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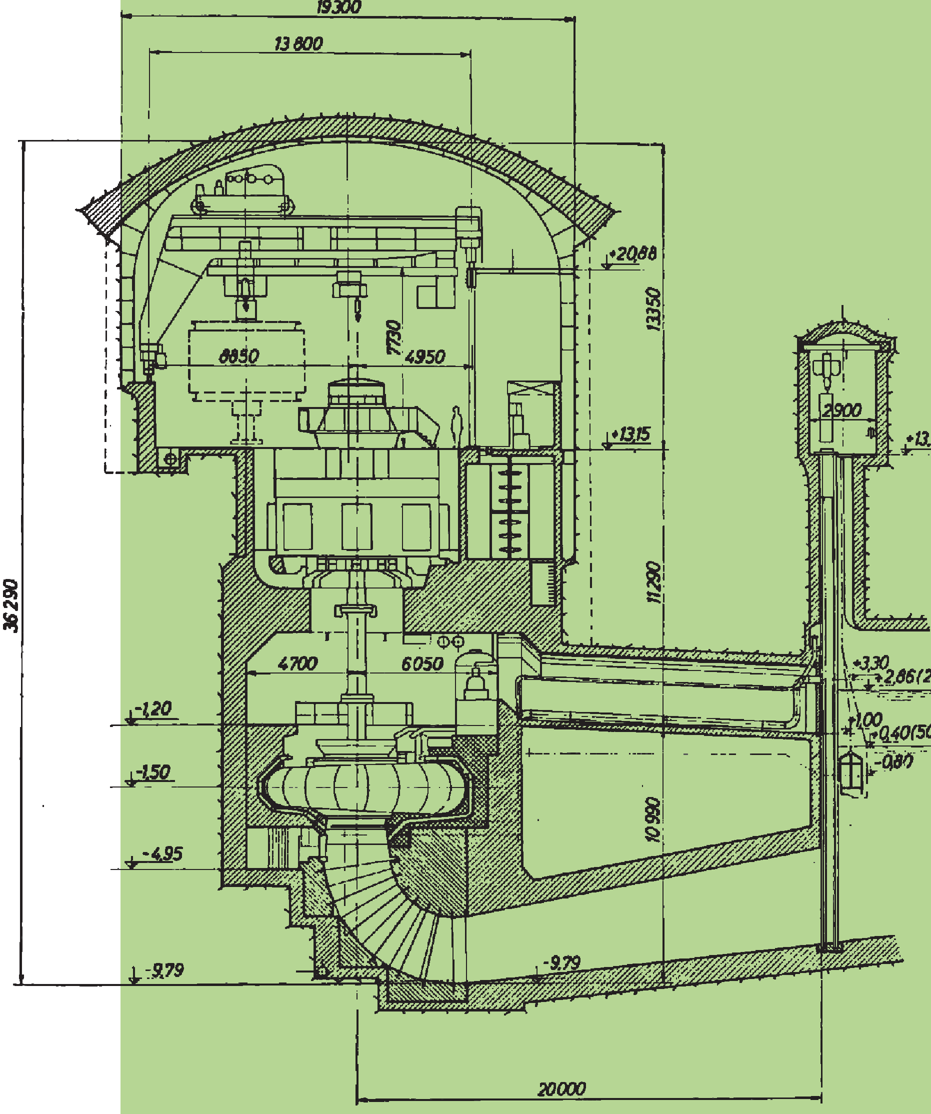

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Pri nastajanju novega izdelka zapolnjujejo izdelovalne tehnologije pravzaprav ves prostor. Glavni ustvarjalci proizvodnih postopkov so izdelovalni stroji, orodja in ljudje, medtem ko sta spremljajoča dejavnika strojna in programska oprema, ki krmilita RK obdelovalne stroje. Poleg krmiljenja, krmilne enote nadzirata obdelovalni stroj prek uvedenih zaznaval in skrbita za zagotavljanje kakovosti postopka in izdelkov.

Tako je ta tematski zvezek namenjen nekaj zanimivim prispevkom različnih avtorjev, in sicer obsega preoblikovanje z valjanjem, tu je uporabljena metoda končnih elementov, odrezovanje in rezalne sile, pri čemer je zajeta napoved rezalnih sil s pomočjo nevronskih mrež, ulivanje in zagotavljanje kakovosti z metodo Šest sigem. Zajeta je tudi zamisel TQM v funkciji celovitega vzdrževanja v podjetju. Prispevki so izbrani z mednarodne konference TMT 2006 in so iz prvotne kratke oblike razširjeni v celovito predstavitev v tem zvezku.

Eden izmed ključnih delov sodobnega in hitrega postopka razvoja izdelkov po sistemu od zamisli do izdelka je ustvarjanje poti orodja med obdelavo glede na želeno geometrijsko obliko izdelka. Pot orodja med postopkom dejansko določa geometrijsko kakovost izdelka in kakovost obdelane površine. V današnjem času je ta del olajšan z možnostjo ustvarjanja poti orodja na površine nepravilnih oblik z uporabo zlepkov. Deli nepravilnih oblik, ki se uporabljajo pri načrtovanju in izdelavi kalupov, matric in aerodinamičnih oblik itn., so zaradi svojih zapletenih oblik običajno izdelani na 3-osnih ali 5-osnih frezalnih strojih. Pri klasičnem postopku ustvarjanja poti orodja po površini nepravilnih oblik so gibi orodja izraženi z linearno interpolacijo. Sodobna metoda interpolacije je na podlagi teoretične krivulje lege orodja, približana z mnogokotnimi črtami. Gibi orodja so posledično zaustavljeni v dotikališčih in v krivinah, kar povzroča vibracije in posledično vpliva na končno kakovost obdelane površine. Z razvojem RK interpolacij, ki sprejemajo zlepke, je seveda še ugodneje če jih resnično tudi znajo uporabljati. Z avtomatizacijo ustvarjanja poti orodja iz površin NURBS, izdelanih s strategijo vzporednih ravnin na 3-osnih RK frezalnih strojih, se dosegajo odlični rezultati z vidika kakovosti obdelanih površin. Eden izmed glavnih vzrokov

Manufacturing processes play the major role in the development of a new product. The main participants in the manufacturing processes are machine tools, tools and people as workers, while affordable hardware and software that represent the logic of CNC machine tools are also important. In addition to control, control units with all their integrated sensors and the machine tool ensure the quality of the machining process and the products.

This thematic issue presents some very interesting papers from a number of authors. It includes forming using a rolling process with the FEM, the cutting process and cutting-force modeling with neural networks, and the casting process and quality assurance based on the six-sigma method. There is also a study of the TQM concept for the overall maintenance of a company. All the papers are collected from the international conference TMT 2006. While they were presented in the proceedings as short papers; here they have been extended especially for this issue.

One of the very important parameters in the rapid, modern development of products, from the idea to the final product, is the path of the cutting tool in the cutting process, based on the requirements of the final product. This basically defines the final geometrical quality and the quality of the machined surface. Nowadays, B-spline curves are of great help when it comes to defining the tool path for irregular surfaces. Parts with irregular shapes that are normally used in designing and manufacturing moulds, matrixes, aerodynamic parts, etc., are, because of their complexity, usually manufactured on 3-axes or 5-axes milling centers. In a conventional determination of cutting-tool paths along irregular shapes, the movements of the tool are defined on the basis of linear interpolation. In modern interpolation methods the position of the cutting tool is approximated with multiple-node lines corresponding to the theoretical curve. Therefore, the movements of the tool are intermitted in nodes and turns. This intermittency causes unfavorable vibrations in the process and affects the quality of the machined surface. With the evolution of CNC interpolators, which are able to import B-spline curves, it is always better if they can also use them in the proper way. With automatic cutting-tool path generation from NURBS surfaces, constructed with a parallel plane methodology on 3-axes milling je v tem, da metoda z uporabo zlepkov določa najmanjše število nadzornih točk, ki podajajo najboljše približevanje različnih položajev orodja.

V času globalizacije, revolucije v računalniški znanosti in prestrukturiranja, ki temelji na načelih reinženiringa, gre vidik razvoja proizvodnih sistemov v smeri zmožnosti in učinkovitosti odprtega in hitrega sistema nadzora kakor tudi kakovosti po načelih celovitega obvladovanje kakovosti (TQM).

Reinženiring in razvoj sistema kakovosti predstavljata moderne tehnike, ki obsegajo vse komponente poslovanja podjetja v funkciji zahtev trga na tehničnem in tudi tehnološkem področju. Pomembna vloga v teh postopkih pripada enemu od ključnih podsistemov proizvodnega sistema. To je vzdrževanje.

Pričakovanje glede zasnove vzdrževanja v prihodnje je celovito proizvodno vzdrževanje (TPM) v funkciji celovitega obvladovanja kakovosti (TQM), v razmerah uporabe novih tehnologij.

Ustrezna zasnova proizvodnega sistema vzdrževanja je pogoj za kakovost izdelkov, medtem ko je celovito preventivno vzdrževanje bistven postopek TQM.

Uporaba metodologije Šest sigem za nenehno izboljševanje postopka je opazna pri številnih postopkih v proizvodnih podjetjih. S tem nam uspe močno zmanjšati izmeček, in to v

centers, the quality of the machined surface can be extremely good. One of the main reasons for this is that B-spline curves determine the minimum number of control points that represent the best approximation to the different positions of the tool.

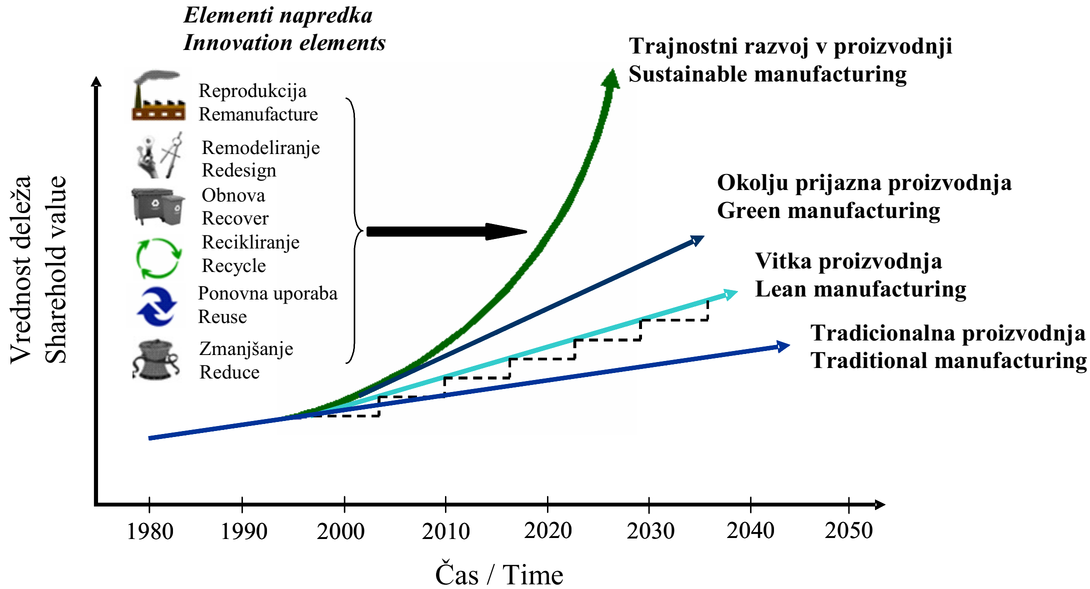
In this time of globalization, the revolution in computer science and re-structions, which are based on the re-engineering principle, the vision of production systems is oriented on the ability and the efficiency of open and rapid inspection systems as well as quality assurance on the principles of overall quality management/assurance (TQM).

Re-engineering and quality-system development represent modern techniques that include all the components of company management as a functional need of the market from the technical as well as from the technological aspects point of view. An important part in this process belongs to one of the key subsystems of the production system, i.e., maintenance.

The expectation of maintenance in the near future is oriented towards overall production maintenance (TPM) in the function of overall quality control (TQM) by using new technologies.

The proper concept of production-system maintenance is the need for quality in the final product, while overall preventive maintenance is important from the view of TQM.

The use of Six-sigma methodology for continuous process improvement is present in many of the processes of manufacturing companies. The



Napredek trajnostnega razvoja glede na ostale že uveljavljene proizvodnje (Jawahir, 2006)
Sustainable manufacturing in comparison to the other manufacturing principles (Jawahir, 2006)

povprečju za 50 odstotkov. Parametri z največjim vplivom na raven izmečka se definirajo v diagramu vzrok - posledica. Po tovrstni analizi se uvede izboljšave in nadzor z uporabo orodij in metod Šest sigem. Rezultati se izkažejo v obliki prihrankov.

Naštete in na kratko opisane metode in postopki v izdelovalni in obdelovalni tehniki se odsevajo v tako imenovanem trajnostnem razvoju obdelav. Le ta na vseh odsekih inženirskega razvoja pri zasnovi izdelka pripomore k prijaznemu odnosu izdelovalne tehnike do narave (zmanjšanje, ponovna uporaba, recikliranje, obnavljanje, remoduliranje in reprodukcija), kakor tudi v pozitivnem odnosu do delavca kot proizvajalca.

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reason is that it is possible to reduce the waste in real situations by an average of 50%. The parameters with the greatest influence on waste are defined on the basis of a cause-consequence diagram. With such an analysis the improvements and control/inspections based on Six-sigma methods are implemented. These results are represented as overall savings.

The presented and briefly introduced methods and ideas in design and manufacturing techniques are reflected in so-called sustainable manufacturing. This represents the idea of manufacturing-process improvement on all the segments in the way of environmentally benign (reduce, reuse, recycle, redesign, remanufacture) as well as the health of workers involved in manufacturing processes.

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Določanje poti orodja površin nepravilnih oblik z zlepki

Tool-Path Generation for Free-Form Surfaces with B-Spline Curves

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Deli nepravilnih oblik, ki se uporabljajo pri načrtovanju in izdelavi kalupov, matric in aerodinamičnih oblik itn., so izdelani na 3-osnih ali 5-osnih frezalnih strojih. Pri običajnem postopku določanja poti površin nepravilnih oblik so gibi orodja izraženi z linearno interpolacijo. S to metodo interpolacije so teoretične krivulje lege orodja aproksimirane z lomljenimi črtami. Gibi orodja so posledično prekinjeni v dotikališčih in v krivinah, kar povzroča vibracije in posledično vpliva na končno obdelano površino. Z razvojem RK interpolatorjev, ki sprejemajo zlepke, je še ugodneje , če jih tudi uporabljajo. Pri našem delu o NURBS površinah izdelanih s strategijo paralelnih ravnin na 3-osnih RK frezalnih strojih smo avtomatizirali določanje poti orodja z zlepki z določitvijo najmanjšega števila nadzornih točk, ki podajajo najboljšo aproksimacijo različnih položajev orodja.

(Ključne besede: strategija vzporednih ravnin, aproksimacije, zlepki, površine nepravilnih oblik)

Free-form parts used in the design and manufacture of molds, dies and aerodynamic shapes, etc., are machined on 3-axis or 5-axis milling machines. In the classical approach of tool-path generation for free-form surfaces, the tool movements are expressed as a linear interpolation. For this method of interpolation, the theoretical curves of the tool positions are approximated with a polygonal line. Consequently, the tool movements are discontinuous in tangency and curvature, which creates vibrations and consequently affects the finish of the surface. With the development of CNC interpolators that accept a B-Spline curve, it has become more advantageous to use them. In our work on the NURBS surfaces machined with a parallel-plane machining strategy on 3-axis CNC milling machines, we automate the generation of the tool path in terms of B-Spline curves by determining the minimum number of control points that give the best approximation to the different tool positions.

(Keywords: parallel-plane machining strategy, curve approximation, B-spline, free-form surface)

0 INTRODUCTION

Free-form parts are used in the design and manufacture of molds, dies, etc., and are machined on 3-axis or 5-axis milling machines. For machining free-form surfaces, we have to consider many aspects, such as surface definition, machining strategies, machining parameters, etc., with the objective to obtain a good surface finish. Generally, three stages are required to obtain the final part: roughing, semi-finishing and finishing. In the roughing stage, the goal is to remove the most material from the initial workpiece as rapidly as possible, by using a large flat-end mill tool, on sequential horizontal cutting planes and keeping only a small thickness of material that is removed in semi-finishing and finishing, generally using ball-end mill tools. To machine these surfaces we have to generate the tool path by calculating the sequence of tool positions from the design surfaces. Tool-path generation methods are classified as either the CC-based method or the CL-based method, depending on the type of tool-path generation surface [1]. In the cutter-contact (CC) based method, the tool-path generation is done on the design surface and the tool paths are generated by sampling a sequence of CC points from the part's surface and then each CC point is converted to a cutter location (CL) point. In the cutter location (CL) based method, the offset surface is generated from the design surface, and then it is used as a path-generation surface. For the two methods, to obtain a good surface finish and a minimum machining time, it is necessary to determine the optimum feed-forward step and the side step. Different problems related to the machining of free-form surfaces have been considered by different researchers. In [2] Choi et al. studied interference avoidance and in [3] they looked at the machining of compound surfaces. Duc [4] studied the parameters that affect the surface quality and proposed generating tool paths in terms of planar B-Spline curves. Yang [5] proposed methods for global and local interference checking and then determined the optimal combination of tool sizes that minimizes the machining times. Park [6] optimized the tool path for a Z-constant machining strategy by considering the machining constraints and the tool-path length. OuYang et al. ([7] and [8]) used the Voronoi diagram and Delaunay triangulation to select the optimal ball-end mill tool to be used for finishing free-form surfaces given by a cloud of points. Jerard et al. ([9] and [10]) considered another aspect, which is the determination of the optimal cutting conditions and in particular the feed rate. Recent research has focused on the machining of free-form surfaces directly from a cloud of points, without the reconstruction of the CAD model of the surfaces. Different methods have been developed for 3-axis machining ([11] to [14]) and for 5-axis machining ([15] and [16]). Jerard et al. ([17] and [18]] proposed methods for the simulation and verification of the generated machining programs. Among the fields of research is the quality of the finished surfaces. For machining these surfaces, different machining strategies are used: isoparametric, Z-constant, parallel plane, etc. The parallel-plane machining strategy permits the machining of multiple adjoining surfaces and guarantees the continuity of the machining. In the classical approach of tool-path generation, the tool movements are expressed as linear interpolations. For this method of interpolation, a polygonal line is used to approximate the theoretical curves of the tool positions. Consequently, the tool movements are discontinuous in the tangency and in the curvature because at each point there is an abrupt change in the direction that creates vibrations and this consequently affects the finish of the surface. With the development of CNC interpolators that accept the B-Spline curve; it is more advantageous to use these interpolators because they minimize vibrations, allow a good surface finish and permit the reduction of the size of the machining program. In our work, from the NURBS surfaces machined with a parallel-plane machining strategy on 3-axis CNC milling machines using the CC-based method, we automate the generation of the tool path with B-Spline curves by determining the minimum number of control points that gives the best approximation to different tool positions with a given accuracy.

1 DEFINITION OF NURBS CURVES AND SURFACES

Different parametric formulations are used in the description of curves, such as Bezier, Rational Bezier, B-Spline and NURBS. However, the most powerful version is the NURBS. A NURBS curve is defined by (n+1) control points P_i with their weight $W_{i,}$ ($0 \leq i \leq n$), knot vector U and degrees p. If all the weights are equal, a NURBS curve becomes a B-Spline curve. A NURBS curve is given by [19]:

$$C(u) = \frac{\sum_{i=0}^{n} N_{i,p}(u) w_i p_i}{\sum_{i=0}^{n} N_{i,p}(u) w_i} \quad (1).$$

Generally, the free-form parts are designed by the junction of an important number of complex surfaces. To describe the shape of these surfaces, the parametric formulation is used with regard their advantages relative to the other formulations. Different parametric formulations are used, such as the Bezier, the Rational Bezier, the B-Spline and the NURBS. However, the most powerful formulation is the NURBS. A NURBS surface is defined by (Fig. 1):

- A network of (m+1)×(n+1) control points $P_{i,j}$ with their weight $W_{i,j}$ ($0 \leq i \leq m$ and $0 \leq j \leq n$),
- Two knot vectors U and V in the u and v directions respectively,
- The degrees p and q in the u and v directions respectively.

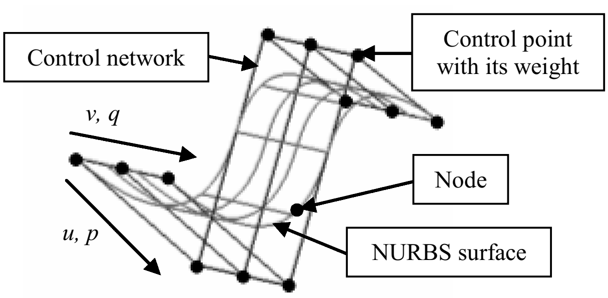


Fig. 1. *Parameters of a NURBS surface*

The NURBS surface is given by ([1] and [20]):

$$S(u,v)=\frac{\sum_{i=0}^{m}\sum_{j=0}^{n}N_{i,p}(u).N_{j,q}(v).P_{i,j}.W_{i,j}}{\sum_{i=0}^{m}\sum_{j=0}^{n}N_{i,p}(u).N_{j,q}(v).W_{i,j}} \quad (2).$$

Where $N_{i,p}(u)$ and $N_{j,q}(v)$ are the B-Spline basis functions of degree p and q respectively. The principal properties of NURBS surfaces are the local modification scheme, the convex hull property and the representation of conic surfaces.

To position correctly the tool relative to the surface during tool-path generation we need to calculate the unit normal vector $\vec{n}(u,v)$ to the surface, which is calculated from the two tangent vectors $\vec{T}_u$, $\vec{T}_v$ to the surface and is given by [20]:

$$\vec{n}=\frac{\vec{T}_u\times\vec{T}_v}{\left|\vec{T}_u\times\vec{T}_v\right|} \quad (3).$$

To the unit normal vector, we need to calculate the principal curvatures k_1 and k_2 [20]. These curvatures are used in the selection of the optimal tool, permitting the machining of the surfaces without interferences.

2 TOOL-PATH GENERATION FOR FREE-FORM SURFACE MACHINING

The following sections describe the necessary steps for generating the tool path with B-Spline curves.

2.1 Interference and tool position relative to the surface

For machining a free-form surface, the tool must be tangent to this surface and generally, for 3-axes CNC machining, a ball-end mill tool is used and its positions are given by [4] (Fig. 2):

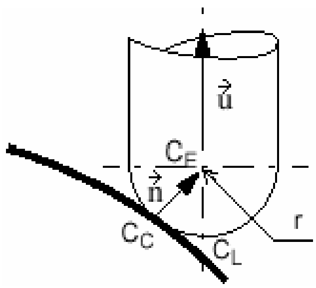


Fig. 2. *Ball-end mill position*

$$\begin{cases}\overrightarrow{OC_E}=\overrightarrow{OC_C}+r\vec{n}\\ \overrightarrow{OC_L}=\overrightarrow{OC_C}+r\vec{n}-r\vec{u}\end{cases} \quad (4).$$

With C_C being the cutter contact, C_E the tool center, C_L the cutter location, $\vec{u}$ the tool-orientation vector and r the tool radius. To avoid the problem of interferences, the radius of the used ball-end mill tool must be less than or equal to the small principal radius of curvature for all the surfaces [2].

2.2 Parallel-plane machining strategy

Different machining strategies are used for machining free-form surfaces: isoparametric, Z-constant, parallel plane, etc. The parallel-plane machining strategy is the most commonly used one for surfaces without vertical regions. This strategy permits the machining of multiple adjoining surfaces and guarantees the continuity of the machining. For this strategy, the tool path is determined from the intersection points of a vertical plane, having any orientation with the surfaces to manufacture. In our work we have considered the one-way and zig-zag sweeping strategies. To machine the surfaces, we need to specify the deviation error and the distance between two consecutive planes. In order to simplify the calculation of the intersection points, the surfaces are triangulated to within a given accuracy.

2.3 Approximation with B-Spline curves

Generally, once the points of intersection are calculated, the linear interpolation is used to express the tool movements. For this kind of interpolation, the size of the machining program is very important, the movements are discontinuous in the tangency and in the curvature at each determined tool position because there is an abrupt change in the direction, which creates vibrations and affects the surface finish. In order to minimize vibrations, to obtain a good surface finish and to reduce the size of the machining program, the tool path is generated in terms of the B-Spline curves. B-spline curves can be generated by interpolation or by approximation, but in our work, the approximation is used because it is more flexible and permits the choice of different parameters of reconstruction and also permits a reduction in the number of control points.

Given $(m+1)$ points Q_k $(0 \le k \le m)$, the approximation with the B-Spline curve consists of fixing the number of control points $(n+1)$ with $(n \le m)$ and the degree p $(1 \le p \le n)$ and then calculating the coordinates of the control points P_i $(0 \le i \le n)$ of the B-Spline curve by applying the least-squares method by minimizing the following function relative to the control points [19]:

$$F(P_i) = \sum_{k=0}^{m} \left| \sum_{i=0}^{n} N_{i,p}(u_k) P_i - Q_k \right|^2 \quad (5).$$

To control the form of the curve, we constrain the curve so it must pass by the first and the last of the data points for each curve. This condition is given by:

$$\begin{cases} P_0 = Q_0 \\ P_n = Q_m \end{cases} \quad (6).$$

To obtain a linear system of equations and to calculate the coordinates of the control points, we need to choose methods for calculating the nodal value u_k for each data point and the knot vector U. The values of the parameters u_k are calculated using the uniformly spaced method, the centripetal method or the chord-length method, and the knot vector is calculated using the uniform method or the average method [19]. With this parameterization, we can generate six different B-Spline curves and consequently, we must choose the best one in terms of their quality.

To qualify the quality of the generated curve, two criteria of accuracy are used [21]:

- The superior error C_1: measures the gap to the less approached point:

$$C_1 = \underset{i=0,\dots m}{Max} \left| Q_i - C(u_i) \right| \quad (7).$$

- The average quadratic error C_2: measures the average error committed at a point:

$$C_2 = \frac{\sqrt{\sum_{i=0}^{m} \left(Q_i - C(u_i)\right)^2}}{m+1} \quad (8).$$

The criteria of precision C_1 and C_2 are both necessary to judge the precision of the obtained curve, but these criteria do not allow us to validate the curve between data points. It is also possible to calculate the deviation between the middle of each segment of data points and the approximated curve.

3 SOFTWARE DEVELOPMENT AND RESULTS

To automate the generation of the tool path with the B-Spline curves and the determination of the minimum number of control points that give the best approximation with an imposed accuracy, we have developed object-oriented software running under Windows using the C++ Builder and the graphics library OpenGL [22]. Fig. 3 shows the flowchart of the developed software.

The generation of the tool path with the B-Spline curves is divided into two stages. In the first stage, the user selects the surfaces to machine and introduces a set of parameters: machining parameters, approximation parameters and methods of parameterization. These parameters are as follows: tool dimensions, feed rate, the distance between two planes, the number of triangles for each surface, the sweeping strategy (zig-zag, one-way), orientation of the vertical plane, points to approximate with the B-Spline curves (cutter contact, tool center, cutter location), degree of the curve, accuracy of the approximation and finally the methods used for the calculation of the nodal values and the knot vector. Generally, the degree is chosen to be equal to 3 in order to obtain a continuity of the curvature and to avoid the problem of oscillations of the curve. Once these parameters are introduced, the software automatically finds the correct orientation for each surface and triangulates it. In the next step, the intersection points between all the positions of the vertical planes and the triangles are calculated with the associated tool-center points and cutter-location points. In the second stage, for each data point, we fix the initial number of control points and the increment value, which are both equal to five because we have found in our tests that generally the approximation converges with a small number of control points. After this, we calculate the nodal values and the knot vector for all the possible combinations, one after another in this order (uniformly spaced method, uniform method), (uniformly spaced method, average

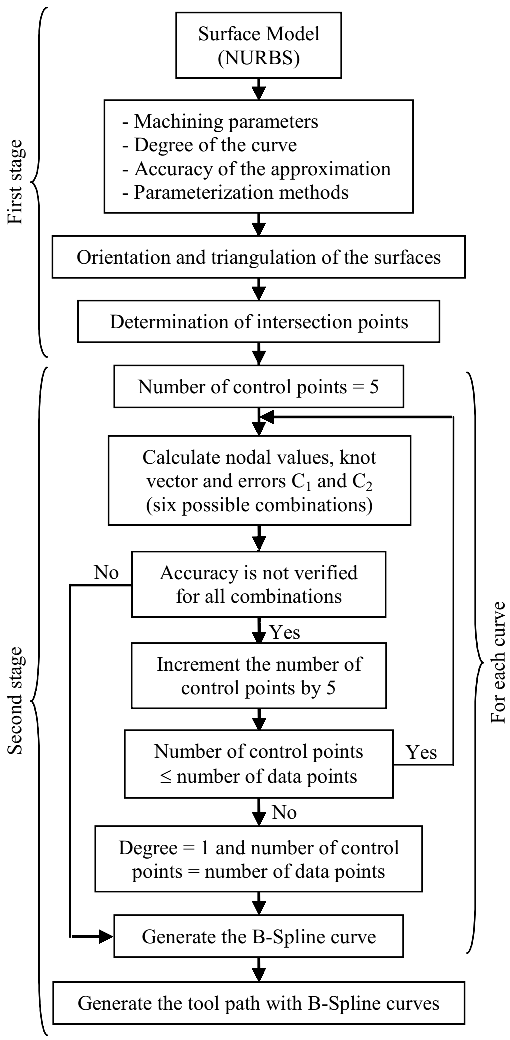


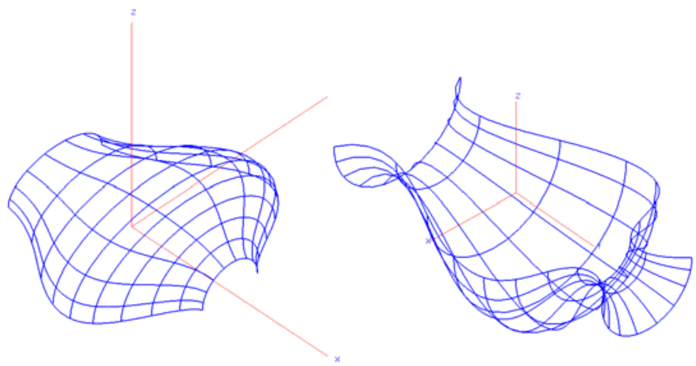
Fig. 3. *Flow chart of tool-path generation with B-Spline curves*

method), (centripetal method, uniform method), (centripetal method, average method), (chord-length method, uniform method), (chord-length method, average method) and simultaneously the errors C_1 and C_2. If the accuracy is verified at least for one combination, a new B-Spline curve is generated and we pass to the next data points. But, if the accuracy is not verified for all the combinations, we increment the number of control points by 5 and we repeat the same steps until verification of the accuracy for at least one combination. In the worst case, if the number of control points is greater than the number of data points, the degree is set to 1 and the number of control points equal to the number of data points. In the end, we obtain a set of B-Spline curves with a minimum number of control points, which are used in the generation of the tool path.

