls of 6 mm diameter, 45 mm bore diameter, and 57 mm pitch diameter of the ball races. The isolation of the rolling bearing to be analysed and the isolation of other parts of the machine were removed in order to increase the effect of the structure-borne noise vibration, which contaminated the signal of the bearing. The vibration produced by the bearing was sensed by means of an ICP accelerometer mounted on the bearing cover. A second ICP accelerometer was attached to a selected point on the test-rig base in order to measure the vibration reference signal. This point was located 40 cm from the bearing and 10 cm from the motor. Therefore, the accelerometer in the bearing sensed the real signal $x[n]$ plus the contaminating noise $N_1[n]$, and the second accelerometer sensed a reference signal $N_2[n]$. Both signals were digitally recorded simultaneously, using a sampling frequency of 1,024 Hz during 10 seconds, so the number of samples collected for each channel was 10,024. A multi-channel digital data-acquisition system was used for this purpose. To avoid aliasing, the signals were processed through low-pass filters with a cut-off frequency of 500 Hz. The signals were then saved as data files in order to be processed later in a workstation lab. The nominal rotational speed of the axis was 780 rpm (13 Hz).

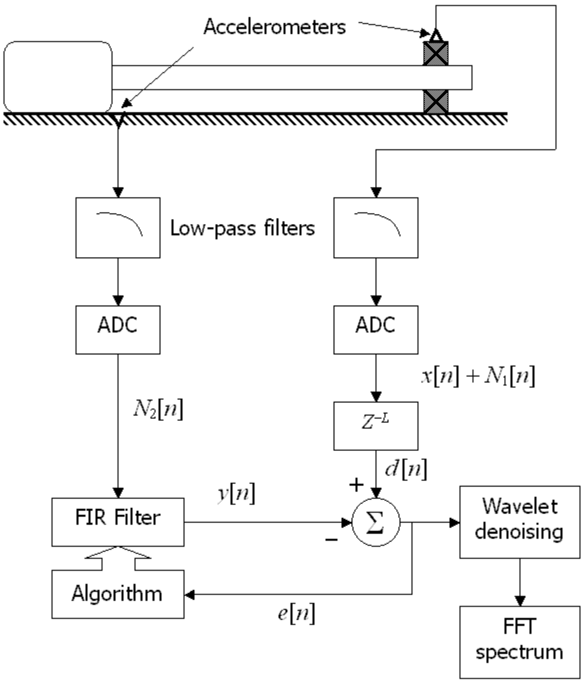

Fig. 1. *Experimental set up*

As can be seen from Fig. 1, the error signal for this application is given by

$$e[n]=x[n]+N_1[n]-y[n]=x[n]+N_1[n]-\sum_{k=1}^{M}w_k N_2[n-k] \quad (7),$$

where M is the number of filter coefficients (taps). Then, the resulting *MSE* (quadratic mean error for real values), is

$$MSE=E\{e^2[n]\}=E\{x^2[n]\}+E\{(N_1[n]-y[n])^2\} \quad (8),$$

where it has been assumed that $x[n]$ is uncorrelated with $N_1[n]$ and $N_2[n]$. Equation (8) shows that if the adaptive filter, having $N_2[n]$ as the input signal, is able to perfectly predict the signal $N_1[n]$, then the minimum value of *MSE* is given by

$$\eta_{\min}=E\{x^2[n]\} \quad (9),$$

where the error signal, in this situation, is the desired signal. The effectiveness of the signal enhancement scheme will depend on the correlation between $N_1[n]$ and $N_2[n]$. From Fig. 1 it can be seen that a delay Z^{-L} is applied to the input. In some applications it is recommended to include this delay of L samples in the reference signal or in the input signal, such that their relative delay yields a maximum cross-correlation between $y[n]$ and $N_1[n]$, reducing the *MSE* [7]. This delay provides a kind of synchronization between the signals involved.

The NLMS and RLS algorithms presented in Eqs. (1)-(6) were implemented in a Matlab computer code to test the performance with the real data.

The following results were obtained with a 10-tap implementation of the adaptive FIR filter shown in Fig. 1. The NLMS and RLS algorithms were used as the adaptive weight-control mechanism.

Figure 2 shows the results of the time signatures at the input and at the output of the FIR filter using both NLMS and RLS adaptive algorithms.

For making a direct graphical comparison between the performance of the RLS and NLMS algorithms, the quadratic mean error (*MSE*) results are shown in Fig. 3. The optimal results for the NLMS algorithm were obtained using μ=0.09 and a delay L=5. For the RLS algorithm the optimal results were achieved using λ=0.999 and a delay of L=5. It was impossible to find proper parameters in order to achieve the convergence at the output of the filter without using a delay at the input. From Fig. 3 it is observed that the *MSE* curves start at zero, rise to a peak, and then decay toward a steady-state value. In addition, it can be observed that the *MSE* curve for the RLS algorithm has the same general shape as that for the NLMS algorithm.

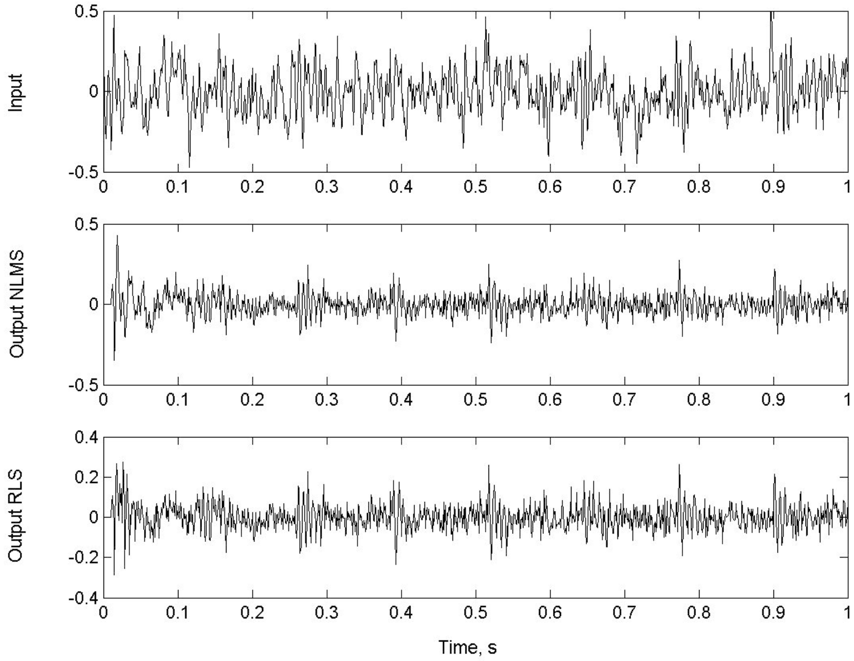

Fig. 2. *Time signals at the input and at the output of the FIR filter using the NLMS and RLS adaptive algorithms*

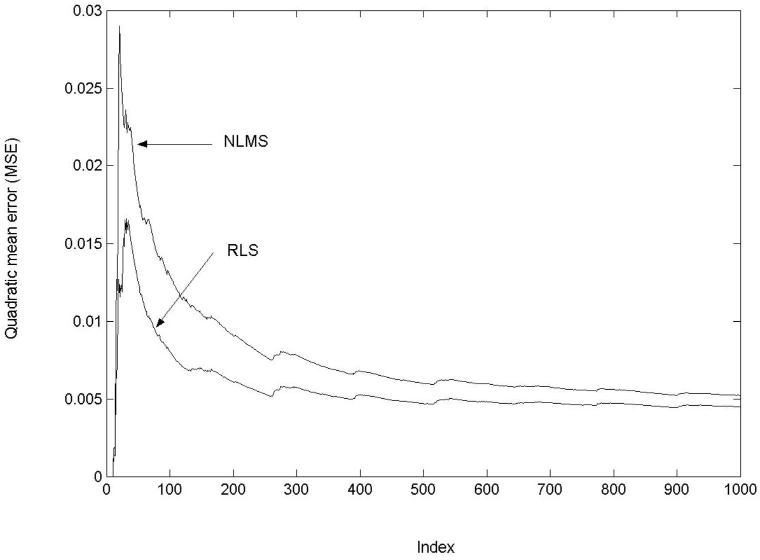

Fig. 3. *Results of the quadratic mean error (MSE) for the RLS and NLMS algorithms*

It is clear that the RLS algorithm shows faster convergence than the NLMS algorithm, which is usual for stationary signals [13]. However, other authors have reported the opposite when dealing with transient signals [17]. From the theory, however, a faster convergence was expected for both algorithms. This fact can be explained because there could be some small degree of correlation between the signal measured at the bearing and the reference signal, which could result in misadjustment.

In addition, walevet transforms were used for de-noising the data. The data was transformed into an orthogonal wavelet basis. Thresholding was applied to shrink the noisy wavelet coefficients and then the modified wavelet coefficients were used to reconstruct the signal by the inverse wavelet transform. Several de-noising schemes were applied, using several wavelets and thresholding methods. For the de-noising process, the best results were obtained from the combination of the db4 (Daubechies

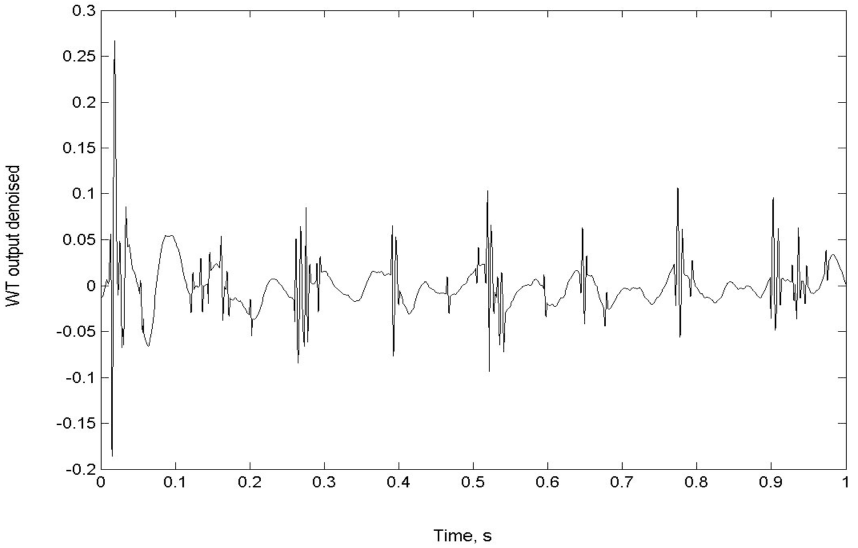

Fig. 4. *Time signal obtained after using the adaptive filtering with the RLS algorithm and then de-noised by means of the wavelet transform (WT)*

4) wavelet [18] and hard thresholding with an interval-dependent threshold setting.

Figure 4 shows the time signal obtained after using the adaptive filtering with the RLS algorithm and then de-noised by means of the wavelet transform (WT). It can be observed that the periodic details of the signal are now revealed, allowing a time waveform analysis.

In Fig. 5 the results of the fast Fourier transfom (FFT) spectra are presented. Figure 5(A) shows the results without using any kind of noise cancellation. Figure 5(B) shows the results using a wavelet transform for de-noising the measured signal without using the adaptive FIR filtering. Finally, Fig. 5(C) presents the results when wavelet de-noising is applied after the signal has been enhanced using the adaptive FIR filter. Clearly, the best results are achieved when both adaptive filtering and wavelet de-noising techniques are applied, so the signal-to-noise ratio for all frequency regions is increased significantly. The upper end of the high-frequency range remained relatively clean due to the low levels of extraneous signal components in this region. Fig. 5(C) clearly shows the presence of a spike in the very-low-frequency region, which corresponds to the shaft's rotational speed (modulation frequency). Also, a spectral peak around 150 Hz and side-bands with a spacing of approximately 8 Hz are observed. From the geometry of the bearing the ball pass frequency inner race (BPFI) is calculated to be approximately 144 Hz [3]. This means that the spectral peak might be indicating some inner race-bearing defect. The sidebands might be related to the cage frequency. One way to study this effect would be to change the rotational velocity of the shaft. Certainly, the resonances should disappear and only the forcing frequencies would remain.

3 CONCLUSIONS

The proposed technique constitutes a successful application of adaptive filtering combined with wavelet thresholding for vibration-signal enhancement when the useful vibration signatures become submerged within the noise and interference from external signals. For this particular application it can be concluded that the rate of convergence of the RLS algorithm is faster than that of the NLMS algorithm, but this is achieved at the expense of a large increase in computational complexity. In addition, the correct selection of the analysing wavelet with different properties is of critical importance for enhancing the fault features in the wavelet analysis.

When just using wavelet de-noising, significant gains in the signal-to-noise ratio are evident

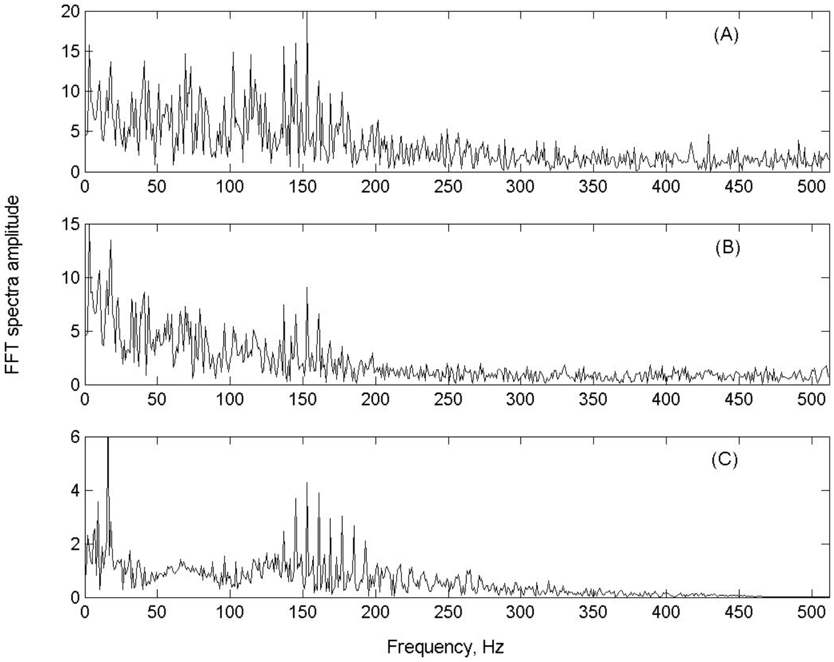

Fig. 5. *Results of the FFT spectra: (A) without noise cancellation; (B) with wavelet de-noising; (C) with wavelet de-noising combined with adaptive FIR filter*

compared to the direct FFT analysis of the noisy measured signal. However, more modest improvements are achieved when compared to the application of a previous adaptive signal enhancement of the measured signal. Used in conjunction with a wavelet de-noising analysis, the technique provides promising, enhanced diagnostic capabilities. The extracted signal also provides a sensitive and accurate basis from which the severity of localised rolling-element bearing faults can be analysed.

Further research will investigate the improvement of the adaptive signal enhancement system by using several vibration reference sensors that will be mounted at various locations on the machine.

4 REFERENCES

[1] Serridge, M. (1989) Fault detection techniques for reliable machine condition monitoring. *Sound and Vibration* 23(5), 18-22.

[2] Krishnappa, G. (1997) Machinery condition monitoring, in Encyclopedia of Acoustics (Edited by M.J. Crocker), *John Wiley and Sons*, New York.

[3] Shahan, J.E., G. Kumperman (1976) Machine element noise, in Handbook of Industrial Noise Control (Edited by L.L. Faulkner), *Industrial Press*, New York.

[4] Altmann, J., J. Mathew (2001) Multiple band-pass autoregressive demodulation for rolling-element bearing fault diagnosis. *Mechanical Systems and Signal Processing* 15(5), 963-977.

[5] Liu, B., S.F. Ling (1999) On the selection of informative wavelet for machinery diagnosis. *Mechanical Systems and Signal Processing* 11(3), 145–162.

[6] Vania, A., P. Pennacchi (2003) Experimental and theoretical application of fault identification measures of accuracy in rotating machine diagnostics. *Mechanical Systems and Signal Processing* (in press).

[7] Diniz, P. (1997) Adaptive filtering: algorithms and practical implementation, *Kluwer Academic*, Norwell, MS.

[8] Widrow, B, S.D. Stearns (1985) Adaptive signal processing, *Prentice Hall*, Englewood Cliffs, NJ.

[9] Wiener, N. (1949) Extrapolation, interpolation, and smoothing of stationary time series, with engineering applications, *MIT Press*, Cambridge, MS.

[10] Widrow, B., J. Glover, J. McCool, J. Kaunitz, C. Williams, R. Hearn, J. Zeidler, M. Dong, R. Goodlin (1975) Adaptive noise cancelling: principles and applications. *Proc. of IEEE* 63(1), 1692-1716.

[11] Haykin, S. (1984) Introduction to adaptive filters, *Macmillan Publ. Co*., New York.

[12] Bitmead, R.R., B.D.O. Anderson (1980) Performance of adaptive estimation algorithms in dependent random environments. *IEEE Trans. Automatic Control* AC-25, 782-787.

[13] Haykin, S. (1996) Adaptive filter theory, 3rd Edition, *Prentice Hall*, Englewood Cliffs, NJ.

[14] Donoho, D.L. (1995) De-noising by soft-thresholding. *IEEE Trans. Information Theory* 41(3), 613 –627.

[15] Barbara, B.H. (1998) The world according to wavelet: the story of a mathematical technique in the making, *A.K. Peters Ltd*., Wellesley, MA.

[16] Pan, Q., L. Zhang, G. Dai, H. Zhang (1999) Two denoising methods by wavelet transform. *IEEE Trans. Signal Processing* 47(12), 3401-3406.

[17] Bershad, N., O. Macchi (1989) Comparison of RLS and LMS algorithms for tracking a chirped signal. *Proc. Int. Conf. on Acoustics, Speech and Signal Processing* ICASSP89, 896-899.

[18] Daubechies, I. (1990) The wavelet transform, time-frequency localisation and signal analysis. *IEEE Trans. Information Theory* 36(5), 961-1005.

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Uporaba tehnologije eksplozijskega navarjanja v postopku izdelave hidravličnih valjev

The application of explosive cladding technology in the process of hydraulic-cylinder production

Vid Jovišević - Mirko Soković

V prispevku sta prikazani tehnologiji oblikovanja drsnih dvojic s standardnim postopkom navarjanja brona z elektrodo in z eksplozijskim navarjanjem pločevine iz brona na drsne ploskve hidravličnega valja. Raziskovane so bile mikrotrdota, mikrostruktura in vezna (strižna) trdnost mejne plasti bimetalnega spoja v prečnem prerezu testnega hidravličnega valja. Primerjalni rezultati uporabe teh dveh tehnologij so podani na podlagi metalografskih in mehanskih raziskav mejne plasti med bronom CuSn6 in jeklom za hidravlične valje Č.1213 (ISO TS5).

(Ključne besede: navarjanje eksplozijsko, valji hidravlični, trdnost strižna, plasti mejne, broni-jekla)

This paper treats the technologies for glide-pairs forming using bronze cladding and using the sheet-bronze explosive cladding technique over the glide surfaces of a steel hydraulic cylinder. In the paper the microhardness, the microstructure and the bond strength of the interface of a bi-metallic joint on the cross-section of the test hydraulic cylinder were investigated. A parallel results survey of the application of these two technologies is shown based on metallographic and mechanical investigations of the interface between the CuSn6 bronze and the TS5 steel cylinder.

(Keywords: explosive cladding, hydraulic cylinder, bond strength, bronze-steel interface)

0 UVOD

Pri postopku izdelave hidravličnih valjev se uporablja tehnologija navarjanja brona z namenom oblikovanja drsnih dvojic, narejenih iz različnih materialov. Tako se izognemo hladnemu zvarjanju (zaribavanju) drsnih dvojic pri preobremenitvah med delom (uporaba valjev na hidravličnih stiskalnicah za upogibanje pločevine).