To demonstrate the automatic generation of the tool path in terms of B-Spline curves, we have considered two different surfaces (Fig. 4).

The dimensions of the first surface are 44 mm × 51 mm × 16 mm and the minimum principal radius of curvature is equal to 4.634 mm. To avoid the problem of interference we have chosen a tool radius equal to 4 mm. The selected parameters for this surface are as follows: feed rate = 50mm/min, distance between two planes = 2 mm, number of triangles in each direction = 200, orientation of the vertical plane = 90°, and degree = 3.

For the accuracy we have considered three values, 0.1, 0.05 and 0.01, and the results for the cutter-contact points, the tool-center points and the cutter-location points are given in Table 1, Table 2 and Table 3, respectively, and Fig. 5 represents the



a- First surface *b- Second surface*

Fig. 4. *The two considered surfaces*

Table 1. *Results of the approximation with the B-Spline curves for the first surface with an accuracy of 0.1*

	C_C points	C_E points	C_L points
Points of intersection	9023	9023	9023
Total number of control points	225	230	230
Percentage of reduction	97.5	97.45	97.45
Error C_1	0.0952	0.0947	0.0947
Error C_2	0.0029	0.002	0.002

Table 2. *Results of the approximation with the B-Spline curves for the first surface with an accuracy of 0.05*

	C_C points	C_E points	C_L points
Points of intersection	9023	9023	9023
Total number of control points	240	230	230
Percentage of reduction	97.34	97.45	97.45
Error C_1	0.0479	0.0497	0.0497
Error C_2	0.0013	0.0014	0.0014

Table 3. *Results of the approximation with the B-Spline curves for the first surface with an accuracy of 0.01*

	C_C points	C_E points	C_L points
Points of intersection	9023	9023	9023
Total number of control points	375	355	355
Percentage of reduction	95.84	96.07	96.07
Error C_1	0.0098	0.0099	0.0099
Error C_2	0.0004	0.0002	0.0002

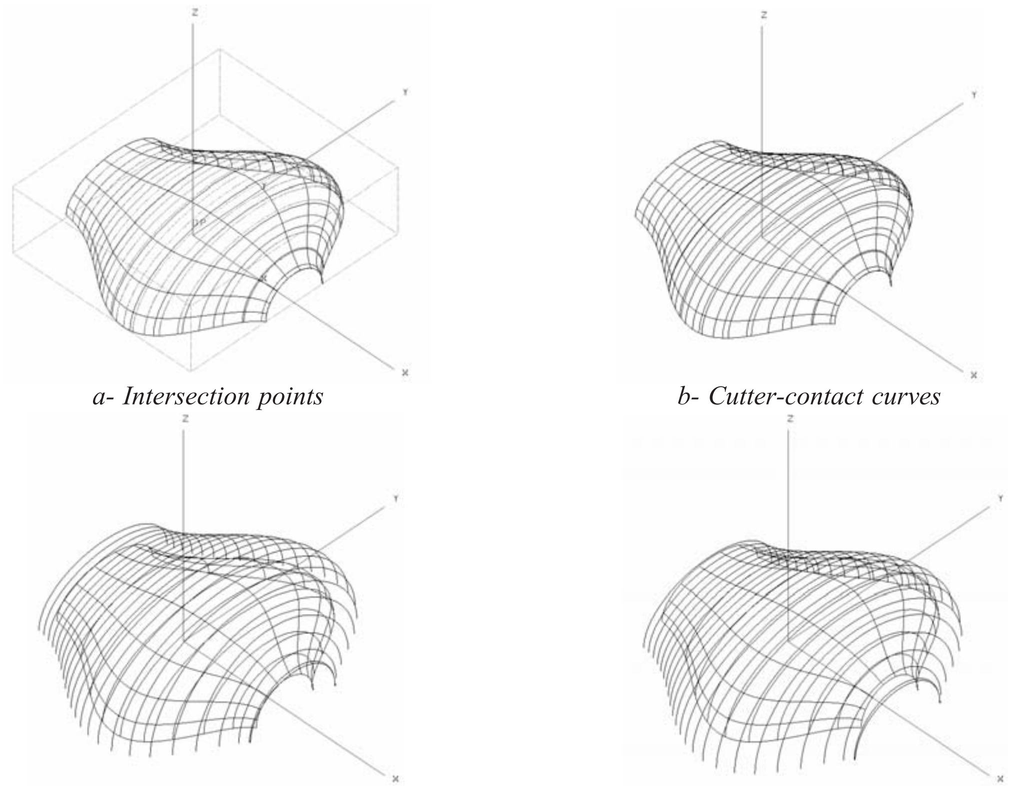
generated curves. The obtained results show a good approximation of the data points with the B-Spline curves and an important reduction in the number of points that exceeds 95 percent. The running times for the three cases are 1 min, 1 min 30 sec, and 2 min 30 sec, respectively, and the maximum number of control points are 10, 15 and 20, respectively.

The dimensions of the second surface are 102 mm × 160 mm × 51 mm and the minimum principal radius of curvature is equal to 12.844 mm. To avoid the problem of interference we have chosen a radius of the tool equal to 10 mm. The parameters for this surface are as follows: feed rate = 50mm/min, distance between two planes = 5mm, number of triangles in each direction = 200, orientation of the vertical plane = 0°, accuracy = 0.1 mm, and degree = 3.

The obtained results from these data are given in Table 4, and Fig. 6 represents the generated curves for the cutter-contact points, the cutter-center points and the cutter-location points. For this example, the maximum number of control points is equal to 10 and the software takes 1 min 30 sec to generate the curves. The results show a good approximation with the B-Spline curves and an important reduction in the number of points that exceeds 97 percent.

It is very important to mention that the percentage of the reduction in the number of control points depends on the number of data points, the distance between these points, the shape of the data points and on the imposed accuracy of the approximation. We must also mention that the maximum number of control points increases with the imposed accuracy.

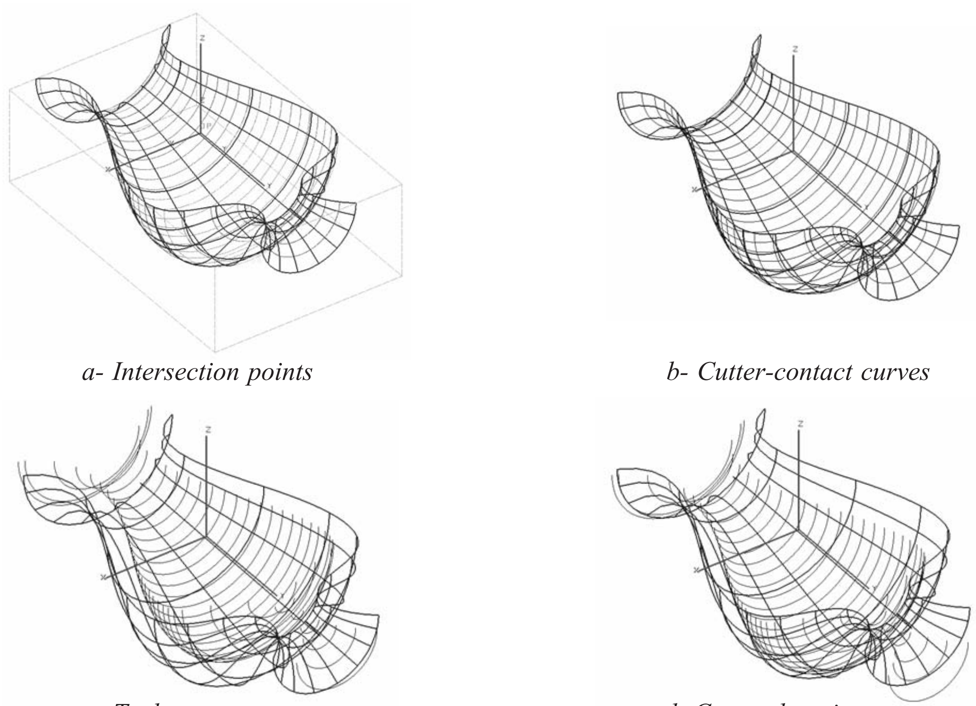
For the generation of the B-Spline curves, the software takes a time that depends on the following parameters: the shape complexity and the dimensions of the surfaces, the distance between two planes, the number of curves and the data points



a- Intersection points *b- Cutter-contact curves*

c- Tool-center curves *d- Cutter-location curves*

Fig. 5. *The first considered surface and the generated B-Spline curves*



a- Intersection points *b- Cutter-contact curves*

c- Tool-center curves *d- Cutter- location curves*

Fig. 6. *The second considered surface and the generated B-Spline curves*

Table 4. *Results of the approximation with the B-Spline curves for the second surface*

	C_C points	C_E points	C_L points
Points of intersection	13033	13033	13033
Total number of control points	330	320	320
Percentage of reduction	97.47	97.54	97.54
Error C_1	0.095	0.1	0.1
Error C_2	0.0026	0.003	0.003

for each curve, the imposed accuracy and the CPU of the computer.

4 CONCLUSION

In this paper we have presented a method that enables us, from CAD models of surfaces, to machine with a parallel-plane machining strategy on 3-axis CNC milling machines, the automatic generation of the tool path with B-Spline curves that satisfy a given accuracy and with a minimum number of control points. These curves make it possible to obtain a good surface finish and an important reduction in the size of the machining program and consequently the necessary memory. The presented method can be used for other machining strategies without much difficulty. In terms of this work, and in order to accelerate the generation of B-Spline curves, it is very important to develop a distributed application because the calculations for each curve can be done on separate computers or a computer with several processors can be used.

In the next step of our work, we would like to verify the obtained results by machining a real part on a CNC machine equipped with this interpolation.

5 REFERENCES

[1] D. V.Sundararajan, K. P. Wright (2003) Zig-zag tool path generation for sculptured surface finishing, *Workshop on Computer Aided Design and Manufacturing*, October 7-9, DIMACS Center, Rutgers University, USA.

[2] B. K. Choi, C. S. Jun (1989) Ball-end cutter interference avoidance in NC machining of sculptured surfaces, *Computer Aided Design*, Volume 21, pages 371-378

[3] B. K. Choi, C. S. Lee, J. S. Hwang and C. S. Jun (1988) Compound surface modeling and machining, *Computer Aided Design*, Volume 20, pages 127-136

[4] E. Duc (1998) Usinage de formes gauches contribution à l'amélioration de la qualité des trajectoires d'usinage, *Thèse de doctorat,* École Normale Supérieure de Cachan, France

[5] D. C. H. Yang, Z. Han (1999) Interference detection and optimal tool selection in 3-axis NC machining of free-form surfaces, *Computer Aided Design*, volume 31, pages 303-315

[6] S. C. Park (2003) Tool path generation for Z-constant contour machining, *Computer Aided Design*, Volume 35, pages 27-36

[7] D. OuYang, B. A. Van Nest, H. Y. Feng (2004) Automatic ball-end milling tool selection from 3D point cloud data, *Flexible Automation and Intelligent Manufacturing*, FAIM2004, pages 253-260, Toronto, Canada.

[8] D. OuYang, B. A. Van Nest, H. Y. Feng (2005) Determining gouge free ball-end mills for 3D surface machining from point cloud data, *Robotics and Computer Integrated Manufacturing*, volume 21, pages 338-345

[9] R. B. Jerard, B. K. Fussell, J. G., Hemmett, M. T., Ercan (2000) Toolpath optimization: A case study, *Proceedings of the NSF Design & Manufacturing Research Conference*, Vancouver, British, Columbia, Jan 3-6.

[10] R. B. Jerard, B. K., Fussell, M. T. Ercan (2001) On-line optimization of cutting conditions for NC machining, *Proceedings of the 2001 NSF Design, Manufacturing & Industrial Innovation Research Conference*, Tampa, Florida , Jan 7-10.

[11] Lin and Liu (1998) Automatic generation of NC cutter path from massive data points, *Computer-Aided Design* volume 30, pages 77–98.
[12] J. W. Choi, S. M. Hur1 and S. H. Lee (2002) Free-form surface generation from measuring points using laser scanner, *International Journal of the Korean Society of Precision Engineering*, Vol. 3, No. 4, pages 15-23.
[13] C. Park (2003) Tool path generation from measured data, *Computer-Aided Design*, volume 35, pages 467–475.
[14] H. Y. Feng, Z. Teng (2005) Iso-planar piecewise linear NC tool path generation from discrete measured data points, *Computer-Aided Design*, volume 37, pages 55–64.
[15] P. Breteau, F. Thiébaut, P. Bourdet, C. Lartigue (2006) Towards an approach for rapid copying of free form surfaces in 5 axis machining, IDMME 2006 Grenoble, France, May 17-19.
[16] K.L. Chui, W.K. Chiu, K.M. Yu (2007) Direct 5-axis tool-path generation from point cloud input using 3D biarc fitting, *Robotics and Computer-Integrated Manufacturing*.
[17] R. B. Jerard, S. Z. Hussaini, R. L. Drysdale, and B. Schaudt (1989) Approximate methods for simulation and verification of numerically controlled machining programs, *The Visual Computer*, Volume 5, no. 6.
[18] R. B. Jerard, R. L. Drysdale, K. Hauck, B. Schaudt, J. Magewick (1989) Methods for detecting errors in sculptured surface machining, *IEEE Computer Graphics and Applications*, Volume 9, pp 26-39, 1989.
[19] J. C. Léon (1991) Modélisation et construction des surfaces pour la CFAO, *Edition Hermes*, France
[20] G. Farin (1992) Courbes et surfaces pour la CGAO, *Edition Masson*, France `
[21] M. Daniel (1989) Modélisation de courbes et surfaces par des B-Spline, Application à la Conception et à la visualisation de formes ", *Thèse de Doctorat*, Université de Grenoble, France
[22] M. Dixon, M. Lima (1997) OpenGL programming guide, *Addisson-Wesley Publishing Company*

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Preizkusna raziskava sinhronizacije dvovretenske stružnice

Experimental Investigation into the Synchronization of a Double-Spindle Lathe

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V prispevku so prikazani rezultati preizkusne raziskave stružnice VENUS 350, izdelane v CBKO iz Pruszkowa (Poljska). RK stružnica je opremljena z dvema vretenoma. Merili smo vrtilne hitrosti obeh vreten, sinhronizacijo napake in pogonske navore motorjev, glavnega in nasprotnega. To omogoča ovrednotenje postopka sinhronizacije.

(Ključne besede: RK stružnice, sinhronizacija, vrtilne hitrosti, servopogoni, pogonski navor)

In this paper we show the results of an experimental investigation of a VENUS 350 lathe, manufacture by CBKO in Pruszkow, Poland. This CNC lathe is equipped with two spindles. We have measured the rotational speeds of both spindles, the synchronization error and the driven moments of the motors, main and opposite. With this information it was possible to evaluate the process of synchronization.

(Keywords: CNC lathe, synchronization, rotational speeds, servo-drives, moment of inertia)

0 INTRODUCTION

Modern CNC lathes are very often equipped with two spindles: the main spindle and the opposite spindle. Such a feature should make complete machining possible, as it means being able to machine first on the right-hand side of the workpiece and then on the left-hand side of the workpiece without stopping the machine tool. The opposite spindle chucks the workpiece on the right-hand side, while the main spindle chucks the workpiece on the left-hand side. This means that there is a short time when the workpiece is chucked on both sides. Of course the spindles, main and opposite, have to have exactly the same rotational speed, i.e., they should be synchronized. But what is important from the point of view of productivity of the machine tool and the quality of the workpiece? First, the time of synchronization should be as short as possible. Second, the moment of chucking the workpiece with the opposite spindle is important from the point of view of the quality of the workpiece due to the possibility of slip between the chuck and the workpiece (if the rotational speed of the workpiece and the opposite spindle differ). The paper shows the results of an experimental investigation of a lathe, manufactured in Poland. Such a CNC lathe is equipped with two spindles. We have measured the rotational speeds of both spindles, the synchronization error and the driven moments of the motors, main and opposite. This made it possible to evaluate the process of synchronization.

1 THE BASIC PROBLEMS OF SYNCHRONIZING A TWO-SPINDLE CNC LATHE

In the newest lathes and turning centers the idea of automatic workpiece reclamping, called the intercept spindle, is used. The idea of such a spindle does not seem to be complicated. There are two spindles: the main (M) and the auxiliary (A), as is shown in Fig. 1a). The main spindle rotates and a workpiece is clamped in the chuck. The second auxiliary spindle may rotates too, and it also has the possibility to move along the lathe axis.

There are two main problems to be solved if such a concept is to work successfully:

- Coaxiality, between the axis of the main spindle and the direction of movement of the auxiliary spindle,
- Synchronization of the rotation speeds of the main and auxiliary spindles.

If the coaxiality of both spindles is insufficient the workpiece may be destroyed during reclamping. The coaxiality of both spindles depends first of all on the geometric accuracy of the machine tool. The newest lathes and centers belong to the high-accuracy group of machine tools and in most cases there is no problem with coaxiality.

More important is the second technical problem, connected with the synchronization of the rotating spindles. Both spindles have to have the same speed at the moment of reclamping. This is a very hard to achieve condition because the drives of the main and auxiliary spindles are independent, and only the CNC has any influence on the actual speeds of the spindles. This problem is the main subject of our paper. We would like to present some results of an investigation performed in CBKO Pruszkow, Poland, where such an idea of reclamping was applied to the Venus 350 CNC lathe [1]. The mechanical and kinematic scheme for the synchronization system is shown in Fig. 1b).

What is important from the point of view of the synchronization of the two spindles?

- The rotational speeds ω_M and ω_A have to be the same at the moment of reclamping;
- The time of synchronization should be as short as possible, for reasons of productivity;
- Defining the moment of reclamping, which means to identify the time when the signal for clamping the chuck of the auxiliary spindle should be sent from the CNC to the chuck;
- What the signal controlling both drives should look like.

Both drives, from the main and auxiliary spindles, work as servodrives, which means that there are two encoders working as feedbacks and the CNC controller, which generates the signals ϕ_{Mgiv} and ϕ_{Agiv} as given values of the rotational motion of both spindles.

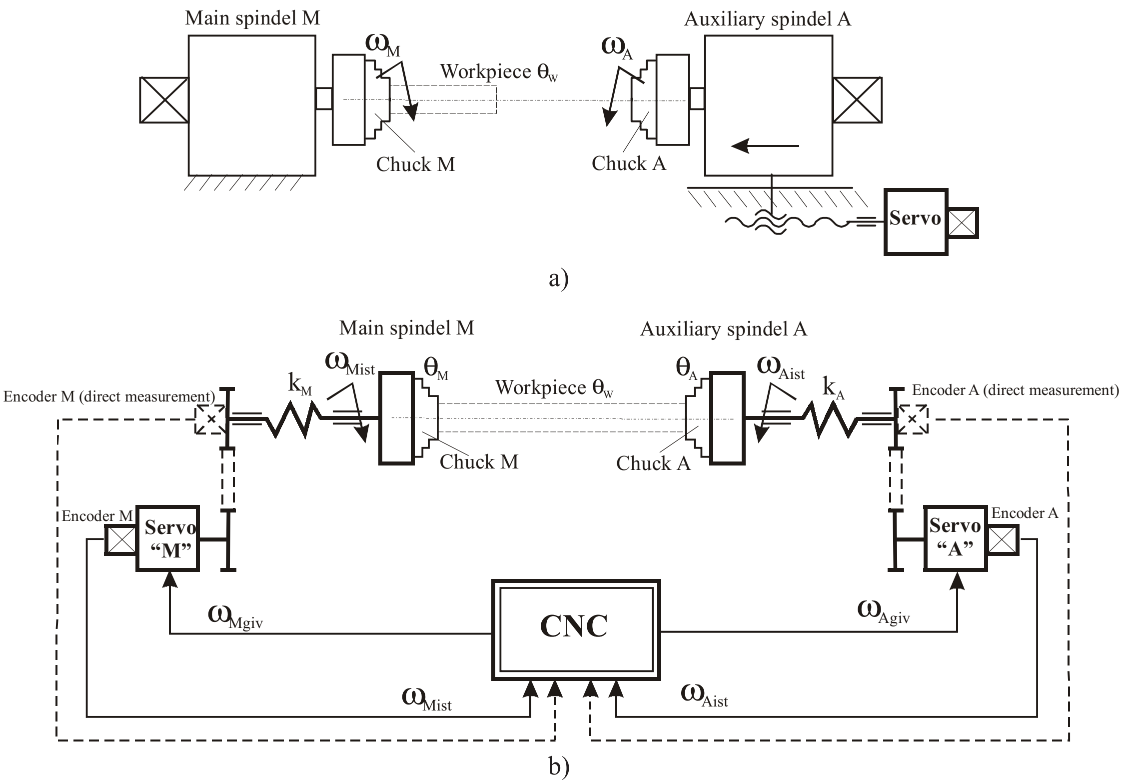

Fig. 1. *Concept of automatic workpiece reclamping using two spindles (a) and* the k*inematic scheme of the synchronization while reclamping the workpiece on the CNC lathe (b)*

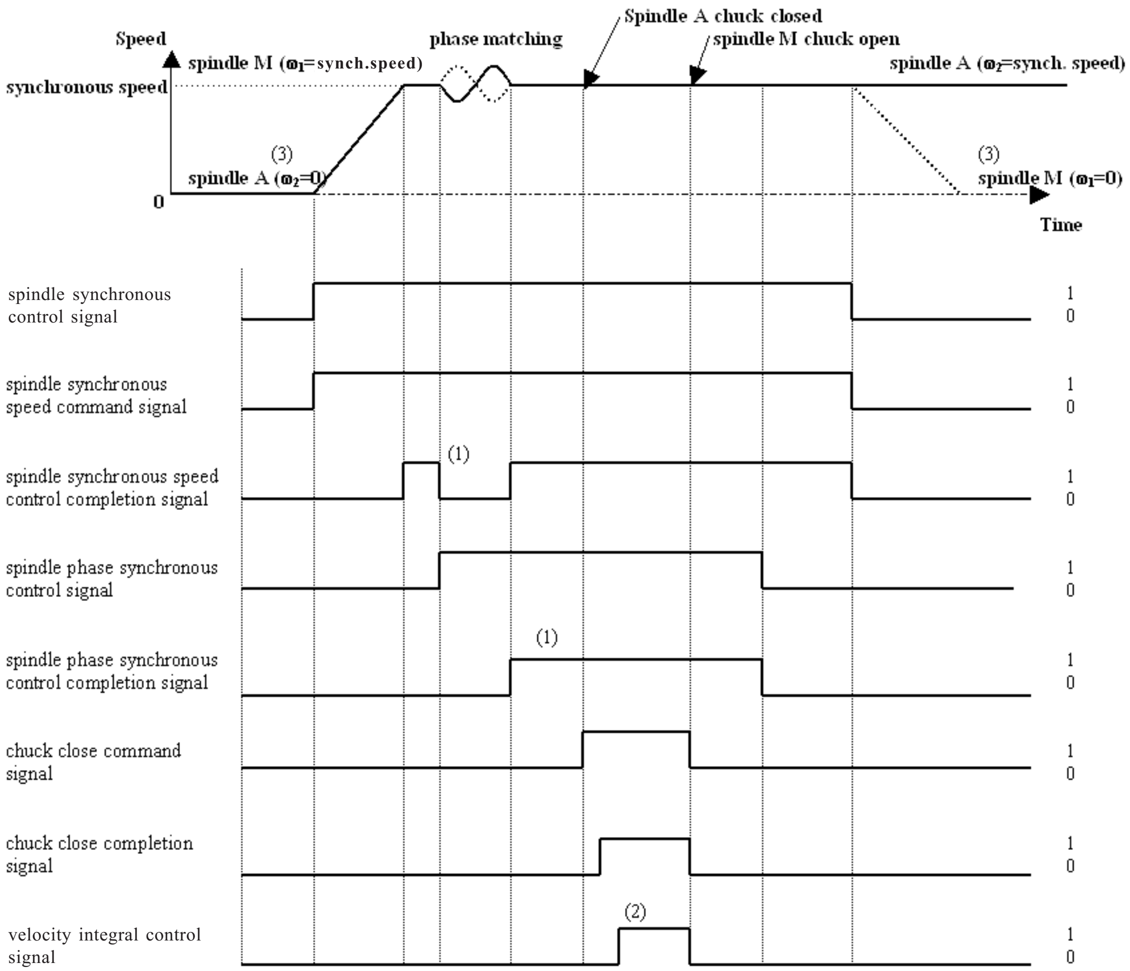

Fig. 2. *Scheme of time performance of the control signals*

The quality of the synchronization process depends first of all on the time performance of the ϕ_{Mgiv} (t) and ϕ_{Agiv}(t) signals, on the stiffness properties k_M and k_A of the mechanical parts of the kinematic chains of both spindles and on the inertial moments Θ_M and Θ_A of the chucks and the workpiece. This means that a special schedule of time performance for all the signals has to be implemented in the CNC controller of the machine tools. Fig. 2 shows an example of such a schedule that we have used in our investigation.

2 EXAMPLES OF EXPERIMENTAL TESTS

We made several experiments using a control algorithm like that in Fig. 2. During the investigation we measured parameters like the moments, M, of both servodrives, the rotational speed, ω, of both drives, and the synchronization error, ε, defined as the difference between the rotational speed of the main and auxiliary spindles. An example of the time performance of the measured parameters during the process of reclamping is shown in Fig. 3 and Fig. 4 (the rotational speeds of both servodrives are shown in rev/min, the moment, M, in Nm, but the synchronization error, ε , is in specific units).

We have made several experiments for different values of the rotational speeds and the time constants of the servodrives [1]. Fig. 3a) presents an example of the time performance of the rotational speed of the main spindle, ω_M, the auxiliary spindle, ω_A, the moment of the main servodrive, M, the synchronization error, ε, for the rotational speed of 1700 rev/min, and the time constant of the servodrives, 30 ms. Fig. 3b) presents another example of the time performance of the rotational speed of the main spindle, ω_M, the auxiliary spindle, ω_A, and the synchronization error, ε, for the same rotational speed of 1700 rev/min, but a longer time constant of the servodrives, 60 ms. Comparing the two it is clear that from the point of view of the synchronization error, ε, the time constant of 60 ms for the servodrives seems to be better than the time constant of 30 ms. For the time constant of 30 ms we can typically observe symptoms of overshoots, like the oscillation of the rotational speed of the auxiliary spindle (for the stationary state of a rotational speed of 1700 rev/min the rotational speed of that spindle reached, in a transient state, up to 2500 rev/min, which means 50% of the stationary state), the synchronization error reached up to 32,000 units and the moment of the auxiliary drive varied by ±100% of the maximum value. For the time constant of 60 ms we observed oscillations too, but these were much smaller. For example, the overshoot of the rotational speed of the auxiliary spindle did not exceed 25% of the rotational speed in the stationary state. The time of the transient state is about 3000 ms, in contrast to the 30 ms time constant, where the time of the transient state was about 50% higher (4500 ms).

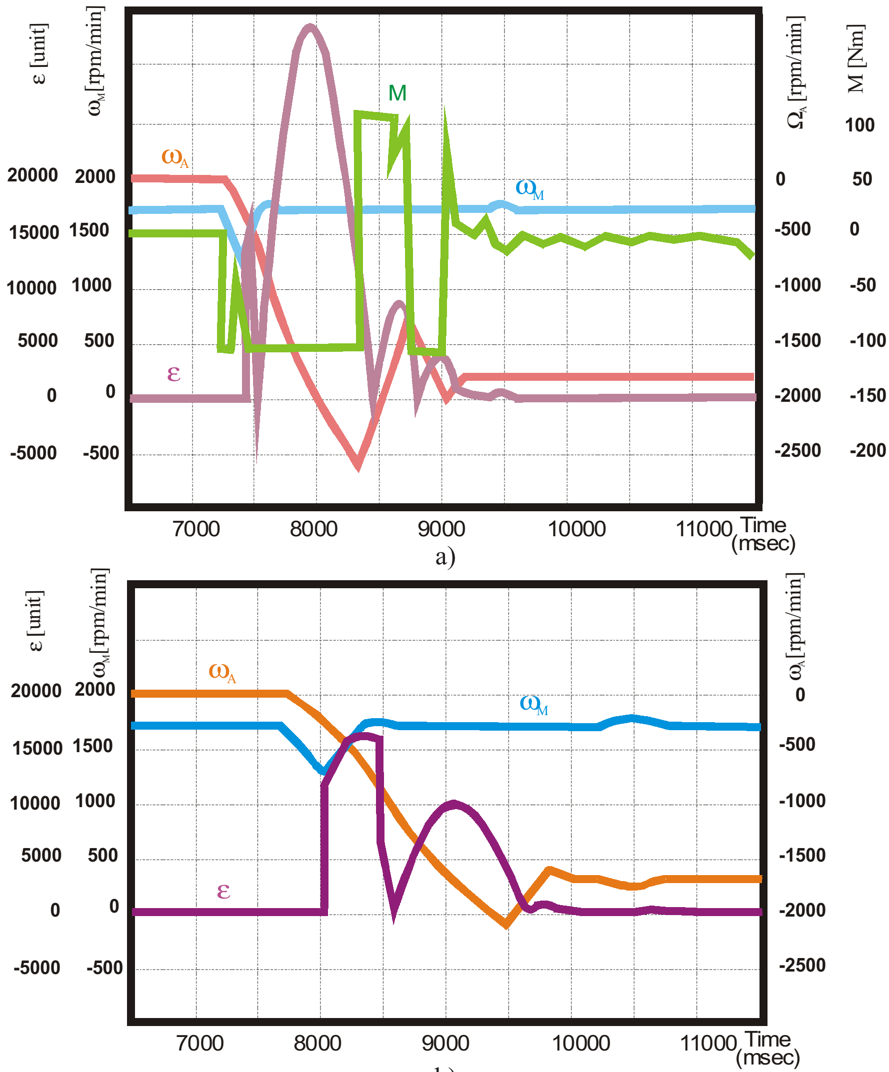

Fig. 4. *Time performance of the rotational speed of the main spindle,* ω_M*, the auxiliary spindle,* ω_A*, the moment of the main servodrive, M, the synchronization error, ε, for a rotational speed of 1700 rev/min: a) time constant of 30ms, b) time constant of 60 ms*

As a general conclusion from our investigation we can say that the problem of synchronizing both spindles during reclamping is a complex and time-consuming process, and the precision and repeatability of the reclamping and the loading of the motors depends on many factors, like:
- the rotational speed of the spindles
- the time constants of both servodrives,
- the quality of the encoders in both drives,
- the quality of the mechanical parts in both the "C and "A" axes.

3 SUMMARY

Our investigation of the synchronization of both spindles while reclamping allows us to make the following conclusions:
- If the rotational speed of the synchronization while clamping is too high the loading on the drives increases a great deal and the time for the process increases (comparing the loading of the drive and the synchronization error while reclamping and after finishing the process, we can say that they differ by a factor of over 100).
- Because the CNC controller has a restriction on the maximum value of the synchronization error, the process of reclamping may fail if the real value of the synchronization error exceeds the limitation value and the machine tool is stopped.
- By finding the appropriate values for the time constants of the servodrives and suitable encoders we were able to increase the rotational speed of reclamping or to decrease the time of the synchronization.

5 REFERENCES

[1] Report of CNC Venus lathe investigation. Machine Tool Research and Design Centre (CBKO) Pruszkow (2005) Poland (not published), (in Polish).
[2] Kosmol J. (1998) Servodrives of numerically controlled machine tools. *Science-Technical Publishing House*, Warsaw (in Polish).

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Določevanje nevtralne točke pri ploskovnem valjanju

Determination of the Neutral Point in Flat Rolling Processes

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Raziskave na področju postopkov valjanja so izrednega pomena, kajti dejstvo je da je bilo veliko število izdelkov med postopkom izdelave vsaj enkrat udeleženo v postopku valjanja. V tem prispevku je analizirano ploskovno valjanje z uporabo analitičnih in metod MKE, z vidika določevanja vpliva zmanjšanja debeline in hitrosti valjanega tračnega jekla ter vpliva tornega količnika na lego nevtralne točke.

Za primerjavo obeh rezultatov modeliranja (analitičnega in MKE) je moč skleniti, da so v dobri sodovisnosti.

V obeh primerih modeliranja je predpostavljeno ravninsko napetostno polje. Na podlagi tega je bila za analizo napetostnega in deformacijskega polja ustvarjena 2-D mreža pri vseh obravnavanih modelih. S takimi modeli je moč določiti premike valjev za različne debeline valjanega tračnega jekla.

Obravnavan proces je štirivaljno oporno valjanje, pri katerem so za analizo mreženi vsi deli z namenom modeliranja napetostnih in deformacijskih polj ter polj pomika in hitrosti.

(Ključne besede: valjanje, modeliranje, metode končnih elementov, SLAB metoda)

Studies of rolling processes are very interesting because a large quantity of produced parts are rolled at some point in their fabrication. In this paper the flat rolling process is analyzed using the FEM and an analytical method in order to determine how the reduction, the velocity of the strip and the frictional coefficient affect the position of the neutral point.

Both the analytical and FEM results are compared and we can say that analytical equations and the FEM modeling are in good agreement.

The plane strain assumption is used in the FEM and in the analytical study, so, in order to study stress and strain, a two-dimensional mesh was considered for all the models. With such models, the deflection of the rolls for different strip thicknesses can be determined.

The studied configuration is a four-high rolling system and the rolls and the strip are meshed in order to obtain their strain, stress, displacements and velocity fields.

(Keywords: rolling, modeling, finite element methods, SLAB method)

0 UVOD

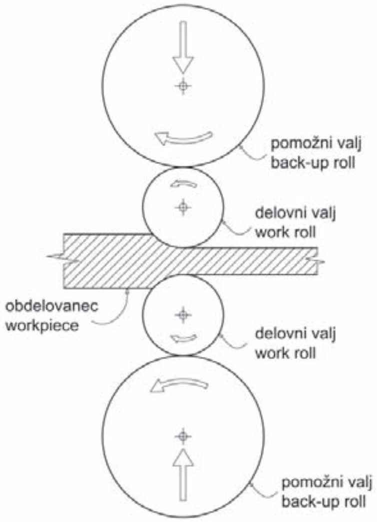
Večina izdelkov na trgu je bila med izdelavo vsaj enkrat vključena v postopek valjanja. Valjanje je postopek plastifikacije materiala, pri katerem se debelina oziroma prerez tračnega jekla zmanjša ali spreminja z uporabo tlačne obremenitve na obdelovanec prek valjev ([1] in [2]). V tem delu je predstavljena primerjava modeliranja postopka z metodo MKE in metodo SLAB ([3] in [4]).

Na sliki 1 je prikazan sistem štirivaljnega opornega valjanja. Tak sistem valjanja je široko

0 INTRODUCTION

Most parts are rolled in at least one of their manufacturing stages. Rolling is a plastic deformation process in which the thickness of a strip or the cross-section of a bar is reduced or changed by applying compressive pressure through a set of rolls ([1] and [2]). In this work, a comparison between a finite element analysis and the SLAB method ([3] and [4]) is presented.

In Figure 1 the four-high rolling configuration is shown. This is a widely used



Sl. 1. *Sistem štirivaljnega opornega valjanja*
Fig. 1. *Four-high rolling mills configuration*

uporabljan, ker so za velika zmanjšanja debeline tračnega jekla potrebne majhne moči. Poleg tega so nadomestni valji ob zamenjavi pri takem sistemu bistveno cenejši od drugih.

Glavni problem pri simuliranju postopkov je popis oz. določitev robnih pogojev sistema. Bolj ko se predpostavljeni robni pogoji ujemajo z dejanskimi, večja je dosežena natančnost simulacijskega modela.

Drugi pomemben vidik, ki mora biti deležen velike pozornosti pri modeliranju, so stiki med posameznimi deli sistema, kar je obravnavano v naslednjem poglavju. Pri simulaciji obravnavanega primera je zaradi geometrijske simetričnosti lahko upoštevana le polovica sistema. To močno zmanjša računski čas brez izgube natančnosti. Ker je dolžina tračnega jekla veliko večja od debeline (1000 mm >> 5 mm), lahko postopek obravnavamo ravninsko, ne da bi pomembno povečali napako modela.

Predmet tega prispevka je določitev položaja nevtralne točke med postopkom valjanja. Izkaže se, da so rezultati, pridobljeni numerično z MKE, primerljivi z rezultati, dobljenimi z metodo SLAB. Za primerjavo

configuration when low power and big reductions are required. Moreover, in this configuration, the rolls are cheaper to replace than in others.

To correctly describe the boundary conditions is one of the most difficult things to do when processes have to be simulated. The more similar the applied boundaries are to those that appear in the real process, the greater the accuracy of the simulation.

Another important aspect to consider is the contact between the different parts of the system. This is discussed in the next section. Only half of the configuration needs to be simulated due to the symmetry of the process. This decreases the calculation time without losing any accuracy. Since the strip's length is much greater than its thickness (1000 mm >> 5 mm) a plain-strain assumption can be employed without any significant loss of precision.

In this paper the location of the neutral point in the rolling processes is studied. The FEM results are compared with those obtained by using the

Preglednica 1. *Simulacije različnih debelin*
Table 1. *Different reductions simulated*

začetna debelina / initial thickness [mm]	5	4,5	4	3,5	3	2,5
končna debelina / final thickness [mm]	2					
zmanjšanje / reduction [%]	60	55,5	50	43	33,3	20

so bila simulirana različna zmanjšanja debeline obdelovanca, kar je prikazano v preglednici 1.

1 ANALIZE MKE IN SLAB

V tem poglavju je predstavljeno modeliranje postopka. Obravnavane izmere valjev so določene na podlagi dejanskega stroja iz industrije [2]. Pomožna oz. oporna valja imata premer 500 mm, medtem ko imata delovna valja premer 200 mm. Začetne in končne debeline tračnega jekla so predstavljene v preglednici 1.

Za modeliranje je najprej potrebno mreženje vseh elementov. Za mreženje sta lahko uporabljeni dve strategiji. Ena od njih je mreženje z majhnimi elementi, pri katerih bodo stiki dobro popisani. Vendar taka metoda močno podaljša računski čas.

Druga možnost je ustvarjanje mreže z večjimi elementi, s tem da se v lokalni okolici stikov, kjer je potrebna večja natančnost, izvede ponovno mreženje z manjšimi elementi ([5] in [6]). Tako je dosežena enaka natančnost ob krajših računskih časih.

V tem prispevku je bila uporabljena slednja metoda, saj obravnava manjše število elementov in tako potrebuje krajše računske čase.

Ponovno mreženje je tu izvedeno le v stičnih območjih, med pomožnim in delovnim valjem ter med delovnim valjem in valjanim tračnim jeklom. Ponovno mreženje v teh območjih je prikazano na sliki 2(a). Pri vseh simulacijah je bilo uporabljeno dvonivojsko ponovno mreženje. S tako metodo je

SLAB method. In addition, different reductions were simulated, as shown in Table 1.

1 FEM AND SLAB ANALYSIS

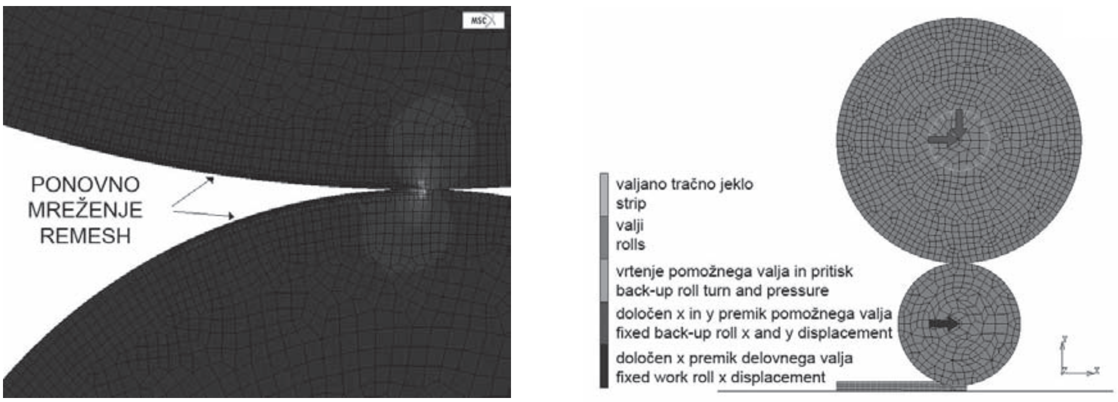
The modeling of the process is presented in this section. The dimensions of the rolls were taken from an actual machine used in industry [2]. The back-up rolls and the work rolls have a diameter of 500 mm and 200 mm, respectively. The initial and final thicknesses of the slabs are presented in Table 1.

Two meshing strategies can be applied to mesh the rolls. Meshing both rolls with a small element, in order to simulate the contacts correctly, is one of them. However, this method will very much increase the computational cost.

Another strategy is to create a mesh with a bigger size of element ([5] and [6]) and introduce a remeshing in the contact zone. This will produce a mesh with a smaller element size in the contact zone, where the precision is needed. This means the same precision, but with a smaller computational cost.

In this paper a second method was employed to reduce the number of elements, which also reduces the time of the calculation.

The remesh is applied to the zone between the back-up rolls and the work rolls and between the work roll and the strip. The remeshing between the rolls during the calculation can be clearly observed in Figure 2 (a). Two levels of remeshing were used in all the simulations. The contact-



(a) Ponovno mreženje v stičnih območjih
(a) Remesh in contact zones

(b) Robni pogoji
(b) Boundary conditions

Sl. 2. *Kriterij ponovnega mreženja in robni pogoji*
Fig. 2.*Remeshing criteria and boundary conditions*

moč dobiti v stičnem območju več vozlišč, kar poveča natančnost določitve stičnega tlaka in gradienta stičnega tlaka.

Za simulacijo postopka valjanja s štirimi valji so potrebni štirje robni pogoji. Prvi je premik valja v smeri *x* (vzporedno osi valjanja), uporabljen v središču delovnega valja. Drugi je pritrditev središča pomožnega valja v obeh smereh (smeri *x* in *y*).

Tretji pogoj je tlak med delovnim in pomožnim valjem, ki neposredno določa potrebno silo za premik delovnega valja. Zadnji robni pogoj je kot zavrtitve pomožnega valja.

Zadnja dva robna pogoja sta določena neposredno iz stikov. Stik med pomožnim valjem in togo gredjo v središču tega valja je deformljiv – tog. V obeh primerih stikov, med tračnim jeklom in delovnim valjem ter med delovnim in pomožnim valjem, sta ta dva obravnavana kot deformljiv – deformljivi stik. Vsi omenjeni robni pogoji so predstavljeni na sliki 2(b).

Z obravnavo zgoraj opisanih stikov se seveda natančnost rezultatov močno poveča, vendar se močno poveča tudi zahtevnost simulacije.

Gibanje pomožnega valja je neposredno povezano s togim stikom (valj – gred). Gibanje je določeno prek gibanja toge gredi, in če je pomožni valj "prilepljen" nanjo, se valj začne gibati, ko se gred obrne.

pressure changes and the contact-pressure gradient can be more accurately described because more nodes exist in the contact zone.

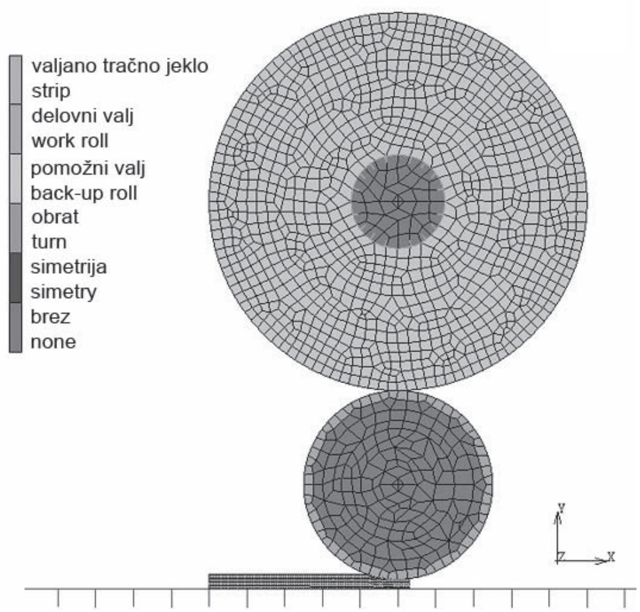
To simulate the four-high rolling process, four boundaries were introduced. The first one is the fixed displacement in the x-axis (parallel to the rolling axis) applied in the center of the work roll back-up roll. Another one is the fixation of the center of the back-up roll in both directions (x-axis and y-axis).

The third condition is the pressure that exists between the back-up roll and the work roll, which introduces the force necessary to move the work roll. The last boundary condition is the turn of the back-up roll.

The last two boundary conditions are introduced by using contacts. The contact between the back-up roll and a rigid circle inside this roll is a deformable-rigid one. Between both the strip and the work roll and between the work roll and the back-up roll a deformable-deformable contact was introduced. These boundary conditions are shown in Figure 2b.

All the above-mentioned contacts increase the accuracy of the solution, but increase significantly the complexities of the simulation.

The motion to the back-up roll is introduced through a contact with a rigid body (a circle). The circle turn is defined through the rigid-body motion option and, as it is glued to the back-up roll, the roll moves as the circle turns.



Sl. 3. *Definicija stikov*
Fig. 3. *Contact definition*

Dodatno je pri simulaciji upoštevana simetrija na podlagi simetričnosti stika togega telesa. Z zamislijo zmanjšanja računskih časov so le zunanji elementi mreže delovnega valja opredeljeni kot stično območje.

Omenjeni stiki so predstavljeni na sliki 3.

Za oba valja je bil izbran linearni elastični model materiala, kjer sta Youngov modul 210 GPa in Poissonov modul 0,3 in predstavljata tipične lastnosti jekla. Za material obdelovanca je bil izbran elasto-plastičen material brez utrjevalnih lastnosti pri deformacijah, in sicer aluminij z Youngovim modulom 70 GPa, Poissonovim modulom 0,3 in zdrsno napetostjo 94,2 MPa.

Tip elementa mreženja v tem prispevku je štirikotnik s popolno integracijo. Po literaturi iz knjižnice elementov MSC ta ponazarja 11. tip elementov [7].

Konvergentna kriterija simulacije sta dva, in sicer pomiki in zaostale napetosti/sile, z namenom določitve bolj natančnih rezultatov. Z izbiro teh dveh konvergentnih kriterijev se sicer računski čas podaljša, vendar se na ta način poveča natančnost rezultatov.

Pomemben dejavnik ostane še velikost časovnih korakov. Le ta je odvisna od več parametrov, to so: velikost elementov mreže, hitrost vrtenja, nelinearnosti: trenje, veliki pomiki in velike deformacije itn.

Rezultati, dobljeni po metodi MKE, so primerjani z analitično metodo SLAB kot primerjavo ([2] in [3]). Nevtralno točko je po metodi SLAB moč izračunati z uporabo enačbe (1) [1]:

Moreover, the condition of symmetry is introduced through the symmetry contact rigid body. In order to decrease the time of the calculation, only the external elements of the work roll were introduced as a contact.

These contacts can be seen in Figure 3.

A linear elastic model was chosen for both rolls with a Young's modulus of 210 GPa and a Poisson's modulus of 0.3 (typical properties for steels). A non-strain hardening elastic-plastic material model was used to simulate the aluminum strip with a Young's modulus of 70 GPa, a Poisson's modulus of 0.3 and a yield stress of 94.2 MPa.

The element type used in this paper is quad for plane strain with full integration, which is number 11 in the element library of MSC [7].

The model is converged in displacement and force residuals in order to ensure accurate results. By using these two convergence criteria, the time of the calculation increases, but a higher accuracy is obtained.

The time step is an important factor to be determined, thus it is greatly influenced by a large number of factors such as element size and rotational velocity, and non-linearities such as friction, large displacements and large deformations, etc.

The results obtained with the FEM are compared with the SLAB analytical method ([2] and [3]). The neutral point can be calculated by the SLAB method using Equation (1) [1]:

$$\frac{h_e}{h_s} = e^{\mu(He - 2H)} \quad (1),$$

kjer je μ Columbov torni koeficient in:

where μ is the Coulomb friction coefficient and:

$$He = 2\sqrt{\frac{R}{h_s}}\tan^{-1}\left(\sqrt{\frac{R}{h_e}}\theta_e\right) \quad (2)$$

$$H = 2\sqrt{\frac{R}{h_s}}\tan^{-1}\left(\sqrt{\frac{R}{h}}\theta\right) \quad (3).$$

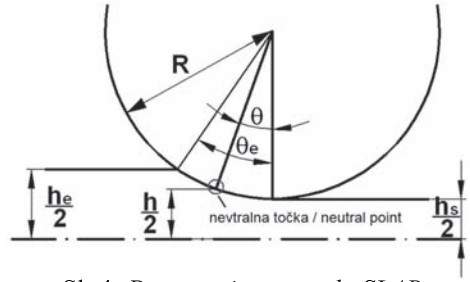
Lego nevtralne točke (h) in kota (θ) je moč določiti s slike 4, kakor določa enačba (4):

The position between the neutral point h and the angle θ can be obtained from Figure 4, as Equation (4) shows:

$$h = h_s + 2R(1 - \cos\theta) \quad (4).$$

Z združitvijo enačb (1) do (4), je lega nevtralne točke analitično določena.

Using Equations (1) to (4), the position of the neutral point can be analytically obtained.



Sl. 4. *Parametri za metodo SLAB*
Fig. 4.*Parameters for the SLAB method*

2 REZULTATI

Lega nevtralne točke, kjer pride do spremembe v zmanjšanju debeline obdelovanca, je bila analizirana z različnimi spremembami modeliranja z MKE. Vsi ti rezultati so primerjani z analitično pridobljenimi na podlagi metode SLAB.

Na podlagi enačb (1) do (4) za različna zmanjšanja (pregl. 1), so bile določene lege nevtralne točke (h). Rezultati teh enačb so predstavljeni na sliki 6(b).

Določitev nevtralne točke po MKE je mogoča na več načinov. Ena od njih je spremljanje hitrosti vozlišča na tračnem jeklu, ki bo v stiku z valjem, in jo primerjati z hitrostjo valja. Ko sta hitrosti enaki, pomeni vozlišče nevtralno točko. To matematično pomeni določevanje nevtralne točke z iskanjem presečišča hitrosti.

Na sliki 5(a) sta prikazana poteka hitrosti vozlišča in valja v odvisnosti od pomika x. Hitrost valja je stalna, in sicer 196,35 mm/s. Ob

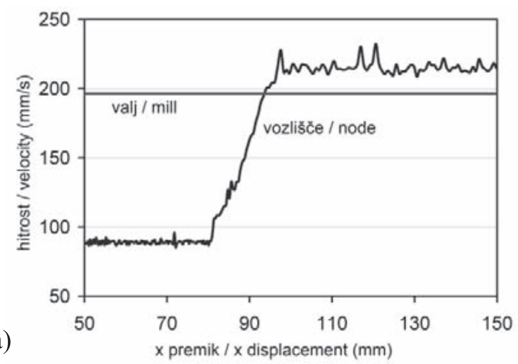
2 RESULTS

From different FEM modelings, the position of the neutral point, when the reduction changes, was obtained. These results were compared with the results obtained using the equations from the SLAB method.

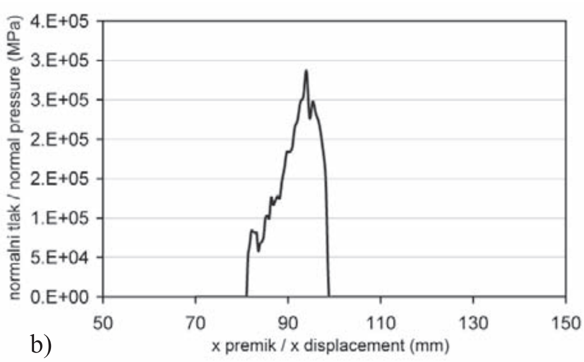
Using Equations (1) to (4), the positions of the neutral point h for each reduction of Table 1 were obtained. The curve obtained using these equations can be seen in Figure 6 (b).

There are several ways of obtaining the position of the neutral point in FEM simulations. Plotting the velocity of a node of the strip surface, which will contact the roll, and comparing it with the roll velocity is one of them. When the node velocity equals the roll velocity, the node will be in contact with the neutral point. So in the search for the intersection the neutral-point position is determined.

In Figure 5 (a) the node-velocity plot and the roll velocity versus the x-displacement is shown. The roll velocity is constant and equal to 196.35



a)



b)

Sl. 5. *Določitev nevtralne točke na podlagi metode MKE, na oba načina: z analizo hitrosti in pravokotnega tlaka stika.(a – vzdolžni premik proti hitrost vozlišča za primer h_e=5 mm, b – vzdolžni premik proti pravokotni tlak za primer h_e=5 mm)*
Fig. 5. *Determination of the neutral point from the FEM by both analyses of the velocity discontinuity and the contact normal pressure (a – Longitudinal displacement vs. Node velocity for the case of h_e=5 mm, b – Longitudinal displacement vs. Normal pressure for the case of h_e=5 mm)*

vstopu obdelovanca je hitrost vozlišča manjša od hitrosti valja in je večja na izstopu. To pomeni, da bo nekje vmes v vsakem primeru točka, ko bosta obe hitrosti enaki, kar pomeni križanje obeh krivulj in se imenuje nevtralna točka. Določitev in lega nevtralne točke je prikazana na sliki 5 a).

Drug način določitve nevtralne točke je iskanje največjega tlaka na zunanjem vozlišču tračnega jekla med postopkom valjanja. Tak način določevanja je prikazan na sliki 5 b).

Dodatni način določitve nevtralne točke je z analizo torne sile stika v odvisnosti od pomika *x*, kakor je prikazan na sliki 6 a). Dejstvo je, da trenje nasprotuje relativnemu premiku površin v stiku. To pomeni, ko ima tračno jeklo manjšo hitrost kakor valj, od vhoda do nevtralne točke, oz. večjo, od nevtralne točke do izstopa, se predznak oz. smer torne sile v nevtralni točki zamenjata in sta nična [6].

Na podlagi slik 5 a), 5 b) in 6 a), dobljenih z MKE, je bilo z veliko natančnostjo moč določiti lego nevtralne točke. Razvidno je tudi, da je nevtralna točka vedno na enaki oddaljenosti od začetka na osi *x*.

Lege nevtralne točke, določene z metodo SLAB ob uporabi enačb (1) do (4) in določene z metodo MKE, so prikazane na sliki 6 b). Očitno je, da imata obe krivulji enak težnjo naraščanja in da je lega nevtralne točke bližje izstopu kakor vstopu.

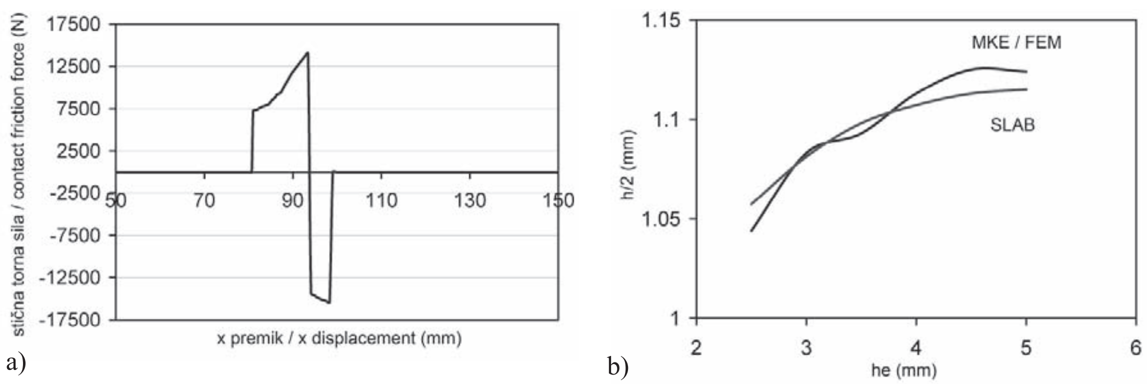
mm/s. The velocity of the node is smaller than the roll velocity at the entrance, but it is higher than the roll velocity at the exit. This means that there will be at least a point were both velocities are equal; that point is the intersection between both curves and it is called the neutral point, which can be clearly determined from Figure 5 a).

Another way to obtain the neutral point is to find the maximum pressure achieved in an external node of the strip while it is being rolled. This pressure evolution can be seen in Figure 5 b).

Another way of obtaining the neutral-point position is to plot the contact friction force versus the x-displacement, as Figure 6 a) shows. The friction opposes the relative displacement of the surfaces in contact. This means that, as the strip has less velocity than the roll from the entrance to the neutral point and a higher velocity from the neutral point to the exit, the frictional force will change its sign at the neutral point, where the frictional force is equal to zero [6].

From Figures 5 a), 5 b) and 6 a) high accuracy in the neutral-point location was obtained with the FEM results. It is possible to see from the three figures that the neutral point is located at the same displacement from the beginning of the *x*-axis.

The position of the neutral point obtained using the SLAB method of Equations 1 to 4 and using FEM modeling is shown in Figure 6 b). As can be seen, both curves have the same tendency and it is clear that the neutral point is closer to the exit than to the entrance.



Sl. 6. *Drug primer določitve nevtralne točke in možnosti primerjave nevtralne točke med analitično in metodo MKE (a – vzdolžni premik proti stična torna sila za primer h_e=5 mm, b – primerjava lege nevtralne točke proti vstopna debelina)*

Fig. 6. *Another way to obtain the neutral point and a comparison of the neutral point for the analytical method and the FEM (a – Longitudinal displacement vs. Contact Frictional Force for the case of h_e=5 mm, b – Comparison of neutral-point location vs. entrance thickness)*

Kljub vsemu je razvidna dobra povezanost med obema metodama (analitično in MKE), čeprav je povezanost boljša pri manjših zmanjšanjih debeline.

Moreover, good agreement between the FEM and the analytical analysis is observed, although the accuracy is greater for small reductions.

3 SKLEPI

V prispevku je predstavljena primerjava modeliranja postopka valjanja z metodama končnih elementov in SLAB. Simulirana so bila različna zmanjšanja debeline tračnega jekla z uporabo štirivaljnega opornega valjanja.