Hidravlični valj in bat kot drsna dvojica pri delovanju hidravličnih stiskalnic običajno niso izpostavljeni posebnim dinamičnim preobremenitvam, ki bi povzročale nenormalno delovanje, ki bi vodilo do hladnega zvarjanja. Vendar se v praksi pojavljajo primeri hladnega zvarjanja teh dvojic. Kot vzroke za te pojave lahko označimo:

- nepravilno definirane tolerance ujemov teh dvojic,
- neustrezno kakovost obdelave drsnih površin,

0 INTRODUCTION

In the process of hydraulic-cylinder production, bronze cladding technology is applied in order to form gliding pairs that are made of various materials. In this way the possibility of the cold welding of the gliding pairs during overloading in the working process (the application of the cylinder on a hydraulic press for sheet-metal bending) is eliminated.

The hydraulic cylinder and the piston, as a gliding pair in the function of hydraulic presses, are not exposed to any special dynamic overloading that can cause an abnormal working process and lead to cold welding, however, in practice there are cases of the cold welding of these pairs. The causes of this cold welding are identified as:

- irregularly defined structure tolerances,
- in adequate processing quality of the gliding surfaces,

- nečistoče v olju,
- kakovost navarjanja brona in
- kakovost samega brona.

Med vsemi navedenimi vzroki so bolj izpostavljeni tisti, ki se kažejo med postopkom navarjanja brona, predvsem zaradi zapletenosti tehnološkega postopka in vpliva varilca nanj. Navarjanje brona je trajen postopek, kar povzroča nastajanje poroznih površin ter pojav trdih con. Vse to vpliva na kakovost drsnih površin in povzroča nezaželene posledice.

Zaradi tega so bile raziskave avtorjev tega prispevka usmerjene na iskanje alternativne tehnologije za oblikovanje drsnih dvojic iz različnih materialov za primer hidravličnih stiskalnic za upogibanje pločevine.

Tehnologija eksplozijskega navarjanja je bila uporabljena za izdelavo bimetalnega materiala (bron, navarjen na jeklo za hidravlične valje), ki bo imel izboljšane fizikalno-mehanske lastnosti pri sami uporabi ([1] in [2]). Ta tehnologija temelji na detonaciji eksploziva, katerega energija se prenaša prek določenega posrednika na material, ki se navarja. Podrobni opis postopka eksplozijskega spajanja je podan v [3] do [5]. Za potrebe teh raziskav so bili poskusi izvedeni v improviziranih razmerah [6]. Rezultati, doseženi z uporabo te tehnologije pri izdelavi hidravličnih valjev stiskalnic za upogibanje pločevine, so podani v nadaljevanju.

1 SEDANJA TEHNOLOGIJA IZDELAVE HIDRAVLIČNIH VALJEV

Proizvodnja hidravličnih valjev (sl. 1) poteka po običajni tehnologiji ([7] in [8]). Kot pomembnejši tehnološki opravili lahko izpostavimo: navarjanje brona z elektrodo na predhodno pripravljeno notranjo površino jeklenega hidravličnega valja ter struženje.

Navarjanje brona se izvaja v naslednjih korakih:

- čiščenje in razmaščevanje površine pred navarjanjem,
- nanašanje topila na površino (*CASTOLIN 18*),
- predgrevanje valja do 300 °C in
- nanašanje (navarjanje) brona na površino z elektrodo *CASTOLIN CP 146*.

Posameznih faz pri opravilu struženja je lahko več in glede na njihovo izvajanje dosežemo ustrezne končne mere valjev.

Sedanji tehnološki postopek izdelave hidravličnih valjev spremljajo naslednje omejitve:

- dirt in the oil,
- bronze cladding quality,
- bronze material quality.

Of all the causes that are given as examples, those which are manifested in the process of bronze cladding are the most obvious, and this is because of the complexity of the technological process and its being subject to the influence of the welder. Bronze cladding has no continuous flow, which leads to the formation of porous surfaces and the appearance of hard zones. This all has an influence on the quality of the gliding surfaces and causes negative results.

For this reason we have investigated alternative gliding-pairs forming technologies from various materials, as in the example of the hydraulic cylinders of presses for sheet-metal bending.

The technology of explosive cladding has been used for the production of bi-metal materials (bronze-clad steel for hydraulic cylinders) featuring high physical-mechanical and service properties ([1] and [2]). This technology is based on an explosive detonation, whose energy is transferred by a special medium to the material that is applied. A detailed description of the explosive technique is given in [3] to [5]. According to the needs of these investigations, the experiments were performed under improvised conditions [6]. The results that are achieved by the application of this technology to the production of the hydraulic cylinders of presses for sheet-metal bending are given in advance.

1 PRESENT TECHNOLOGY FOR THE PRODUCTION OF HYDRAULIC CYLINDERS

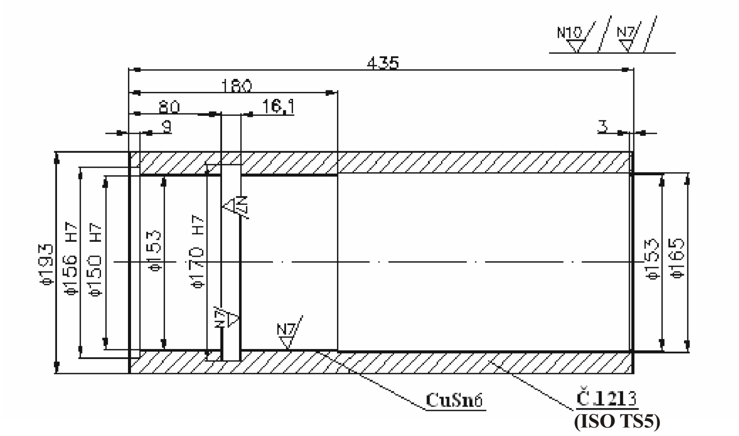
The production of hydraulic cylinders (Fig. 1) is carried out according to standard technology ([7] and [8]). The main operations are bronze cladding on the previously prepared inner surface of the steel hydraulic cylinder and turning.

The bronze cladding is carried out as follows:

- cleaning and removing grease from the surface before cladding,
- application of dissolving material on the surface (*CASTOLIN 18*),
- cylinder pre-warming up to 300 °C,
- application (cladding) of bronze on the surface using electrode *CASTOLIN CP 146*.

The particular phases during the turning operation are numerous, and according to the sequence in which they one performed, the final measures of the cylinder are achieved.

The present technological process of the hydraulic- cylinder production is limited by the following:



Sl. 1. *Hidravlični valj*
Fig. 1. *Hydraulic cylinder*

- poroznost navarjene plasti brona,
- potrebe po uvajanju opravila žarjenja zaradi pojava trdih con in
- težave pri izdelavi utora za tesnilo zaradi trdih con na meji (spoju) med bronom in jeklom.

Omenjene omejitve so temelj za oblikovanje zahtev po uvajanju novih tehnologij za ustvarjanje drsnih dvojic v izdelavi hidravličnih valjev.

2 TEHNOLOGIJA EKSPLOZIJSKEGA NAVARJANJA PRI IZDELAVI HIDRAVLIČNIH VALJEV

Tehnika eksplozijskega navarjanja je metoda deformacijskega oblikovanja, ki izrablja energijo ob detonaciji eksploziva. Ta energija se prenaša po zraku, vodi, pesku ali materialih PVC na material, ki se preoblikuje.

Količina eksploziva in sredstvo, prek katerega se prenaša energija, sta elementa za določanje celotne potrebne energije za preoblikovanje. To energijo je zelo težko nadzirati zaradi vpliva številnih neznanih dejavnikov ter nezmožnosti oblikovanja matematičnih modelov. Zaradi tega določamo elemente za doseganje zahtevane kakovosti postopka oblikovanja s številnimi poskusi.

Z detonacijo eksploziva ustvarimo zelo visoke tlake, ki so potrebni za preoblikovanje kovin in zlitin v zelo kratkem času, kolikor traja sam postopek. Doseganje predpisane kakovosti izdelka zagotavljamo z:

- vrsto eksploziva,
- s tehnološkimi karakteristikami eksploziva,
- lego namestitve eksploziva,
- delovnim sredstvom, v katerem poteka postopek in

- the porosity of the cladded bronze layer,
- the need to introduce of heating operations because of the appearance of hard zones,
- the difficulties in cutting a groove for gasket because of the hard zones on the boundary where the bronze and steel join.

The limitations given are the basic ones for making requests to introduce new technologies for the gliding pair's formation in hydraulic-cylinder production.

2 EXPLOSIVE CLADDING TECHNOLOGY IN HYDRAULIC-CYLINDER PRODUCTION

Explosive cladding is a method of processing by deforming that uses the energy of explosive detonation. Air, water, sand or PVC are the materials used to transmit this energy.

The size of the explosion and the average energy transmission are the elements for defining of total energy needed for the deforming. This energy is hard to control because of the influences of unknown factors and the impossibility of performing mathematical models. Thus, numerous experiments are used to determine the elements to achieve the demanded quality of processing.

With explosive detonation, the very high pressures needed for metal shaping are provided in a very short time. The production quality depends on the following:

- the type of explosive,
- the technological properties of the explosive,
- the place for setting the explosion,
- the working medium in which the process is being

- izkušnjami na področju preoblikovanja z eksplozivom.

Omenjene lastnosti eksplozijskega navarjanja so uporabljene v izdelavi hidravličnih valjev kot alternativa običajnem navarjanju brona z elektrodo na notranjo površino valja.

Dotikalna drsna površina je vgrajena v hidravlični valj z uporabo tehnike eksplozijskega navarjanja po naslednjem tehnološkem postopku:

- priprava cevi iz pločevine iz brona CuSn6,
- varjenje cevi iz brona vzdolž sestava oboda valja,
- postavitev cevi v valj,
- postavitev eksploziva v notranjost valja,
- postavitev valja v vodo,
- proženje eksplozije v notranjosti valja.

Rezultat opisanega tehnološkega postopka je spojitev brona (cevi) na notranjo površino valja.

3 EKSPERIMENTALNO DELO

Zmožnosti uporabe tehnologije eksplozijskega navarjanja, v primerjavi s sedanjo običajno tehnologijo navarjanja brona z elektrodo na notranjo površino hidravličnega valja, so določene na podlagi metalografskih in mehanskih raziskav spoja bimetalne plasti (valj iz jekla Č. 1213, navarjen z bronom CuSn6). Metalografske raziskave so bile opravljene na vzorcih, odvzetih iz hidravličnega valja, ki je bil navarjen z bronom po običajni tehnologiji in iz valja, pri katerem je bila uporabljena tehnologija eksplozijskega navarjanja. Načrt jemanja vzorcev je prikazan na sliki 2.

carried out,

- the experiences in the field of explosive shaping.

The given possibilities of explosive cladding are applied in hydraulic-cylinder production as an alternative to the standard operation of bronze cladding on the inner surface of the cylinder.

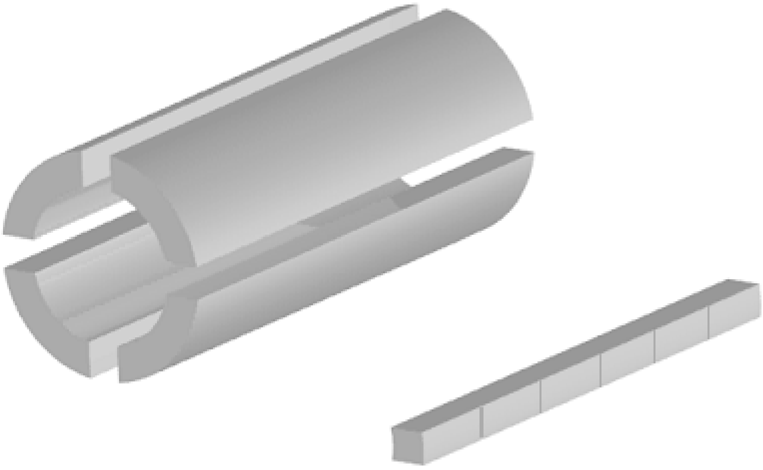
The contact gliding surface is built in the hydraulic cylinder by the application of explosive cladding technology according to the following procedure:

- preparation of tubes from bronze sheet metal,
- bronze tube welding along the connection line,
- placing the tube into the cylinder,
- placing the explosive inside the cylinder,
- placing the cylinder into the water,
- explosion initiation inside the cylinder.

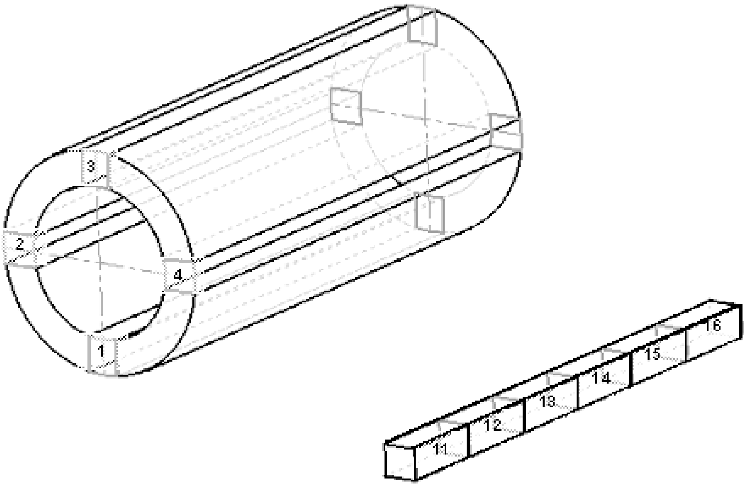
As a result the bronze sheet-metal tube on the inner surface of the cylinder is applied.

3 EXPERIMENTAL WORK

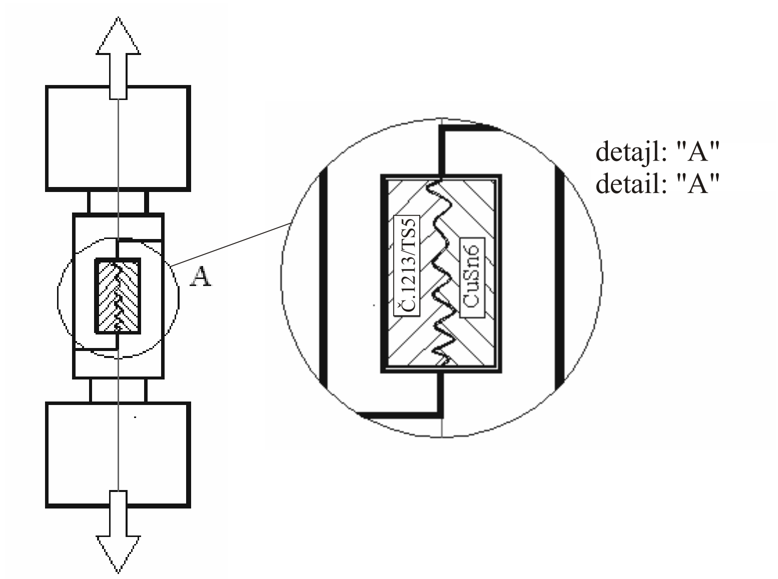
The possibilities of applying explosive cladding technology rather than the present standard bronze cladding technology on the inner surface of a hydraulic cylinder are determined on the basis of metallographic and mechanical investigations of the joint of the bi-metal layer (TS5 steel cylinder clad with CuSn6 bronze). Metallographic investigations were carried out on samples taken from a hydraulic cylinder on which standard bronze cladding on the inner surface was performed, and also from a hydraulic cylinder on which explosive cladding technology was applied. The plan of investigated samples is given in Fig. 2.



Sl.. 2. *Načrt jemanja vzorcev*
Fig. 2. *Plan of investigated samples*



Sl. 3. *Določanje lege jemanja vzorcev*
Fig. 3. *Determining the position of the investigated samples*



Sl. 4. *Preizkušanci, ki omogočajo vzporedno delovanje strižnih sil glede na spoj*
Fig. 4. *Test tubes that enable the parallel action of shear forces in relation to the joint*

Glede na podani načrt je bilo pripravljenih 24 vzorcev, na katerih so potekale raziskave spoja bron/jeklo za običajno tehnologijo navarjanja in tudi za tehnologijo eksplozijskega navarjanja (sl. 3).

Za določanje največje strižne trdnosti mejne plasti spoja bron/jeklo so bili izdelani posebni preizkušanci, ki so omogočali vzporedno delovanje strižnih sil glede na spoj (sl. 4).

According to the given plan, 24 samples were prepared, on which the investigation of the bronze/steel joint was carried out for the standard bronze cladding technology and also for the explosive cladding technology (Fig. 3).

For testing the maximum shearing stresses at the bronze/steel joint interface a special shaped test is used, this enables the parallel action of shearing forces in relation to the connection (Fig. 4).

3.1 Vzorci, narejeni po običajni tehnologiji navarjanja brona

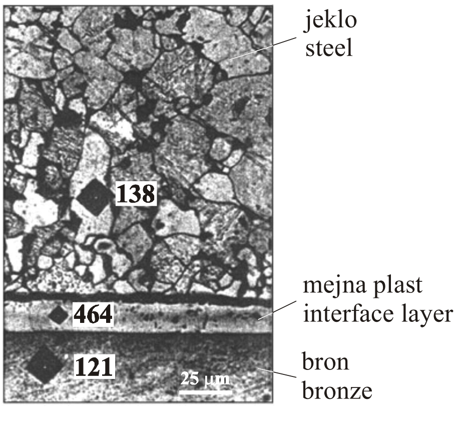
Mikrostruktura vmesnika med bronom in notranjo površino jeklenega valja v primeru običajnega postopka navarjanja z elektrodo je prikazana na sliki 5. Močno so izražene tri cone:
- bron,
- jeklo in
- mejna plast.

Strukturi brona in jekla sta ločeni z vzporedno oblikovano vezno plastjo, ki povezuje ta dva osnovna materiala. Zaradi svoje izrazite ravnosti ta vezna plast ne zagotavlja velike trdnosti materiala (natezne, strižne).

Rezultati meritev strižne trdnosti vezne plasti pri različnih vzorcih, narejenih z navarjanjem z elektrodo, so zelo spremenljivi (198,8 ± 50,5 MPa), kar je posledica kakovosti navarjanja brona in je odvisna od dela posameznega varilca. Mikrostruktura površine striga v vezni plasti bron/jeklo pri vzorcu, ki je bil navarjen z elektrodo, je prikazana na sliki 6. Porušitev zaradi delovanja strižnih napetosti je potekala vzdolž vezne plasti povišane trdote.

3.2 Vzorci, narejeni po tehnologiji eksplozijskega navarjanja

Mikrostruktura mejne plasti bron/jeklo po eksplozijskem navarjanju je prikazana na sliki 7. Zaradi velikega specifičnega pritiska po eksploziji se je mikrostruktura spremenila v ozki coni dotika



Sl. 5. *Območje spoja in rezultati merjenja mikrotrdote $HV_{0.01}$ (vzorci standardno navarjeni z bronom)*

Fig. 5. *Joint region and the results of $HV_{0.01}$ microhardness tests (samples after standard bronze cladding)*

3.1 Samples made using the standard bronze-cladding technology

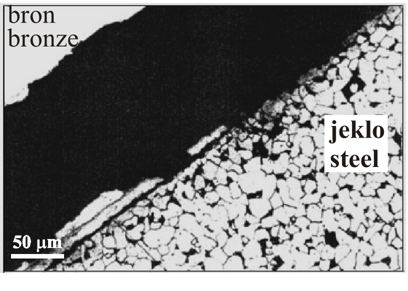
The microstructure at the interface between the bronze and the inner surface of the steel cylinder in the standard process of cladding by electrode is shown in Fig. 5. There are three zones:
- Bronze,
- Steel,
- Joint interface.

The structure of the bronze and steel is separated parallels by the formed layer that joins these two basic materials. Because of its flat configuration, this joint layer does not guarantee that the material is very strong (stretching, shearing).

The results of shear-strength measurements in the joint interface of the different samples, which are made by electrode cladding, are variable (198.8 ± 50.5 MPa), which is the result of a bronze-welding quality that depends on the welder’s work. The microstructure of the sheared surface for the bronze/steel interface by electrode cladding is shown in Fig. 6. The fracture due to shearing stresses occurs on the interface layer of great hardness.