Lega nevtralne točke je bila določena na tri različne načine: Določitev točke, pri kateri se zamenja predznak torne sile stika, analizo spremembe hitrosti in iz vidika pravokotnega tlaka v stiku. Kot končni rezultat določitve nevtralne točke je bilo predstavljeno povprečje vseh treh metod, z namenom določitve natančnih numeričnih rezultatov.

Prikazano je bilo, da se nevtralna točka nahaja blizu izstopa obdelovanca iz postopka valjanja. Poleg tega je bila dokazana dobra soodvisnot med analitično metodo SLAB in numerično MKE.

3 CONCLUSIONS

In this study a comparison between the FEM and the SLAB method was made. Different reductions were simulated, employing a four-high rolling mills configuration.

The neutral-point position for those reductions was determined in three different ways: finding the point where the change in the direction of the contact frictional force occurs, analyzing the change in the velocity, and from the contact normal pressure. The final results were obtained as the mean value of the three ways of measuring the neutral point. This was done with the aim of obtaining good accuracy in the numerical results.

It was shown that the neutral point is close to the exit of the rolling process. Moreover, good agreement exists between the FEM and the SLAB method.

5 LITERATURA
5 REFERENCES

[1] W. L. Roberts. (1978) Cold rolling of steel, *Marcel Dekker*.

[2] A. I. Tselikov, V. V. Smirnov. (1965) Rolling mills, *Metallurgizdat*, Moscú.

[3] D. Kumar, U. S. Dixit. (2006) A slab method study of strain hardening and friction effects in cold foil rolling process, *J. Mater. Process. Technol*., 171, 331–340, 2006.

[4] M. Kazeminezhad, A. Karimi Taheri. (2006) Calculation of the rolling pressure distribution and force in wire flat rolling process, *J. Mater. Process. Technol.*, 171, 253–258, 2006.

[5] Z. Pater. (2006) Finite element analysis of cross wedge rolling, *J. Mater. Process. Technol*., 173, 201–208, 2006.

[6] J. Reyero, J. León, R. Luri, C.J. Luis. (2006) Comparative analysis between FEM and SLAB method for flat rolling process, *TMT 2006*, pp. 781-784.

[7] MSC. Marc Mentat, Volume B: Element types.

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Razvoj sklopke s spremenljivim trenjem z uporabo delovnega sredstva

Development of the Variable Friction Clutch Applying the Functional Medium

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Razvit je bil nov funkcionalen material, poznan kot elektro-reološki gel (ERG), ki spreminja površinsko trenje glede na priključeno električno polje. Pričakovano je bilo, da lahko ERG uporabimo kot strojni element za prenos sile kakršna je sklopka, saj se lahko sila trenja na površini ERG električno uravnava. Enostransko vzorčene elektrode, ki so na izolacijsko osnovo urejene izmenično kot anode in katode, so v nedavni študiji o elektro-reološki tekočini (ERT) predlagane, da poenostavijo sestavo električne napeljave. V tej študiji so enostransko vzorčene elektrode uporabljene na ERG. Numerično in eksperimentalno je raziskan vpliv vzorca enostranske elektrode na učinek ERG. Na podlagi rezultatov vrednotenja elektrodnega vzorca, je razvit element sklopke ERG, ki uporablja enostransko elektrodo z optimalnim vzorcem elektrode. Značilka ERG sklopke je eksperimentalno ovrednotena. Sklopka ERG kaže odlično delovanje za statične in dinamične značilke pri prenosu vrtilnega navora. Enota ERG prikazuje odlično delovanje prenosa vrtilnega navora. Spremembe prenesenega vrtilnega navora so širokega območja in enakomerne v odzivu na variacije v priključenem električnem polju.

(Ključne besede: funkcionalni materiali, elektro-reološke tekočine, viskoelastične lastnosti, torne sklopke)

A new functional material known as electro-rheological gel (ERG) that shows variable surface friction according to an applied electric field has been developed. It was expected that ERG could be applied to a machine element to transfer force such as a clutch, because the frictional force of an ERG surface can be controlled electrically. The one-sided patterned electrodes, which arrange anode and cathode alternately on the insulating base, are proposed in a recent study of electro-rheological fluid (ERF) to simplify the structure of the wiring. In this study, one-sided patterned electrodes are applied to an ERG, and the influence of the pattern of the one-sided electrode on the ERG effect is numerically and experimentally investigated. Based on the results of the electrode pattern evaluation, an ERG clutch element, using the one-sided electrodes with an optimum electrode pattern, is developed and the performance of the ERG clutch is experimentally evaluated. The ERG clutch shows excellent performance for static and dynamic characteristics in torque transfer, and an ERG clutch unit shows excellent performance for torque transfer. The transferred torque changes widely and smoothly in response to the variation of the applied electric field.

(Keywords: functional materials, ER fluids, viscoelastic properties, friction clutch)

0 UVOD

Elektro-reološka tekočina (ERT) ([1] do [4]) je vrsta funkcionalne tekočine z viskoelastičnimi lastnostmi, ki se spreminjajo z intenzivnostjo priključenega električnega polja. Ob priključitvi visokega električnega polja (npr.: 1 kV/mm) delci, potopljeni v osnovno olje, težijo k oblikovanju verig, imenovanih grozdi [1]. To ovira prosti pretok osnovnega olja, kar povzroči strižne napetosti in

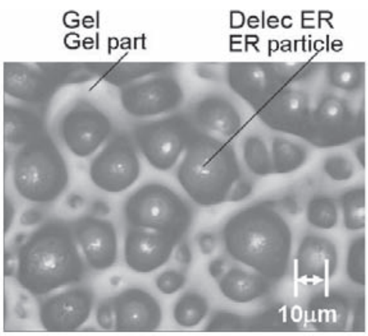
0 INTRODUCTION

Electro-rheological fluid (ERF) ([1] to [4]) is one type of functional fluid with viscoelastic properties that vary with the intensity of an applied electric field. When a high electric field (e.g., 1 kV/mm) is applied, the particles suspended in the base oil tend to form chains called clusters [1]. This inhibits the free flow of the base oil, causing the shear yield stress and the apparent viscosity to očitno povečanje viskoznosti. Lastnosti ERT so bile izkoriščene za nadzor delovanja strojnih elementov. ERT so bile uporabljene v strojnih elementih kot so spremenljivi blažilniki in sklopke ([5] in [6]). Vseeno pa imajo ERT pomanjkljivosti, namreč usedanje delcev ER in zahtevajo tesnilni mehanizem. Usedanje delcev ER zmanjšuje učinke ER in se odziva v majhni stabilnosti naprave ER. Z namenom obvladati usedanje in tako izboljšati delovanje naprav ERT smo s strjevanjem ERT razvili nov funkcionalni material imenovan elektro-reološki gel (ERG) ([7] do [11]). Razviti ERG ni tekočina, temveč trden material, podoben gumi. ERG, ki je sestavljen iz delcev ER in silikonskega gela, spreminja površinsko trenje glede na priključeno električno polje. Ta značilnost se imenuje učinek ERG.

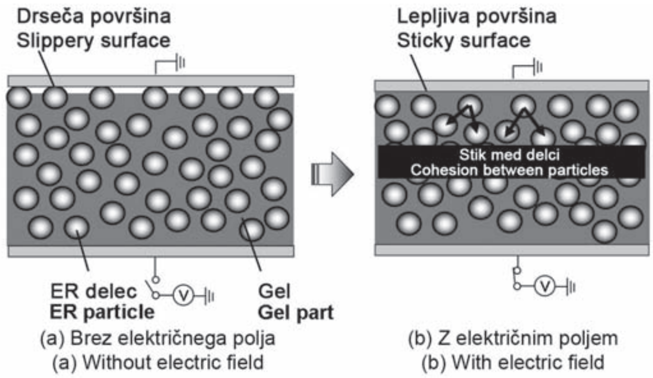
Učinek ER ERT izvira iz lastnosti, da delci ER, potopljeni v osnovno olje, v navzočnosti električnega polja oblikujejo verigo imenovano grozd. Po drugi strani se mehanizem učinka ERG pojavi zaradi sprememb v stičnih razmerah na meji med elektrodo in ERG kot odziv na spremembo jakosti električnega polja [11]. ERG je sestavljen iz delcev ER in silikonskega gela, kakor je prikazano na sliki 1. Mehanizem spremembe v površinskem trenju in adhezija sta ponazorjena na sliki 2. Začetno stanje sendvičev ERG med parom elektrod je prikazano na sliki 2(a). Strižna sila med zgornjo elektrodo in ERG je v odsotnosti električnega polja zelo majhna, ker je zgornja elektroda podprta z drsečimi delci ER, ki molijo iz površine gela. V primeru močnega električnega polja pa v nasprotju, zgornja elektroda ustvari stik z lepljivo površino gela, ker se plavajoči delci umaknejo v gel, kakor

increase. The properties of ERFs have been exploited to control the performance of machine elements, and ERFs have been applied to machine elements such as variable dampers and clutches ([5] and [6]). However, ERFs have disadvantages, namely, the sedimentation of the ER particles and the requirement for a seal mechanism. The sedimentation of ER particles reduces the ER effects and results in the poor stability of ER devices. In order to suppress the sedimentation and thereby improve the performance of ERF devices, we developed a new functional material called electro-rheological gel (ERG) ([7] to [11]) by gelling an ERF. The developed ERG is not a fluid but a solid material like rubber. The ERG, which is composed of ER particles and silicone gel, varies its surface friction according to an applied electric field. This characteristic is called the ERG effect.

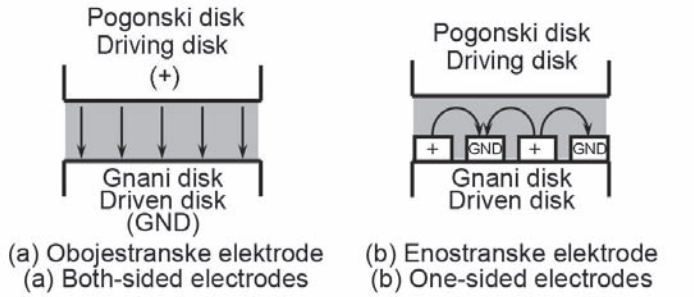
The ER effect of ERFs originates from the fact that the ER particles suspended in the base oil form a chain called a cluster in the presence of an electric field. On the other hand, the mechanism for ERG effect is due to the changes in the contact conditions at the interface between the electrode and ERG, in response to a change in the intensity of the electric field [11]. The ERG is composed of ER particles and silicone gel, as shown in Fig. 1. The mechanism for the change in the surface friction and adhesion is illustrated in Fig. 2. The initial state of the ERG, sandwiched between a pair of electrodes, is shown in Fig. 2(a). The shear force between the upper electrode and the ERG is very low in the absence of an electric field because the upper electrode is supported by slippery ER particles protruding from the gel's surface. In contrast, the upper electrode makes contact with the sticky gel surface in the presence of a high electric field because the protruding particles retract into the



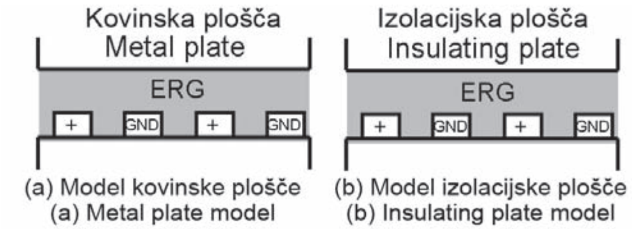
Sl. 1 *Površina ERG*
Fig. 1. *Surface of the ERG*



Sl. 2. *Mehanizem učinka ERG*
Fig. 2. *Mechanism of ERG effect*



Sl. 3. *Osnutek obojestranskih in enostranskih elektrod*
Fig. 3. *Concept of both-sided electrodes and one-sided electrodes*



Sl. 4. *Dva tipa modelov*
Fig. 4. *Two types of models*

je prikazano na sliki 2(b). Tako se zaradi adhezijskih sil gela, ki splava nad površino ERG, poveča strižna sila. Pričakuje se, da je ERG lahko uporabljen v napravi za prenos sile, ker je lahko sila trenja površine ERG električno nadzorovana [11].

Pričujoči prispevek predlaga razpored enostranske elektrode z ERG z namenom poenostaviti sestavo žičnih povezav in omogoča uporabo teh funkcionalnih materialov in različnih polj. Slika 3 prikazuje osnutek električnega polja z uporabo razporeda obojestranskih in enostranskih elektrod. V primeru obojestranskih elektrod nastanejo vzporedne električne silnice, kakor prikazuje slika 3(a). Po drugi strani v primeru enostranske elektrode nastanejo zapletene električne silnice. Učinek ER ERT je bil potrjen z uporabo enostranskih elektrod z ERT [12]. V primeru ERG lahko učinek ERG pridobimo z električnim poljem, ki potuje prek ERG, kar je prikazano na sliki 3(b). Sestava je lahko poenostavljena z uporabo enostranske elektrode, ko je ERG uporabljen v napravah z vrtilnim delom, kakršna je sklopka. V tem prispevku je numerično in eksperimentalno raziskan vpliv vzorca enostranske elektrode na učinek ERG. Na temelju rezultatov vrednotenja vzorcev elektrode je bil razvit element sklopke ERG z razporedom enostranske elektrode. Delovanje sklopke ERG je bilo ovrednoteno s preizkusi.

gel, as shown in Fig. 2(b). Therefore, the shear force increases because of adhesive force of the gel emerging at the ERG's surface. It is expected that the ERG could be used in a force-transfer device, because the frictional force of the ERG's surface can be electrically controlled [11].

The present paper proposes that the one-sided electrode configuration is applied to the ERG in order to simplify the wiring structure and enable the application of this functional material in various fields. Figure 3 shows the concept of an electric field using both-sided and one-sided electrode configurations. As shown in Fig. 3(a), parallel lines of electric force are generated for both-sided electrodes. On the other hand, complicated electric lines are generated for the one-sided electrode configuration. The ER effect of the ERF has been confirmed using one-sided electrodes with an ERF [12]. In the case of the ERG, the ERG effect can be obtained when the electric field passes through the ERG, as shown in Fig. 3(b). When the ERG is used in a device with a rotating part, such as a clutch, the structure can be simplified by using the one-sided electrode configuration. In this paper, the relation between the pattern of the one-sided electrodes and the ERG effect is investigated numerically and experimentally. Based on the results of the electrode-pattern evaluation, an ERG clutch element with a one-sided electrode configuration was developed and the performance was evaluated experimentally.

1 ZVEZA MED NASPROTNIM MATERIALOM IN UČINKOM ERG

1.1 Model za numerično analizo

V predhodni študiji je bilo potrjeno, da je učinek ERG močno odvisen od priključenega električnega polja [11]. Električno polje v razporedu enostranske elektrode potuje prek ERG in je zahtevnejše kakor v primeru razporeda obojestranske elektrode. Poleg tega velja, da se porazdelitev električnega polja v ERG izredno spremeni v odvisnosti od lastnosti materiala plošče nasproti enostranske elektrode (nasprotne plošče) in vzorca enostranske elektrode.

Z namenom, da se razišče vpliv lastnosti materiala na porazdelitev električnega polja, je bila izvedena numerična analiza električnega polja za dva tipa modelov, prikazanih na sliki 4; prvi je *model kovinske plošče, drugi pa model izolacijske plošče*. Pri modelu kovinske plošče je za nasprotno ploščo uporabljen kovinski material, ki je električno neozemljen. V drugem primeru, tj. model izolacijske plošče, je za nasprotno ploščo uporabljen izolacijski material. Za numerično analizo je uporabljen ANSYS 9.0.

Model za analizo električnega polja je podrobno ponazorjen na sliki 5. Uporabljen je dvorazsežni model in opravljena je analiza z MKE. Specifična induktivna kapacitivnost ERG in izolacijske plošče iz bakelita so določene na 30,0

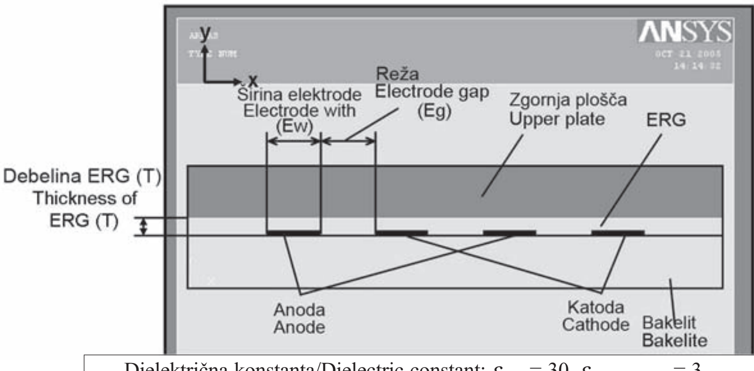
1 RELATION BETWEEN THE OPPOSITE MATERIAL AND THE ERG EFFECT

1.1 Model for numerical analysis

In a past study it was confirmed that the ERG effect relies strongly on the applied electric field [11]. The electric field in a one-sided electrode configuration passes through the ERG, and is more complex than that in a both-sided electrode configuration. In addition, it is considered to remarkably change the electric field distribution in ERG according to material properties of a plate opposite to the one-sided electrodes (opposite plate) and pattern of the one-sided electrodes.

In order to investigate the influence of the material properties on the electric field distribution, a numerical analysis of the electric field was performed for two types of models shown in Fig 4; one is *the metal-plate model* and the other is *the insulating-plate model*. In the metal-plate model, a metallic material is used as the opposite plate, which is electrically floated from ground. On the other hand, in the insulating-plate model, insulating material is used as the opposite plate. ANSYS 9.0 was used for the numerical analyses.

The detail of the model for the electric field analysis is illustrated in Fig. 5. A 2-dimensional model was used and a FEM analysis was carried out. The specific inductive capacity of the ERG and the insulating plate of bakelite was set to 30.0 and 3.0 respectively, which was measured using an



Dielektrična konstanta/Dielectric constant: $\varepsilon_{ERG} = 30$, $\varepsilon_{Bakelit/Bakelite} = 3$
T = 0,3 Ew = 1 mm; Eg = 1 mm
Število elementov/Number of elements: 20580
Analiza stanja zgornje plošče: (a) Kovina: konstanta površina poteciala
Analysis condition of upper plate: (a) Metal: surface potential constant
(b) Izolator: zgornja plošča $\varepsilon = 3$
(b) Insulator: upper plate $\varepsilon = 3$

Sl. 5. *Dejanski model za analizo električnega polja*
Fig. 5. *Actual model for the electric-field analysis*

mm oz. 3,0 mm, in so merjene z metodo elektrodne kapacitivnosti. Debelina ERG je določena na 0,3 mm. Širina elektrode in reža med njimi je 1,0 mm. Istosmerna napetost 900 V je priključena na anodo, medtem ko je katoda ozemljena (0 V).

1.2 Vpliv lastnosti materiala nasprotne plošče na porazdelitev električnega polja

Porazdelitev električnega polja v ERG za enostranske elektrode je ponazorjena na sliki 6. Pri modelu kovinske plošče, prikazanem na sliki 6(a), električna silnica nastane pravokotno iz anode do nasprotne kovinske plošče in prav tako iz nasprotne plošče do katode. Potrjeno je, da ima nasprotna kovinska plošča polovico medelektrodnega potenciala, ko je plošča električno neozemljena. V modelu izolacijske plošče, prikazanem na sliki 6(b), električne silnice nastanejo iz anode do katode ukrivljene oblike in gredo tudi skozi izolacijsko nasprotno ploščo. Vseeno pa gre večina električnih silnic vodoravno na površino ERG in ne more vstopiti na nasprotno ploščo pravokotno, ker je specifična induktivna kapaciteta ERG znatno večja od nasprotne plošče.

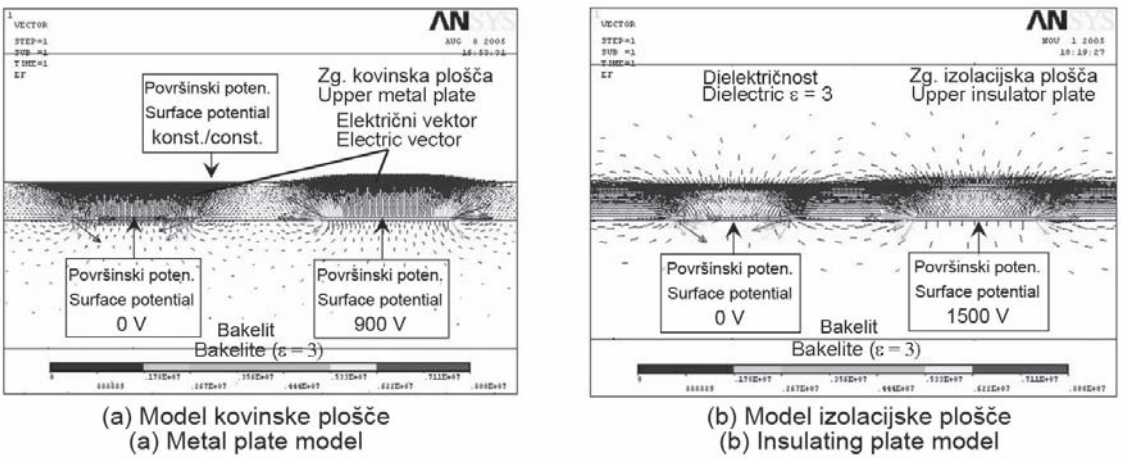
Povprečno električno polje je dobljeno iz rezultatov numerične analize v pravokotni smeri za oba primera modelov, kakor je povzeto v preglednici 1. Domneva se, da je učinek ERG, še posebej komponenta, pravokotna na površino ERG (komponenta y), odvisen od intenzivnosti električnega polja, ker je ta učinek medploskovni pojav med površino ERG in nasprotno ploščo.

electrode-capacitance method. The thickness of the ERG was also set to 0.3 mm. The width and the gap of the electrodes was fixed to 1.0 mm. A DC 900 volts was applied to the anode, while the cathode was connected to ground (0 V).

1.2 The influence of the material property of the opposite plate on the electric-field distribution

The distribution of the electric field in the ERG for the one-sided electrode is illustrated in Fig.6. In the metal-plate model shown in Fig. 6(a), the electric line of force is generated perpendicularly from the anode to the opposite metal plate, and also from the opposite plate to the cathode. It was confirmed that the opposite metal plate had half of the inter-electrode's potential when the plate was electrically floated from ground. In the insulating-plate model, shown in Fig. 6(b), the electric lines of force in the arched shape were generated from the anode to the cathode, and also go thorough the insulating opposite plate. However, most of the electric lines of force go horizontally on the surface of the ERG and cannot enter the opposite plate perpendicularly because the specific inductive capacity of the ERG is set much higher than that of the opposite plate.

From the result of the numerical analysis, the average electric field in the perpendicular direction is obtained in both models, as summarized in Table 1. The ERG effect is supposed to depend on the intensity of the electric field, especially the component perpendicular to the ERG's surface (the y component), because this effect is an interfacial phenomenon



Sl. 6. *Porazdelitev električnega polja za oba modela*
Fig. 6. *Distribution of electric field in each model*

Povprečna intenzivnost električnega polja komponente y na površini ERG v kovinskem modelu je bistveno večja kakor v izolacijskem modelu.

1.3 Preizkusno ovrednotenje učinka ERG

Z namenom ovrednotenja veljavnosti rezultatov numerične analize je učinek ERG za oba modela preizkusno potrjen. Enostranske elektrode so narejene iz plošč za tiskana vezja (TV - PCB). TV se množično uporabljajo v elektroniki in računalniški industriji. Tanke bakrene črte na izolacijski plastični plošči omogočajo povezave med elektronskimi komponentami v obtoku. Enostranske elektrode s postopkom jedkanja preprosto izdelamo z uporabo TV. Enostranske elektrode so oblikovane tako, da je razmik med elektrodami 1 mm. Vsaka elektroda je 1 mm široka s površino elektrode 70×50 mm, kar je prikazano na sliki 7(a). 0,3 mm debela plošča ERG je pritrjena na enostransko elektrodo, kakor je prikazano na sliki 7(b). Osnovno delovanje ERG na enostranski elektrodi je ovrednoteno s preprostim preizkusom, shematično prikazanim na sliki 8. Plošča ERG na enostranski elektrodi je pritrjena na osnovno ploščo in nasprotna plošča je postavljena na ERG ploščo. Nasprotna plošča je aluminijasta oz. bakelitna plošča. Strižno gibanje nasprotne plošče je ustvarjeno z mikrometrskim vijakom z motornim pogonom. Strižna sila je merjena z uporabo obremenilne celice z merilnikom napetosti, ki je pripeta na drsno ploščo. Premik nasprotne plošče je merjen z vrtilnim tokovnim zaznavalom pomika. Obnašanje strižne sile je ovrednoteno s spreminjanjem jakosti električnega polja od 0 do 1,5 kV/mm. Strižna dolžina je nastavljena na 600 μm, medtem ko je strižna hitrost naravnana na 30 μm/s.

Povezava med nastalo strižno napetostjo in spremenljivo jakostjo električnega polja je prikazana na sliki 9, kjer je strižna napetost

between the ERG's surface and the opposite plate. The average electric field intensity of the y component at the surface of the ERG in the metal model is considerably higher than in the insulating model.

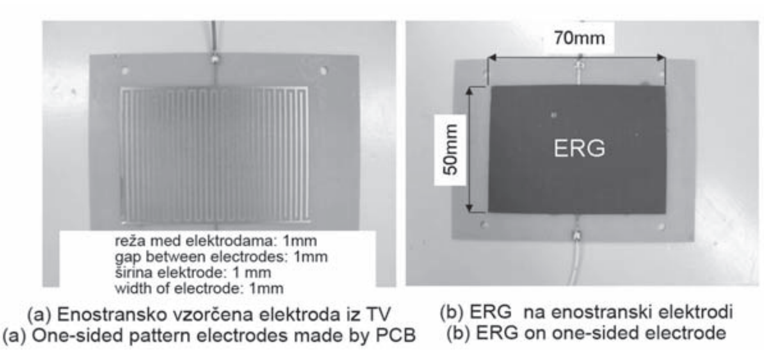
1.3 Experimental evaluation of the ERG effect

In order to evaluate the result of the numerical analysis for its validity, the ERG effect in both models was evaluated experimentally. One-sided electrodes were made from printed circuit boards (PCBs). PCBs are widely used in the electronics and computer industries. Thin copper lines on an insulating plastic board enable the connection between electronic components on the circuit board. One-sided electrodes using PCB plates can be fabricated easily by the process of etching. The one-sided electrode is designed to have a 1-mm gap between the electrodes. Each electrode is 1-mm-wide and the electrode area is 70×50 mm, as shown in Fig. 7(a). A 0.3-mm-thick ERG sheet was molded on the one-sided electrodes as shown in Fig. 7(b). The basic performance of the ERG on a one-sided electrode was evaluated by the simple test schematized in Fig. 8. The ERG sheet on the one-sided electrodes was fixed on the baseplate and the opposite plate was placed on the ERG's sheet. An aluminum plate and a bakelite plate were prepared as the opposite plates. A shear motion was applied to the opposite plate using a micrometer screw with a motor drive. The shear force was measured using a strain-gauge load cell attached to the slider plate. The displacement of the opposite plate was measured using the eddy-current displacement sensor. The behavior of the shear force was evaluated by varying the electric-field intensity from 0 to 1.5 kV/mm. The shear length was set to 600 μm, while the shear speed was adjusted to 30 μm/s.

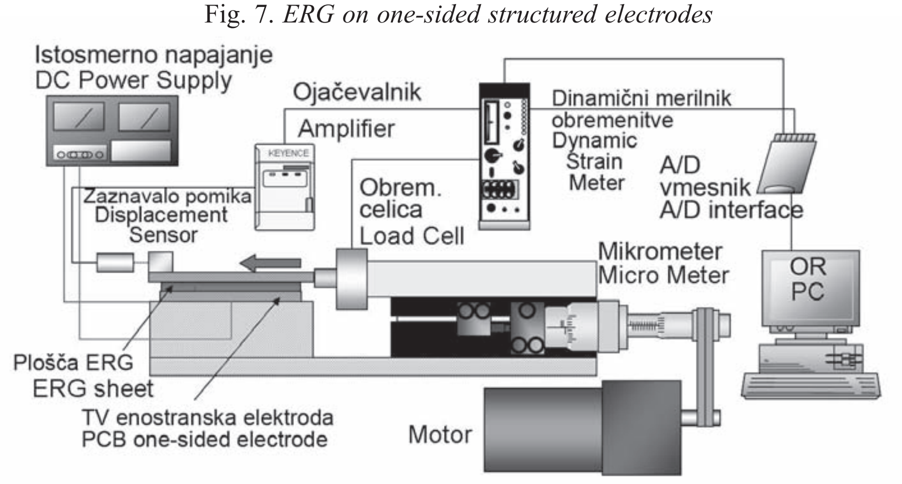
The relationship between the generated shear stress and the variable electric-field intensity is summarized in Fig. 9, where the shear stress is

Preglednica 1. *Povprečno električno polje komponente y [numerično]*
Table 1. *The average electric field of the y component [numerical]*

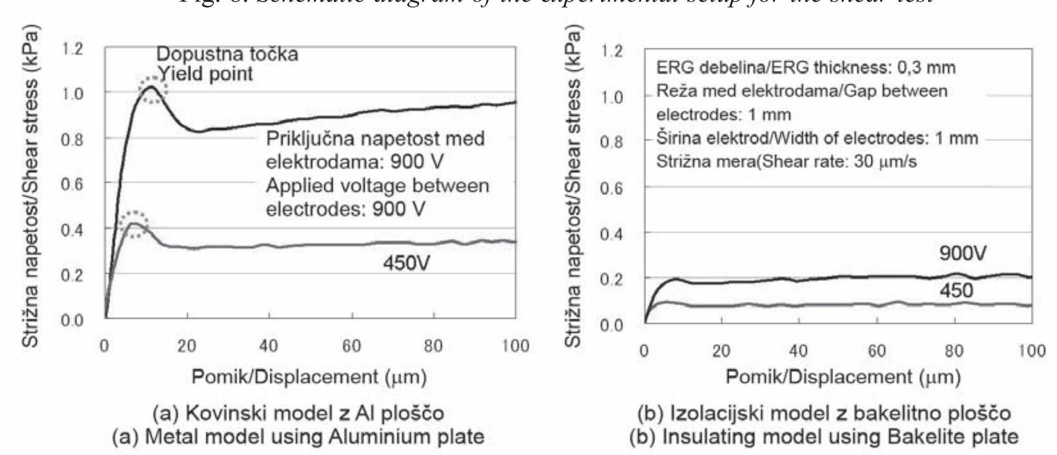
	model kovinske plošče metal plate model	model izolacijske plošče insulating plate model
povprečna jakost električnega polja komponente y [V/mm] average electric field intensity of y component [V/mm]	1000	70



Sl. 7. *ERG na enostransko sestavljeni elektrodi*
Fig. 7. *ERG on one-sided structured electrodes*



Sl. 8. *Shema preizkusa za strižni test*
Fig. 8. *Schematic diagram of the experimental setup for the shear test*

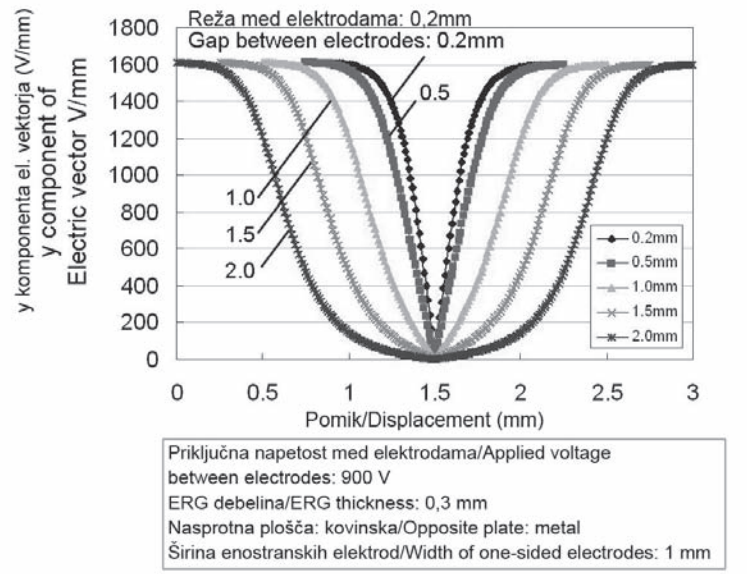


Sl. 9. *Povezava med strižno napetostjo in električnim poljem [s preizkusom]*
Fig. 9. *Relation between the shear stress and electric field [experimental]*

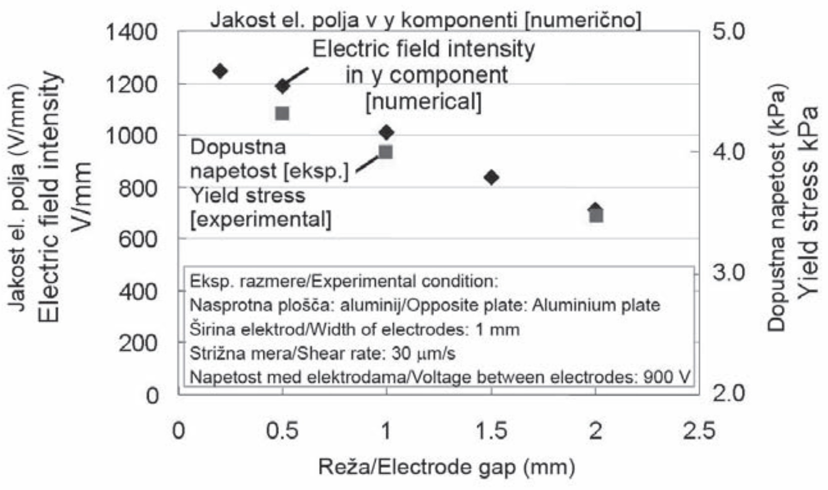
izračunana s količnikom med izmerjeno strižno silo in površino ERG. Razumljivo je, da je učinek ERG ustvarjen v enostranskih elektrodah. Ob premiku nasprotne plošče za vrednost okrog 15 μm plošča ERG popusti. Višje dopustne napetosti so dobljene pod večjimi jakostmi električnega polja. Ustvarjena

calculated by dividing the measured shear force by the surface area of the ERG. Clearly, the ERG effect is generated in one-sided electrodes. When the displacement of the opposite plate exceeds a certain value of about 15μm, the ERG sheet yielded. Higher yield stresses were obtained with higher electric-dopustna napetost je skoraj sorazmerna priključenemu električnemu polju. Ko je priključeno električno polje višje od 2 kV/mm nastane dielektrični zlom. Do dopustne točke se strižna napetost spreminja linearno s pomikom. Nad to točko se strižna napetost le malo poveča. To zaradi zdrsa med površino nasprotne plošče in ploščo ERG. Ob primerjavi kovinskega modela z izolacijskim, je pri kovinskem modelu nastala strižna napetost bistveno večja, kakor v primeru izolacijskega modela pri enaki velikosti priključene napetosti. Zaradi tega je odločeno, da je model s kovinsko ploščo uporaben za element sklopke ERG,

field intensities. The generated yield stress is almost in proportion to the applied electric field. However, when the higher electric field above 2kV/mm was applied, the dielectric breakdown occurred. Up to the yield point, the shear stress varies linearly with displacement. Above the yield point, the shear stress increases only gradually. This is due to the slip between the surface of the opposite plate and the ERG sheet. Compared with the metal model and insulating model, the generated shear stress in the metal-plate model is much higher than in the insulating model under the same applied voltage. Consequently, it is clear that the metal-plate model



Sl. 10. *Porazdelitev y komponente električnega vektorja v primeru različnih rež med elektrodami [numerično]*
Fig. 10. *Distribution of y component of electric vector in case of various electrode gap [numerical]*



Sl. 11. *Razmerje med električnim poljem in dopustno napetostjo kot funkcija reže elektrod*
Fig. 11. *Relation between electric field and yield stress as function of electrode gap*

saj ob priključitvi električnega polja lahko pričakujemo širše spremembe prenesenega vrtilnega navora.

Numerični in preizkusni rezultati kažejo, da je nastala strižna napetost zaradi učinka ERG odvisna od povprečne jakosti električnega polja v smeri komponente y na površino ERG.

2 OBLIKA REŽE ELEKTRODE

2.1 Postopek

Povezava med vzorcem enostranske elektrode in nastalim električnim poljem na površini ERG je raziskana z namenom določiti potrebno obliko za učinkovit vpliv ERG. Numerična analiza je bila izvedena tudi v primeru raziskovanja vpliva reže elektrode na porazdelitev električnega polja v ERG. Numerični model je pokazal enako kakor na sliki 5. Širina elektrode je nespremenjena, 1,0 mm, medtem ko se širina reže spreminja med 0,2 mm in 2,0 mm. Priključen medelektrodni potencial med anodo in katodo je 900 V.

Trije tipi enostranskih elektrod, katerih reže med elektrodami so 0,5, 1,0, 2,0 mm, so bili izdelani. Nastali učinki ERG v vsaki enostranski elektrodi so ovrednoteni s preizkusi pri enaki priključeni napetosti.

2.2 Povezava med režo elektrode in učinkom ERG

Intenzivnost električnega polja komponente y z različnimi režami med elektrodami je bila ovrednotena. Slika 10 prikazuje obnašanje intenzivnosti električnega polja na površini ERG med dvema elektrodama. Intenzivnost električnega polja nekaj nad središčem elektrode (položaj = 0, 3,0) postane velika, ker se intenzivnost električnega polja v sredinski točki med dvema elektrodama zmanjša skoraj na 0 V/mm. Dobljeno razmerje med povprečno vrednostjo električnega polja in režo elektrode je predstavljeno na sliki 11. Z manjšanjem reže elektrode se jakost električnega polja na površini ERG poveča. Strižni test s preizkusno postavitvijo, prikazano na sliki 8, je bil uporabljen tudi za raziskovanje razmerja med dopustno napetostjo in režo elektrode. Aluminijasta plošča je uporabljena za nasprotno ploščo. Preostale preizkusne razmere so enake, kakor so opisane v odstavku 1.3. Potrjeno je, da dopustna strižna

is useful for the ERG clutch element since a wider change of transferred torque with the applied electric field can be expected.

These numerical and experimental results indicate that the generated shear stress due to the ERG effect depends on the average electric field intensity of the y component at the surface of the ERG.

2 DESIGN OF THE ELECTRODE GAP

2.1 Procedure

The relation between the pattern of one-sided electrodes and the generated electric field at the ERG's surface is investigated in order to determine the design necessary to obtain an efficient ERG effect. To investigate the influence of the electrode gap on the distribution of the electric field in the ERG a numerical analysis was also carried out. The numerical model is the same as the one shown in Fig.5. The width of the electrodes was fixed at 1.0 mm, while the gap was varied from 0.2 mm to 2.0 mm. The applied inter-electrode potential between the anode and cathode was 900 V.

Three types of one-sided electrodes, with electrode gaps of 0.5, 1.0, 2.0mm, were prepared and the generated ERG effects in each one-sided electrode under the same applied voltage were evaluated experimentally.

2.2 Relation between the electrode gap and the ERG effect

The electric field intensity of the y component was evaluated for various electrode gaps. Figure 10 shows the behavior of the electric-field intensity on the ERG's surface between the two electrodes. The electric-field intensity just above the center of the electrodes (position=0, 3.0) becomes high while the electric field intensity at the middle point between the two electrode decreases to almost 0 V/mm. The relationship obtained between the average value of the electric field and electrode gap is presented in Fig. 11. As the electrode gap decreases, the electric-field intensity at the ERG's surface increases. To investigate the relation between the yield stress and the electrode gap, the shear test was also carried out using the experimental setup shown in Fig.8. An aluminum plate was used as the opposite plate. Other experimental conditions were the same as described in Section 2.3. It was confirmed that the napetost kaže enako težnjo kakor jakost električnega polja. Ponovljivost numerične analize v tem prispevku je velika.

3 RAZVOJ ENOTE SKLOPKE ERG

3.1 Sestava sklopke ERG

Elektroda za predlagano sklopko ERG je razvita na temelju rezultatov numerične analize električnega polja. Sestava enostranske elektrode za sklopko ERG je prikazana na sliki 12 in ima elektrodno režo 0,2 mm in elektrodo širine 1,0 mm. Premer enostranskih elektrod je 30 mm. Slika 13 prikazuje sestavo naprave s sklopko ERG. Sklopka ERG je sestavljena iz dveh osi z diskoma na eni strani. ERG na enostranski elektrodi je povezan z diskom na podrejeni osi. Vneseni vrtilni navor je iz glavne strani prenesen na podrejeno stran prek ERG. Dolžina obeh osi je 50 mm s premerom 12 mm, premer obeh diskov pa je 40 mm. Razmere v stiku med površino ERG in glavnim diskom so pomembne, če želimo dobiti učinkovit vpliv ER. Zaradi tega je na glavni disk vstavljena malo elastična guma, tako da ima glavni disk enakomeren stik z ERG, postavljenim na podrejeni strani. Ko se glavna os vrti z indukcijskim motorjem, je lahko vrtilni navor, ki je prenesen iz glavne strani na podrejeno, spremenjen v odvisnosti od priključenega električnega polja na ERG.

3.2 Preizkusna postavitev in postopek

Statična značilka sklopke ERG je vrednotena tako, da je preneseni vrtilni navor merjen ob priključitvi stalne napetosti. Shema

yield shear stress shows the same tendency as the intensity of the electric field. The repeatability of the numerical analysis in this paper is high.

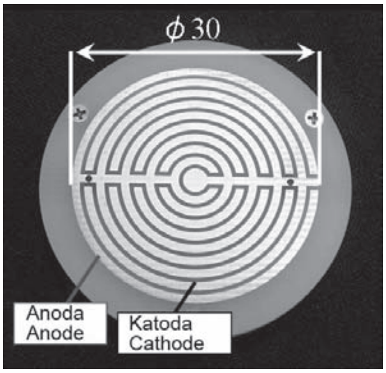
3 DEVELOPMENT OF THE ERG CLUTCH UNIT

3.1 Structure of the ERG clutch

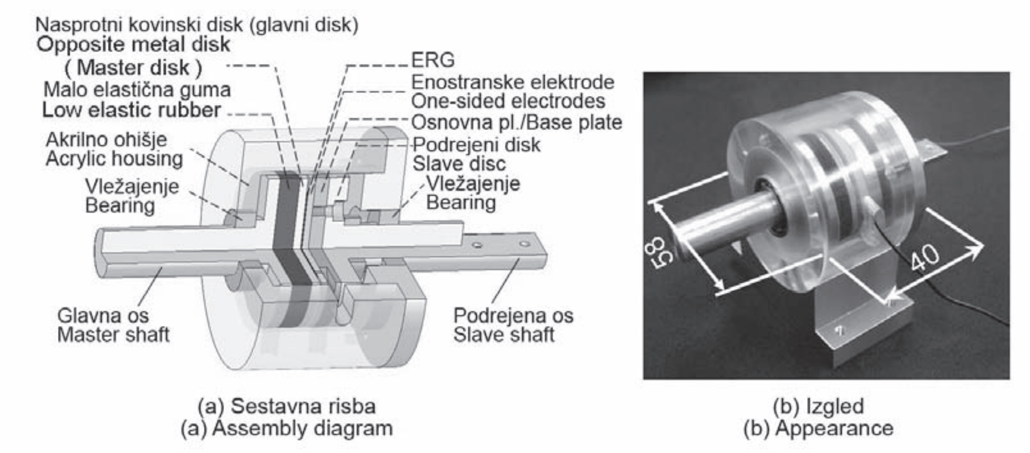
The electrode for the proposed ERG clutch was designed using the results from the numerical analysis of the electric field. The one-sided electrode configuration for the ERG clutch is shown in Fig. 12, and has a 0.2-mm electrode gap and an electrode width of 1.0 mm. The diameter of the one-sided electrodes is 30 mm. Figure 13 illustrates the structure of the ERG clutch device. The ERG clutch is composed of two shafts with the disks on one side. The ERG on the one-sided electrode is set up with the disk of the slave shaft. The input torque is transferred from the master side to the slave side through the ERG. The length and the diameter of the master and slave shafts are 50 mm and 12 mm, respectively, and the diameter of each disk is 40 mm. To obtain an efficient ER effect, the condition of the contact between the ERG's surface and the master disk is important. Thus, a low elastic rubber is inserted at the master disk, so that the master disk has uniform contact with the ERG, placed on the slave side. When the shaft of the master side is rotated by the induction motor, the transferred torque from the master side to the slave side can be changed in response to the applied electric field to the ERG.

3.2 Experimental setup and procedure

To evaluate the static performance of the ERG clutch, the transferred torque was measured under an applied constant voltage. A schematic of



Sl. 12. *Enostranske elektrode s širino 1mm in režo 0,2 mm*
Fig. 12. *One-sided electrodes with 1mm width and 0.2 mm gap*



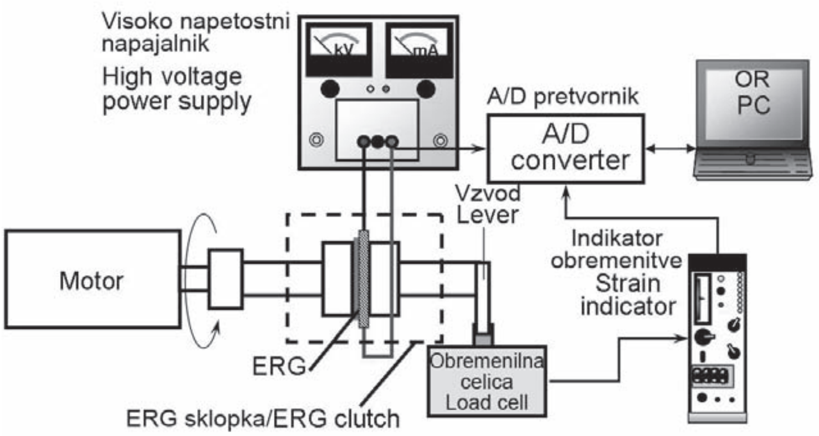
Sl. 13. *Sestava sklopke ERG*
Fig. 13. *Structure of the ERG clutch unit*

preizkusne postavitve je podana na sliki 14. Glavna os je prek spoja povezana z osjo motorja. Vzvod za merjenje vrtilnega navora je pritrjen na podrejeno os in nameščen na obremenilno celico. Ko se glavna os vrti s stalno hitrostjo, je na ERG priključeno električno polje, preneseni vrtilni navor pa je zaznan z obodno silo na koncu vzvoda. Preneseni vrtilni navor lahko izračunamo iz zmnožka zaznane sile in dolžine vzvoda (46,5 mm).

Dinamična značilka naprave za prenos vrtilnega navora s sklopko ERG je prav tako ovrednotena z merjenjem induciranega prenesenega vrtilnega navora ob priključitvi spremenljive napetosti, npr. sinusni ali pravokotni signal vhodne napetosti. Namesto visokonapetostnega vira uporabljenega pri statičnem testu, je bil v tem primeru uporabljen funkcijski generator v kombinaciji z visokonapetostnim močnostnim

the experimental setup used is shown in Fig. 14. The master shaft is connected to a motor shaft through a coupling. The lever used for measuring the torque is attached to the slave shaft, and is set on a load cell. When the master shaft is rotated at constant speed and an electric field is applied to the ERG, the transferred torque is sensed as the tangential force at the top of the lever. The transferred torque can be calculated by multiplying the sensed force by the length of the lever (46.5 mm).

The dynamic performance of the torque-transfer device with the ERG clutch is also evaluated by measuring the induced transferred torque under an applied variable voltage, e.g., a sinus or square wave of the input voltage. Instead of the high-voltage power supply used in the static test, a function generator was used in combination with a high-voltage power amplifier. The



Sl. 14. *Eksperimentalna postavitev za merjenje vrtilnega momenta*
Fig. 14. *Experimental setup for measuring torque*

ojačevalnikom. Preneseni vrtilni navor je merjen z merilnimi lističi obremenilne celice.

3.3 Statična značilka sklopke ERG

Slika 15 prikazuje rezultate statičnega testa, ko je na enostransko elektrodo priključena napetost, ki se zvišuje v korakih po 300 V od 0 do 900 V. Zelo jasna razlika je opažena med vsakim povišanjem napetosti. Višje ko je priključeno električno polje, večji je dobljeni vrtilni navor.

Preizkusni podatki so primerjani s teoretično oceno. Preneseni vrtilni navor s sklopko ERG je določen kot:

$$T = \int_0^R \tau_y \times 2\pi r \times r \mathrm{d}r \quad (1),$$

kjer je τ_y dopustna napetost ERG in R polmer diska; $\tau_y \approx 6$ kPa pri jakosti električnega polja 1,5 kV/mm pri strižni stopnji 30 μm/s ob uporabi obojestranskih elektrod s polmerom R = 15 mm. V predhodni študiji je bilo razjasnjeno, da je napetost tečenja zaradi učinka ERG ustvarjena sorazmerno s priključenim električnim poljem [11]. Povprečno električno polje na površini ERG znaša 1,25 kV/mm pri priključeni napetosti 900 V na enostranske elektrode z režo 0,2 mm, kakor je prikazano na sliki 11. Tako je izračunana τ_y enaka 4,8 kPa teoretični vrtilni navor T, izračunan z enačbo (1), pa približno 0,032 Nm. Ta je manjši od preizkusno merjenega vrtilnega navora. Šteje se, da vrtilna hitrost glavnega diska vpliva na preneseni vrtilni navor. Slika 16 prikazuje zvezo med prenesenim vrtilnim navorom in vrtilno frekvenco glavnega diska ob priključitvi napetosti 900 V. Višja vrtilna frekvenca se kaže v višjih prenosih vrtilnega momenta. Spremenljivka t_y v enačbi (1) je odvisna od jakosti električnega polja na površini ERG in drsne hitrosti (vrtilna hitrost diska sklopke). Vrednost τ_y (= 6 kPa pri 1,5 kV/mm) vstavljena v enačbo (1) je bila veljavna pri zelo majhnih drsnih hitrostih (30 mm/s). Tako je pri zelo majhnih hitrostih (skoraj 0 min^{-1}) na sliki 16 dobljeni teoretični vrtilni moment blizu usklajenosti z izmerjenim.

3.4 Dinamična značilka sklopke ERG

Vrednoten je tudi dinamični odziv prenesenega vrtilnega navora na priključeno napetost. Slika 17 prikazuje rezultate postopnega

transferred torque is measured by a strain-gauge load cell.

3.3 Static performance of the ERG clutch

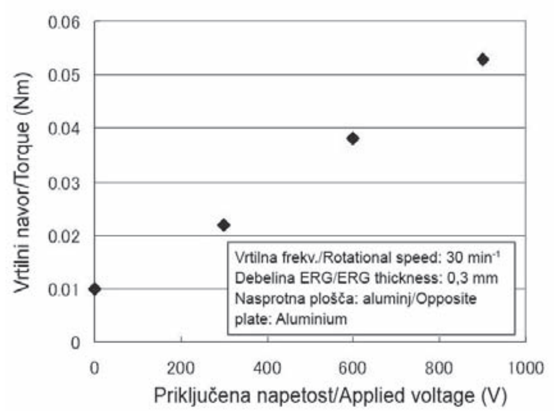
Figure 15 shows the static test results when the applied voltage to a one-sided electrode is raised in increments of 300 V from 0 to 900 V. A very clear distinction is observed between each voltage step. The higher the applied electric field, the higher the torque obtained.

The experimental data is compared with the theoretical estimate. The transferred torque using an ERG clutch is defined as:

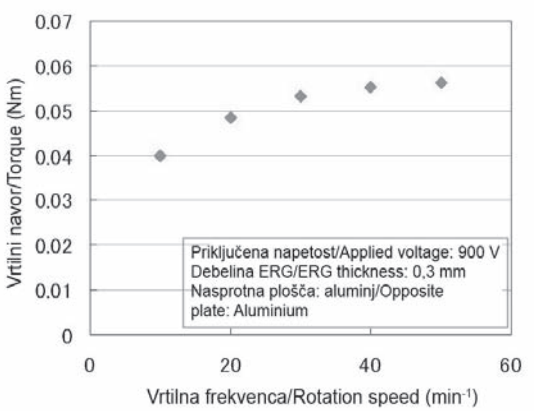
where τ_y and R are the ERG yield stress and the disk radius, respectively; $\tau_y \approx 6$ kPa at a 1.5kV/mm electric-field intensity under a 30μm/s shear rate when using the both-sided electrodes and R = 15 mm. In a past study, it was made clear that the yield stress due to ERG effect is generated in proportion to an applied electric field [11]. The average electric field at the surface of the ERG is obtained at 1.25kV/mm at an applied voltage of 900V to the one-sided electrodes with a 0.2-mm gap, as shown in Fig. 11. Therefore, τ_y is calculated as 4.8kPa and the theoretical torque T is also calculated using Equation (1) to be roughly 0.032 Nm. This is lower than the experimentally measured torque. It is thought that the rotational speed of the master disk influences the transferred torque. Figure 16 shows the relation between the transferred torque and the rotating speed of the master disk under an applied voltage of 900V. A higher rotating speed results in higher torque transfers. The variable τ_y in Eq. (1) depends on the electric-field intensity at the ERG's surface and sliding speed (the rotational speed of the clutch disc). The value of τ_y (= 6 kPa at 1.5 kV/mm) substituted into Eq. (1) was, however, valid at a very low sliding speed (30 μm/s). Therefore, at a very low speed (almost 0 min^{-1}) in Fig.16, close agreement is obtained between the theoretical torque and the measured one.

3.4 Dynamic performance of the ERG clutch

An evaluation is made for the dynamic response of the transferred torque to the applied voltage. Figure 17 shows the results of the step-



Sl. 15. *Zveza med prenesenim vrtilnim navorom in jakostjo električnega polja [s preizkusi]*
Fig. 15. *Relation between transferred torque and electric field intensity [experimental]*



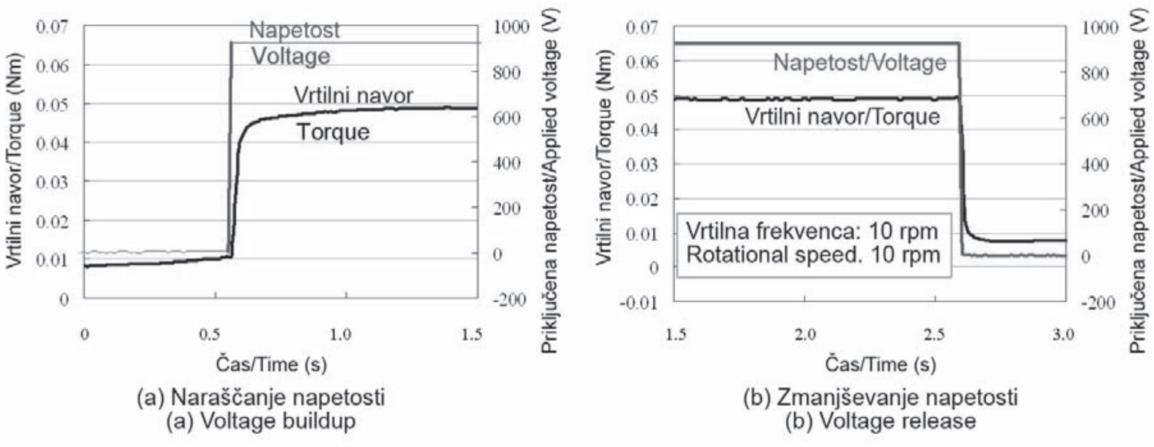
Sl.16. *Zveza med prenesenim vrtilnim navorom in vrtilno frekvenco [s preizkusi]*
Fig. 16. *Relation between transferred torque and rotating speed[experimental]*

odzivnega testa. Čas dviga in padca napetosti sta lahko izračunana z uporabo časovne stalnice. Slika 17(a) prikazuje zvezo med odzivom prenesenega vrtilnega navora in dvigom napetosti, iz katere lahko izračunamo odziv sistema. Celotni odmik časa pri dvigu napetosti znaša 20 ms. Slika 17(b) prikazuje izpis za padec napetosti. Celotni odmik časa pri padcu vrtilnega navora je 16 ms. Odziv učinka ER v ERG na priključeno električno polje je skoraj enak kakor v primeru ERT.

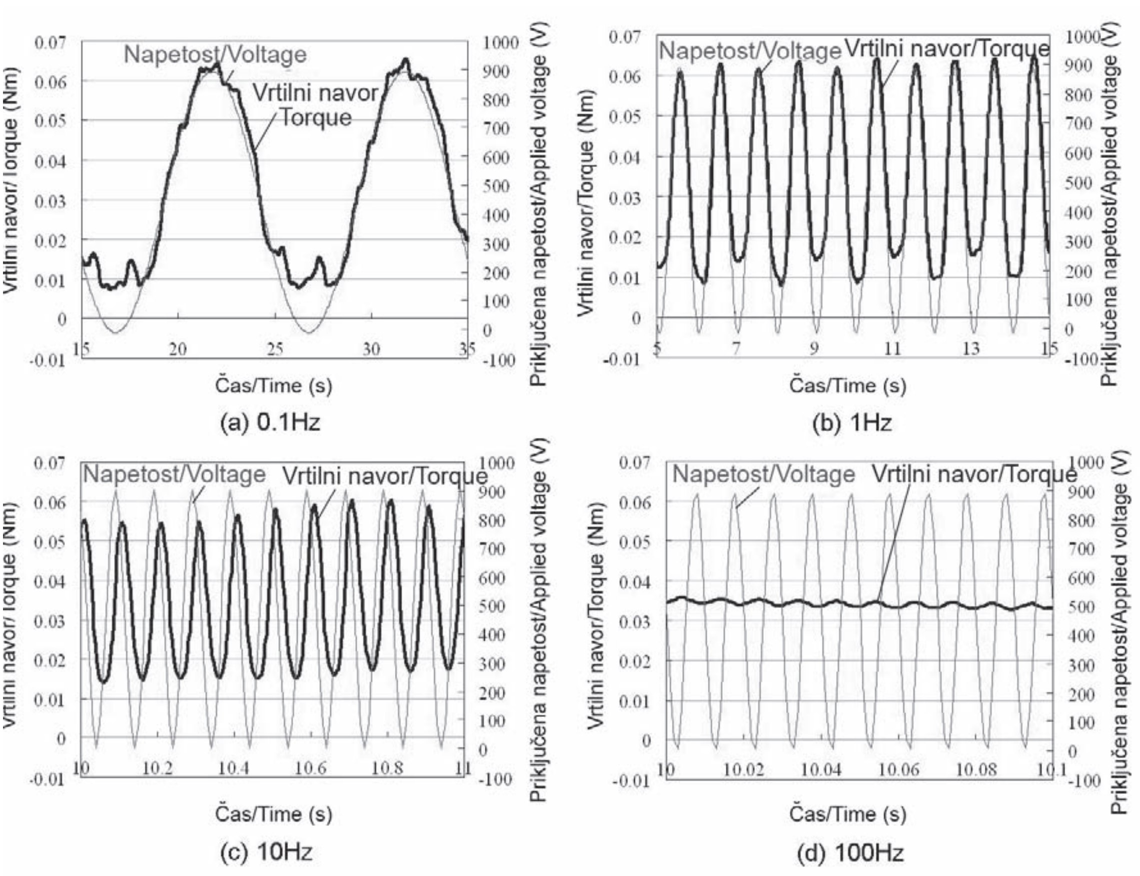
Povezava med jakostjo električnega polja in prenesenim vrtilnim navorom pri priključeni sinusoidni napetosti (V_{maks} = 900 V) in vrtilni frekvenci gnanega motorja 30 min^{-1} je raziskana z namenom določitve frekvenčnih značilnosti prenesenega vrtilnega navora. Slika 18 prikazuje rezultate testa frekvenčnega odziva pri frekvencah

response test. The voltage build-up time and the release time can be calculated using a time constant. Figure 17(a) shows the relationship between the response of the transferred torque and the voltage build-up, from which the system response could be calculated. The total delay in the build-up time is calculated as 20 ms. Figure 17(b) shows a plot of the voltage release. The total delay for the released torque is 16 ms. The response of the ER effect in the ERG to an applied electric field is almost the same as that of an ERF.