3.2 Samples made using explosive cladding technology

The microstructure at the bronze/steel interface after explosive cladding is shown in Fig. 7. Because of the great and specific pressure after the explosion the microstructure was changed in the narrow contact zone



Sl. 6. *Površina porušitve zaradi strižnih napetosti (standardno navarjanje brona)*

Fig. 6. *Fracture surface due to shearing stresses (standard bronze cladding)*

dveh materialov, kar je vplivalo na oblikovanje valovite dotikalne površine med bronom in jeklom, ki pa je zelo značilna za takšen tip spajanja (sl. 8). Takšna oblika spoja bolje prenaša obremenitev. Vrednosti mikrotrdote, izmerjene na eksplozijsko navarjenem vzorcu, so podane na sliki 9.

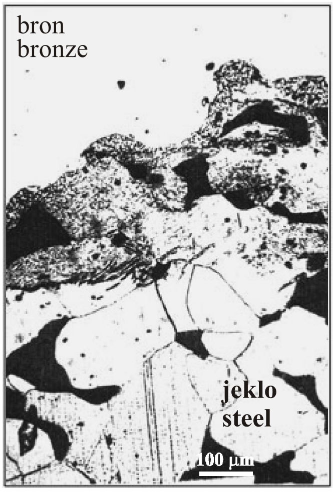
Pri eksplozijskem navarjanju imamo zelo majhno spremenljivost rezultatov strižne trdnosti pri različnih vzorcih (382,1 ± 11,5 MPa), v primerjavi z vzorci, ki so bili standardno navarjeni z elektrodo.

Rezultati meritev globine penetrirane plasti valovite oblike (sl. 10) na vseh štirih skupinah

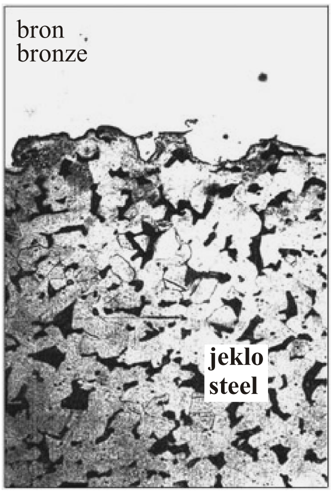
of two materials, which had an influence on the forming of a wavy joining surface between the bronze and the steel. The wavy shape of the contact layer is characteristic for this type of joint, which is shown in Fig. 8. This way of connecting has a greater ability to carry a load. The values of the microhardness that are measured on the explosive cladded samples are shown in Fig. 9.

During explosive cladding there is a very small variability in the shear strengths of the samples (382.1 ± 11.5 MPa) in comparison to the samples made by standard electrode cladding.

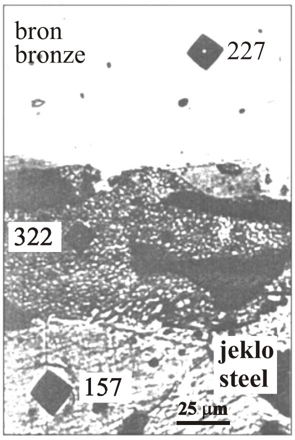
The measurement results for the penetrated layer of the wavy shape on four groups of samples



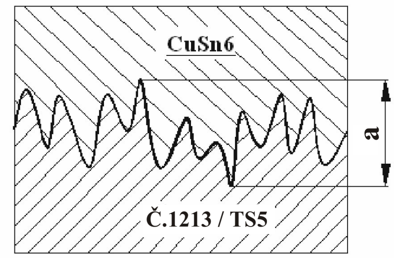
Sl. 7. *Mikrostruktura spoja bron/jeklo (eksplozijsko navarjanje)*
Fig. 7. *Microstructure of the bronze/steel joint (explosive cladding)*



Sl. 8. *Značilna valovita oblika dotikalne površine (eksplozijsko navarjanje)*
Fig. 8. *Characteristic wavy shape of contact layer (explosive cladding)*



Sl. 9. *Območje spoja in rezultati merjenja mikrotrdote* $HV_{0,01}$ *(vzorci eksplozijsko navarjeni)*
Fig. 9. *Joint region and the results of* $HV_{0.01}$ *microhardness tests (explosive cladding)*



Sl. 10. *Značilna valovita oblika mejne plasti pri eksplozijskem navarjanju*
Fig. 10. *Characteristic wavy shape of interface layer by explosive cladding*

Preglednica 1. *Globina valovitosti penetrirane plasti (a) na različnih eksplozijsko navarjenih vzorcih (glede na sl. 3)*
Table 1. *Depth of wavy-shaped penetrating layer (a) on the different explosive clad samples (according to Fig. 3)*

Številka vzorca Sample number	**a mm**	**Številka vzorca Sample number**	**a mm**	**Številka vzorca Sample number**	**a mm**	**Številka vzorca Sample number**	**a mm**
11	0,12	21	0,14	31	0,12	41	0,12
12	0,24	22	0,18	32	0,14	42	0,10
13	0,40	23	0,18	33	0,12	43	0,18
14	0,30	24	0,18	34	0,16	44	0,24
15	0,28	25	0,18	35	0,16	45	0,20
16	0,26	26	0,18	36	0,18	46	0,16

Preglednica 2. *Primerjava mikrotrdot v spoju bron/jeklo na vzorcih pri različnih tehnologijah navarjanja*
Table 2. *Comparison of the microhardness of the joint of (bronze/steel) bi-metal samples for different cladding technologies*

Cone spoja površin Joint surface zones	**Mikrotrdota / Microhardness $HV_{0.01}$**	
	Navarjanje z elektrodo Electrode cladding	**Eksplozijsko navarjanje Explosive cladding**
bron / bronze	121	227
mejna plast / interface layer	464	322
jeklo / steel	138	157

vzorcev so podani v preglednici 1. Ugotovljena povprečna globina plasti, ki je bila a = 0,18 mm, omogoča visoko raven varnosti spoja bron/jeklo. Prikazi posameznih spojev bron/jeklo za prvo skupino vzorcev od 11 do 16 (sl. 3) so zbrani na slikah 11a do 11f.

4 RAZPRAVA

Mejna plast med bronom in jeklom na vzorcih, narejenih z običajnim navarjanjem brona, je zelo trda in povezuje dve strukturi, ki pa zaradi izrazite ravnosti ne zagotavlja velike strižne trdnosti ter dobrega dotika dveh različnih materialov.

Mikrotrdota mejne plasti je manjša v primeru vzorcev narejenih z eksplozijskim navarjanjem (pregl. 2), kar je z vidika obdelave z odrezovanjem bolj ugodno.

Vrednosti strižne trdnosti pri vzorcih, narejenih s standardnim postopkom navarjanja z elektrodo, so zelo spremenljivi (198,8 ± 50,5 MPa), kar je posledica kakovosti navarjanja brona in je odvisna od dela varilca. Pri eksplozivnem navarjanju pa je spremenljivost razmeroma majhna (382,1 ± 11,5 MPa).

Mikrostruktura in površina striga mejne plasti bron/jeklo pri navarjanju z elektrodo je

are given in Table 1. The average width of the layer, which is a = 0.18 mm, is set, and that enables a high level of bronze/steel joint safety (Fig. 10). The survey of the bronze/steel interface is given for the first group of samples, from 11 to 16 (Fig. 3), in Figs. 11a to 11f.

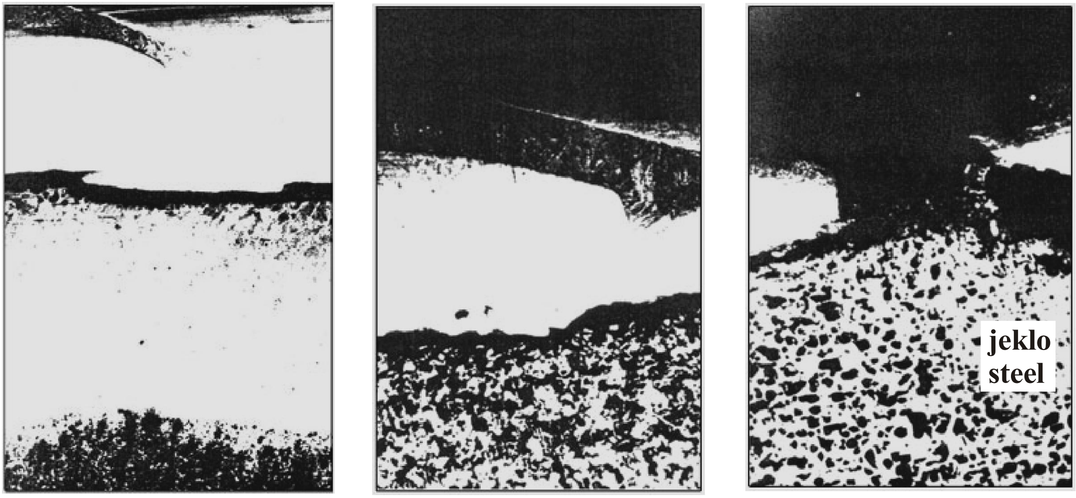
4 DISCUSSION

The interface layer between the bronze and the steel for samples made using standard bronze cladding is very hard and joins two structures, but because of its flat configuration it does not guarantee great shearing strength and good contact between the two materials.

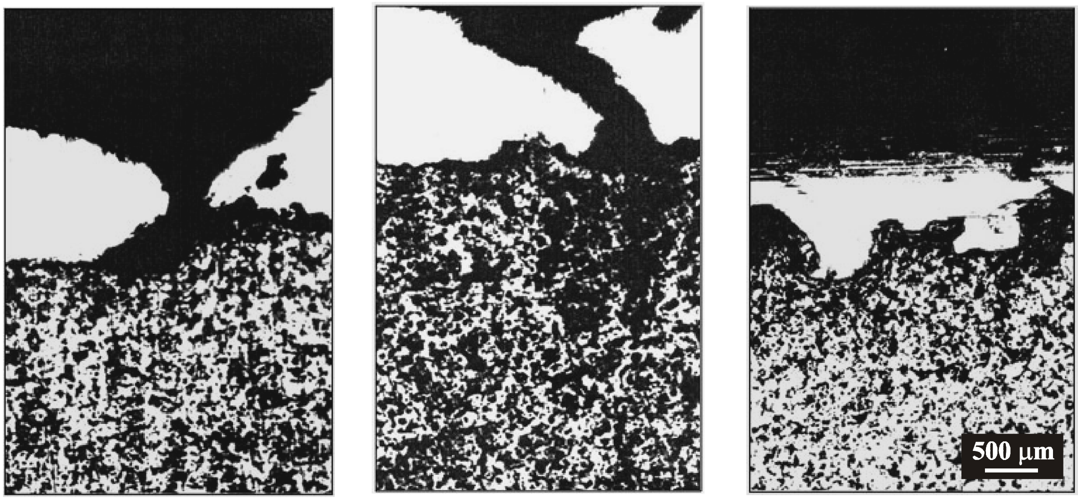
The hardness of the interface layer is less in the case of the samples made by explosive cladding, which is more satisfactory considering the cutting processes (Tab. 2).

The shearing stresses of the samples made by standard electrode cladding have a very variable character (198,8 ± 50,5 MPa), which is the result of bronze-welding quality that depends on the welder's work. By using explosive cladding there is very little deviation of the shearing stresses (382,1 ± 11,5 MPa).

The microstructure and the sliding surface at the bronze/steel interface using electrode cladding



a - vzorec 11/sample 11 b - vzorec 12/sample 12 c - vzorec 13/sample 13



d - vzorec 14/sample 14 e - vzorec 15/sample 15 f - vzorec 16/sample 16

Sl. 11. *Morfologija mejne plasti bron/jeklo, značilna za obravnavane raziskave v tej študiji (vzorci po eksplozijskem navarjanju)*

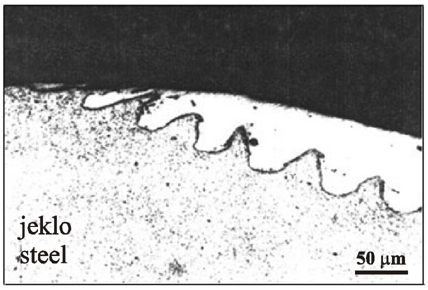
Fig. 11. *Morphology of the bronze/steel interfaces typical of the investigations discussed in this study (samples after explosive cladding)*

prikazana na sliki 6. Porušitev zaradi strižnih napetosti je potekala vzdolž mejne plasti z veliko trdoto.

Mikrostruktura in površina ločevanja v mejni plasti bron/jeklo eksplozijsko navarjenih vzorcev sta prikazani na sliki 12. Kot posledica strižnih napetosti je potekala porušitev v coni brona, kar pomeni, da je vezna plast, nastala z uporabo tehnologije eksplozijskega navarjanja, večje trdote in strižne trdnosti.

are shown in Fig. 6. The fracture during shearing stresses happens along the joint layer of great hardness.

The microstructure and the shape of the sliding surface in the bronze/steel interface after explosive cladding are shown in Fig. 12. As a result of sliding, a fracture occured along the bronze zone, which means that the joint layer is formed according to the technology of explosive cladding with greater hardness and shearing strength of the material.



Sl. 12. *Oblika površine ločevanja v mejni plasti bron/jeklo pri eksplozijsko navarjenih vzorcih*
Fig. 12. *Shape of the sliding surface in the bronze/steel interface by the explosive clad samples*

5 SKLEPNE UGOTOVITVE

Rezultati raziskav kažejo, da imajo hidravlični valji, narejeni po tehnologiji eksplozijskega navarjanja, boljše strukturne in mehanske lastnosti v mejni plasti bron/jeklo v primerjavi s hidravličnimi valji, narejenimi z običajnim navarjanjem brona z elektrodo.

Valovita dotikalna površina med bronom in jeklom, ki nastane pri postopku eksplozijskega navarjanja, ima bistveno večjo strižno trdnost v primerjavi z ravno dotikalno površino, ki nastane pri običajnem postopku navarjanja brona. To potrjujejo rezultati doseženih strižnih napetosti, pri katerih so srednje vrednosti teh napetosti pri vzorcih, ki so bili eksplozijsko navarjeni, bistveno večje od povprečnih vrednosti pri vzorcih, ki so bili navarjeni po običajni tehnologiji.

Na podlagi doseženih rezultatov pri uporabi eksplozijskega navarjanja v proizvodnji hidravličnih valjev, ki so podani v prispevku, lahko sklepamo, da je mogoče omenjeno tehnologijo uspešno uporabiti in ustvariti boljše rezultate v primerjavi s sedanjo tehnologijo. Kljub temu je uporaba te tehnologije omejena zaradi naslednjih razlogov:

1. drsne lastnosti pločevine iz brona, ki se uporablja pri eksplozijskem navarjanju, je treba preveriti s kemičnimi analizami;
2. ni definiranih obdelovalnih sistemov, na katerih bi bilo mogoče nadzorovati energijo, ki nastane ob eksploziji;
3. potrebe po preverjanju rezultatov raziskav v dejanskih razmerah uporabe drsne dvojice pri delovanju hidravličnih stiskalnic za upogibanje.

5 CONCLUSIONS

The results of our investigations show that hydraulic cylinders made using explosive cladding technology have better structural and mechanical properties at the bronze/steel interface compared to hydraulic cylinders made using standard bronze cladding.

A wavy contact surface between the bronze and the steel that appears with explosive cladding technology gives considerably greater shearing strength to the material compared to the flat connecting surface that appears with the classical bronze cladding method. This is confirmed by the results of the shearing stresses, where the average shearing-stress value for samples made with explosive cladding technology is greater than the shearing-stress average value for the samples made with classical bronze-cladding technology.

According to the results of the explosive cladding technology in hydraulic-cylinder production, it can be concluded that this technology is successfully applied and that better results than with the present technology are achieved. However, the application of this technology is limited, for the following reasons:

1. The gliding properties of the bronze sheet metal that is applied by the explosion need to be checked by chemical analyses.
2. There are no defined systems of processing with which the energy dissipation during the explosion could be controlled.
3. There is a need to check the results in real conditions for a gliding pair during the work of the hydraulic press for sheet-metal bending.

6 LITERATURA
6 REFERENCES

[1] Crossland, B. (1982) Explosive welding of metals and its applications, *Oxford University Press*, New York.
[2] Kosec, B., L. Kosec, S. Petrović, V. Gontarev, G. Kosec, M. Gojić, P. Škraba (2003) Analyssis of low-carbon steel/tantalum interface after explosive welding, *Metalurgija* 42, št. 3, 147-151.
[3] Petrović, S. (1988) Fizika eksplozije, *Mašinski fakultet Univerziteta u Sarajevu*, Sarajevo.
[4] Kosec, B., L. Kosec, G. Čevnik, P. Fajfar, M. Gojić, I. Anžel (2004) Analysis of interface at explosive welded plates from low-carbon steel and titanium, *Metalurgija* 43, št. 2, 83-86.
[5] Dyja, H., A. Maranda, R. Trebinski (2002) Explosive techniques in the materials engineering, *TU Czestochowa*, Poland, Series Metallurgy No. 20.
[6] N.N. (1997) Results of metallographic and mechanical testing of bronze/steel joining in hydraulic cylinder, Project report, *Steel foundry "Jelšingrad"*, Banja Luka, (in Serbian).
[7] Jovišević, V., V. Todić (1998) "Ekspert" - technological system for design of hydraulic cylinders technology, *Proceedings of the 27th Int. symposium of production engineering of Yugoslavia*, Niš-Niška Banja, (in Serbian).
[8] Jovišević, V. (1997) Development of design and optimisation model of technological process for metal forming system production, based on group technology and data base, Doctoral dissertation, *Faculty of Mechanical Engineering, University of Belgrade*, (in Serbian).

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Motnje v postopku hlajenja koruznega zrnja v vertikalnih gravitacijskih sušilnicah

Disturbances in the Process of Corn-Grain Cooling in Vertical Gravity Dryers

Tajana Krička - Neven Voća - Željko Jukić - Darko Kiš - Sandra Voća

Postopek sušenja koruznega zrnja običajno poteka tako, da zrnje vstopi v predel za ohlajevanje z vlažnostjo, ki je 2,0% nad ravnovesnim stanjem. Poleg tega, da se zrnje ohladi, se v predelu za ohlajevanje tudi osuši za 1,5% do 2,0%. Vendarle pa smo z našo raziskavo pokazali, da obstajajo tudi primeri, ko koruzno zrnje v predelu za ohlajevanje rehidrira za 0,65% do 4,26%.

Naša raziskava je vključevala tudi analizo vlažnosti koruznega zrnja vzdolž vodoravnega prereza hladilnika. V odvisnosti od mesta zbiranja vzorcev je razlika v vlažnosti koruznih zrn nihala od 1,99% do 4,35% ter v nekaterih skrajnih primerih dosegla celo 10,0%.

Ti pojavi so povzročili večjo porabo energije, zmanjšanje zmogljivosti sušilnice in neenakomerno osušenost koruznega zrnja.

(Ključne besede: rehidracija, cone hladilne, sušenje, zrnje koruzno)

The process of corn-grain drying is usually conducted in such a way that corn grains come into a cooler zone at a moisture level that is 2.0% higher than the equilibrium level. As well as being cooled, the corn grains in the cooler zone also get dried by between 1.5% and 2.0%. However, our research has shown that this is not always the case, since corn grains are sometimes re-hydrated in the cooler zone by 0.65% to 4.26%.

Our research also included an analysis of the moisture levels of corn grains in the horizontal section of the cooler zone. Depending on the location, the difference in the moisture levels of the corn grains varied from 1.99% to 4.35%, reaching as much as 10.0% in some extreme cases.

This resulted in a higher energy consumption, a decrease in capacity and heterogeneously dried corn grains.