To characterize the frequency characteristics of the transferred torque, the relationship between the electric-field intensity and the transferred torque is investigated under an applied sinusoidal voltage (V_{max} = 900 V) at a driven motor rotation speed of 30 min^{-1}. Figure 18 shows the results of the component of electric vector in case of the



Sl. 17. *Rezultat postopnega odzivnega testa [s preizkusi]*
Fig. 17. *Result of step response test [experimental]*



Sl. 18. *Rezultat frekvenčnega odzivnega testa [s preizkusi]*
Fig. 18. *Result of frequency response test [experimental]*

napetosti 0,1; 1,0; 10 in 100 Hz. Razvidno je, da se preneseni vrtilni navor enakomerno spreminja s sinusoidno napetostjo do frekvence napetosti 10 Hz. Pri 100 Hz se preneseni vrtilni navor le malo spreminja. Slika 19 prikazuje razmerje amplitud priključenega električnega polja in prenesenega vrtilnega navora. Amplitudno razmerje pri 0,1 Hz je določeno kot 1, tj., 0 dB. Slika 20 prikazuje fazno razliko med priključenim električnim poljem in prenesenim vrtilnim navorom. Rezultati nakazujejo, da je odrezna frekvenca za sistem prenos vrtilnega navora 18 Hz.

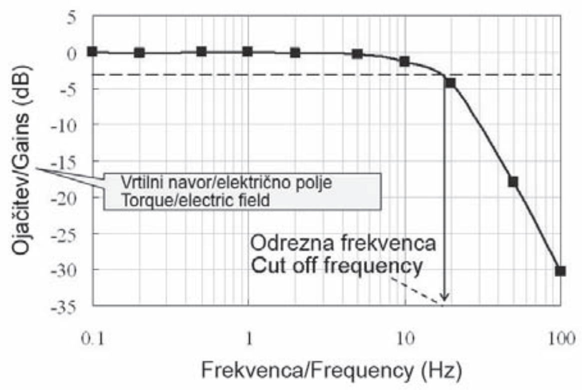
frequency-response test at voltage frequencies of 0.1, 1.0, 10 and 100 Hz. Clearly, the transferred torque varies smoothly with the sinusoidal voltage until a voltage frequency of 10 Hz. However, at 100 Hz, the transferred torque hardly changes. Figure 19 shows the ratio of the amplitude of the applied electric field to that of the transferred torque. The amplitude ratio at 0.1 Hz is defined as 1, i.e., 0 dB. Figure 20 shows the phase difference between the applied electric field and the transferred torque. The results indicate that the cut-off frequency for the torque-transfer system is 18 Hz.

4 SKLEP

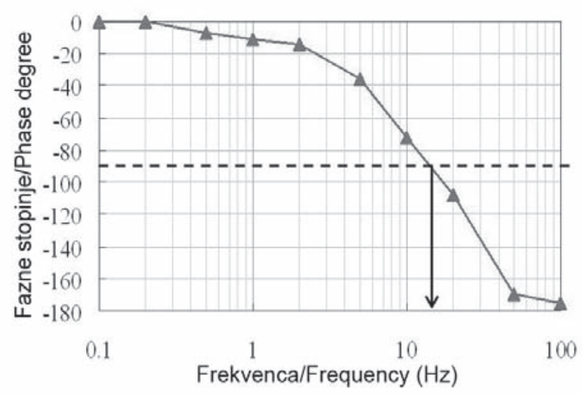
Prispevek predlaga, da se elektro-reološki gel (ERG), ki spreminja svojo površinsko lastnost v skladu s priključenim električnim poljem, lahko uporabi kot torna sklopka. Z namenom doseči učinkovit vpliv ER v sestavu enostranske elektrode je numerično in preizkusno raziskan vpliv vzorca

4 CONCLUSION

This paper proposes that electro-rheological gel (ERG), which changes its surface property according to an applied electric field, can be utilized for a friction clutch. In order to obtain an efficient ER effect in a one-sided electrode configuration, the relation between the electrode pattern and the ER effect is evaluated both



Sl. 19. *Zveza med ojačitvijo in frekvenco [s preizkusi]*
Fig. 19. *Relation between gain and frequency [experimental]*



Sl. 20. *Zveza med fazo in frekvenco [s preizkusi]*
Fig. 20. *Relation between phase and frequency [experimental]*

elektrode na učinek ERG. Na podlagi rezultatov vrednotenja vzorcev elektrode je razvita oblika enostranskih elektrod za sklopko ERG. Izdelan je prototip sklopke ERG. Razvita sklopka ERG kaže odlične lastnosti za prenos vrtilnega navora. Preneseni vrtilni navor se ob priklopu različnih napetosti na široko in enakomerno spreminja. Odziv prenesenega vrtilnega navora na priključeno električno polje je dovolj hitro za praktično uporabo, časovna stalnica je približno 20 ms.

Čeprav sklopka ERG ni primerna za ostre in težke razmere, kakor je avtomobilska torna sklopka, ker je ERG mehkejši od materialov splošno uporabljenih za lamele sklopk. Tako menimo, da je lahko sklopka ERG uporabljena za natančne stroje in v primeru majhnih vrtilnih frekvenc.

numerically and experimentally. On the basis of the result of the electrode-pattern evaluation, the shape of the one-sided electrodes for an ERG clutch is designed and the prototyping of the ERG clutch unit is carried out. The developed ERG clutch unit shows excellent performance for torque transfer. The transferred torque changes widely and smoothly under the application of various voltages. The response of the transferred torque to an applied electric field is fast enough for a practical application, and the time constant is approximately 20 ms.

Though the ERG clutch is not suitable for severe and hard conditions, such as the friction clutch of a vehicle, because the ERG is softer than the materials used for general clutch plates. Therefore, we consider that the ERG clutch can be used for a precision machine and under the conditions of a low rotational speed.

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5 LITERATURA
5 REFERNCES

[1] Tomas C. and Halsey (1992) Electrorheological fluids, *Science*, Vol.258, No.5083 (1992) 761-766.
[2] M. Nakano and T. Nagata (2002) ER properties and flow-induced microstructures of an ER fluid between two parallel disk electrodes in squeeze flow mode, *International Journal of Modern Physics B*, Vol. 16, No. 17 & 18, (2002), pp. 2555-2561.
[3] T. Aoyama and I. Inasaki (1997) Application of electrorheological fluid dampers to machine tool elements, *Annals of the CIRP*, 46/1, (1997), pp. 309-312.
[4] A. Inoue et al (2001) Caster-walker with intelligent brakes employing ER fluid composed of liquid crystalline polysiloxane, *Proceedings of the 8th international conference ERMR2001,*(2001), pp. 23-29.

[5] K. Koyanagi and J. Furusho (2004) Progress of passive-type force display dystem with ER fluid devices, *Proceedings of the 9th international conference ERMR 2004*, (2004), pp.546-552
[6] Jian Zhang et al (2004) Development of a new linear guide system with electrically controllable damper using liquid crystalline polymer, *Proceedings of the 9th international conference ERMR 2004*, (2004), pp.902-908
[7] K. Matsuura et al (2002) Smooth tactile display in mouse using electro-rheological gel, *Proceedings of the2002 International Symposium on Industrial Electronics (IEEE-ISIE 2002)*, L'Aquila, Italy, July 8-11, (2002), pp.424-429.
[8] Y. Kakinuma et al (2005) Basic properties of gel-structured electro-rheological fluids, *International Journal of Modern Physics B*, Vol. 19, Nos.7-9 (2005) 1339-1345.
[9] Y. Kakinuma et al (2004) Development of gel-structured electro-rheological fluids and their application to mechanical damper elements, *8th IEEE International Workshop on Advanced Motion Control (AMC'04)*, Kawasaki, Japan, March 25 - 28, (2004), pp.541-545.
[10] Y. Kakinuma et al (2004) Development of gel-structured electro-rheological fluids and their applications to the control of positioning, *8th International Research/Expert Conference (TMT 2004)*, Neum, Bosnia and Herzegovina, September 15 -19, (2004), pp.459-462.
[11] Y. Kakinuma et al (2006) Application of ER gel with variable friction surface to the clamp system of aerostatic slider, *Precision Engineering*, Vol. 30 (2006) pp. 280-287.
[12] N. Takesue et al (2002) Electro-rheological effects of liquid crystalline polymer on one-sided pattern electrodes, *Journal of Applied Physics*, Vol.91, No3 (2002) 1618-1623.

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Nevronske mreže za napovedovanje sile pri vrtanju

Drilling-Force Forecasting Using Neural Networks

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Nevronske mreže so orodje za pomoč pri napovedovanju, ki je uporabno na najrazličnejših področjih. Na podlagi podatkov iz nadzora postopka lahko napovedo lastnosti izdelka že med samim izdelovalnim postopkom. Narava časovne dinamike postopkov je pri tem lahko zelo pestra - od zelo dinamične do navidezno ustaljene. Naš cilj je izdelati bazo podatkov za obdelovalni stroj. Na podlagi zbranih podatkov bo v prihodnje mogoče napovedovati rezalne sile in rezalni navor za nove materiale, ki jih bomo obdelovali z odrezovanjem. Z napovedanimi silami pa bo nenazadnje mogoče tudi napovedati obrabo orodij.

(Ključne besede: obdelovalni stroji, baze podatkov, sile vrtanja, napovedi, nevronske mreže)

Neural networks are a forecasting tool that can be applied in many fields. Process sensing and data acquisition, for example, can be used to improve both the machinability and product properties during the manufacturing process. The time dynamics of these processes may be anywhere from highly dynamic to quasi-stationary. Our goal was to create a machinability database. The collected data will provide a basis for forecasting the cutting forces and cutting torque for new materials in the future. The force forecasts will also allow tool-wear monitoring and prediction.

(Keywords: machinability, databases, drilling forces, forecasting, neural networks)

1 NEVRONSKE MREŽE

1.1 Zgradba

Nevronske mreže so ena od možnosti strojnega učenja. Delo z nevronskimi mrežami omogočajo moderni programi, to so Matlab, NeuroSolution, SNS itn. Temelj uporabnosti nevronskih mrež je njihova učljivost. Nevronske mreže je moč naučiti oz. trenirati tako, da opravljajo določeno funkcijo, pri kateri se uspešnost učenja preverja z dodatnim testiranjem.

Nevronske mreže spadajo med metode umetne inteligence. Za reševanje problemov v proizvodnem strojništvu uporabljamo poleg nevronskih mrež tudi mehko logiko [11], evolucijsko računanje, genetske algoritme in genetsko programiranje [12], "multi agent tehnologijo" [13] ter sorodne tehnologije in metode.

Da bi načelo učenja kar najbolj ustrezalo človeškemu mišljenju, so umetne nevronske mreže (UNM) zasnovane po vzorcu nevronskih mrež v možganih. Le-te so fiziološki temelj za človekovo učenje in na splošno za mišljenje. Kakor v

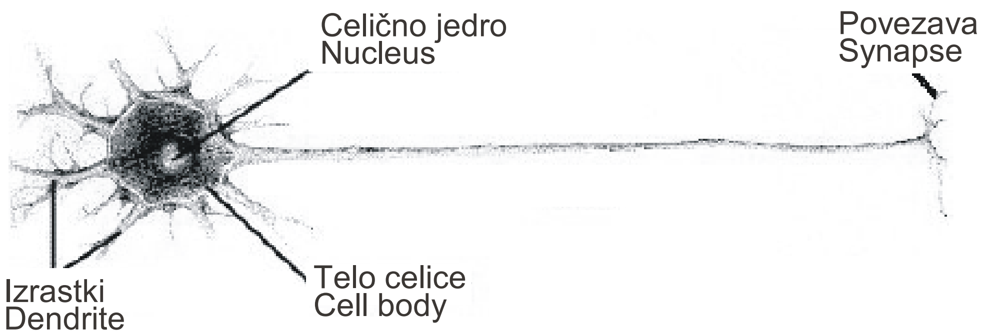
1 NEURAL NETWORKS

1.1 Structure

Neural networks are a subtype of machine learning. Computer programs such as Matlab, NeuroSolution, SNS, etc. allow data analysis with neural networks. The foundation for the usability of neural networks is their learning ability. Neural networks can be trained to execute a certain function and the success of the training can be verified by subsequent testing.

Neural networks (NN) are methods of artificial intelligence. For industrial problems solutions we used by NN also fuzzy logic [11], GA (genetic algorithm) and genetic programming [12], multi agent technology [13] and some more additional methods.

In order to make the artificial neural network (ANN) learning principle similiar to human thinking ANNs have been designed on the basis of the neural networks found inside the brain. These networks are the physiological foundation for human learning and for thinking in general. As in the brain, data is



Sl. 1. *Zgradba nevrona*
Fig. 1. *Neuron structure*

možganih, se tudi v umetnih nevronskih mrežah podatki prenašajo po nevronih. Nevroni imajo v obeh primerih enako zgradbo. Najpomembnejši sestavni deli nevrona so telo celice, izrastki in vlakna (sl. 1).

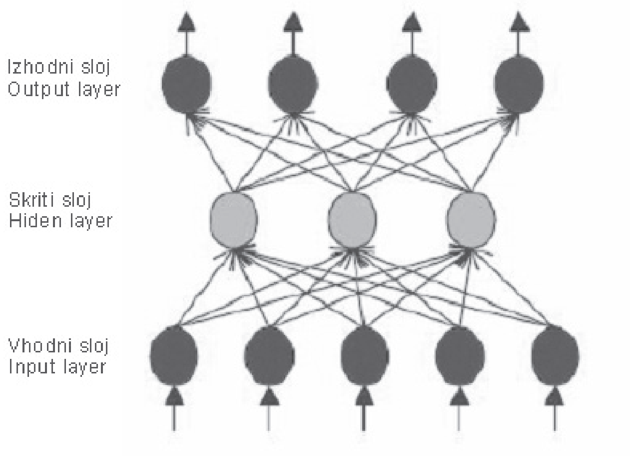
Nevronska mreža sestoji iz skupka nevronov in skupka uteži. Obnašanje mreže je močno odvisno od vplivov med tema skupkoma. UNM imajo vedno tri različne ravni nevronov, pri čemer sta prva in zadnja raven vidni, vmesna raven pa je skrita. Prva raven je vhodni vmesnik, zadnja pa izhodni vmesnik. Srednja raven je skrita in pogosto ni znano, kakšni postopki se odvijajo v njej. Srednjo raven zato praviloma obravnavamo kot črno škatlo. Skrita raven je po eni strani temelj za učinkovitost nevronskih mrež, po drugi strani pa prav zaradi njega ni mogoče sklepati o logičnih ozadjih napovedi (sl. 2) [1].

Ta model ustreza t.i. skritemu modelu Markova, ki dela z naključnimi stanji. Naloga pri tem je na podlagi zaporedja vidnih znakov

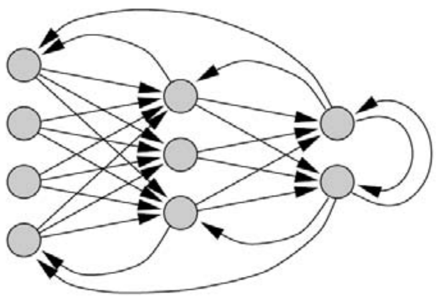
transferred in artificial neural networks through neurons. The structure of the neurons is the same in both cases. The essential parts of a neuron are the soma, the dendrites and the axon (Fig.1).

A neural network consists of a block of neurons and a block of weights. The performance of a network depends heavily on the interactions between these two blocks. ANNs usually have three different layers of neurons, the first and the last layer being visible and the intermediate layer being hidden. The first layer is the input interface and the last layer is the output interface. The intermediate layer is hidden, and often it is not clear what kind of processes are taking place inside it. The intermediate layer is therefore normally treated as a black box. The hidden layer, on the one hand, represents the foundation for the efficiency of neural networks, but on the other hand, also makes it impossible to make any conclusions about the logical background of a network's forecasts (Fig. 2) [1].

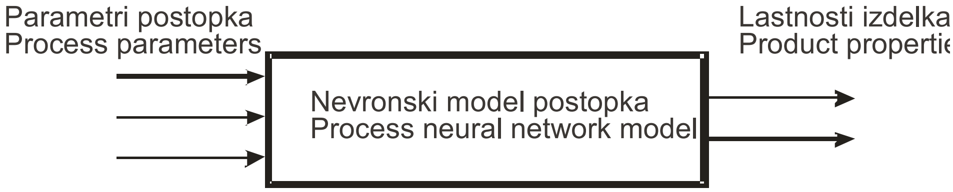
This model corresponds to the so-called Hidden Markov model that works with random states. The



Sl. 2. *Zgradba nevronske mreže*
Fig. 2. *Neural network structure*



Sl. 3. *Mreža s povratnim učenjem*
Fig. 3. *Network with backpropagation in learning*



Sl. 4. *Blokovna shema nevronskega modela postopka*
Fig. 4. *Block diagram of process neural network model*

ugotavljati zaporedje skritih stanj. Za reševanje tega problema se uporablja t.i. vnaprejšnji algoritem.

Pri napovedovanju gre torej za naprej usmerjene mreže. Pri naprej usmerjenih mrežah se podatki prenašajo od nevronov na nižjih ravneh v nevrone na višjih ravneh, pri katerih so povezave usmerjene naprej.

Pri nadzorovanem povratnem učenju (*"nazaj"* – sl. 3) mrež gredo v vstopne nevrone vstopni parametri, v izstopne nevrone pa želeni izstopi. Povratna mreža se tako uči povezav med vhodi in izhodi [2]. Povratne mreže imajo poleg vstopnih in izstopnih nevronov tudi poljubno število skritih nevronov, ki so prav tako razdeljeni v ravni. Vsaka raven, tako vstopna kot izstopna raven, sta v celoti povezani z naslednjo višjo ravnijo, medtem ko drugih povezav praviloma ni. Tako število skritih ravni kakor njihovo velikost (število nevronov) je treba določiti za vsak problem posebej. Pri večini uporab zadostujeta ena ali dve skriti ravni, le redko je potrebna še tretja raven. Slika 3 prikazuje triravensko povratno mrežo s štirimi vstopnimi, dvema izstopnima in tremi skritimi nevroni.

1.2 Potrebni podatki in delo s podatki

Nevronska mreža lahko opiše obnašanje sistemov tudi v tistih primerih, pri katerih znani

challenge is to determine the sequence of hidden states from the sequence of observable parameters. This problem is solved by using a so-called *forward*-algorithm.

Forecasting, therefore, involves *feedforward* networks. In *feedforward* networks, data is transferred from lower-layer neurons to higher-layer networks and the connections are directed forwards.

In supervised backpropagation networks (Fig. 3) the input neurons are fed with the input parameters and the output neurons are fed with the desired outputs. This is how a backpropagation network is trained to recognise the relations between inputs and outputs [2]. In addition to the input and output neurons, backpropagation networks also include an arbitrary number of hidden neurons, which are arranged into layers as well. Each layer – including the input and output layers – is entirely connected to its successor layer; there are usually no other connections. The number of hidden layers and their size (i.e., the number of neurons) has to be determined for each problem individually. Most applications can be adequately covered with one or two hidden layers, a third level is rarely used. Fig. 3 presents a three-layer backpropagation network with four input, two output and three hidden neurons.

1.2 Necessary data and data handling

A neural network is capable of describing the performance of a system even if the existing vstopni podatki ne pokrivajo celega delovnega območja. Napovedi pa bodo zanesljive le pod pogojem, da uporabljene vstopne informacije izpolnjujejo določene najmanjše zahteve na obravnavanem oz. želenem delovnem območju.

Glede na vrsto naloge se je treba odločiti, ali razpoložljivi nabor podatkov zadostuje ali ne. Vsak podatkovni zapis je sestavljen iz n parametrov postopka in m lastnosti izdelka (sl. 4). Nevronska mreža običajno potrebuje več sto podatkovnih zapisov oz. odvisno od zahtevnosti naloge.

1.3 Učenje in testiranje

Učenje in testiranje sta najpomembnejša sestavna dela nevronske mreže, saj šele učenje in testiranje določita lastnosti nevronske mreže. Prvi korak učenja je vnos vprašanj z znanimi odgovori. Sledi primerjava odgovora mreže z znanimi pravilnimi odgovori. Nato se prilagajajo uteži povezav med posameznimi nevroni, dokler mreža ne da pravega odgovora. Postopek se ponavlja, dokler ni UNM ustrezno naučena. Pričakovani rezultat je nevronska mreža, ki lahko odgovarja tudi na vprašanja z neznanimi odgovori. Za preizkušanje pravilnosti sledijo testi z drugimi vprašanji, na katera so odgovori že znani. Če daje nevronska mreža pričakovane odgovore, je učenje končano, v nasprotnem primeru je potrebna nova učna doba. Postopek je tako iterativne narave in se izvaja tako dolgo, da so izračunani rezultati oz. napovedi zadovoljivi/-e.

1.4 Prezasičenost mreže

Če konec postopkov učenja in testiranja ni povsem jasno definiran, se pojavi problem

input data does not cover the whole operating range. However, the forecasts are only reliable if the input information fulfils certain minimum requirements on the operating or needed range.

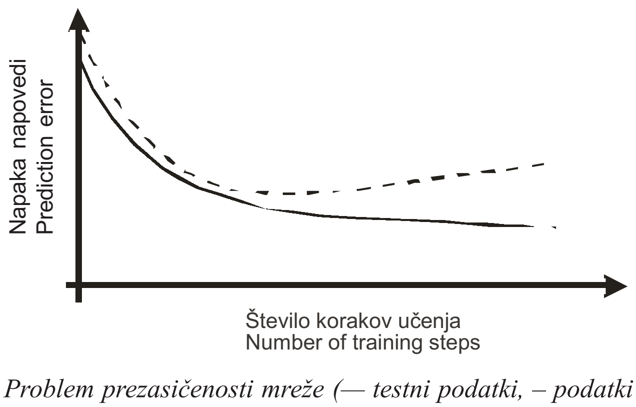
Depending on the setting of the task at hand, one has to decide if the available database is sufficient or not. Each data record consists of n process parameters and m product properties (Fig. 4). A neural network usually requires a couple of hundred data records, depending on the complexity of the task to solve.

1.3 Training and testing

Training and testing are the most important parts of a neural network, since it is the training and testing that determines the properties of a neural network. In the first step of the training, questions with known answers are entered. The network's response is then compared to the known correct answers. Next, the weights of the connections between individual neurons are altered until the network provides the correct answer. This procedure is repeated until the ANN is properly trained. The expected result is a neural network that is capable of responding to questions with yet unknown answers. The correctness is then verified with other questions, for which the answers are already known. The training terminates if the neural network is able to provide the expected answers, otherwise a new training sequence follows. This process is executed for as long as it is necessary in order to obtain satisfactory results.

1.4 Overfitting of ANN

In the case when the end of the training and testing sequences is not clearly defined, we are



Sl. 5. *Problem prezasičenosti mreže (— testni podatki, – podatki učenja)*
Fig. 5. *The overfitting problem (— test data, – training data)*

prezasičenosti mreže. Nevronska mreža je tedaj preveč specializirana za uporabljene učne dobe. Drugačne učne dobe zato dajejo druge rezultate. V fazi učenja se zmožnost razporeditve podatkov z vsakim naslednjim korakom sprva povečuje. V nekem trenutku pride do zasičenja, v tem trenutku se začne zmožnost razporeditve podatkov zmanjševati. Zasičena UNM je preveč prilagojena sestavi učnih podatkov in ni več usmerjena na dejansko obliko zgradbe, ki se jih mora naučiti. Pogosto ni preprosto prepoznati, kdaj je prišlo do zasičenja, mogoče pa je vnaprej napovedati, da bo kmalu prišlo do njega (sl. 5).

Iz tega izhaja, da število učnih korakov ne sme biti preveliko, saj nevronska mreža sicer zaradi problema prezasičenosti izgubi zmožnost posploševanja. Mreža zbira vse več podrobnosti o učnih podatkih, ki niso bistveni za rezultat testiranja. Nevronski mreži se tako sicer res zmanjša pogostnost napak pri posebnih podatkih, s katerimi pretežno zalagamo mrežo, izgubi pa zmožnost posploševanja, ki jo potrebuje za učinkovito delo, tj. zmožnost napovedati kar največ različnih primerov. Rezultat prenasičenja so zelo specializirane mreže, ki lahko izpolnjujejo svojo nalogo za določene uporabe, vendar so največkrat preveč specializirane.

Problemu se je mogoče izogniti z izvajanjem testov z neodvisnimi testnimi dobami med učenjem. Pri tem dobimo neodvisne reference, ki jih lahko uporabimo za razpored.

1.5 Napovedi z nevronskimi mrežami

Napovedi je mogoče razložiti tudi kot napoved časovnih vrst z več ali manj šuma, pri čemer se časovna vrsta ravna po neki posredni zakonitosti. Matematični in statistični postopki, ki se uporabljajo za preprosto napovedovanje, v bistvu obravnavajo dve posebni vrsti problemov. Problem je bodisi mogoče opisati z velikim številom linearnih spremenljivk, katerih medsebojne povezave so preproste (linearne), ali pa ga je mogoče opisati z malo spremenljivkami, katerih medsebojne povezave so bolj zahtevne narave ([3] in [4]).

2 PREIZKUS

Cilj preizkusa je bila določitev značilk rezalnega postopka vrtanja z meritvami sil in navorov.

confronted with the network overfitting problem. This means that the neural network is too specialised for the training sequences that were used. Other training sequences then yield different results. In the learning phase, the ability to classify the data at first increases with every subsequent step. However, at a certain moment overfitting occurs and the network's data-classification ability starts to decrease. An ANN with overfitting is too adapted to the structure of training data and is no longer oriented on the actual form of structures it was supposed to train on. Recognising overfitting is often not an easy task, but it is possible to anticipate that it is going to occur soon (Fig. 5).

We can conclude that the number of training steps should not be too large, or else the neural network will lose its generalisation ability due to the overfitting problem. The network collects more and more details about training data, which are not relevant for the testing result. This may increase the frequency of errors for the special data, which is mostly fed to the network, but the network also loses its generalisation ability, which is necessary for efficient work, i.e., the ability to forecast many different cases. The result of overfitting is very specialised networks that may be able to fulfil their tasks for certain applications, but are mostly overly specialised.

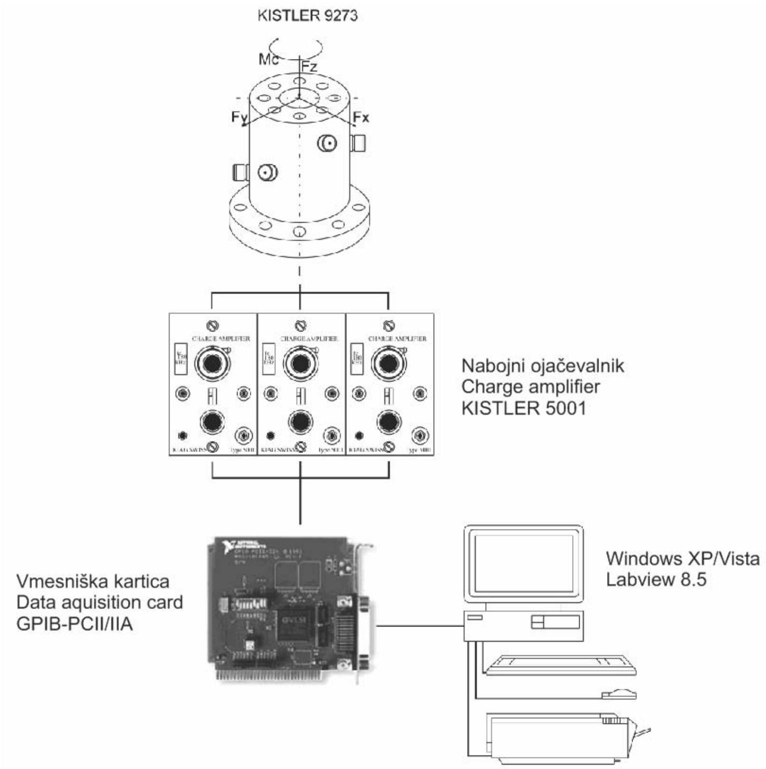
The problem can be avoided by executing tests with independent test sequences during the training. This yields independent references that can be used for the configuration.

1.5 Using neural networks for forecasting

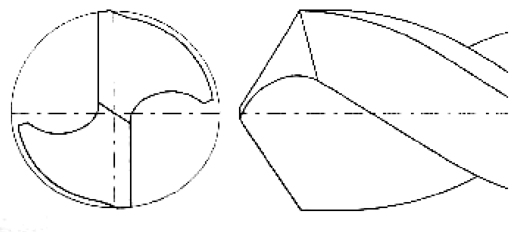
A prediction can also be interpreted as a forecast of a time series containing more or less noise, whereas the time series follows some implicit law. Mathematical and statistical procedures used for simple forecasting basically deal with two special types of problems. The problem can either be described by a large number of linear variables having simple (linear) interdependencies, or it can be described by a smaller number of variables with more complex interdependencies ([3] and [4]).