(Keywords: re-hydration, cooling zones, drying, corn grains)

0 UVOD

Kmetijske zrnate pridelke običajno sušimo v navpičnih gravitacijskih sušilnicah. Te sušilnice so sestavljene iz dveh delov: dve tretjini sta namenjeni sušenju, ena tretjina pa hlajenju. Med postopkom sušenja se vlažnost zrnja zmanjša do določene ravni, ki je odvisna od vrste sušenega zrnja (oljnice ali žitarice), od njegove uporabe in od načrtovane dobe njegovega skladiščenja. Po končanem postopku sušenja segreto zrnje ohladimo v predelu za ohlajevanje, tako da je temperatura zrnja, ki zapušča sušilnik, 5°C nižja od temperature zunanje okolice. Poleg tega, da se ohladi, se zrnje tudi

0 INTRODUCTION

Agricultural grain products are usually dried in vertical gravity dryers. These vertical gravity dryers consist of two zones: two-thirds of the dryer is the drying zone and one-third is the cooling zone. During the process of drying, the moisture level in the grain is decreased to a certain level, depending on the type of grain being dried (oilseed or cereal), on how it will be used in the future and on the planned period of storage for the grain. After the drying process the warm grain is cooled in the cooling zone in order to keep the temperature of the grain as it exits the dryer 5ºC less than the temperature of the external environment. In addidodatno osuši za 1,5 do 2,0%, ker v predelu za ohlajevanje vroče zrnje pride v stik z vlažnim zrakom in med njima nastane termodinamični stik. Vlažni zrak namreč odvede toploto segretega zrnja in se tako segreje. Hkrati obe sredstvi tudi izmenjata vlago, pri čemer poteka prenos vlage v obeh smereh. Smer prenosa vlage je odvisna od delnega tlaka vlage na površini zrnja in od tlaka vlažnega zraka, kajti tako zrnje kakor tudi vlažen zrak se nagibata k termodinamičnemu ravnovesju.

Na Hrvaškem se že več let srečujemo s problemom ohlajanja zrnja, ki je del postopka sušenja v navpičnih gravitacijskih sušilnicah. V zgodnjih sedemdesetih letih smo opazovali pomembne učinke hitrosti hlajenja zrnja, ki sledi postopku njegovega sušenja, ter ugotovili tesno povezavo med povečano poškodovanostjo zrnja in povečano hitrostjo hlajenja [1]. Prav tako smo opazili, da v primeru sušenja pri različnih hitrostih ni prišlo do odvisnosti med povečano poškodovanostjo zrnja in povečano hitrostjo sušenja, če smo zrnje ohlajali počasi. Ugotovili smo tudi, da različni hibridi kažejo različne hitrosti sproščanja vode iz zrnja, kar je posledica razlik v sestavi semenskih mešičkov. Sestava semenskih mešičkov kaže največjo odpornost do sproščanja vode, oziroma do oddajanja vodne pare v času sušenja ([2] in [3]). Na temelju predhodnih del številnih avtorjev sta Martins in Stroshine [4] raziskala vpliv vlažnosti koruznega zrnja na hitrost sušenja zrnja. V raziskavi sta za vsak hibrid uporabila tri različne ravni vlažnosti zrnja; za raziskavo sta porabila tri leta. Avtorja sta ugotovila, da so se hibridi obnašali različno v različnih vremenskih razmerah v posameznih letih raziskovanja. Ta ugotovitev je številne druge avtorje vzpodbudila, da so začeli raziskovati in ugotavljati problem “motenj” v hladilniku sušilnice. V raziskavi, ki so jo izvedli Katić in Krička [5] ter Krička in Pliestić [6], so avtorji ugotovili, da koruzno zrnje ob vstopu v hladilnik ni bilo dovolj osušeno in da je bila razlika med vlažnostjo zrnja ob vstopu in izstopu iz hladilnika -3.81%.

Namen številnih nadaljnjih študij je bila tudi določitev razlike v vlažnosti zrn ob izstopu iz hladilnika, saj so raziskave pokazale, da je bila povprečna vlažnost zrnja v silosih 15,50%, medtem ko je v zapisniku osuševalnega postopka povprečna vlažnost znašala 13,50%. Z zapisovanjem podatkov o homogenosti mase v sušilnici so avtorji ugotovili, da so vzorci vsebovali zrnje z 11,0% vlažnostjo, da

tion to being cooled down, the grain is also dried by an additional 1.5% to 2.0%, because in the cooling zone the hot grain comes into contact with the humid air, and there is thermodynamic contact between the two media. The surrounding humid air conducts the heat away from the hot grain and, as a consequence, becomes hotter in the process. At the same time, the two media exchange moisture, with the moisture transfer occurring in both directions. The direction of the transfer of the moisture depends on the partial pressure of the moisture on the grain surface and the pressure of the humid air, because both the grain and the humid air tend to reach a state of thermodynamic equilibrium.

For a number of years Croatia has encountered problems with grain cooling during the drying process in vertical gravity dryers. Significant effects of the cooling speed after the drying of the grain were observed in the early 1970s, and a close correlation was found between increased grain damage and increased cooling speed [1]. It was also observed that when drying at various speeds, there was no correlation between increased grain damage and increased drying speed if a slow cooling speed was used. It was also found that different hybrids exhibit a variety of water-release rates from the grain, resulting from differences in the grain’s pericarp structure. This pericarp structure shows the greatest resistance to the passage of water, i.e., the transfer of water vapour during the drying process ([2] and [3]). Based on the work of a number of authors, Martins and Stroshine (1987) [4] researched the influence of corn-grain moisture on the drying speed of the grain. The research was conducted using three different grain-moisture levels for each hybrid, and took a total of three years. The authors found that the hybrids exhibited different behaviours, depending on the weather conditions for the particular year. This led a number of authors to begin researching and defining the problem of the “disturbance” in the cooler of the dryer. In the research conducted by Katić and Krička (1988) [5] and Krička and Pliestić [6], it was determined that the corn grain was not dry enough when it entered the cooler, and that the difference in the grain’s moisture level between its entering and exiting the cooler was -3.81%.

The aim of numerous studies was also to determine the difference in the moisture levels of the grain as it exited the cooler, because it was found that the average grain moisture level in silo units was 15.50%, whereas it was 13.50% in the drying record books. By keeping records of the homogeny of the mass in the dryer, it was found that samples pa je bilo v masi tudi zrnje, katerega vlažnost se je povzpela na 16,0% ali celo 17%. Z obdelavo podatkov vzorčnih meritev so tudi dokazali, da se je razlika v vlažnosti zrn gibala med -1,25% in -4,35% ([7] do [9]).

Neizenačenost v vlažnosti koruznih zrn ob izstopu iz sušilnice vpliva na mikrobiološke in toksikološke značilnosti zrnja pa tudi na neoporečnost zrnja, ki je potrebna za nadaljnjo predelavo. Nekateri avtorji ([3], [10] do [12]) trdijo, da ima preveč osušeno zrnje (pod 6% vlažnostjo) večji delež proteina zaradi koncentracije suhe snovi, a da to hkrati vodi tudi do zmanjšane prebavljivosti proteina, oziroma do njegovega denaturiranja in zmanjšane topljivosti. Ti avtorji so tudi opozorili, da s povprečno 14% vlažnostjo ni mogoče zagotavljati neoporečnih mikrobioloških in toksikoloških značilnosti mase koruznega zrnja, saj takšna masa vsebuje zrnje z zelo majhno vlažnostjo (do 4,7%) in tudi zrnje z veliko vlažnostjo (do 20,4%).

Z zapisovanjem podatkov o kakovosti koruznega zrnja, skladiščenega po končanem postopku sušenja, ter uporabo zaznaval in mikrobiološke analize smo ugotovili, da zrnje ne ustreza zahtevanim mikrobiološkim kriterijem. To pomeni, da zrnje ni primerno za skladiščenje, saj se je v času skladiščenja kvarilo, na njem pa se je pojavljala plesen; dodati je sicer treba, da se to ni dogajalo z vsemi zrni. Ugotovili smo tudi, da se število pokvarjenih zrn povečuje z daljšanjem dobe skladiščenja. Medtem ko smo ugotavljali, zakaj zrnje ni primerno za skladiščenje, čeprav ima ob izhodu iz sušilnice zadovoljivo vlažnost, smo v hladilnem delu sušilnika opazili določene motnje. Nadaljnja raziskava je pokazala na očitno razliko med povprečno vlažnostjo vzorčnega koruznega zrnja, vzetega z vrha sušilnice, ter zrnja, vzetega iz transporterja. Še večje razlike pa smo ugotovili med posamičnimi zrni, zajetimi vzdolž prereza sušilnice.

Cilj našega dela je bil raziskati in pojasniti pojav, ki se dogaja v hladilniku.

1 MATERIALI IN METODE

Raziskava je potekala ob sušilnih napravah v Republiki Hrvaški, v skladu s “Predpisi za izgradnjo in ocenjevanje sušilnih naprav za kmetijske pridelke” in je trajala pet let. Zahtevane parametre raziskave smo določili z definiranjem vhodne in izhodne energije ter količine vode. Za določitev motenj v hladilniku sušilnice smo

contain grains with 11.0% moisture, but there were also grains with a moisture content as high as 16.0 to 17.0%. Processing the sample-measurement data proved that the differences in the moisture in the grain range from -1.25% to -4.35% ([7] to [9]).

The differences in corn-grain moisture at the exit of the dryer influence the microbiological and toxicological properties of the grain as well as its acceptability for food processing. Some authors ([3], [10] to [12]) claim that an over-dried grain (under 6% moisture) has a larger protein content due to dry-matter concentration, but that this also leads to lower protein digestibility, i.e., its denaturation, and lower solubility. These same authors determined that it is impossible to maintain acceptable microbiological and toxicological properties of the corn-grain mass with an average moisture level of 14%, because such a mass contains grains with moisture levels as low as 4.7% and as high as 20.4%.

By keeping a record of the quality of stored corn grain after drying, using sensory and microbiological analysis, it was found that the grain does not satisfy the required microbiological criteria. This means that the grain is not suitable for storing, and while the grain was being stored it tended to spoil and fungus appeared; however, this was not the case for all grains. The number of spoiled grains was also found to increase with longer storage times. While looking for the reason why the corn grain is not suitable for storage, despite a satisfactory corn-grain moisture level at the exit of the dryer, certain disturbances in the cooling zone of the dryer were found. The investigation revealed a noticeable difference between the average moisture levels of the corn-grain samples taken from the top of the dryer and those taken from the exit transporter. Even larger differences were noticed in certain samples taken along the cut of the dryer.

The aim of our research was to explore and to explain this phenomenon that is taking place in the cooler.

1 MATERIALS AND METHODS

The research was conducted at drying facilities in the Republic of Croatia in accordance with the “Regulations for the construction and evaluation of drying facilities for agricultural products” over a period of five years. The required parameters for the research were set by fixing the quantities of input and output energy and the amount of water. In order to determine the disanalizirali parametre, ki so opisani v naslednjem odstavku.

Da bi prišli do sklepov raziskave vzdolž vodoravnega prereza, smo analizirali temperaturo in vlažnost zrn, ki vstopajo v sušilnico (A). Nato smo ista parametra ocenili vzdolž poševnega prereza pokrova sušilnice na treh točkah – na začetku, v sredini in na koncu – odvisno od lege vetril v sušilnici (B). Ista parametra, temperaturo in vlažnost zrn, smo preverili tudi ob izhodu iz sušilnice (C). Da bi lahko sledili spremembam vzdolž vodoravnega prereza, smo merili tudi temperaturo in relativno vlažnost zunanjega zraka. Da pa smo lahko sledili spremembam vzdolž navpičnega prereza hladilnika v sušilnici, smo določili maso ob vhodu in izhodu iz sušilnice, prav tako pa tudi vlažnost in temperaturo zrn ob vhodu in izhodu iz sušilnice. Določili smo tudi vlažnost in temperaturo zrn ob vhodu in izhodu iz hladilnega dela, pa tudi temperaturo in relativno vlažnost zunanjega zraka. Vzorčno zrnje smo vzdolž prereza sušilnice jemali s posebnimi kleščami.

Vlažnost koruznih zrn smo določili z običajno vzorčno metodo, tj. s sušenjem vzorcev zrn v laboratorijski sušilnici in z uporabo hitrega merilnika vlage (Dickey John GAC 2000). Razmere v okolju – temperaturo in relativno vlažnost zunanjega zraka – smo merili z psihrometrom; hitrost zraka v sušilnici pa smo določili z digitalnim anemometrom. Temperaturo zraka in zrnja v sušilnici smo merili z merilno glavo PT (PT 100 in PT 1000), temperaturo koruznega zrnja zunaj vročega zračnega toka pa smo merili z digitalnim termometrom s toleranco ±0,1°C.

Da bi določili razliko v masi zrnja ob vhodu in izhodu sušilnice, smo uporabili tehnično skalo z natančnostjo razreda A. Vzdolž vodoravnega prereza sušilnice smo vzorce zajemali s posebnimi kleščami. Te vzorce smo vzeli na začetku, v sredini in na koncu pokrova sušilnice. Da bi ugotovili stopnjo enakomernosti osušenih zrn, smo morali zajeti vzorčno zrnje na različnih mestih v hladilniku sušilnice. Vzorce koruznih zrn smo zajeli ob vhodu v sušilnico in tik pod krivino izpustne enote. Da bi preverili delovanje hladilnika vzdolž navpičnega prereza sušilnice in ugotovili mogočo “nepravilnost hladilnika”, smo vzorce zrn zajeli ob vhodu in izhodu iz sušilnice. Upoštevali smo tudi vzorec celotne mase. Izgube zaradi nepravilnosti v

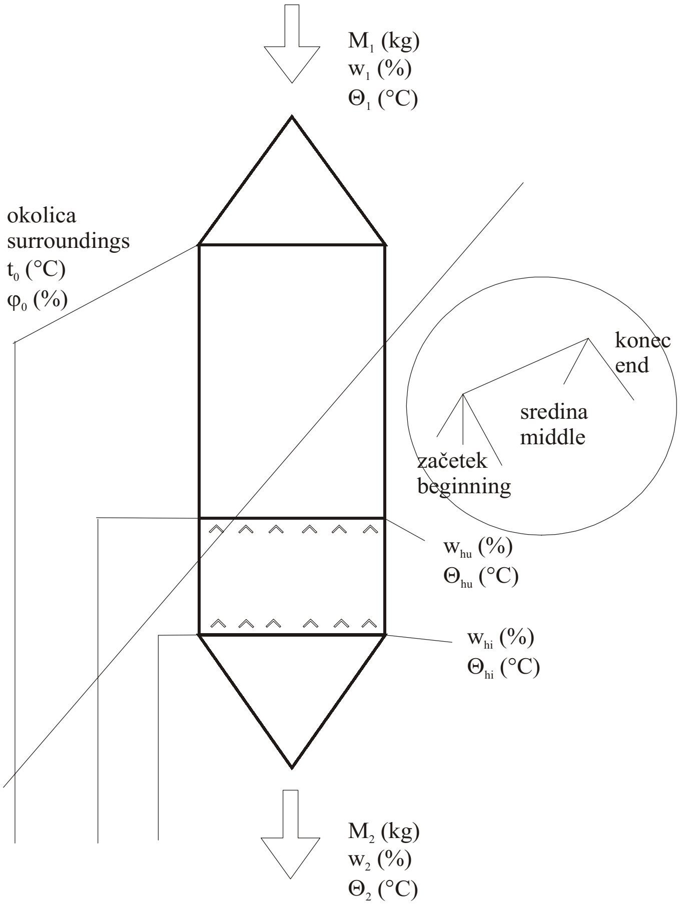
turbances in the cooler of a dryer, the following parameters, described in the next paragraph, were analyzed.

In order to draw conclusions about the horizontal cut, the temperature and the moisture levels of the grains entering the dryer (A) were analyzed. Next, the same parameters were assessed at the diagonal cut of the top at three places – at the beginning, the middle and the end of the top – depending on the locations of the ventilators in the dryer (B). The same parameters, the moisture levels and the temperature of the grains, were taken at the exit of the dryer (C). In order to track changes along the horizontal cut we also measured the temperature and the relative humidity of the surrounding air. In order to track changes along the vertical cut of the cooler in the dryer we fixed the mass at the entrance and at the exit of the dryer, as well as the humidity and the temperature of the grains at the entrance and the exit of the dryer. We also fixed the moisture levels and the temperature of the grains at the entrance and the exit of the cooling zone, as well as the temperature and the relative humidity of the surrounding air. The grain samples from the cut of the dryer were taken using special pliers.

The corn-grain moisture level was determined using the standard etalon method, i.e., by drying the grain samples in a laboratory dryer and using a quick moisture-measuring meter (Dickey John GAC 2000). The environmental conditions – the temperature and the relative humidity of the air surrounding the dryers – were measured with a psychrometer, and the speed of the air in the dryer was determined with a digital anemometer. The temperatures of the air and the grain in the dryer were measured with PT probes (PT 100 and PT 1000), whereas the temperature of the corn grains outside the hot air stream was measured using a digital thermometer with an uncertainty of ±0.1ºC.

In order to determine the difference in the grain mass at the dryer’s entrance and exit we used a technical scale with class “A” precision. Samples were taken from along the horizontal cut of the dryer using special pliers. These samples were taken at the beginning, the middle and the end of the dryer top. In order to determine the uniformity of the dried grains, it was necessary to take samples at various places in the dryer’s cooler. The corn-grain samples were taken at the entrance to the dryer and immediately under the concave discharge. In order to examine the operating of the cooler along the vertical cut of the dryer, and to locate possible “cooler disorder”, the grain samples were taken at the entrance and at the exit of the dryer. An overall sample was also taken. The losses due to irregularities in the process were expressed postopku smo izrazili z razliko med maso ob vstopu v sušilnico in maso ob izhodu iz sušilnice. Slika 1 kaže parametre, ki smo jih upoštevali in mesta, na katerih smo te parametre merili.

using the difference between the dryer-entry mass and the dryer-exit mass. Figure 1 shows which parameters were taken into account and the locations where they were measured.



Legenda:

M_1 (kg/h)	masa koruznega zrnja ob vhodu v sušilnico
M_2 (kg/h)	masa koruznega zrnja ob izhodu iz sušilnice
w_1 (%)	vlažnost koruznega zrnja ob vhodu v sušilnico
θ_1 (°C)	temperatura koruznega zrnja ob vhodu v sušilnico
W_{HU} (%)	masa koruznega zrnja ob izhodu iz sušilnice
θ_{HU} (°C)	temperatura koruznega zrnja ob vhodu v sušilnico
w_{HI} (%)	vlažnost koruznega zrnja ob izhodu iz hladilnega dela sušilnice
θ_{HI} (°C)	temperatura koruznega zrnja ob izhodu iz hladilnega dela sušilnice
w_2 (%)	vlažnost koruznega zrnja ob izhodu iz sušilnice
θ_2 (°C)	temperatura koruznega zrnja ob izhodu iz sušilnice
t_0 (°C)	temperatura zunanjega zraka
φ_0 (%)	relativna vlažnost zraka

Key:

M_1 (kg/h)	corn-grain mass at the entrance to the dryer
M_2 (kg/h)	corn-grain mass at the exit of the dryer
w_1 (%)	corn-grain moisture at the entrance to the dryer
θ_1 (°C)	corn-grain temperature at the entrance of the dryer
W_{HU} (%)	corn-grain mass at the exit of the dryer
θ_{HU} (°C)	corn-grain temperature at the entrance to the dryer
w_{HI} (%)	corn-grain moisture at the exit of the dryer's cooler
θ_{HI} (°C)	corn-grain temperature at the exit of the dryer's cooler
w_2 (%)	corn-grain moisture at the exit of the dryer
θ_2 (°C)	corn-grain temperature at the exit of the dryer
t_0 (°C)	surrounding air temperature
φ_0 (%)	relative air humidity

Sl. 1. *Prikaz merjenih parametrov*
Fig. 1. *Diagram of measured parameters*

2 REZULTATI RAZISKAVE IN RAZPRAVA

2.1 Razprava o rezultatih, pridobljenih vzdolž vodoravnega prereza hladilnika

Preglednica 1 prikazuje meritve, izvedene vzdolž vodoravnega prereza sušilnice; preglednica 2 prikazuje meritve, izvedene na različnih mestih v obdobju petih let in so utemeljene na meritvah iz

2 RESEARCH RESULTS AND DISCUSSION

2.1 Discussion based on the results from the horizontal cut of the cooler

Table 1 shows the measurements taken from along the horizontal cut of the dryer; Table 2 shows the measurements from various locations during the period of five years, based on the measurements

Preglednica 1. *Prikaz meritev vlažnosti glede na čas in mesto analize zrnja vzdolž vodoravnega prereza sušilnice*

Table 1. *Chart of moisture-content measurements with respect to the time and the location of the sample along the horizontal cut of the dryer*

Zaporedna št. meritev		**Izbrani pokrovi sušilnice / Tops**						**w**	**w_r**
No. of measurement		**6**	**5**	**4**	**3**	**2**	**1**	**(%)**	**(%)**
1.	zač/beg	9,3	12,7	7,9	8,8	9,6	9,1	9,8	12,8
	sre/mid	13,5	10,6	7,4	7,0	8,9	14,0		
	kon/end	11,6	7,3	5,2	14,2	10,0	9,9		
2.	zač/beg	11,2	9,6	11,7	9,8	9,6	11,5	10,3	12,1
	sre/mid	11,8	13,0	8,4	9,2	11,7	14,0		
	kon/end	10,3	8,2	5,4	6,9	12,9	11,0		
3.	zač/beg	9,0	12,6	7,4	8,1	9,6	10,1	9,7	11,6
	sre/mid	8,7	9,2	7,4	8,5	9,2	10,9		
	kon/end	8,8	7,6	4,9	5,7	11,1	8,5		
4.	zač/beg	8,2	11,6	8,3	7,3	9,1	10,6	9,2	11,6
	sre/mid	10,8	7,5	9,5	8,3	10,0	9,5		
	kon/end	10,1	9,2	4,7	7,3	12,3	11,7		
5.	zač/beg	9,2	12,9	10,3	9,0	9,9	10,2	9,8	12,4
	sre/mid	14,1	11,1	8,6	8,7	13,2	10,3		
	kon/end	9,6	7,6	5,6	7,9	9,8	8,6		
6.	zač/beg	9,4	14,0	10,3	7,5	8,9	9,3	9,4	12,4
	sre/mid	10,9	12,2	9,1	9,0	11,0	13,1		
	kon/end	8,9	7,3	5,1	6,6	9,9	8,5		
7.	zač/beg	8,5	10,7	8,0	9,5	9,1	9,9	8,7	12,3
	sre/mid	8,5	9,7	8,5	7,9	10,0	10,3		
	kon/end	7,6	7,3	4,5	6,0	10,3	9,9		
8.	zač/beg	8,9	11,2	9,1	8,8	10,2	10,4	10,4	13,4
	sre/mid	11,6	13,5	10,4	8,5	10,3	12,8		
	kon/end	8,9	9,2	6,0	8,9	14,1	14,5		
Povp. na pokrovu Average per top	zač/beg	9,21	11,91	9,13	8,60	9,50	10,14		
	sre/mid	11,24	10,85	8,66	8,39	10,53	11,86		
	kon/end	9,46	7,96	5,18	7,98	11,30	10,33		
NKO LSD	zač/beg	n.s.	n.s.	n.s.	n.s.	n.s.	*		
	sre/mid	n.s.	n.s.	n.s.	**	**	*		
	kon/end	n.s.	**	n.s.	**	**	n.s.		
Seštevek vseh meritev Total of all measurements		**(n = 144) 9,55 (n = 8) x = 12,36**							

Legenda:

w (%) povprečna vsebnost vlage vzdolž prereza

w_r (%) vlažnost na transporterju

NKO najmanjše kvadratno odstopanje, odstopanje rezultatov meritev na vzorcih iz različnih točk vzdolž vsakega pokrova

* označuje pomembnost pri 5% verjetnosti, kakor to določa test F

** označuje pomembnost pri 1% verjetnosti, kakor to določa test F

Key:

w (%) average moisture content along the cut

w_r (%) moisture on the exit transporter

LSD least-square deviation, deviation of the results obtained for different points along each top

* denotes significance at the 5% level of probability, as determined by the F test

** denotes significance at the 1% level of probability, as determent by the F test

Preglednica 2. *Povprečne vrednosti vlažnosti koruznega zrnja in njegove temperature, pridobljene v petih letih*

Table 2. *Average values of the corn-grain moisture content and the corn-grain temperature sampling conducted over the five-year period*

Leto raziskave Year of research	**Vzorec Sample**	**Povprečna vrednost Average value**		**Razpon vsebnosti vlage Range of moisture content w**			**t_o (°C)**	**φ_o (%)**
		w (%)	**θ (°C)**	**min (%)**	**max (%)**	**Δw (%)**		
1	A	29,80	9,32	25,70	32,70			
	B	9,55	12,70	4,50	14,50	10,0		
	C	12,36	11,30	11,60	13,40		4,6	81,30
2	A	34,45	14,50	33,10	36,70			
	B	12,27	13,10	9,40	15,00	5,6		
	C	14,34	12,20	13,86	14,55		3,2	80,60
3	A	33,48	5,03	28,79	35,71			
	B	11,20	21,18	8,20	16,20	8,0		
	C	12,74	15,48	11,50	14,00		-0,2	92,50
4	A	35,10	19,6	32,80	36,59			
	B	9,13	25,5	8,20	14,02	5,82		
	C	13,47	25,2	12,00	14,75		19,3	83,70
5	A	33,31	19,46	31,40	34,92			
	B	7,90	26,91	5,50	9,58	4,08		
	C	13,75	26,10	12,80	14,95		19,7	82,90

Legenda:
A zrnje ob vstopu v sušilnico*
B zrnje ob vodoravnem preseku sušilnice**
C zrnje tik pred krivino izpustne enote*
* povprečna vrednost predstavlja 8 posamičnih meritev za w in 8 meritev za q
** povprečna vrednost predstavlja 144 posamičnih meritev za w in 144 meritev za θ

Key:
A grain entering the dryer *
B grain at the horizontal cut of the dryer **
C grain immediately before the concave discharge*
* one average represents 8 separate measurements for w and 8 for q
** one average represents 144 separate measurements for w and 144 for θ

preglednice 1. Preglednica 2 navaja povprečno vlažnost zrnja in temperaturo ob vhodu v sušilnico, pa tudi njune vrednosti, dobljene vzdolž vodoravnega prereza sušilnice in tik pred krivino izpustne enote. Preglednica 2 prikazuje tudi razpon od najmanjše do največje vlažnosti zrnja.

Rezultati meritev kažejo, da je v povprečju pod pokrovi 3, 4 in 5 največja vsebnost vlage zrnja ugotovljena ob začetku pokrovov, pod pokrovoma 1 in 6 pa je bila največja vsebnost vlage ugotovljena na sredini. Mesto ob koncu pokrova 2 je imelo največjo vsebnost vlage. Če opazujemo razlike med povprečnimi vrednostmi vlage pod posameznimi pokrovi, tj. med vzorčnimi zrni, zajetimi na začetku, sredini in koncu pokrova, lahko povzamemo, da so največje razlike v vsebnosti vlage v vzorcih, zajetih na začetku in koncu ugotovljene pod pokrovi 2, 3, 4 in 5, medtem ko je pri pokrovih 1 in 6 največja razlika v vsebnosti vlage ugotovljena med vzorci, zajetimi

shown in Table 1. The table shows the average grain humidity and the temperature at the entrance to the dryer, as well as those along the horizontal cut of the dryer and immediately before the concave discharge. The table also shows the range of the minimum and maximum grain-moisture content.

The results indicate that, on average, for tops 3, 4 and 5 the highest moisture content was found at the beginning of the tops, whereas with tops 1 and 6 the highest moisture content was, on average, detected in the middle. The end of top 2 had the highest moisture content. If we observe the differences between the average moisture values inside a single top, i.e., between the grain samples taken from the beginning, the middle and the end of a top, we can conclude that the largest differences in grain-moisture content between the samples taken at the beginning and the end of a top are found for tops 2, 3, 4 and 5, whereas tops 1 and 6 exhibit the na začetku in na sredini. Največja povprečna razlika v vsebnosti vlage, tj. 3,99%, je bila ugotovljena pod pokrovom 5, najmanjša povprečna razlika, tj. 0,62%, pa pod pokrovom 3.

Obdelava statističnih podatkov (enosmerna analiza) je pokazala na statistično pomembno razliko v vsebnosti vlage v vzorčnih zrnih, vzetih na začetku, sredini in koncu posameznega pokrova. V primeru vzorcev izpod pokrovov 1 in 3 nismo ugotovili statistično pomembnih razlik v vsebnosti vlage; pač pa smo našli pomembne razlike pri zrnih, zajetih izpod pokrovov 2, 4, 5, in 6. Statistično pomembno razliko v vsebnosti vlage smo ugotovili med vzorci, vzetimi na začetku in koncu pokrova 2, in sicer z 1-odstotno toleranco. Pri pokrovu 4 smo opazili statistično pomembno razliko v vsebnosti vlage med vzorci, vzetimi s sredine in s konca, in sicer z 1-odstotno toleranco. Enake rezultate z enako toleranco smo ugotovili tudi pod pokrovom 5, pod pokrovom 6 pa smo s 5-odstotno toleranco ugotovili pomembno razliko med vzorci, vzetimi na začetku in koncu, pa tudi med vzorci, vzetimi s sredine in konca.

Preglednica 2 vsebuje povprečja vsebnosti vlage in temperature koruznega zrnja vzdolž vodoravnega prereza hladilnika sušilnice in okoliškega zraka na vseh mestih zajema vzorcev v obdobju petih let. Očitno je, da se je največja razlika v vsebnosti vlage v zrnju (10,0%) vzdolž vodoravnega prereza sušilnice pojavila v prvem letu, čeravno smo tega leta izmerili tudi najnižjo povprečno vsebnost vlage (29,80%). Najmanjšo razliko v vsebnosti vlage v zrnju (4,08%) vzdolž vodoravnega prereza sušilnice smo opazili v zadnjem letu naše raziskave.

Očitno je tudi, da v nobenem letu zrnje ni bilo zadovoljivo ohlajeno, kar pomeni, da je temperatura zrnja ob izhodu iz hladilnika presegala dovoljeno razliko 5°C, tj. največjo dovoljeno temperaturno razliko med zrnjem in zunanjim zrakom. Ta razlika je bila največja v tretjem letu raziskave (15,68%).

To leto je bilo tudi najbolj mrzlo, kar povejo podatki temperature zunanjega zraka; za to leto je bila značilna tudi največja povprečna relativna vlažnost zraka (92,50%). Preglednica 2 prikazuje tudi razliko v povprečni vsebnosti vlage v zrnju tik pred krivino izpustne enote. Največjo povprečno vlažnost smo opazili v drugem letu raziskave pri vzorcih, zajetih tik pred krivino izpustne enote (14,34%), najnižjo vlažnost pa smo opazili v prvem letu raziskave pri vzorcih, zajetih tik pred krivino izpustne enote (12,36%).

largest moisture-content difference between the grain samples taken at the beginning and the middle of the top. The biggest average difference in grain moisture, i.e. 3.99%, was found for top 5, and the smallest average difference was found for top 3, i.e. 0.62%.

The statistical data processing (uni-directional variant analysis) showed a statistically significant difference in the moisture content of the corn-grain samples taken from the beginning, the middle and the end of a single top. No statistically significant difference in the moisture content was observed for the place where the samples were taken for the samples from tops 1 and 3. However, a significant difference was found for tops 2, 4, 5 and 6. A statistically justified difference in the grain moisture content between the samples taken at the beginning and the end was found at top 2, with an uncertainty of 1%. Top 4 showed a statistically significant difference in grain moisture content between the samples taken from the middle and the end of the top, with an uncertainty of 1%. The same results with the same error were found for top 5, whereas top 6 showed a significant difference between samples taken at the beginning and the end, as well as between the samples taken from the middle and the end, with an uncertainty of 5%.

Table 2 contains the corn-grain moisture content and temperature averages along the horizontal cut of the dryer's cooler and the surrounding air at all locations during the period of five years. It is clear that the biggest difference in the grain moisture content (10.0%) along the horizontal cut of the dryer appears in the first year, although we measured the lowest average grain moisture content (29.80%). The least difference in grain moisture content (4.08%) along the horizontal cut of the dryer was observed during the last year of the study.

It is also clear that in none of the years were the grains cooled sufficiently, which means that the grain temperature at the exit of the cooler was higher than the allowed 5°C difference, i.e., the maximum temperature difference allowed between the grain and the surrounding air. This difference was the largest in the third year of the study (15.68%).

This year was also the coldest, as can be seen from the air-temperature data; it also had the highest average relative air humidity (92.50%). In addition, table 2 shows the difference in average grain moisture content immediately before the concave discharge. The highest average humidity was observed during the second year of the study in the samples taken immediately before the concave discharge (14.34%), whereas the lowest humidity was observed in the first year of the study in the samples taken immediately before the concave discharge (12.36%).

Po postopku ohlajanja v hladilniku je toplo zrnje ohlajeno in dodatno osušeno za 1,5% do 2,0%. A v primerih, ko sta postopka izmenjave energije in snovi motena in ko se zrnje v hladilniku navlaži, govorimo o »motnji v hladilniku«.

Vemo, da se v nekaterih sušilnicah zrnje vzdolž vodoravnega prereza stolpa osuši neenakomerno, tako da se vlažnost nekaterih zrn ob izhodu iz sušilnice razlikuje od vlažnosti celotne mase, kar pa ni posledica neenakomernega sušenja nekaterih hibridov zaradi njihove morfologije ali neenakomernega sušenja, povezanega z različnimi vstopnimi vsebnostmi vlage v zrnju, na kar so opozorili Martins in Stroshine, [4] ter Bratko, [10]. Ta pojav (neobičajno obnašanje koruznega zrnja v času skladiščenja) lahko razložimo z absorpcijsko izotermo, ki je značilna za žitarice. Zrnje, ki se je po končanem postopku osuševanja spet navlažilo, spremeni svojo absorpcijsko izotermo. Ta sprememba nastane zaradi nepovratnih sprememb v strukturi zrnja in vodi v histerezo, ki ustvarja 1,5 do 2,0-odstotno razliko v vlažnosti zrn.

Vse te spremembe so pravzaprav posledica slabe gradnje stolpa sušilnice in transportnih elementov. Kolikor vemo, doslej podobnih raziskav še ni bilo in zato ne moremo primerjati rezultatov naše študije z ustreznimi rezultati predhodnih študij.

2.2 Razprava o rezultatih, pridobljenih vzdolž navpičnega prereza hladilnika

Preglednica 3 vsebuje pregled meritev "motenj v hladilniku", pridobljenih v času petletne raziskave.

Preglednica 3 vsebuje povprečja »motenj v hladilniku« v času petletne študije sušilnice. Podatki nazorno kažejo, da se je temperatura zrnja v hladilniku znižala, pa tudi, da se je zrnje med postopkom ohlajanja dodatno navlažilo, namesto da bi izgubilo del svoje vlažnosti. Količino vlage,

The warm grain, after the process of drying, is both cooled and additionally dried in the cooler by 1.5% to 2.0%. However, when the processes of exchange of energy and matter are disturbed, and the grain in the cooler acquires moisture, "a cooler disturbance" occurred.

It was observed that some dryers dry the grain unevenly along the horizontal cut of the tower, so the grain moisture in some samples at the exit of the dryer differs from the overall sample, which does not result from the uneven drying of some hybrids because of their morphology, or unevenness in drying as a result of different input grain moisture, as noticed by Martins and Stroshine, (1987) [4] and Bratko, (1990) [10]. This phenomenon (the unusual behaviour of the corn grain during storage) can be explained based on the sorption isotherm common to cereal. The grain that became moist again after drying changes its sorption isotherm. This change occurs as result of irreversible changes in the grain structure, which results in hysteresis, producing the moisture difference of 1.5–2.0%.

All these changes actually result from bad construction of the tower of the dryer and the transporting elements. As far as we are aware, similar research has not so far been conducted, so we were unable to compare the results from this study with the relevant results from the previous studies.

2.2 Results and discussion based on measurements from the vertical cut of the cooler

Table 3 contains a chart of measurements of "cooler disturbances" obtained during the five-year study.

Table 3 contains averages of the "cooler disturbances" during the five-year period of the study of the dryers. The data clearly indicate that the grain temperature in the cooler decreased, but the data also indicate that the grain acquired additional moisture during the process of cooling, instead of losing an additional

Preglednica 3. *Povprečja "motenj v hladilniku" za čas petletnega študija sušilnice*
Table 3. *"Cooler disturbance" averages in the five-year study of dryers*

Leto raziskave Year of research	**M_1 (kg/h)**	**M_2 (kg/h)**	**w_1 (%)**	**θ_1 (°C)**	**w_{HU} (%)**	**θ_{HU} (°C)**	**w_{HI} (%)**	**θ_{HI} (°C)**	**w_2 (%)**	**θ_2 (°C)**	**t_0 (°C)**	**φ_0 (°C)**
1	24.937	20.508	31,71	37,45	10,58	75,82	11,23	27,19	12,90	21,1	23,0	62,70
2	42.832	36.200	26,37	18,67	10,81	46,75	12,04	18,79	12,88	18,67	5,5	92,5
3	21.522	17.953	29,32	20,24	10,10	73,60	11,73	27,65	11,78	27,20	15,5	74,3
4	27.160	21.996	34,45	14,50	12,94	48,00	14,28	4,40	14,34	12,20	3,2	80,6
5	41.405	33.330	33,88	10,0	12,33	53,70	13,40	20,70	12,74	21,18	-1,0	92,5

ki jo zrnje absorbira v hladilniku, lahko izračunamo na podlagi razlike vsebnosti vlage v zrnju ob vhodu v hladilnik in izhodu iz hladilnika; ta razlika pa je posledica nepravilnega vodenja osuševalnega postopka. Preglednica 4 vsebuje podatke, ki kažejo izgube ugotovljene v petletnem obdobju raziskave na sušilnih napravah. Preglednica pokaže, da je do največje izgube (Δw, kg/dan) prišlo v drugem letu raziskave (-20163,9 kg/dan), najmanjšo izgubo pa smo opazili v zadnjem letu raziskave (-3740,9 kg/dan). Poleg zmanjšane zmogljivosti sušilnice, vključene v raziskavo, smo ugotovili tudi povečano porabo goriva. Preglednica 5 vsebuje podatke o urnem povečanju porabe goriva, pa tudi o povečanju stroškov, ki so ga povzročile “motnje v hladilniku”.

Za osušitev 100 kilogramov koruznega zrnja je potrebno 3,5 kilogramov goriva, čigar trenutna cena na Hrvaškem je €0,73 za liter, oziroma €0,93 za kg [13]. Podatki v preglednici 5 kažejo, da je do največje finančne izgube prišlo v drugem letu raziskave, torej v letu največjih »motenj v hladilniku«. To je povsem razumljivo, saj zmnožek povečane izgube in cene goriva pokaže tudi povečano finančno izgubo.

amount of moisture. The amount of moisture the grain absorbs in the cooler can be calculated from the difference in the corn-grain moisture content at the entrance to the cooler and at the exit of the cooler; this difference is the consequence of irregular management of the drying process. Table 4 contains data showing the losses determined during the five-year period of the research on the drying facilities. The table indicates that the biggest loss (Δw, kg/day) occurred during the second year of the study (-20163,9 kg/day), whereas the smallest loss was observed in the final year of the study (-3740,9 kg/day). As well as a capacity decrease for the dryers included in this research, the fuel consumption was found to increase. Table 5 contains data on the increased hourly fuel consumption, as well as on the higher costs resulting from “cooler disturbances”.

Drying 100 kilograms of corn requires 3.5 kilograms of fuel. This fuel is currently priced at €0.73/l in Croatia, i.e., €0.93/kg [13]. The data in table 5 indicate that the biggest financial loss occurred in the second year of the study, in the same year that the “cooler disturbance” was the largest. This can be easily explained, the greater loss multiplied by the price of fuel results in a greater financial loss.

Preglednica 4. *Količina absorbirane vode v koruznem zrnju v času ohlajanja*
Table 4. *Amount of re-hydrated water in the corn grain during the cooling process*

Leto raziskave Year of research	**Δw_h (%)**	**Δw (kg/h)**	**Δw (kg/day)**
1	-0,65	-532,08	-12,769,9
2	-1,23	-840,16	-20,163,9
3	-1,63	-335,49	-8,051,8
4	-1,34	-353,71	-8,489,0
5	-1,07	-155,87	-3,740,9

Preglednica 5. *Poraba goriva (izgube), prikazana s količinami in stroški, ki so posledica rehidracije koruznega zrnja v času ohlajanja*
Table 5. *Fuel consumption (losses), shown with the quantities and costs resulting from corn-grain rehydration during the cooling process*

Leto raziskave Year of research	**Povečana poraba goriva / Increased fuel consumption**			
	Količine / Quantities		**Stroški / Costs**	
	(kg/h)	**(kg/day)**	**(€/h)**	**(€/day)**
1	18,62	446,9	17,76	423,18
2	29,41	705,9	27,85	668,43
3	11,74	281,8	11,12	266,84
4	12,38	297,1	11,72	281,33
5	5,46	131,0	5,17	124,05

Če si predstavljamo, da zunanji zrak ohlaja koruzno zrnje, potem razumemo, da je celotna površina zrnja mejna plast, na kateri se tlak vodne pare stabilizira. Na to mejno plast in stabiliziran tlak vplivajo značilnosti notranjega dela zrnja, ki mora vrhnjo plast oskrbeti z zadostno količino vode, kadar ta izpareva s površine. Toda pot vode iz notranjosti proti površini je težka, zato mejna plast zrnja ne dobiva zadovoljive oskrbe z vodo iz notranjosti, saj se voda giblje skozi celične membrane s pomočjo kapilarnih sil, termodifuzije in osmoze. Površina zrnja je zato slabo oskrbljena z vodo, kar pomeni, da je vlaga na površini zrnja nižja od vlage v njegovem jedru.