2 THE EXPERIMENT

The experiment was set up to measure the drilling-force characteristics. We have measured the feed



Sl. 6. *Shema merilne verige za merjenje podajalnih sil in rezalnega navora*
Fig. 6. S*cheme of the measurement system for measuirng the feed force and the cutting torque*



Sl. 7. *Rezalno orodje – vijačni sveder*
Fig. 7. *Cutting tool – drill*

Merili smo podajalno silo (F_f) in rezalni navor (M_c) pri širšem naboru vrtilne frekvence in podajanja.

Merilna veriga (sl. 6) je bila sestavljena iz vrtalnega stroja DALMASTROJ SPLIT, dinamometra KISTLER 9273, digitalizatorja HP 54501A in računalnika s programskim paketom LABVIEW. Uporabljeni material je bilo jeklo 4742 UTOPN 1.2312 (40CrMnMoS8-6) [5]. Premer orodja je bil 8 mm (sl. 7). Rezultati meritev so zbrani v preglednici 1.

3 IZVEDBA NEVRONSKE MREŽE

Za ustvarjenje in učenje nevronske mreže smo uporabili Neural Network Toolbox (NNT), ki

force (F_f) and the cutting torque (M_c) over a range of different values of cutting speed and feed rate.

The measurement chain (Fig. 6) consisted of a DALMASTROJ SPLIT drill machine, a KISTLER 9273 dynamometer, a HP 54501A oscilloscope and a personal computer with LABVIEW software. The test material used was 4742 UTOPN WNr 1.2312(40CrMnMoS8-6) steel [5]. The tool diameter was 8 mm (Fig. 7). The measurement results are collected in Table 1.

3 NEURAL NETWORK REALISATION

The Neural Network Toolbox (NNT) was used to create and train the neural network. The

Preglednica 1. *Rezultati meritev – povprečna podajalna sila in povprečni rezalni navor*
Table 1. *Eksperimental results – averaged feed force and averaged cutting torque*

f **[mm/vrt]**	v_c **[m/min]**	***n*** **[min^{-1}]**	***Mc*** **[Nm]**	***Ff*** **[N]**
0,050	6,28	250	1,735	930,621
0,080	12,56	500	2,776	1488,994
0,100	18,84	750	3,470	1861,243
0,120	20,72	825	4,267	1969,824
0,125	25,12	1000	4,445	2051,900
0,150	31,4	1250	5,334	2462,280
0,175	37,68	1500	6,223	2872,660
0,200	43,96	1750	6,266	3362,057
0,225	50,24	2000	7,049	3782,314
0,250	56,52	2250	7,833	4202,571
0,275	62,8	2500	8,616	4622,828
0,300	69,08	2750	9,399	5043,086
0,325	75,36	3000	10,182	5463,343
0,350	81,64	3250	10,966	5883,600
0,375	87,92	3500	11,749	6303,857
0,400	94,20	3750	12,532	6724,114
0,425	100,48	4000	13,315	7144,371
0,450	106,76	4250	14,099	7564,628
0,475	113,04	4500	14,882	7984,885
0,500	119,32	4750	15,665	8405,143

razširja možnosti uporabe paketa MATLAB. Orodna knjižnica programskega paketa MATLAB Neural Network Toolbox vsebuje vse običajne metode nevronskih mrež, hkrati pa daje tudi veliko različnih učnih algoritmov. Kakor druge orodne knjižnice programskega paketa MATLAB tudi Neural Network Toolbox prevzame zelo veliko spretnega dela, uporabnik pa se lahko osredotoči le na bistvo problema. Na voljo so orodja za ustvarjanje, upodobitev, izvedbo in posnemanje različnih vrst mrež. Delali smo v ukazni vrstici z vnaprej definiranimi ukazi in v grafičnem uporabniškem vmesniku GUI. Rezultate iz grafičnega uporabniškega vmesnika MATLAB je mogoče izvoziti (okno *Workspace*), prav tako je podatke mogoče uvoziti v grafični uporabniški vmesnik [6].

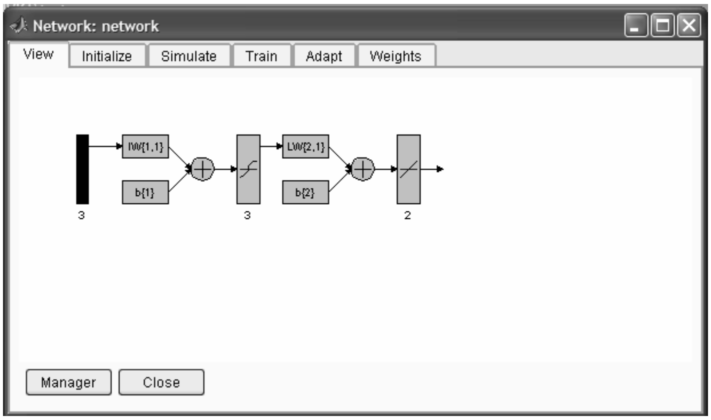
Mrežo ustvarimo v oknu Create New Network. V tem oknu definiramo sestavo mreže in vse funkcije, ki jih uporablja mreža. Vstopne podatke predstavljajo meritve dinamičnih in statičnih komponent sil in navorov. Vstopni podatki: n [min^{-1}], f [mm/vrt], v_c [m/min], izstopni podatki pa: M_c [Nm], F_f [N] ([7] in [8]).

Ustvarjena je bila nevronska mreža vnaprejšnjega tipa *3-3-2* in vrsta povratne mreže. Ta vrsta mreže uporablja pri prilagajanju utežnih

Neural Network Toolbox includes all the current neural network methods and makes available a number of different training algorithms. Like the other MATLAB toolboxes, the Neural Network Toolbox takes over the majority of the routine work, so the user can concentrate on the essential problems. NNT expands the possibilities of use for the MATLAB package. Tools for creating, visualising, realising and simulating different types of networks are available. In this work we used a command line with predefined commands, as well as a graphical user interface (GUI). The results can be exported from the MATLAB graphical user interface (*Workspace* window), and the data can also be imported into the graphical user interface [6].

The network is created in the Create New Network window. The network structure and all the functions used by the network are defined in this window. The measurements of the dynamic and static forces were used as input data. The input data are n [min^{-1}], f [mm/rev], and v_c [m/min], and the output data are M_c [Nm] and F_f [N] ([7] and [8]).

The backpropagation *3-3-2* type neural network was created with the subtype feed-forward backpropagation type of network. This network type uses the reverse-error propagation method for

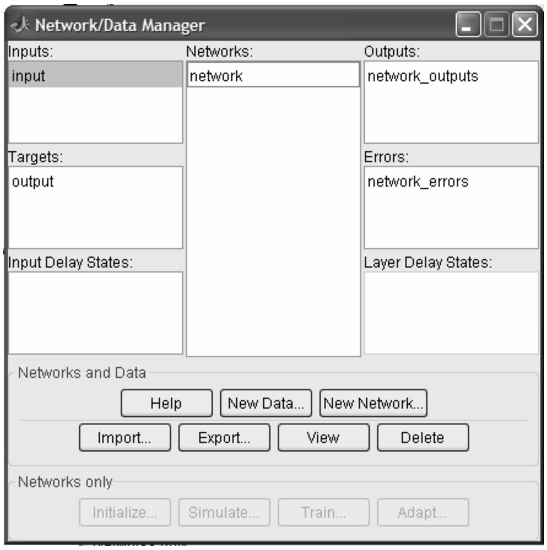


Sl. 8. *Grafični prikaz nevronske mreže*
Fig. 8. *Graphical overview of used neural network*

koeficientov metodo povratnega učenja. Območje vhodnih podatkov je moč določiti v polju INPUT RANGES, kjer izberemo vstopno datoteko.

GUI nntool v paketu MATLAB 7 ustvari na podlagi vnesenih nastavitev skupinsko shemo nevronske mreže (sl. 8). V izbranem primeru lahko prepoznamo tri vstopne nevrone, tri skrite nevrone in dva izstopna nevrona. To zadostuje, saj mora mreža napovedovati tako podajalno kakor rezalno silo ([9] in [10]).

Vstopna raven (IN: vstopni nevroni) so izmerjene vrednosti, ki so bile med delom prepoznane kot najprimernejše. Srednja raven (SN: skriti nevroni) je t.i. skrita raven, katere

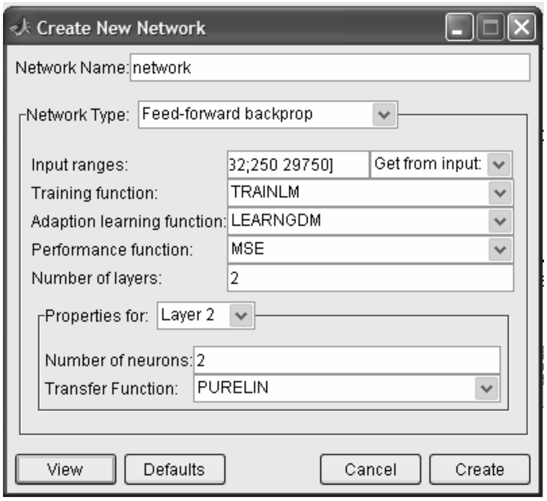


Sl. 9. *Obravnava po uvozu vstopno-izstopnih podatkov*
Fig. 9. *Network/Data Manager after importing the input/output data*

altering the weight of the coefficients. The input data range is set in the INPUT RANGES field, where the input file option has to be selected.

The MATLAB 7 GUI nntool uses the entered settings to create the neural network's block diagram (Fig. 8). In the current problem it is possible to input three neurons, three hidden neurons and two output neurons. This will suffice, as the network is supposed to forecast the feed force as well as the cutting torque ([9] and [10]).

The input layer (IN: input neurons) are the measured values, which were found to be the most suitable in the course of the project. The intermediate layer (HN: hidden neurons) is the so-



Sl. 10. *Okno za ustvarjanje nevronske mreže*
Fig. 10. *Interface window for neural network creation/preparation*

velikost je bila med delom optimizirana na tri nevrone. Zadnji nevron (IN: izstopni nevron) pa je izstopna veličina.

Za učenje mreže so bile izbrane naslednje funkcije [8]:

- *TRAINING FUNCTION* (uporabljena je bila TRAINLM)
- *ADAPTATION LEARNING FUNCTION* (kot učna funkcija za prilagajanje uteži pri povratnem učenju je bila nastavljena LEARNGDM)
- *PERFORMANCE (*Izbrana je bila MSE (Mean Square Error). Ta funkcija uporablja srednjo vrednost kvadratične napake)

Vstopna raven v Matlabu ne spada med ravni ki sodelujejo pri preračunavanju, zato ji ni treba določiti nobenih funkcij.

- *TRANSFER FUNCTION*. Izbrana mreža ima skrito raven s tremi nevroni, sprožilna funkcija je TANSIG. V izhodnem nivoju sta dva nevrona, sprožilna funkcija pa je PURELIN.

Tansigm pomeni sigmasto funkcijo (1), kjer je oblika funkcije:

called hidden layer that was optimised to include three neurons during the project. The last neuron (ON: output neuron) is the output parameter.

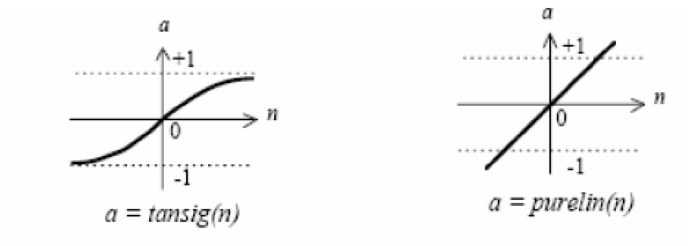
In this case the following functions used by the network and sets for the training method were selected [8]:

- *TRAINING FUNCTION* (we used TRAINLM)
- *ADAPTATION LEARNING FUNCTION* (we used the LEARNGDM learning function for backpropagation/bias)
- *PERFORMANCE* (for the predictor we used the Mean Square Error)

The input layer is not involved in Matlab's calculations, so no functions have to be assigned to it.

- *TRANSFER FUNCTION*. The selected network has a hidden layer with three neurons; the activation function is TANSIG. The output layer has two neurons and the PURELIN activation function.

Tansig is the sigmoid function (1), where the function's shape is defined as:



a) b)

Sl. 11. *Oblika uporabljenih funkcij*
Fig. 11. *Structure of the used functions*

$$a = \frac{2}{1+e^{-2n}} - 1 \qquad (1).$$

Purelin je linearna funkcija (sl. 11) z naslednjimi lastnostmi:

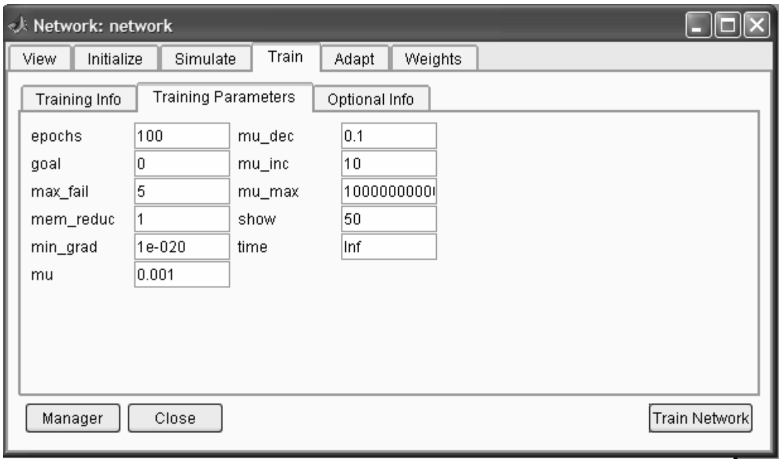
Med učenjem imamo pregled nad naslednjimi parametri: učna funkcija, število dob (definirano število in število že končanih dob), srednja vrednost kvadratične napake (dejanska in zahtevana vrednost), gradient (dejanska vrednost in vrednost, pri kateri se postopek učenja konča). Nastavitev parametrov mreže za učenje je prikazana na sliki 12, potek učenja pa na sliki 13.

Nevronske mreže je mogoče v celoti ustvarjati in učiti v Matlabu. Naučene mreže je nato zaradi enostavnosti in preglednosti mogoče predstaviti in uporabiti v Simulinku (sl. 14).

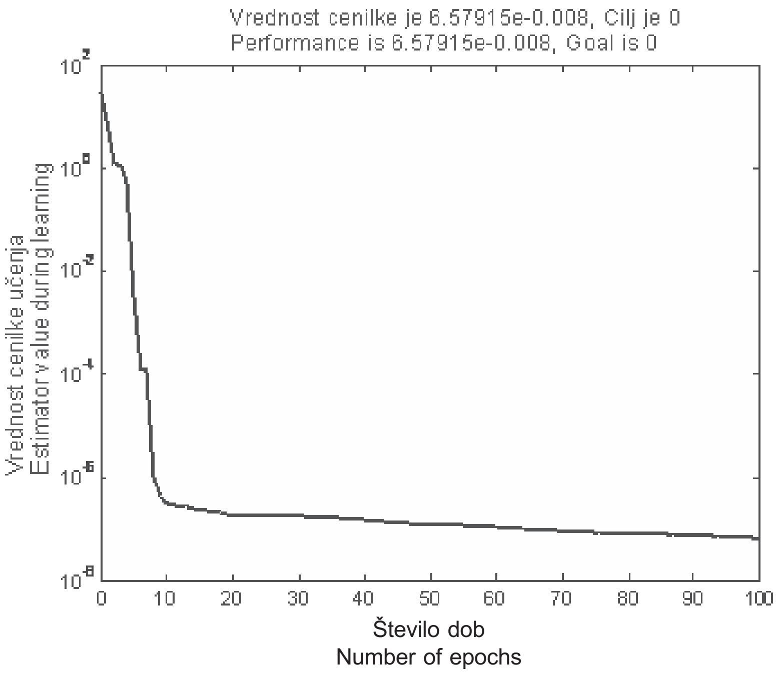
Purelin is a linear function (Fig. 11) with the following characteristics:

The following parameters are the output during the training: the training function, the number of epochs (predefined and elapsed), the mean square error (actual and specified value), and the gradient (actual value and value that terminates the training procedure). The network parameter settings for the training are shown in Fig. 12 and the training process performance is shown in Fig. 13.

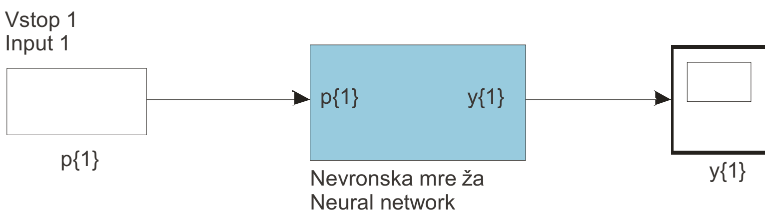
The neural networks can be created and fully trained in Matlab. The trained networks can also be embedded and simulated in Simulink because of their user friendliness and transparency (Fig. 14).



Sl. 12. *Nastavitev parametrov nevronske mreže*
Fig. 12. *Setting the neural network training parameters*



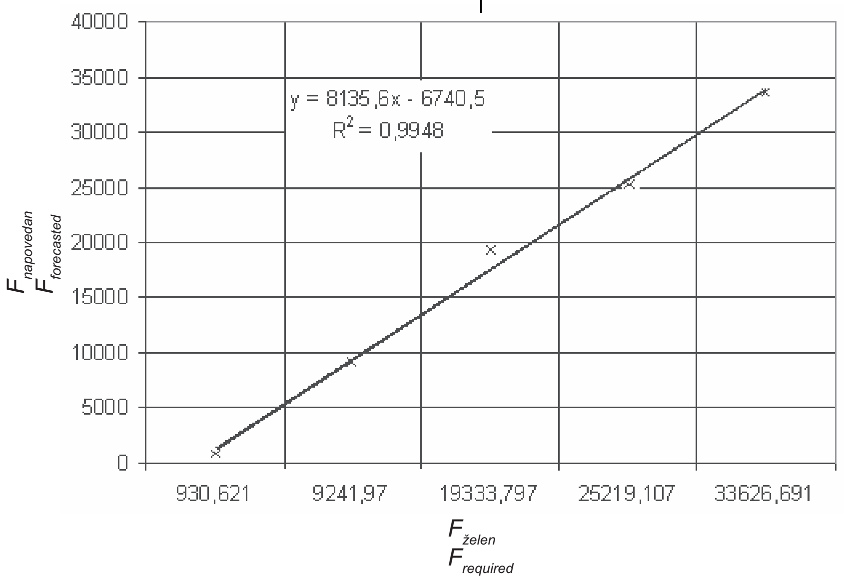
Sl. 13. *Potek postopka učenja*
Fig. 13. *Training process performance*



Sl. 14. *Nevronska mreža kot podsistem v Simulinku*
Fig. 14. *Neural network as a subsystem in Simulink*

Preglednica 2. *Napovedane testne vrednosti*
Table 2. *Predicted test values*

Želene vrednosti Vanted values		Napovedane vrednosti Predicted values	
M_c [Nm]	F_f [N]	M_c [Nm]	F_f [N]
1,735	930,621	1,712	931,213
17,225	9241,97	17,431	9238,673
36,033	19333,8	37,827	19322,82
47,002	25219,11	45,977	25221,23
62,671	33626,69	63,971	33618,17



Sl. 15. *Odvisnost med želeno in napovedano podajalno silo (x – meritve, – linearna odvisnost F_f)*
Fig. 15. *The correlation between the required and the forecasted feed force (x – measurement, – linear aproximation F_f)*

V preglednici 2 so testne vrednosti, s katerimi nevronska mreža ni imela opravka (niso bili vgrajeni v postopek učenja mreže). Odvisnost med napovedanimi in želenimi vrednostmi je prikazana na slikah 15 in 16.

Odvisnost med obema vrednostma bi bilo mogoče še izboljšati, če bi uporabili več učnih podatkov, a je kljub temu treba poudariti, da so dobljeni rezultati v okviru naših pričakovanj.

4 SKLEP

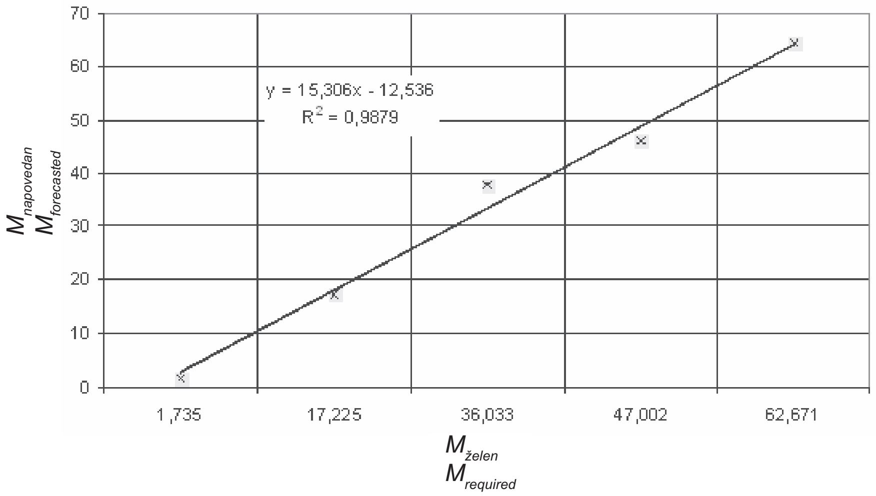
Opisana tehnika napovedovanja z nevronskimi mrežami tako ni omejena samo na nekatere tehnologije. Njene uporabe najdemo na najrazličnejših področjih (vremenskih napovedih, napovedih obnašanja postopkov itn.). Število vstopnih in izstopnih parametrov pri nevronskih mrežah je

Table 2 shows the test values that have not been seen by the neural network. The correlation between the forecasted and the required values is shown in Figures 15 and 16.

The correlation between both values could be further improved by using more training data. However, the obtained results are still within our expectations.

4 CONCLUSION

The described forecasting technique is not limited to any technology, its applications can be found in various fields (weather forecasting, the prediction of process behaviour, etc.). The number of the neural network's input and output parameters is arbitrary. In addition to that, the neural networks



Sl. 16. *Odvisnost med želenim in napovedanim rezalnim navorom (x – meritve, – linearna odvisnost M_f)*

Fig. 16. *The correlation between the required and forecasted cutting torque (x – measurement, – linear aproximation M_f)*

poljubno. Nevronske mreže so razen tega poljubno razširljive, uporabe pa so lahko tudi močno nelinearne. Algoritmi v orodnih knjižnicah paketa MATLAB omogočajo hitro in učinkovito reševanje nalog.

Iz prispevka je razvidno, da je moderne metode modeliranj postopkov moč uporabiti tudi na odrezovalnih postopkih. In sicer za napovedovanje rezalnih sil/navorov pri določenih parametrih odrezovanja.

Sile oz. navori pri odrezovanju pa predstavljajo značilno cenilko obnašanja samega postopka. Posredno se kažejo na vibracijah in obrabi orodja. Tako je na podlagi te zamisli mogoče napovedovati tudi obrabo rezalnih orodij.

are optionally expandable and the applications can be highly non-linear. The algorithms included in MATLAB Toolboxes enable quick and efficient problem solving.

This paper proves that modern methods for process modelling can also be used for metal-cutting processes, in particular for the prediction of cutting forces/torques corresponding to the cutting parameters (feed, speed, depth, etc.)

While forces and torques during the cutting processes represent the dominant estimator for the cutting process' status, and they both have an influence on the cutting-tool wear, vibrations, etc., based on this idea it is also possible to predict the amount of cutting-tool wear.

5 LITERATURA
5 REFERENCES

[1] Zakharian, S. (1998) Neuronale Netze für Ingenieure: Arbeits- und Übungsbuch für regierungstechnischen Anwendungen. *Vieweg-Verlag*.

[2] http://www.ece.ubc.ca/~elec592/PDFfiles/Backpropagation.pdf

[3] Armarego, E.J.A., Smith, A.J.R., Gong, Z.J. (1990) Four plane facet point drills – Basic design and cutting model predictions. *STC C 39/1/1990*, p. 41

[4] Korošec, M., Balič, J., Kopač, J.: (2005) Neural network based manufacturability evaluation of free form machining. *Int. j. mach. tools manuf.* [Print ed.], January 2005, vol. 45, iss. 1, str. 13-20.

[5] Krajnik, P., Korošec, M., Pušavec, F., Kopač, J.: Multiple layer perceptron simulation and advanced metamodelling of centreless grinding process. *AMPT 2006*, Las Vegas, NV, July 30-August 3, 2006.

[6] Matlab 7 Help

[7] Scherer, A. (1997) Neuronale Netze. Grundlagen und Anwendungen, *Vieweg-Verlag*.

[8] Tič, R. (1994) Možnost kontrole vrtanja s pomočjo nevronskih mrež. Diplomska naloga visokošolskega študija, *Univerza v Ljubljani, Fakulteta za strojništvo*.
[9] Matlab select 2/03 http://www.mathworks.com/company/newsletters/matlab_select/files/matlab_select_02-03.pdf
[10] http://www.boerde.de
[11] Tsourveloudis, N., Ioannidis, S., Valavanis, K. (2006) Fuzzy surplus based distributed control of manufacturing systems, Advances in Production Engineering & Management, Vol. 1, No. 1, December 2006.
[12] Balič J. (2006) Intelligent CAD/CAM systems for CNC programming - An overview, Advances in Production Engineering & Management, Vol. 1, No. 1, December 2006.
[13] Nestler A., Dang T. N. (2008) The application of multi-agent systems for process management and NC data transfer aided by a DNC system, Advances in Production Engineering & Management, Vol. 3, No. 1, January 2008, on-line November 2007: www.apem-journal.org.

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Vzdrževanje v zasnovi celovitega obvladovanja kakovosti

The Role of Maintenance in the Total Quality Management Concept

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V času globalizacije, revolucije v računalniški znanosti in spreminjanja, ki temelji na načelih re-inženiringa, gre vizija razvoja proizvodnih sistemov v smeri zmožnosti in učinkovitosti odprtega in hitrega sistema nadzora kakor tudi kakovosti po načelih celovitega obvladovanje kakovosti (COK - TQM). Re-inženiring in razvoj sistema kakovosti predstavljata moderne tehnike, katere zajemajo vse komponente poslovanja podjetja v funkciji zahtev trga na tehničnem kot tudi tehnološkem področju. Posebna vloga v teh postopkih pripada enemu od ključnih podsistemov proizvodnega sistema, a to je vzdrževanje. Pričakovanje glede zasnove vzdrževanja v prihodnje je celovito proizvodno vzdrževanje (CPV - TPM) v funkciji celovitega obvladovanja kakovosti, v pogojih uporabe novih tehnologij. Ustrezna zasnova proizvodnega sistema vzdrževanja je pogoj za kakovost proizvoda, medtem ko je celovito preventivno vzdrževanje bistven pristop COK-a.

(Ključne besede: proizvodni sistemi, vzdrževanje, celovito proizvodno vzdrževanje, celovito obvladovanje kakovosti)

In the era of globalization, the computer science revolution and the restructuring based on the principles of re-engineering, the vision of the production-system development consists of the following: efficiency, effectiveness, an open and rapid control system as well as the quality with a total quality management (TQM) approach. Re-engineering and the development of the quality system represent modern techniques that embrace all the business components of the enterprise in the function of market demands and technical as well as technological range. The special role taken in those processes belongs to one of the principal subsystems of the production systems, i.e., maintenance. The future prospect of the maintenance concept is total productive maintenance (TPM) as part of TQM, on the condition of the application of new technologies. A suitable concept for production-system maintenance is the condition for the quality of the product, whereas total preventive maintenance is the essential TQM approach.

(Keywords: production systems, maintenance, total productive maintenance (TPM), total quality management (TQM))

1 MAINTENANCE IN THE QMS PROCESS MODEL AND THE NET OF QUALITY

The basic conditions for fulfilling maintenance requirements (machines, various types of equipment and tools) include the control and maintenance of systems in a working state, preventive activities for eliminating and/or decreasing system failures, corrective maintenance, the reduction of external influences on machines and equipment as well as their functioning, operational safety, optimal costs, etc.

Maintenance offers the necessary preconditions for a product to gain its planned characteristics in harmony with the corresponding requirements of the EU, referred to as “the new approach”. In order to accomplish its mission, maintenance as a process must match the requirements of the ISO 9000 standard and be created according to the Process Model (Fig. 1) ([1] and [2]).

Maintenance, as a process in the Net of Quality, can be seen through three principal conception groups (see Fig. 2) ([1] and [3]).

- A - the analysis of the effectiveness of the system and maintenance resources,
- PMt - the Process of Maintenance - activity and results,

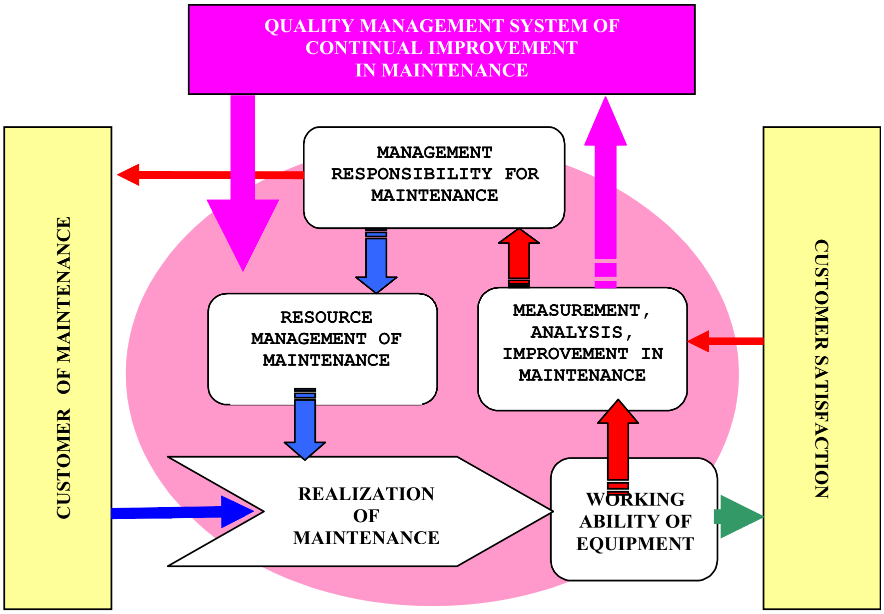

Fig. 1. *Process model of maintenance in the QMS*

- IPMt – the improvement of the constituent process of maintenance.