Tako je, na primer, vsebnost vlage v jedru zrnja 14% pri temperaturi 25°C in tlaku vodne pare 2216 Pa. Hkrati pa je vlažnost mejne plasti 10%, njena temperatura 15°C, tlak vodne pare pa zgolj 618 Pa. Kadar je temperatura zunanjega zraka 10°C, njegova vlažnost 90% in je tlak vodne pare v zraku 1104 Pa, voda iz zraka preide na zrnje zaradi razlike med tlakom zrnja in tlakom zraka, kar pomeni, da se zrnje navlaži.

Če celotni postopek opazujemo na diagramu *h-x*, opazimo, da ima zrak, ki zapušča hladilnik, manjšo vsebnost vode kakor zunanji zrak ter da je absolutna vsebnost vlage v zraku večja ob vhodu v sušilnico kakor ob izhodu iz nje. Zanimivo je dejstvo, da je zrak, ki zapušča hladilnik, toplejši od zraka, ki vstopa v hladilnik. Osuševanje zraka je povzročilo zmanjšanje njegove specifične toplotne kapacitete in tako je, kljub prenosu energije v postopku kondenzacije vode na zrnju, preostala energija povečala temperaturo zraka. Če primerjamo rezultate, ki smo jih dosegli med petletno raziskavo, z rezultati, ki so jih pridobili drugi avtorji, je očitno, da so naši izsledki primerljivi z doslej objavljenimi tovrstnimi podatki.

3 SKLEP

Na podlagi petletne raziskave “motenj v hladilniku” navpične gravitacijske sušilnice, lahko naredimo naslednje sklepe:

Pojav “motenj” v hladilniku moramo opazovati na dva načina:

- vzdolž navpičnega prereza sušilnice,
- vzdolž vodoravnega prereza sušilnice.

1. “Motnje v hladilniku” lahko definiramo kot pojav v predelu za ohlajevanje, ki povzroča, da se osušeno zrnje navlaži, oziroma rehidrira med

If we think of a corn grain being cooled by the surrounding air, then the whole of its surface can be thought of as a boundary layer where the water vapour pressure stabilizes. This boundary layer and the stabilized pressure are influenced by the properties of the inner part of the grain, which has to supply the surface with a sufficient amount of water, if water evaporates from the surface. However, movement of the water from the inner part towards the surface is difficult, and so the boundary layer does not have an adequate supply of water from the inner part because water moves through the cell membranes by means of capillary forces, thermo-diffusion and osmosis. The surface of the grain is, as a result, poorly supplied with water, which means that the grain’s moisture on the surface is lower than the moisture in the centre.

For instance, the centre of the grain has a moisture content of 14% when the temperature is 25ºC and the water vapour pressure is 2216 Pa. At the same time the boundary layer’s moisture content is 10%, with a temperature of 15ºC and a water vapour pressure of only 618 Pa. If the surrounding air temperature is 10ºC and the air humidity is 90% with the water vapour pressure in the air equal to 1104 Pa, water from the air will move into the grain because of the pressure difference between the grain and the air, i.e., the grain will get moist.

If the whole process is observed on an h-x diagram we can see that the air leaving the cooler has lower water content than the surrounding air, and the absolute air humidity content is higher at the entrance to the dryer than at the exit. It is interesting to note that the air exiting the cooler is warmer than the air entering the cooler. Drying the air reduced its specific warmth capacity, so although the energy was transferred in the process of water condensation on the grain, the remaining energy raised the air temperature. If we compare the results obtained in the five-year study with the results obtained by other authors, it is clear that the results are significant in terms of the results from other references.

3 CONCLUSION

Based on a five-year study of “cooler disturbance” in a vertical gravity dryer the following conclusions can be drawn:

The phenomenon of “cooler disturbance” must be observed in two ways:

- along the vertical cut of the dryer,
- along the horizontal cut of the dryer.

1. “Cooler disturbance” can be defined as a phenomenon in the cooling zone resulting in the dried grain becoming moister or re-hydrated in the dryer

postopkom ohlajevanja v sušilnici.

2. Pojav "motenj v hladilniku" vzdolž vodoravnega prereza sušilnice povzroča širok razpon vsebnosti vlage v koruznem zrnju, kar nadalje povzroča kvarjenje zrnja v času skladiščenja in znižanje njegove hranljivosti.
3. "Motnje v hladilniku" vzdolž navpičnega prereza sušilnice povzročajo zmanjšanje kapacitete sušilnice in povečanje porabe goriva. Posledica tega pa je zmanjšana finančna učinkovitost sušilnice.
4. "Motnjam v hladilniku" vzdolž vodoravnega prereza sušilnice se lahko izognemo s pravilno gradnjo stolpa sušilnice, ki naj ima primerno velikost pokrovov, primerno hitrost zraka in pravilno zgrajeno in prilagojeno krivino izpustne enote ob izhodu iz sušilnice.
5. "Motnjam v hladilniku" vzdolž navpičnega prereza sušilnice se lahko izognemo s pravilnim uravnavanjem delovanja sušilnice, tako da je vlažnost koruznega zrnja ob vhodu v sušilnico večja od vlažnosti pri higroskopični izravnavi ter da je razlika med tlaki v komorah sušilnice pravilno uravnana.

during the process of cooling.

2. The phenomenon of "cooler disturbance" along the horizontal cut of the dryer results in a wide range of corn-grain moisture contents, which finally results in spoiling of the grain during storage and a reduction in its nutritious properties.
3. "Cooler disturbance" along the vertical cut of the dryer results in a reduction of the dryer's capacity and an increased fuel consumption. As a result, the financial effectiveness of the dryer is reduced.
4. "Cooler disturbance" along the horizontal cut of the dryer can be avoided by correctly constructing the dryer tower, having a suitable size for the tops, an appropriate air speed, as well as a correctly constructed and adjusted concave discharge at the exit of the dryer.
5. The phenomenon of "cooler disturbance" along the vertical cut of the dryer can be avoided by regular adjustment of the dryer's operation, so that the corn grains have a higher humidity than hygroscopic balance when entering the cooler and that the pressure difference between the pressure of the chambers of the dryer is correctly adjusted.

4 LITERATURA
4 REFERENCES

[1] Katić, Z. (1971) Utjecaj brzine hladjenja zrna kukuruza nakon sušenja na kvalitet zrna i mogućnost povećanja kapaciteta sušara. Dissertation. *Faculty of Agriculture University of Zagreb*, Zagreb.

[2] Katić, Z. (1985) Istodobno sušenje kukuruznog zrna raznih sorata i hibrida različite vlage na početku sušenja. *Symposium Proceedings. I International Symposium of Technologists for Drying and Storing*, Stubičke Toplice. 86 – 104.

[3] Jukic, Ž., T. Krička, N. Voća, S. Voća (2002) Technological procedure of perforating as factor of drying speed, *Proc. of the 1^{st} Int. conf. "Energy – Saving Technologies for Drying and Hygrothermal Processing"*, Moscow, Russia, 104-108.

[4] Martins, J.H., R.L. Stroshine (1987) Difference in drying efficiencies among corn hybrids dried in a high-temperature column batch dryer, *ASAE Paper No. 87-6559*, St. Joseph, MI 49085.

[5] Katić, Z., T. Krička (1988) Procesi u hladnjaku sušare. *Symposium Proceedings. IV International Symposium of Technologists for Drying and Storing.* Stubičke Toplice, 93 – 109.

[6] Krička, T., S. Pliestić (1994) Primjena brzine sušenja zrna kukuruza u zavisnosti o hibridu. *Agronomski glasnik 6/1994*, Zagreb.

[7] Čuhnil, Z. (1988) Neujednačenost izlaznih vlažnosti zrna iz vertikalne sušare - iskustvo PIK-a "Garešnica". *Symposium Proceedings. IV International Symposium of Technologists for Drying and Storing. Stubičke Toplice*, 282 – 290.

[8] Nemeny, M., I. Czaba, A. Kovacs Pannon, I. Farkas (1994) Drying characteristics of maize hybrids components. *Hungarian Agricultural Engineering.* No. 7, 40 – 41.

[9] Krička, T., S. Pliestić, N. Dobričević, Z. Katić (1999) The rehidration of maize kernels on cooler zone. *Symposium Proceedings. XV International Symposium of Technologists for Drying and Storing,* Stubičke Toplice, 1 – 11.

[10] Bratko, J. (1990) Neujednačenost vlage zrna kukuruza na izlazu iz sušare. *Symposium Proceedings. VI International Symposium of Technologists for Drying and Storing*. Tuheljske Toplice, 108 – 116.
[11] Katić, Z. (Ed.) (1997) Sušenje i sušare u poljoprivredi, *Multigraf doo*. Zagreb.
[12] Krička, T., N. Voća, Z. Jukić (2001) Technological and nutritional characteristics of kernel of maize exposed to "cooking treatment". *Czech Journal of Animal Science.* 46 (5), 213 – 216.
[13] Krička, T. (1997) PROHES, National Energy Programme. *Energy Institut "Hrvoje Požar",* Zagreb.

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Pregled tehnologije brizganja prašnatih materialov

Overview of the Powder Injection Moulding Technology

Boštjan Berginc - Karl Kuzman

V prispevku je narejen pregled tehnologije brizganja prahu. Opisane so postopkovne in oblikovne omejitve, konkurenčne tehnologije in tržne niše ter znane uporabe. Po tem postopku je mogoča izdelava zelo zapletenih izdelkov, mikro- in dvokomponentnih izdelkov, mogoča pa je tudi razširitev tehnologije na področje termopreoblikovanja in pihanja, kjer ta tehnologija ni tako uveljavljena. Predstavljene so mehanske lastnosti izdelkov in njihova odvisnost od parametrov postopka, kemične strukture delcev in nekaterih metalurških spremenljivk.

Prikazana je tudi stroškovna analiza tehnologije brizganja prahov in odrezovanja z velikimi hitrostmi, iz katere je razvidno področje uporabnosti posamezne tehnologije

Prispevek je namenjen predvsem načrtovalcem novih izdelkov, ki bodo v svoje delo vključevali tudi to tehnologijo in vsem tistim posameznikom in podjetjem, ki se s to tehnologijo še niso srečali.

(Ključne besede: brizganje prahu, pregledi tehnologij, omejitve, analize stroškov)

In this paper an overview of the powder injection moulding (PIM) process has been made. In the paper the process and shape restraints, alternative technologies, market niche and existing applications of the technology are described. Using PIM it is possible to produce highly complicated, micro and two-component parts. The mixtures used for PIM can also be used for thermoforming and blow moulding. In this paper are also presented the mechanical properties of the manufactured components and their dependence on the process parameters, chemical structure of powders and some metallurgic variables. Furthermore, the cost analysis comparison between the PIM and high speed cutting (HSC) is made.

This paper is meant for the designers of new parts, who would like tp apply this technology and for certain individuals and companies who haven't come across this technology yet.

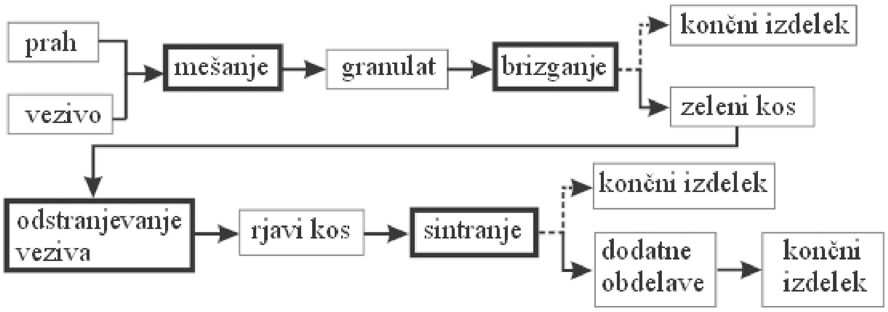
(Keywords: powder injection moulding, overview, restraints, cost analysis)

0 UVOD

V poplavi tehnologij, ki se pojavljajo na trgu, morajo biti podjetja oz. posamezniki previdni pri izbiri prave tehnologije za izdelavo določenega izdelka. Vsaka tehnologija ima svoje prednosti in seveda tudi pomanjkljivosti v primerjavi s konkurenčnimi tehnologijami. Tako so nekatere primernejše za manjše serije zahtevnih izdelkov, druge pa za velike serije manj zahtevnih izdelkov. Zgodovina tehnologije brizganja prahov sega v trideseta leta dvajsetega stoletja, ko je Schwartzwalder izdelal prve izdelke iz keramike po tehnologiji brizganja prahov ([1] in [2]). Zaradi patentov se je, do 90. let, razvijala le počasi. Danes pa je to tehnologija, ki lahko na področju velikih serij, majhnih in zahtevnih izdelkov konkurira oz. prevladuje nad drugimi tehnologijami. Možnost predelave velikega števila materialov, možnost reproduciranja detajlov (Near Net Shape oz. Net Shape) in dobre mehanske lastnosti izdelkov so glavne prednosti te tehnologije.

1 TEHNOLOGIJA IN TEHNOLOGIČNOST

Postopek izdelave z brizganjem prašnatih materialov (BPM - angl. powder injection molding), je kombinacija tehnologij injekcijskega brizganja polimerov in stiskanja prahov. Pri tem postopku se



Sl. 1. *Faze tehnologije brizganja prašnatih materialov*

mešanico veziva in trdnih prašnatih delcev vbrizgne v kalupno votlino orodja. Mešanica zavzame obliko kalupnih votlin in po strditvi nastane “zeleni” kos z omejenimi mehanskimi lastnostmi, v nekaterih primerih pomeni to že končni izdelek (plastomagneti). Iz zelenega kosa se nato odstranjuje vezivo s postopki kemične in/ali toplotne obdelave. Pri tem nastane “rjavi” kos, ki vsebuje majhen delež veziva (» 3%) in je zelo krhek. Rjavi kos se nato sintra v peči, kjer (pri)dobi končne izmere in mehanske lastnosti. Pri sintranju se pojavijo, na račun povečevanja gostote, veliki skrčki 15 do 25%, kar otežuje doseganje ozkih toleranc. Izdelek se po potrebi mehansko ali toplotno obdela. Na sliki 1 je prikazana celotna veriga postopka.

Z brizganjem prahov se lahko predeluje veliko materialov: jekla (nerjavno jeklo, hitrorezno jeklo itn.), železove zlitine (Fe-Ni, Fe-Si, Fe-Mo), preostale zlitine (inconel, niobijeve, bakrove, volframove težke zlitine itn.), titan, zlato, nikelj, karbidne trdine, oksidi (Al_2O_3, ZrO_2, CeO_2 itn.), kermeti itn. ([1], [3] in [4]). Velikost keramičnih delcev je <1 mm, za kovine je značilna velikost delcev od 15 do 30 mm, za izdelavo magnetov pa se uporabljajo delci večji od 250 mm.

S tehnologijo brizganja prahov, se lahko izdelujejo mikro izdelki, dvokomponentni izdelki, mogoča pa je tudi izdelava s pihanjem in termopreoblikovanjem [5]. Sestavljanje izdelkov iz dveh materialov je mogoče že v orodju ali pa z združitvijo dveh zelenih kosov. Pri dvokomponentnih izdelkih je potrebno, da imata materiala približno enako toplotno razteznost, podobne zgoščevalne lastnosti med sintranjem, enako velikost in obliko delcev ter da izkazujeta dobre povezovalne lastnosti med delci. Poleg lastnosti prašnatih delcev pa so zelo pomembni tudi parametri postopka. Najpomembnejša je začetna faza sintranja, ko so vezi med delci šibke in se morajo zgoraj navedene lastnosti najbolj ujemati ([6] in [7]). Dvokomponentni izdelek bi lahko bil izdelan iz magnetnega in nemagnetnega materiala ali pa bi bila površina izdelka iz obrabno odpornejšega, dražjega materiala, jedro pa iz cenejšega materiala ([1] in [8]).

Mehanske lastnosti izdelkov, izdelanih z brizganjem prahov, so v večini primerov enake oziroma zaradi možnosti nadzora mikrostrukture, celo boljše od mehanskih lastnosti izdelkov, narejenih iz surovcev. Mehanske lastnosti sintranih materialov so odvisne od poroznosti, vključkov, nečistoč, gostote po sintranju, velikosti zrn, oblike in velikosti por ter drugih metalurških spremenljivk ([3] in [9]). Na mehanske lastnosti in mikrostrukturo jekel in železovih zlitin močno vpliva tudi delež ogljika, ki nastane zaradi degradacije veziv pri sintranju [10]. Ker so mehanske lastnosti izdelkov, narejenih z brizganjem prahov, odvisne od številnih dejavnikov, prihaja do odstopanj. Zato je verjetnost porušitve materiala pri določeni obremenitvi podana z naslednjo enačbo:

$$P(\sigma)=1-e^{\left[-\left(\frac{\sigma}{\sigma_0}\right)^M\right]} \qquad (1).$$

P(σ) pomeni verjetnost porušitve pri obremenitvi σ, σ_0 je karakteristična trdnost materiala, *M* pa je Weibullov modul. Modul pomeni širino porazdelitve trdnosti, pri kateri lahko pride do porušitve. Večja vrednost modula pomeni ožjo porazdelitev, torej manjšo verjetnost, da bi do porušitve prišlo pri manjših obremenitvah od karakteristične. Vrednost modula se giblje od 8 do 14, z večjimi napori pa je mogoče doseči vrednosti od 20 do 25. V preglednici 1 so podani nekateri materiali, njihove lastnosti in Weibullov modul [3].

Za nerjavno jeklo 316L so značilne gostote po sintranju od 93 do 99,95 odstotkov teoretične gostote, v skladu s tem pa je meja plastičnosti od 170 do 345 MPa. Povprečna meja plastičnosti je 220 MPa, raztezek pa je od 18 do 81 odstotkov [3].

Preglednica 1. *Mehanske lastnosti izdelkov, izdelanih z brizganjem prahov*

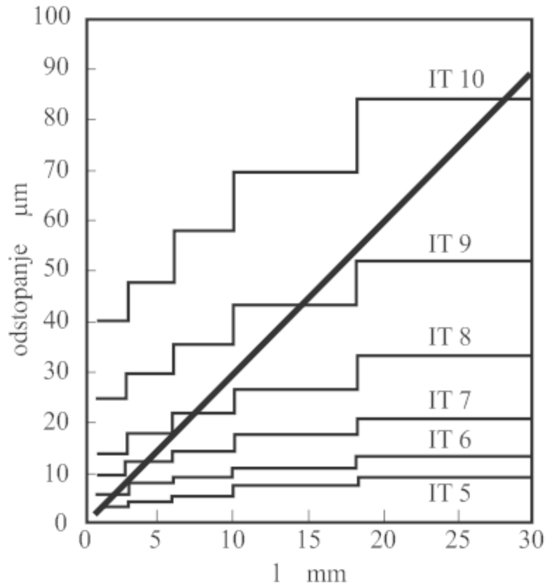
Material	$\frac{\rho}{\rho_0}\cdot 100$ **%**	R_M **MPa**	**Weibullov modul**
Al_2O_3	98	385	9
SiC	98	400	10
WC-10Co	99,95	1410	12
ZrO_2-$3Y_2O_3$	95	230	12

2 POSTOPKOVNE IN OBLIKOVNE OMEJITVE

Tako kakor vsaka tehnologija se tudi brizganje prašnatih materialov srečuje s postopkovnimi in oblikovnimi omejitvami. Čeprav je za izdelavo s tem postopkom na voljo veliko število materialov, jih obstaja nekaj, katerih predelava je otežena, če ne celo nemogoča. Spojinam, ki vsebujejo naslednje elemente, se je treba izogibati: berilij (strupen, hitro oksidira – mogoča predelava), svinec in mangan (strupena in hitro hlapljiva), cink (hitro hlapljiv), natrij in tantal (reaktivna), magnezij (reaktiven in hitro oksidira), aluminij (hitro oksidira), oksidi indija in kositra (nestabilni med sintranjem). Nekateri elementi so škodljivi za zdravje, drugi pa so zaradi velike reaktivnosti in hitrega nastajanja oksidov neprimerni za sintranje ([3] in [11]). V preglednici 2 so prikazani splošni kriteriji za brizgane izdelke iz prašnatih materialov.

Preglednica 2. *Splošni kriteriji za brizganje prašnatih materialov [3]*

Lastnosti	**Najmanjše**	**Največje**	**Tipične**
debelina s (mm)	0,2	25	10
variacije v debelini stene	brez	100x	2x
dolžina l (mm)	2	1000	100
tolerance/odstopanje (%)	0,03	2,0	0,3
masa m (g)	0,02	20000	40
material	elementi	kompoziti	zlitine
proizvodnja (kos/leto)	200	20.000.000	150.000



Sl. 2. *Spreminjanje tolerančnega območja glede na velikost izdelka [12]*

Izdelava zahtevnih in zapletenih izdelkov ob zmožnosti reproduciranja detajlov, je ena izmed glavnih prednosti te tehnologije, čeprav obstajajo tudi določene oblikovne omejitve. V veljavi je neko splošno pravilo, ki pravi, da če je izdelek mogoče izdelati s postopkom brizganja polimerov, potem je primeren tudi za izdelavo z brizganjem prašnatih materialov. V izdelku tako ne more biti zaprtih, votlih prostorov, v majhnih luknjah ne sme biti previsnih mest, najmanjši polmer na vogalih mora biti večji od 0,08 mm, najmanjša luknja ima premer 0,1 mm in na dolgih izdelkih je priporočljiva uporaba izmetalnih kotov (2°). Ostri prehodi so nezaželeni zaradi neenakomerne porazdelitve gostote, zaradi česar se pojavijo zvijanje, neenakomerno krčenje itn ([1] in [3]). Na izdelku pa so lahko previsna mesta, zunanji in notranji navoji (izdelava slednjih je priporočljiva s sekundarnim opravilom), globoke in ozke luknje, stranske luknje itn.

Na sliki 2 so prikazani odstopki v odvisnosti od velikosti izdelka. Do velikosti izdelka 3 mm je z brizganjem prahov mogoče doseči tolerančne vrste IT5 in IT6 (odstopek do 10 mm). S povečevanjem izdelka pa se premosorazmerno povečujejo tudi odstopki, ki so pri izmeri 25 mm 80 mm oz. spadajo v tolerančni razred IT10. Za izdelovanje velikih izdelkov (10 kg), se ta tehnologija uporablja le izjemoma. Težave, ki se pri tem pojavijo, so počasno odstranjevanje veziva in veliki odstopki zaradi krčenja.

3 TRG

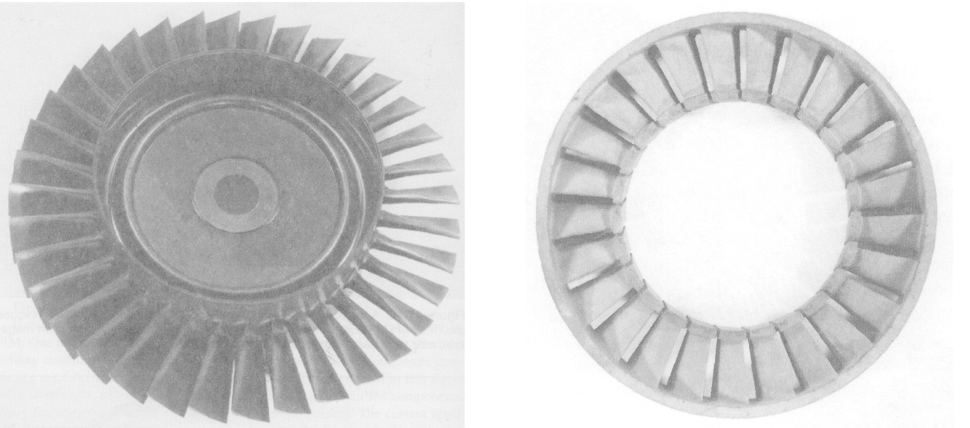
Izdelki, izdelani s to tehnologijo, so konkurenčni predvsem na področju velikih serij in zahtevnejših oblik. Na tem področju je lastna cena, v primerjavi s konkurenčnimi tehnologijami, najnižja. Poleg tega pa je izbira materialov zelo široka. Tako se lahko izbira med nerjavnimi jekli, orodnimi jekli, karbidnimi trdinami, kermeti, oksidi, zlitinami itn. Izdelki iz različnih vrst nerjavnih jekel in Fe zlitin zasedajo polovico trga, približno četrtino trga pa zavzemajo izdelki iz aluminijevega oksida (Al_2O_3) in kremenovega stekla SiO_2 ([3] in [13]). Ker trdota materiala ne vpliva na predelavo, se lahko izdelujejo izdelki z veliko odpornostjo proti obrabi.

Takšni primeri so: šobe za peskanje, pršilne in raketne šobe, okrovi ročnih ur, injektorji, rezalna orodja, svedri itn. [2]. Izdelki se lahko uporabljajo še v medicinske namene (bio-vsadki, kirurška orodja, ortodontski aparati), avtomobilski industriji (sestavni deli v motorju, deli za zračne blazine), računalništvu (deli trdih diskov), telekomunikacijah (spoji na optičnih kablih) itn.

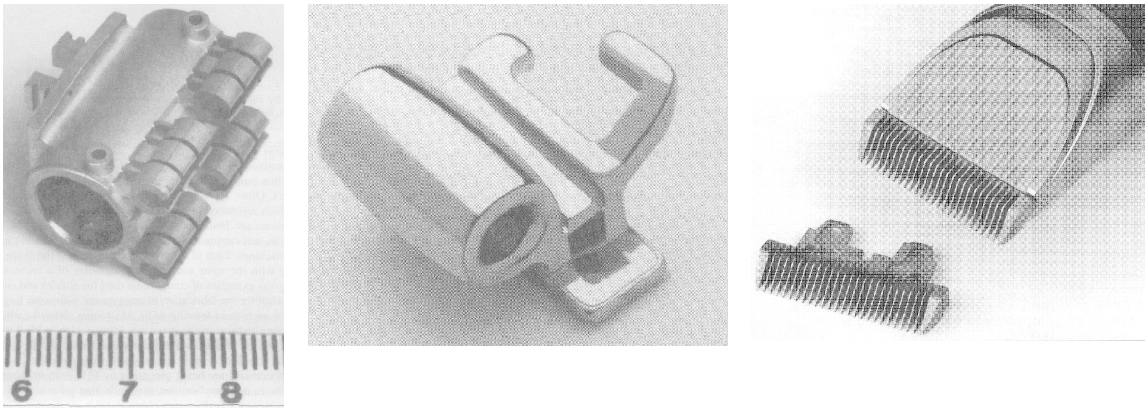
Za injekcijske igle, s katerimi se vbrizgavajo radioaktivni izotopi pri kemoterapiji, se izdelujejo okrovi iz volframovih zlitin. Izdelujejo se keramični vstavki, ki omogočajo izdelavo ultrazvočnih posnetkov arterij od znotraj.

S to tehnologijo se izdelujejo tudi kompoziti, utrjeni z vlakni oz. delci. Osnova kompozitov je kovinska oz. keramična matrica, v katero se doda ojačitve iz različnih karbidnih trdin (TiC, SiC) in keramike (Al_2O_3). Vlakna se usmerijo v smeri toka taline, kar povzroči anizotropne lastnosti, in v tej smeri izboljšajo mehanske lastnosti izdelka. Usmeritev vlaken je mogoča s pravilno postavitvijo ustja in konstrukcijo izdelka, pri tem pa je uporaba programov računalniško načrtovanje in inženirstvo obvezna ([3] in [14]).

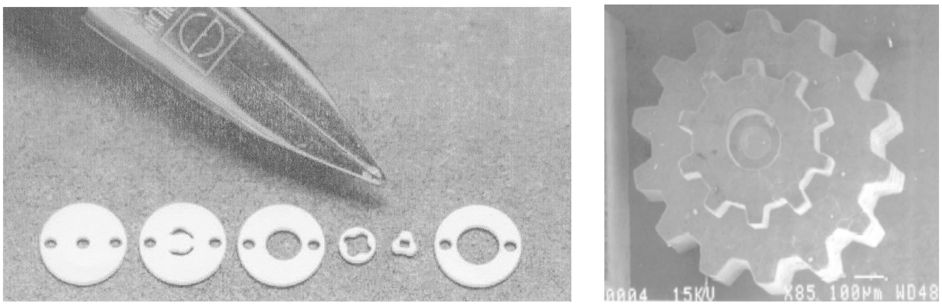
Tudi na področju mikro izdelkov se brizganje prahov kaže kot perspektivna tehnologija.



Sl. 3. *Komponente plinske turbine avtomobilskega motorja iz SiC [3]*



Sl. 4. *Na sliki levo je sestavni del trdega diska, v sredini je nastavek za stalni ortodontski aparat, desno pa je rezilo brivnika [3]*



Sl. 5. *Na sliki levo so komponente mikročrpalke, na desni sliki pa je mikrozobnik*

Mogoča je namreč izdelava izdelkov velikosti pod 100 mm, s tem da je najmanjša mogoča izmera 50 mm. Ti izdelki se uporabljajo predvsem v medicini, kemijski industriji, informatiki, komunikacijah, biotehnologiji, za mikrozaznavala in mikroizvršilnike itn. ([15] do [17]). Mogoča je tudi izdelava mikroizdelkov iz dveh komponent, kar bi se izkoristilo pri izdelavi mikromotorjev in pogonov [18]. Na sliki 5 so sestavni deli mikro črpalke in mikrozobnik, katerega najmanjši zob ima debelino 50 mm. Stranica kvadrata notranjega rotorja črpalke meri 390 mm, najmanjša debelina izdelkov je 80 mm, povprečna debelina pa 450m.

Uporaba materialov z veliko toplotno prevodnostjo in majhnim toplotnim raztezkom je zelo razširjena v mikroelektroniki, računalništvu in telekomunikacijah. Materiali kakor so volfram-baker, aluminijev nitrid in molidben-baker se težko obdelujejo v zapletene oblike s konkurenčnimi tehnologijami, zato so idealni materiali za BPM [3].

Izdelava magnetov, ki se magnetijo neposredno v orodju za brizganje, je pomembna tržna niša za tehnologijo brizganja prahov. Po tem postopku se izdelujejo feritni magneti [19], magneti iz materialov redkih zemelj, iz zlitin NdFeB itn. Izdelujejo se tudi plastomagneti, ki vsebujejo 10 % veziva (PA oz. PPS) in 90 % magnetnih trdih delcev (NdFeB). Ti magneti predstavljajo končni izdelek že po brizganju in se ne sintrajo ([20] in [21]).

Mogoča je izdelava vsadkov iz biomaterialov kakršen je Ti-6Al-4V/HA. Hidroksiapatit (HA) je material, ki je združljiv s kostmi v človeškem telesu, vendar ima to pomanjkljivost, da je krhek. Z dodatkom titanove zlitine se mu mehanske lastnosti močno izboljšajo in je primeren za izdelavo vsadkov. Štirideset odstotna poroznost teh biokomponent omogoča pretakanje tekočin, ki so pomembne za življenje ([22] do [24]).

4 KONKURENČNE TEHNOLOGIJE

Konkurenčne tehnologije, s katerimi se lahko izdelujejo podobni izdelki kakor z brizganjem prašnatih materialov, so: tlačno litje, stiskanje prahov, mehanska obdelava z odrezovanjem, litje v formo s staljivim jedrom in izostatsko stiskanje. Na sliki 6 je prikazana konkurenčnost tehnologije brizganja prahov glede na obseg proizvodnje in

Sl. 6. *Položaj tehnologije brizganja prahov, glede na konkurenčne tehnologije [3]*

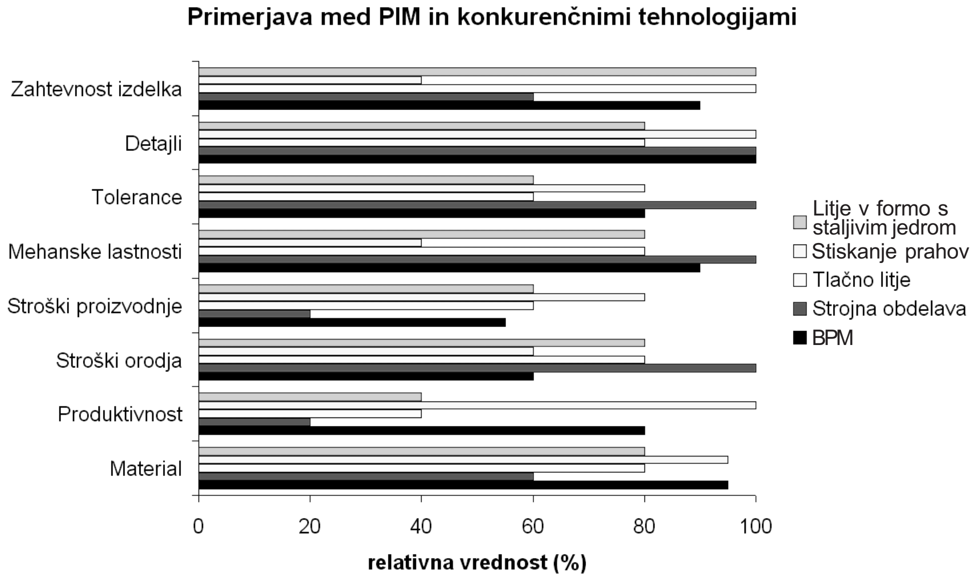
zahtevnost izdelka v primerjavi s preostalimi tehnologijami.

Ta shema je zelo splošna, saj se zahteve razlikujejo od izdelka do izdelka, vendar daje nek splošen pregled področij, na katerih prevladuje posamezna tehnologija. Tehnologije brizganja prahu ni priporočljivo uporabljati za manj zapletene izdelke v velikih serijah, saj na tem področju prevladujeta stiskanje prahov in tlačni liv. Lahko pa se uporablja za manjše serije (200 kos), zelo zapletenih izdelkov iz keramičnih materialov.

Na sliki 7 je narejena primerjava med določenimi lastnostmi teh tehnologij. Iz diagrama je razvidno, da je pomanjkljivost tehnologije brizganja prahov v velikih stroških orodja in proizvodnje, prednost pa je velika izbira materialov, dobre mehanske lastnosti, zahtevnost izdelka in izdelava detajlov. Izdelujejo se lahko detajli velikosti 50 do 100 mm, saj majhne velikosti delcev prahu zapolnijo celotno kalupno votlino v orodju.

V primerjavi s stiskanjem prahov se pri brizganju prašnatih materialov v večini primerov dosegajo večje končne gostote in s tem boljše mehanske lastnosti. Pri stiskanju je gostota pogosto okoli 85%, pri brizganju prahov pa nad 94% teoretične gostote. Neenakomerna porazdelitev gostote je pri stiskanju prahov pogost pojav, posebej pri visokih izdelkih. Posledica tega je neenakomerno krčenje pri sintranju, zato se ti izdelki sintrajo pri nižjih temperaturah, pri katerih je krčenje manjše in s tem tudi manjša končna gostota ([1] in [12]).

Tlačno litje je tehnologija za izdelavo zahtevnih izdelkov v velikih serijah iz zlitin z nizkim tališčem – Mg, Al, Zn itn. Pomanjkljivosti pa so omejeno število uporabnih materialov, sekundarna opravila in draga orodja ter njihovo vzdrževanje.



Sl. 7. *Primerjava med brizganjem prahov in konkurenčnimi tehnologijami ([1], [3] in [12])*

Litje v formo s staljivim jedrom je stara tehnologija za izdelavo zapletenih izdelkov v serijah do 40000 kosov. Pomanjkljivosti so slaba kakovost površine, veliko ročnega dela, tehnologija je primerna samo za taljive materiale.

Mehanska obdelava z odrezovanjem je uveljavljen postopek in primeren tako za zahtevne kakor za manj zahtevne izdelke v manjših serijah. Pomanjkljivosti so: izmet od 30 do 60%, za obdelavo primerni le določeni materiali, majhne serije (do največ 8000 kosov) [12].

5 STROŠKOVNA PRIMERJAVA MED BRIZGANJEM PRAŠNATIH MATERIALOV IN ODREZOVANJEM Z VELIKIMI HITROSTMI

Pri tej analizi je narejena primerjava med dvema konkurenčnima tehnologijama. Stroškovna analiza je narejena za serije od 100 do 300.000 kosov. Po obeh tehnologijah se je izdeloval izdelek, ki je prikazan na sliki 8. Vsi izračuni, enačbe, diagrami in komentarji so podrobneje opisani v [25]. Simulacija odrezovanja je narejena s programom HyperMill. Stroški orodij in strojne ure so bili določeni na podlagi povpraševanj med tujimi in slovenskimi podjetji. Čas brizganja je bil določen na podlagi praktičnih preizkusov. V ceni strojne ure je upoštevana bruto plača delavca, amortizacija stroja (dve izmeni, pet let – 4000 h), energijski stroški in stroški porabe materialov (plini). Niso pa bili upoštevani stroški režije, ki bi bili v obeh primerih enaki, tako da ne vplivajo na natančnost rezultatov.

Pri analizi nismo upoštevali določenih dejavnikov, ki tudi vplivajo na lastno ceno. Ta dva dejavnika sta hrapavost površine in tolerance. Dejavnika imata v praksi velik pomen, za splošno primerjavo stroškov med tema dvema tehnologijama pa ju ni bilo treba upoštevati.

5.1 Stroškovna analiza injekcijskega brizganja prahu

Pri tej tehnologiji na lastno ceno izdelka najbolj vplivajo stroški materiala, orodja in mešanja, saj v nekaterih primerih presežejo 70 % lastne cene. Preostali stroški so še stroški brizganja, sintranja in odstranjevanja veziva. Za ta primer je bil uporabljen material Catamold $FeSi_3$ podjetja BASF, ki je v obliki granulata, tako da so stroški priprave materiala že všteti v ceno materiala. Trdota materiala je 120 do 160 HV, gostota 7,5 g/cm^3, velikost izdelka pa je 56×17,6×4.
Skupni stroški na izdelek so tako:

$$C_{MIM} = C_{OBk} + C_B + C_{OV} + C_S + C_{M1} \qquad (2),$$

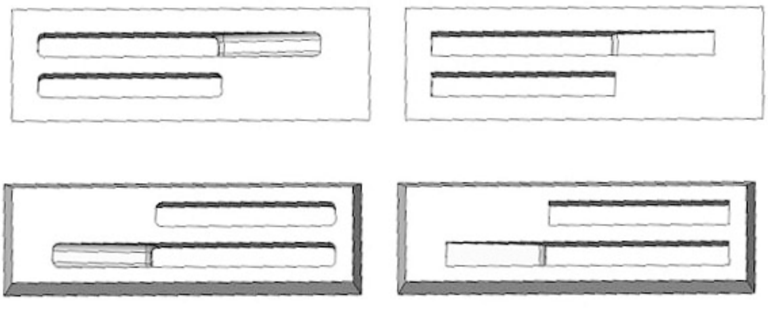
kjer so:
C_{OBk} – stroški orodja za brizganje na kos,
C_B – stroški brizganja,
C_{OV} – stroški odstranjevanja veziva,
C_S – stroški sintranja,
C_{M1} – cena materiala.

<u>Stroški orodja</u>

Orodja za brizganje se po navadi amortizirajo glede na število brizgalnih ponovitev, ki pomenijo dobo trajanja orodja. Za to orodje smo, zaradi abrazivnosti brizgane mešanice, predvidevali, da je doba trajanja okoli 300.000 ponovitev, tj. 600.000 kosov. Po tem času bi bila potrebna obnova orodja. Orodje je dvognezdno, cena po ponudbi je 4500 €.

<u>Stroški brizganja</u>

Strojna ura brizganja na stroju s silo zapiranja 600 kN je v Evropi 10 €/h. Na stroške brizganja vplivajo strojna ura brizganja, čas, število kalupnih votlin v orodju, material izdelka, izdelek itn.



Sl. 8. *Levo je model izdelka za odrezovanje z velikimi hitrostmi, desno za brizganje prašnatih materialov*

V strojni uri brizganja pa so zajeti nespremenljivi stroški amortizacije in spremenljivi stroški električne energije, vode, vzdrževanje itn.

Stroški odstranjevanja veziva

Izbrana peč za odstranjevanje veziva ima zmogljivost 100 l, kar je enako 1860 kosov. Postopek odstranjevanja veziva poteka pri 110 °C z dušikovo kislino HNO_3>98%. Tehnični čas odstranjevanja veziva je 2,5 h, čas ročnega dela je 1h, čas segrevanja in ohlajanja pa 1h. Skupni čas odstranjevanja veziva za ta izdelek je tako 4,5 h. Cena strojnega dela za ponovitev v peči velikosti 100 l je 20 €/h. Cena dušikove kisline je 21 €/liter, cena dušika je 1 €/m^3, cena peči za odstranjevanje je 120000 €.

Peč z prostornino 100 litrov je bila izbrana tudi zato, ker je čas odstranjevanja približno trikrat krajši od časa sintranja. Zato je bila za sintranje izbrana peč s prostornino 300 l, v kateri se lahko naenkrat sintra 5600 izdelkov.

Stroški sintranja

Sintranje $FeSi_3$ poteka v zaščitni atmosferi vodika čistosti 99,998% in s točko rosišča pri temperaturi nižji od –40 °C. Skupni čas sintranja je 18 h, strojna ura pa je 30 €/h. Stroški vodika so 2 €/m^3, cena 300 litrske peči pa je okoli 300.000 €.

Stroški materiala

Cena granulata Catamold $FeSi_3$ podjetja BASF je 20 €/kg. Masa izdelka je 19 g. Izvirnemu materialu se lahko dodaja reciklat, ki pa bistveno ne vpliva na ceno. Cena materiala je 0,38 €/kos.

V preglednici 3 so predstavljene cene za injekcijsko brizganje kovinskega prahu za različne serije. Vidi se, da se cena z naraščanjem serije znižuje, kar je pričakovano. Razvidno je tudi, da je pri večjih serijah vpliv cene materiala na lastno ceno največji.

Preglednica 3. *Skupna cena glede na serije*

Št. izdelkov kos	Stroški odstranjevanja €/kos	Stroški sintranja €/kos	Stroški orodja in brizganja €/kos	Material €/kos	Skupaj	
					€/kos	SIT/kos
10	8,85	53,1	521,8	0,374	594,05	139601
100	0,885	5,31	52,19	0,374	59,76	14044
1000	0,088	0,531	5,23	0,374	6,33	1488,5
10000	0,047	0,094	0,538	0,374	1,07	252,0
50000	0,047	0,094	0,12	0,374	0,65	152,2
300000	0,047	0,094	0,033	0,374	0,46	109,0

5.2 Izračun stroškov izdelave pri rezkanju z velikimi hitrostmi (RVH)

Na začetku je treba poudariti, da z rezkanjem RVH ni mogoče do potankosti izdelati tega izdelka zaradi ostrih robov. Zato je bilo treba rahlo spremeniti konstrukcijo izdelka, kar se v praksi velikokrat izvaja (sl. 8). Konstrukcijo izdelka je namreč treba prilagoditi tehnologiji, s katero se bo ta izdelek izdeloval.

Pri odrezovanju je skupni strošek na izdelek enak:

$$C_{VHO} = C_1 + C_2 + C_3 + C_{M2} \tag{3},$$

kjer so:

C_{VHO} – skupni stroški obdelave na kos,
C_1 – nespremenjeni stroški obdelave,
C_2 – stroški obdelave,
C_3 – stroški menjavanja orodja,
C_{M2} – stroški materiala.

Nespremenjeni stroški odrezovanja:

So stroški priprave in konca obdelave (vpenjanje obdelovancev, pisanje programov) in režijski stroški za serijo ter stroški, nastali zaradi napak v postopku. Zadnja dva dejavnika v preračunih nista bila upoštevana.

Stroški materiala

Izdelki se bodo izdelovali iz surovca velikosti 64×26×8 mm. Podatki o ceni razrezanih surovcev so zaradi težav pri dostopu do podatkov približni in so ocenjeni na okoli 3 €/kg. Stroški materiala za kos so tako: $C_{M2} = 0,3 \ € / kos$.

Stroški obdelave

Za določitev stroškov odrezovanja je bilo najprej treba določiti tehnološke čase posamezne stopnje odrezovanja. Pri simulaciji odrezovanja smo uporabili dva rezkarja z ravnim rezalnim delom s premeroma 10 in 2 mm ter dva rezkarja z zaokroženim rezalnim delom s premeroma 10 in 1 mm. Osnovni material oz. podlaga orodja je karbidna trdina s prevleko. Parametri in časi odrezovanja so podani v preglednici 4. Pri določevanju parametrov smo se opirali na praktične izkušnje in posvetovanja s strokovnjaki iz prakse ter na katalog orodij.

Za določitev stroškov odrezovanja je treba upoštevati tudi obrabo orodja med obdelavo. Čas obstojnosti smo na podlagi praktičnih izkušenj in posvetovanja zaradi poenostavitve izbrali za vsa orodja enak 150 min. Podatki v katalogu se nanašajo na točno določen material obdelovanca in orodja, na določene parametre obdelave in na določen stroj. V praksi pa se velikokrat določa obstojnost orodja s preizkusi.

Cena strojne ure rezkanja z veliko hitrostjo je 17 €/h, ob upoštevanju, da je cena stroja okoli 200.000€. V tej ceni so všteti stroški amortizacije stroja, plača delavca, poraba električne energije itn. Pripravljalno-zaključni čas je določen na 2 uri.

5.3 Razlaga rezultatov

Rezultati analize so prikazani na sliki 9. Razvidno je, da so stroški izdelave z brizganjem pri majhnih serijah zelo veliki. To je predvsem posledica dragega orodja. Nasprotno so stroški izdelave z rezkanjem z velikimi hitrostmi, pri majhnih serijah razmeroma majhni in se z naraščanjem števila kosov rahlo manjšajo. Pri vrednosti 2000 do 3000 kosov je lastna cena izdelka za obe tehnologiji približno enaka. Na lastno ceno izdelka, izdelanega z odrezovanjem, zelo vpliva čas obstojnosti orodja. Obstojnost orodja v tem primeru ni bila določena na podlagi praktičnih preizkusov, kar bi bilo za natančnejšo določitev vsekakor potrebno. Pri večjih količinah pa je lastna cena izdelka, izdelanega po tehnologiji brizganja prahov, veliko manjša. Teh rezultatov se ne sme posploševati na vse izdelke, saj je vsak izdelek zgodba zase. Rezultati se ujemajo tudi z diagramom na sliki 6, kjer je prikazano, da je mehanska obdelava primerna za manjše serije do 10.000 kosov.

6 SKLEP

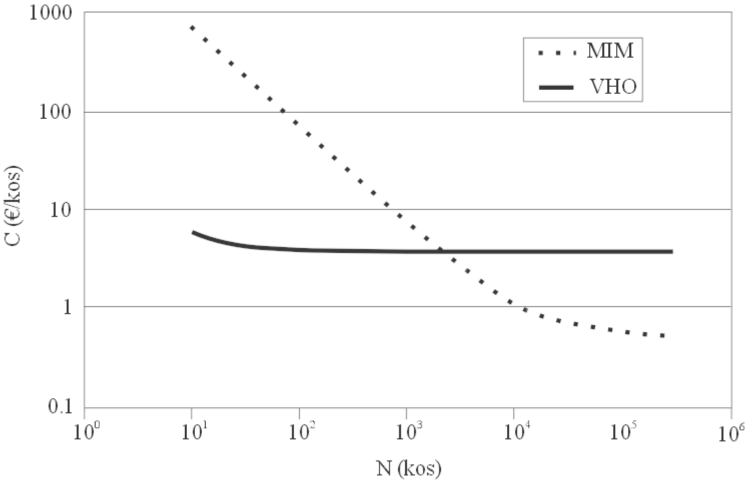
Tehnologija brizganja prašnatih materialov je najbolj razširjena v Severni Ameriki, Azija in Evropa pa zaostajata. V Sloveniji je tehnologija v takšni ali drugačni obliki že opazna, vendar še zdaleč niso izkoriščene vse zmogljivosti. Uporabnost tehnologije

Preglednica 4. *Časi in parametri obdelave pri RVH*

	Obdelava	d mm	f_z mm/zob	n vrt/min	a_p mm	f mm/min	t_{mo} s	t_t min
1	grobo rezkanje	10	0,046	6400	2	1200	3	1:26
2	grobo rezkanje	2	0,01	30000	0,5	900	3	0:57
3	profiliranje	10	0,1	6400	/	3000	3	2:28
4	profiliranje	1	0,01	30000	/	1300	3	0:25
5	grobo rezkanje	10	0,046	6400	2	1200	3	0:58
6	profiliranje	1	0,01	30000	/	1300	3	0:25

Preglednica 5. *Stroški odrezovanja za serijo 1000 kosov*

Serija kos	Nespremenjeni stroški €/kos	Stroški obdelave €/kos	Stroški orodja 1 ϕ10 r. €/kos	Stroški orodja 2 ϕ2 r. €/kos	Stroški orodja 3 ϕ1 k. €/kos	Stroški orodja 4 ϕ10 k. €/kos	Stroški materiala €/kos	Lastna cena €/kos	Lastna cena SIT/kos
1000	0,024	1,88	0,680	0,098	0,162	0,669	0,299	3,814	896



Sl. 9. *Primerjava lastne cene izdelka glede na serijo za MIM in VHO*

je omejena predvsem na izdelavo majhnih in zapletenih izdelkov v velikih serijah.

V primerjavi med tehnologijo brizganja prašnatih materialov in obdelavo z velikimi hitrostmi, se je pokazalo, da vsaka tehnologija zaseda svoje področje. Obstajajo pa tudi izjeme, ki jih v neke splošne sheme in diagrame ni mogoče uvrstiti, ker cena ne igra glavne vloge.

Ob vse večji konkurenci azijskih držav se je tudi v Sloveniji treba zavedati, da je vpeljava novih, inovativnih tehnologij nujna. Zato je želja avtorjev, da se ta tehnologija uveljavi v slovenskih podjetjih.

7 LITERATURA

[1] German, R.M. (1990) Powder injection molding, *Metal Powder Industries Federation*, New Jersey.

[2] German, R.M. (1999) Wear applications offer further growth for PIM, *Metal Powd Rep,* Vol. 54, Issue 6, June 1999, 24-28.

[3] German, R.M., A. Bose (1997) Injection molding of metals and ceramics*, Metal Powder Industries Federation*, New Jersey.

[4] Maca, K., M. Trunec, J. Cihlar (2002) Injection moulding and sintering of ceria ceramics, *Ceramics International,* Vol. 28, Issue 3, 337-344.

[5] Evans, J.R.G., J. Greener (1999) Elongational flow processing of ceramics, *J Mater Proces Technol,* Vol. 96, Issues 1-3, Nov. 1999, 143-150.

[6] Heaney, D.F., P. Suri, R.M. German (2003) Defect-free sintering of two material powder injection molded components – Part 1: Experimental investigations, *J Mater Scien,* Vol. 38, Issue 24, Dec. 2003, 4869-4874.

[7] Suri, P., D.F. Heaney, R.M. German (2003) Defect-free sintering of two material powder injection molded components – Part 2: Model, *J Mater Scien,* Vol. 38, Issue 24, Dec 2003, 4875-4881.

[8] Tan, L.-K., R. Baumgartner, R. M. German (2001) Powder injection molding of bi-metal components*, International Congress on Powder Metallurgy,* New Orleans, May 2001.

[9] Sung, H.J., T.K. Ha, S. Ahn, Y.W. Chang (2002) Powder injection molding of a 17-4 PH stainless steel and the effect of sintering temperature on its microstructure and mechanical properties, *J Mater Proces Technol,* Vol. 130-131, Dec. 2002, 321-327.

[10] Wu, Y., R.M. German, D. Blaine, B. Marx, C. Schlaefer (2002) Effects of residual carbon content on sintering shrinkage, microstructure and mechanical properties of injection molded 17-4 PH stainless steel, *J Mater Scien,* Vol. 37, Issue 17, Sep. 2002, 3573-3583.

[11] www.morganadvancedceramics.com;

[12] Berginc, B. (2003) Brizganje kovinskega in nekovinskega prahu, *Diplomska naloga univerzitetnega študija*, Ljubljana.

[13] Cornwall, R.G., R. M. German (2001) An analysis of the powder injection molding industry global market, *International Congress on Powder Metallurgy,* New Orleans, May 2001.

[14] Loh, N.H., S.B. Tor, K.A. Khor (2001) Production, of metal matrix composite part by powder injection molding, *J Mater Proces Technol,* Vol. 108, Issue 3, Jan. 2001, 398-407.

[15] Liu, Z.Y., N. H. Loh, S. B. Tor, K.A. Khor, Y. Murakoshi, R. Maeda, T. Shimizu (2002) Micro-powder injection molding, *J Mater Proces Technol,* Vol. 127, Issue 2, Sep. 2002, 165-168.

[16] Gietzelt, T., V. Piotter, R. Ruprecht, J. Hausselt (2002) Manufacturing of isolated ceramic microstructures, *Microsystem Technologies*, Vol. 9, Num. 1-2.

[17] Merz, L., S. Rath, V. Piotter, R. Ruprecht, J. Hausselt (2004) Powder injection molding of metallic and ceramic microparts, *Microsystem Technologies*, Vol. 10, Num. 3.

[18] Rota, A.C. New features in material issues for metallic micro components by MIM, *Fraunhofer Institute for Manufacturing and Advanced Materials (IFAM)*, Bremen, Germany.

[19] Lee, S.H., W.Y. Jeung (2001) Anisotropic injection molding of strontium ferrite powder using PP/PEG binder system, *J Magnetism and Magnetic Mater*, Vol. 226-230, Part 2, May 2001, 1400-1402.

[20] Šuštaršič, B., S. Kobe, B. Saje (1999) Izdelava plastomagnetov NdFeB z injekcijskim brizganjem, *Kovine, zlitine, tehnologije*, Vol. 33, Dec. 1999, 117-124.

[21] Ma, B.M., J.W. Herchenroeder, B. Smith, M. Suda, D.N. Brown, Z. Chen (2002) Recent development in bonded NdFeB magnets, *J Magnetism and Magnetic Mater*, Vol. 239, Issues 1-3, Feb. 2002, 418-423.

[22] Thian, E.S., N.H. Loh, K.A. Khor, S.B. Tor (2002) Microstructures and mechanical properties of powder injection molded Ti-6Al-4V/HA powder, *Biomaterials*, Vol. 23, Issue 14, Jul. 2002, 2927-2938.

[23] Thian, E.S., N.H. Loh, K.A. Khor, S.B. Tor (2001) Effects of debinding parameters on powder injection molded Ti-6Al-4V/HA composite parts, *Advanced Powder Technologies*, Vol 12, Sep. 2001 361-370.

[24] Thian, E.S., N.H. Loh, K.A. Khor, S.B. Tor (2002) Ti-6Al-4V/HA composite feedstock for injection molding, *Material Letters*, Vol. 56, Oct. 2002, 522-532.

[25] Berginc, B. (2004) Optimiranje obdelovalnih tehnologij, Podiplomski seminar, mentor dr. prof. J. Kopač.

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DOMAČE REVIJE

EGES, Energetika, gospodarstvo in ekologija skupaj, Ljubljana
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dne 25. marca 2005: Marko PRATNEKAR, Urban MOŽINA.

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Strojniški vestnik - Journal of Mechanical Engineering 51(2005)4, 231-232
Navodila avtorjem - Instructions for Authors

Navodila avtorjem - Instructions for Authors

Članki morajo vsebovati:
- naslov, povzetek, besedilo članka in podnaslove slik v slovenskem in angleškem jeziku,
- dvojezične preglednice in slike (diagrami, risbe ali fotografije),
- seznam literature in
- podatke o avtorjih.

Strojniški vestnik izhaja od leta 1992 v dveh jezikih, tj. v slovenščini in angleščini, zato je obvezen prevod v angleščino. Obe besedili morata biti strokovno in jezikovno med seboj usklajeni. Članki naj bodo kratki in naj obsegajo približno 8 strani. Izjemoma so strokovni članki, na željo avtorja, lahko tudi samo v slovenščini, vsebovati pa morajo angleški povzetek.

Za članke iz tujine (v primeru, da so vsi avtorji tujci) morajo prevod v slovenščino priskrbeti avtorji. Prevajanje lahko proti plačilu organizira uredništvo. Če je članek ocenjen kot znanstveni, je lahko objavljen tudi samo v angleščini s slovenskim povzetkom, ki ga pripravi uredništvo.

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Članek naj bo napisan v naslednji obliki:
- Naslov, ki primerno opisuje vsebino članka.
- Povzetek, ki naj bo skrajšana oblika članka in naj ne presega 250 besed. Povzetek mora vsebovati osnove, jedro in cilje raziskave, uporabljeno metodologijo dela,povzetek rezulatov in osnovne sklepe.
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- Teorija.
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- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
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- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

OBLIKA ČLANKA

Besedilo članka naj bo pripravljeno v urejevalnilku Microsoft Word. Članek nam dostavite v elektronski obliki.

Ne uporabljajte urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata.

Enačbe naj bodo v besedilu postavljene v ločene vrstice in na desnem robu označene s tekočo številko v okroglih oklepajih

Papers submitted for publication should comprise:
- Title, Abstract, Main Body of Text and Figure Captions in Slovene and English,
- Bilingual Tables and Figures (graphs, drawings or photographs),
- List of references and
- Information about the authors.

Since 1992, the Journal of Mechanical Engineering has been published bilingually, in Slovenian and English. The two texts must be compatible both in terms of technical content and language. Papers should be as short as possible and should on average comprise 8 pages. In exceptional cases, at the request of the authors, speciality papers may be written only in Slovene, but must include an English abstract.

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The paper should be written in the following format:
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- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

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Texts should be written in Microsoft Word format. Paper must be submitted in electronic version.

Do not use a LaTeX text editor, since this is not compatible with the publishing procedure of the Journal of Mechanical Engineering.

Equations should be on a separate line in the main body of the text and marked on the right-hand side of the page with numbers in round brackets.

Enote in okrajšave

V besedilu, preglednicah in slikah uporabljajte le standardne označbe in okrajšave SI. Simbole fizikalnih veličin v besedilu pišite poševno (kurzivno), (npr. *v, T, n* itn.). Simbole enot, ki sestojijo iz črk, pa pokončno (npr. ms^{-1}, K, min, mm itn.).

Vse okrajšave naj bodo, ko se prvič pojavijo, napisane v celoti v **slovenskem jeziku**, npr. časovno spremenljiva geometrija (ČSG).

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v ločljivosti, primerni za tisk, v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Diagrami in risbe morajo biti pripravljeni v vektorskem formatu.

Pri označevanju osi v diagramih, kadar je le mogoče, uporabite označbe veličin (npr. *t, v, m* itn.), da ni potrebno dvojezično označevanje. V diagramih z več krivuljami, mora biti vsaka krivulja označena. Pomen oznake mora biti pojasnjen v podnapisu slike.

Vse označbe na slikah morajo biti dvojezične.

Preglednice

Preglednice morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot preglednica 1, preglednica 2 itn. V preglednicah ne uporabljajte izpisanih imen veličin, ampak samo ustrezne simbole, da se izognemo dvojezični podvojitvi imen. K fizikalnim veličinam, npr. *t* (pisano poševno), pripišite enote (pisano pokončno) v novo vrsto brez oklepajev.

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Seznam literature

Vsa literatura mora biti navedena v seznamu na koncu članka v prikazani obliki po vrsti za revije, zbornike in knjige:

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[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

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.).

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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.

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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.

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[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

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