Each of these groups behaves in accordance with the law of Deming's circle of quality (PDCA-circle).

A - Analysis of the effectiveness of the system and maintenance resources

Elements that are particularly important for an analysis of the maintenance process refer to maintenance resources as inputs as well as the system effectiveness as a measure of the maintenance success.

- Maintenance Resources - material, equipment, tools, methods and labour.
- Effectiveness is a function of time and it consists of reliability, availability and the convenience of maintenance.

Analysis (A) of the system's effectiveness and the methodology of maintenance indicates:

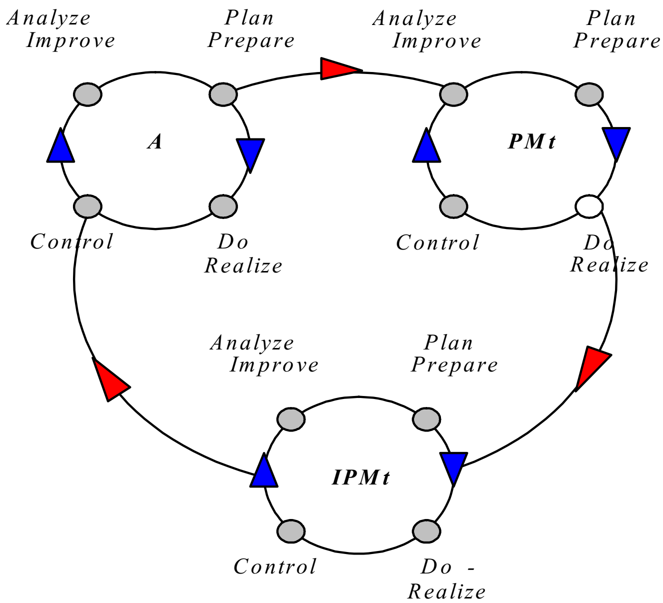

Fig. 2. *Maintenance in the Net of Quality - Deming's circle of quality*

- the level of the system's effectiveness,
- the influence of each component on the effectiveness,
- the distribution law - statistical control,
- the behaviour of the system over time.

PMt - the process of maintenance, activity and results

The maintenance process (PMt) involves preparing maintenance, executing tasks, final works and inspection during all the work phases, which represents an all-round PDCA-cycle.

IPMt - improving the process of maintenance

Improving the maintenance process involves changes to all of the elements in the structure of the maintenance. These changes, such as re-engineering, ought to unravel according to Deming's PDCA- cycle, in order to satisfy the quality system and acquire the expected results.

Improving the process of maintenance consists of:

- a change in the structure of the production system,
- a change in the concept of maintenance,
- a change in the control of spare parts and materials,
- a change in the organisation, the structure of the working forces and the motivation,
- a change in the maintenance status of the production system, etc.

2 MAINTENANCE ADJUSTMENT FOR THE DEVELOPMENT OF TQM

TQM is accomplished according to categories, which are divided into six groups [1]. In this paper the access to TQM is analyzed as a function of maintenance ([4] to [6]).

Group I: Changing traditional maintenance

- **Just in time, overload with stocks**
  The just-in-time approach supports the business function of maintenance relating to:
  - the planning of maintenance activities,
  - the managing of stock resources and maintenance activities,
  - the managing of maintenance expenses for all categories (spare parts, materials, equipment, work, etc.),
  - the reversible information about activity execution.
- **Statistical control of the process**
  The applied methods include the following: Pareto analysis, histogram, control diagrams, Ishikawa diagrams, Taguchi method, factor analysis, complex analysis, and effectiveness in terms of probability as a function of time.
- **Cycles of quality**
  This approach is based on several key principles, of which the most important are:
  - self-organization in the work place,
  - the investigation of work processes (technique and technology),
  - the work on continuous improvement of the system (and quality),
  - the development of communication, operational work meetings,
  - the continuous training of employees.
- **Total quality control (TQC)**
  This is the aim of reaching quality in some or all the works in all processes.

Group II: Applying scientific methods to maintenance

- **Total preventive maintenance (TPvMt) – the complete representation of preventive maintenance - scientific prevention** ([1] and [5])
  The relation between TQM and the maintenance system lies in the word "total", which refers to both control and quality. Quality control in the production system would not be "total" if it did not apply to maintenance. Advanced production technologies demand a new approach to maintenance, and this new approach demands the application of advanced technologies and new methods in the domain of maintenance.
  The accuracy of the equipment and its ability to produce what is designed for the first and each subsequent time depends on the condition of production equipment and the quality of the equipment maintenance. Consequently, the basic principle of the quality system is respected.
  The aim of TPvMt is to master all the segments of a business system and to prevent a state of non-quality in the domain of its functions.
  Reaching TPvMt is a long process that is based on a scientific approach along with the application of scientific methods and the tools of quality:
  - Defining the place of maintenance in the business-production system and constant exploration of those relations.

- ABC (Pareto) analysis of the equipment's characteristics (the importance of the organisation, reliability, availability and productivity of the technological system).
- Systemization of the causes of failures based on a diagram of "causes-effects" (Ishikawa diagram).
- Defining the method of diagnosing the equipment's condition.
- Defining the methods of preventive maintenance according to the type of equipment and the causes of failure.
- Defining the development time and the improvement of preventive maintenance.
- In all phases of preventive-maintenance development the education of the employees is tightly connected to new technologies, new methods of maintenance, new tools of quality in the domain of maintenance, etc.

• **Taguchi method - scientific design**
The Taguchi method is part of the integral access to product design, process and the quality system, which is supported by principles such as:
- defining the quality loss-function,
- the continuous improvement of quality,
- decreasing the costs as a condition for success in the market,
- decreasing the withdrawal of performance in the function of the continuous improvement of quality, etc.

• **Quality techniques - scientific recognition**
Quality techniques represent an approach to quality based on a scientific methodology. They represent the sum of knowledge (the accuracy of information, analysis, synthesis, and control) focused on the satisfaction of the needs and demands of customers. Some methods are described within the ISO 9004-4 standards, for instance:
- the histograms for a visual presentation of information,
- the control diagram and charts,
- the ABC (Pareto) diagram,
- the Ichikawa diagram,
- the diagram of dispersion,
- the Tree diagram,
- the expert systems for decision aids, etc.

• **High-technology cycles - scientific application**
High-technology cycles behave like quality cycles, by engaging in such a way that high technology comes to be in the function of the majority of employees, and consequently adds to the improvement of quality.
Not only does high technology contribute to the improvement of quality, it also generates new technologies.

Group III: Equal distribution of work functions

This very important paradigm of quality control is characterized by four principle approaches:
1. Equal distribution of automation - spare time,
2. Equal distribution of new technologies - customer satisfaction,
3. Equal distribution of the functions of quality-customer comprehends your work,
4. Equal distribution of the enterprise quality - increase of the process ability.

Group IV: Re-engineering of the process - maintenance

Re-engineering and the quality system are the main concepts of enterprise development, regardless of their proportion and profit. They are imperative for the development of all business components and market competition and they reflect on all the business elements of an enterprise.

Group V: Including the customer in the process

This approach group enables the adaptation of the organization to the demands and needs of the customer, which has a particular contribution to TQM development and embraces the following:
- designing with the help of the customer - including the customer in the system,
- controlling by organisation with the help of the customer,
- Kansai engineering - including the latent wishes of the customers and employees.

Group VI: Quality of knowledge (learning, reviewing and implementing the acquired knowledge)

The quality of knowledge within the organization depends on the efforts in:
- creating technologies of knowledge, i.e. artificial intelligence,
- accelerating the changes in knowledge in order that the work becomes educational,
- the quality that transforms all the employees into researchers in the function of improving the work processes,

- international competition, which reinforces the organization in the battle for survival,
- information technologies, global and local webs for computer utilization in each work place.

3 TOTAL PRODUCTIVE MAINTENANCE

Total Productive Maintenance (TPM) is a maintenance program that involves a newly defined concept for maintaining plants and equipment. The goal of the TPM program is to markedly increase production (effective production time, decrease of system failures, decrease of production and maintenance costs, etc.) while at the same time increasing employee morale and work satisfaction ([5] and [6]).

TPM emphasises maintenance as an important as well as necessary component of business. Maintenance is no longer regarded as a non-profit activity. The downtime for maintenance is scheduled as part of the manufacturing day and, in some cases, as an integral part of the manufacturing process. The goal is to keep emergency and unscheduled maintenance to a minimum.

3.1 The Pillars of TPM

J. Venkatesh [7] has depicted Total Productive Maintenance as a model in the form of a house with a roof carried by seven pillars and a base that consists of five layers, whose names begin with the letter "S" (Fig. 3)

Each pillar represents a whole in itself and is integrated into the process of maintenance as an inseparable part that makes TPM a totality.

Pillar 1 - Jishu Hozen

This pillar is geared towards developing operators to enable them to take care of small maintenance tasks, thus liberating the skilled maintenance people to spend time on more value-added activities and technical repairs. The operators are responsible for maintaining their equipment in order to prevent it from deteriorating.

Pillar 2 - Kaizen

"Kai" means change, and "Zen" means good (for the better).
Kaizen stands for small improvements; however, it is carried out on a continual basis and involves all the people in the organization. Kaizen is the opposite of big radical innovations. Kaizen requires no or little investment. The principle behind it is that "a very large number of small improvements are more effective in an organizational environment than a few improvements of large value".

Pillar 3 - Planned Maintenance

The aim is to have trouble-free machines and equipment producing defect-free products for total customer satisfaction. This breaks down the

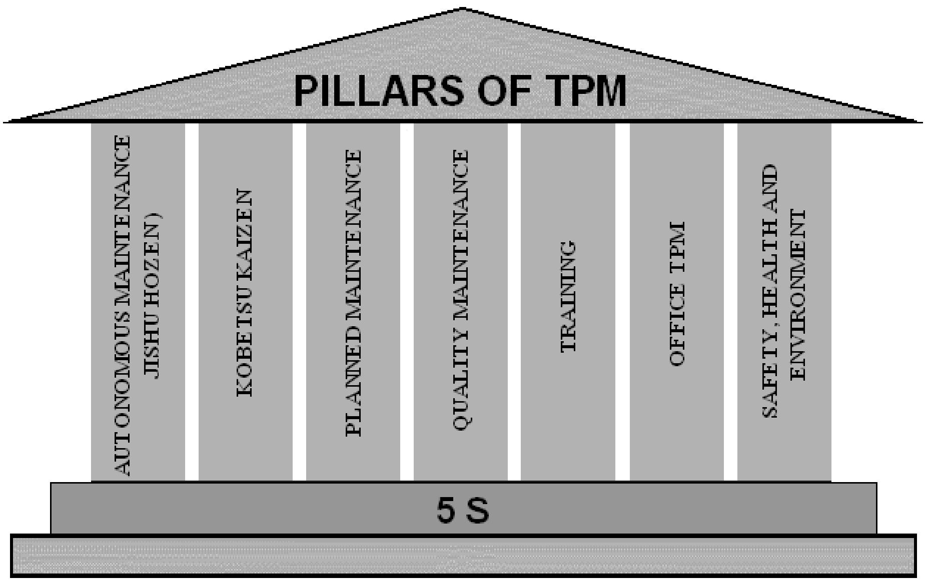

Fig.3. *The pillars of TPM [7]*

maintenance into four "families" or groups, as defined earlier.
- preventive maintenance
- breakdown maintenance
- corrective maintenance
- maintenance prevention – proactive maintenance

With planned maintenance we evolve our efforts from a reactive to a proactive method and use trained maintenance staff to help train the operators to maintain their equipment better.

Pillar 4 - Quality Maintenance

The aim is customer delight as a result of the highest quality through defect-free manufacturing. The focus is on eliminating non-conformances in a systematic manner, much like Focused Improvement. We gain an understanding about which parts of the equipment affect the product quality and begin to eliminate current quality concerns, then move to potential quality concerns. The transition is from reactive to proactive (Quality Control to Quality Assurance).

Target:
- Achieve and sustain zero customer complaints.
- Reduce in-process defects by 50%.
- Reduce the cost of quality by 50%.

Pillar 5 - Training

The aim is to have multi-skilled revitalized employees whose morale is high and who are eager to come to work and perform all the required functions effectively and independently. Education is given to operators to upgrade their skills. It is not sufficient to know only "Know-How", they should also learn "Know-why". Through experience they can master the "Know-How" in order to overcome and solve certain problems. They do this without knowing the root of the problem and why they are doing so. Hence, it becomes necessary to train them on knowing "Know-why".

The employees should be trained to achieve the four phases of skill. The goal is to create a factory full of experts. The different phases of skill are:
- Phase 1: Do not know.
- Phase 2: Know the theory but cannot do.
- Phase 3: Can do but cannot teach.
- Phase 4: Can do and teach.

Pillar 6 - Office TPM

Office TPM should be started after activating the four other pillars of the TPM (JH, KK, QM and PM). Office TPM must be followed to improve productivity, efficiency in the administrative functions and identify and eliminate losses. This includes analyzing processes and procedures with the aim to increase office automation.

Pillar 7 - Safety, Health and Environment

Target:
- Zero accidents,
- Zero health damage,
- Zero fires.

In this area the focus is on creating a safe workplace and a surrounding area that is not damaged by processes or procedures. This pillar will play an active role in each of the other pillars on a regular basis.

3.2 Basis - 5S

Table 1 shows the meaning of each of five letters "S" in Japanese, with their equivalents in English[6]. Problems cannot be clearly seen if a workplace is unorganized. Cleaning and organizing the workplace helps the team to discover and solve problems. Making problems visible is the first step towards improvement.

1. Seiri - Sort out

This means sorting and organizing the items as critical, important, frequently used items, useless

Table 1. *The equivalent meanings of "5S"*

Japanese Term	English Translation	Equivalent 'S' term
1. Seiri	Organisation	Sort
2. Seiton	Tidiness	Systematise
3. Seiso	Cleaning	Sweep
4. Seiketsu	Standardisation	Standardise
5. Shitsuke	Discipline	Self-discipline

or items that are not needed at the moment. Critical items should be kept for use in the immediate vicinity and items that will not be used in the near future should be stored elsewhere. As a result of this step, the search-time is reduced.

2. Seiton - Organize

The concept here is that "Each item has a place, and only one place".

The items should be placed back after use in the same place.

3. Seiso - Shine the workplace

This involves cleaning the workplace, free of burrs, grease, oil, waste, scrap, etc. There should be no loosely hanging wires or oil leakage from the machines.

4. Seiketsu - Standardization

Employees need to discuss together and decide on standards for keeping the work place, machines and paths neat and clean. These standards are implemented for a whole organization and are inspected randomly.

5. Shitsuke - Self-discipline

Considers 5S as a way of life and brings about self-discipline among the employees of the organization. This includes wearing badges, following the work procedures, punctuality, dedication to the organization, etc.

4 SIMILARITIES AND DIFFERENCES BETWEEN TQM AND TPM

The TPM program closely resembles the popular Total Quality Management (TQM) program. Many of the tools, such as employee empowerment, benchmarking, documentation, etc., used in TQM are used to implement and optimize TPM ([2] and [7]).

The similarities between TQM and TPM are:

- Total commitment to the program by upper-level management is required in both programmes.
- Employees must be empowered to initiate corrective action.
- A long-range outlook must be accepted, as TPM may take a year or more to implement and is an ongoing process. Changes in the employees' mindset toward their job responsibilities must take place as well.

The differences between TQM and TPM are summarized in Table 2.

5 REENGINEERING, QUALITY SYSTEM AND MAINTENANCE

The development of 21st-century society is characterized by three main trends: globalization, the computer science revolution and the restructuring of production systems (industry) based on the principles of re-engineering (Business Process Reengineering - BPR), where maintenance plays a special role ([5] and [8]).

In technical-technological reengineering, maintenance has the role of enabling and maintaining new as well as pre-existing production capacities. Similarly, maintenance is subjected to its own re-engineering.

In re-engineering, the process of implementing the quality system is realized slowly at its beginning (see Fig. 4). After re-engineering (BPR), the business results (BR) increase to a certain level (t1). A further increase in the business results (after t1) prolongs the improvement of the quality system (QMS). Maintenance (M), as logistics, enables the verification of the complete cycle of re-engineering and the quality system [5].

Maintenance is the tool for the implementation of the QMS to the level of a TQM, under the condition of aspiring to a TQM.

Table 2. *The differences between TQM and TPM*

Category	TQM	TPM
Object	Quality (Output and effects)	Equipment (Input and cause)
Means of attaining the goal	Systematize the management, and it is software oriented	Employees participation, and it is hardware oriented
Target	Quality for IPMt	Elimination of losses and wastes.

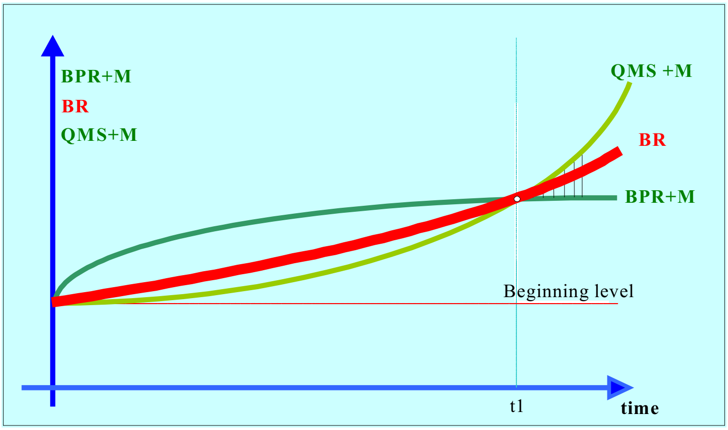

Fig. 4. *Business-result (BR) change of a production system in the function of re-engineering (BPR), quality management system (QMS) and maintenance (M)*

Table 3. *Characteristics of the company "ŽITOPROMET" A.D. business moves during the period of the investigation*

Year	Investments (currency)	Description of reengineering activities and quality	QMS Advancement	Business results - BR Profit (currency)
I	1,453,571	Construction of a 1000 tonne silo, investments in the preparation of projects, etc., equipment, training of the employees in production and maintenance **Preparing QMS documentation**	20%	12,857
II	1,354,014	Reconstruction of equipment, train tracks, telephone network, construction of a 1000 tonne silo, training of the employees in production and maintenance **Preparing QMS documentation**	30%	42,121
III	457,500	Procuring process equipment, laboratory equipment, training of employees in the production and maintenance **Certifying QMS**	50%	77,950
IV	568,000	Installation of equipment, training of the employees in production and maintenance. **Applying certified QMS**	70%	291,265
V	510,891	Reconstruction of various pieces of equipment, training of the employees in production and maintenance. **Advancing QMS**	80%	182,520
VI	570,748	Procuring new computer equipment, computer networking, training of employees. **Advancing QMS - Winning the "Oscar of Quality"**	90%	227,551

On the other hand, the culture of the QMS to the level of the TQM is suitable for alterations in business components until the achievement of business excellence.

*The **nature of re-engineering** makes the organization different, while the **nature of TQM** makes the organization better.*

5.1 Investigation results of QMS's influence on business results in real conditions

The investigation is based on the hypothesis (Fig. 4) that the quality system represents a superstructure above the system re-engineering; in other words, it represents an incentive to reach a higher level of business success within an enterprise until a need appears for new re-engineering.

The object of the investigation is the company Žitopromet A.D. - Spuž, Montenegro, winner of the Oscar of Quality (SRJ) in the year 2000 in the category of small and medium-sized enterprises (SMEs), whose QMS was certified by an RW TÜW evaluation body from Essen. This company produces various sorts of flour.

The results were gathered over a period of six years in which this company implemented the re-engineering of all the production systems (increasing capacities and broadening the product range) and at the same time intensively advanced the quality system by lowering the costs, increasing revenues and gaining competitiveness in the market.

Table 3 shows the data on investing in re-engineering, the degree of advancement in the function of the quality system and the results of the business-result changes that appeared as a consequence of the latter.

Through contemplating and analysing the results that show the following: investments in re-engineering (BPR), degree of the quality system (QMS) advancement and growth of business results (BR) expressed through profit, one can derive a diagram that confirms the hypothesis about the influence of re-engineering and the quality system on the profit growth as an indicator of business success (see Fig. 5).

6 CONCLUSIONS

1. Today, with competition in industry at an all-time high, TPM may be the only thing that stands between success and total failure for some companies. It has been proven, as a program, to work. It can be adapted to work not only in industrial plants, but in construction, building maintenance, transportation, and in a variety of other domains.
2. Employees have to be educated and convinced that TPM is not just another "program of the month" and that management is totally committed to the program and the extended time frame necessary for full implementation. If everyone involved in a TPM program does his or her part, an unusually high rate of return compared to the resources invested may be expected.
3. The quality of the knowledge within the organization depends on the given efforts in:
   - creating technologies of knowledge, i.e. artificial intelligence,
   - accelerating the changes in knowledge, so that work becomes learning,
   - the quality that transforms all the employees into researchers in the function of the improvements of work processes,

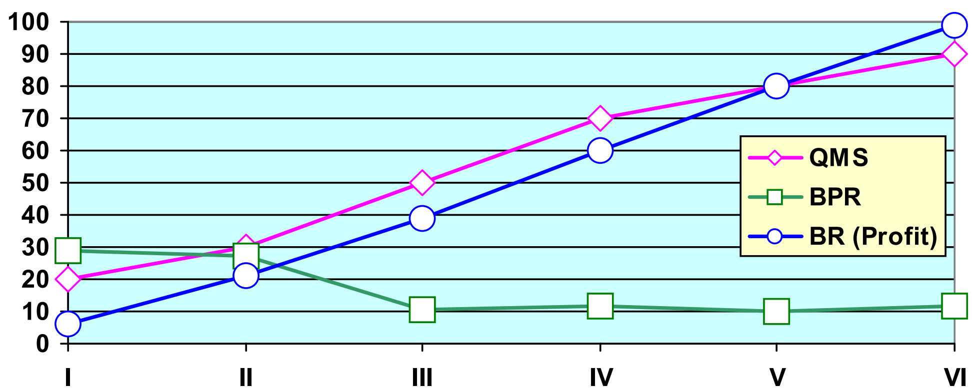

Fig. 5. *Business-result (BR) advancement of company "Žitopromet" in terms of the reengineering (BPR) and the quality management system (QMS)*

- the international competition, which reinforces organization for the battle for survival,
- information technologies, global and local webs for computer utilization at each work place.

4. Maintenance has the highlighted adjustment for the application of TQM, whose reversible effect creates the conditions for the development of the total preventive maintenance (TPvMt), as the method of scientific prevention.
5. The achieved level of the quality system in the domain of maintenance can be determined and measured according to all the alteration categories in the access to total quality.
6. Adaptation of the system to the QMS quality standards up to the TQM level represents a necessary superstructure of re-engineering in order to reach higher business results.
7. The business system and all the business subsystems as well as the maintenance need to fulfil three conditional levels of work in order to reach, maintain and improve TQM:
   - the work performance,
   - the work improvement,
   - the advancement of the improved work.

7 REFERENCES

[1] Bulatovic, M. (1998) Maintenance of the production systems in function of improvement of quality according to JUS ISO 9000 Standards, *Conference JUSK*, Kopaonik, Yugoslavia.
[2] Narayan, V. (2004) Effective maintenance management: Risk and reliability strategies for optimizing performance, *Industrial Press*.
[3] Bulatović, M. (1996) Investigation of increasing the effectiveness of systems in the processing industry by predication and prevention failures, Doctor Dissertation, *Mechanical Faculty, Podgorica*, Yugoslavia.
[4] R.T. Greene (1993) Global quality, *ASQC Quality Press*, Milwaukee.
[5] Perović, M. (1998) Management, computer science, quality, *CIM centre, Mechanical Faculty, Kragujevac*, Yugoslavia.
6] Legat, V. (2004) Maintenance management using quality approach, *Technical Faculty, Department for Quality and Dependability of Machines*, Prag.
[7] Venkatesh, J. (2007) An introduction to total productive maintenance (TPM), www.plant – maintenance.com.
[8] Zelenović, D. (1996) Reengineering of work processes, *ITC*, Novi Sad, Yugoslavia.

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Nenehno izboljševanje tlačnega litja s postopkom Šest sigem

Continuous Improvements in Die-Casting Using a Six Sigma Approach

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Prispevek se ukvarja z uporabo metodologije Šest sigem za nenehno izboljševanje procesa tlačnega litja aluminija. Projekt izboljšanja Šest sigem je vpeljan v proces tlačnega litja aluminija z namenom zmanjšati obdelovalni izmeček s povprečnih 4,12 % na manj ko 2 % ter materialni izmeček z 11,43 % na manj ko 4 % v povprečju. Parametri z največjim vplivom na količino izmečka so določeni v diagramu vzrok - posledica, analizirani, izboljšani, ker je to potrebno, in nadzorovani z uporabo orodij in metod Šest sigem. Začetni cilji projekta niso povsem doseženi, narejene so bile večje izboljšave procesa tlačnega litja, ki so dale značilne prihranke.

(Ključne besede: metodologija Šest sigma, tlačno litje, aluminij, nenehne izboljšave)

This paper deals with the application of a Six Sigma methodology to the continuous improvement of an aluminium die-casting process. A Six Sigma improvement project was initiated in an aluminium die-casting process, with the aim to reduce the amount of machining scrap from an average of 4.12% to less than 2%, and the amount of material scrap from 11.43% to an average of less than 4%. The parameters with a major influence on the level of scrap were defined in a cause-and-effect diagram, analyzed, improved where necessary, and put under control using Six Sigma tools and methods. Although the initial project goals were not completely met, major die-casting process improvements were made, resulting in significant savings.

(Keywords: Six Sigma, die-casting, aluminium, continuous improvements)

0 UVOD

Zaradi velike količine izmečka v procesu tlačnega litja aluminija se je pričel izvajati projekt izboljšanja Šest sigem. Glavna namena projekta se nanašata na zmanjšanje ravni odkritega izmečka pri tlačnem litju, ki v povprečju dosega 4,12 %, kakor tudi izmečka pri obdelavi, ki v povprečju znaša 11,43 %. Cilja projekta Šest sigem sta: zmanjašanje izmečka pri tlačnem litju na manj ko 2 % in izmečka pri obdelavi na manj ko 4 %.

Skladno z metodologijo DMAIC, prvi korak je bil merjenje ravni celotnega izmečka in določanje deleža v odstotkih za posamezne vrste izmečka. Poroznost, s svojim deležem več kakor 80 %, je bila ugotovljena kot najizrazitejša vrsta izmečka pri tlačnem litju (sl. 1).

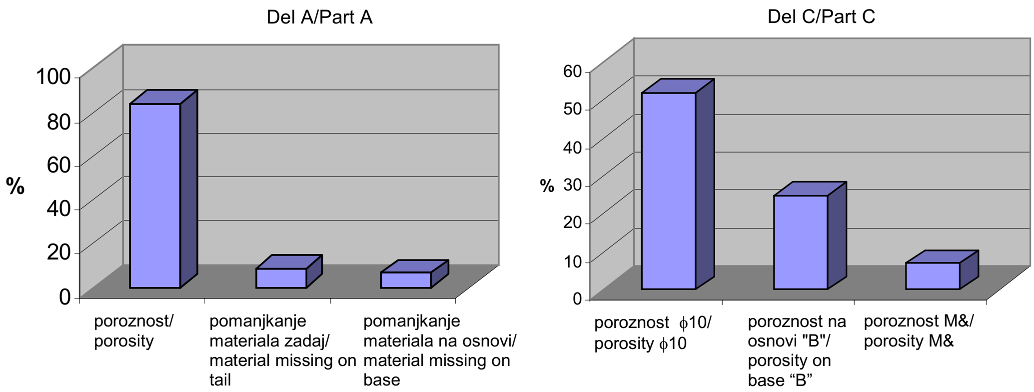
Analiza izmečka pri obdelavi pa je pokazala, da sta izmeček, povzročen s pršenjem kalupov, in

0 INTRODUCTION

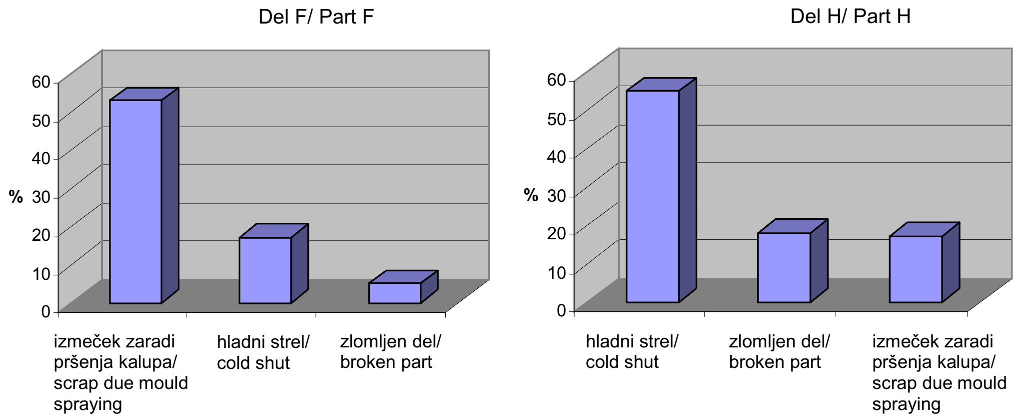
Due to the high level of scrap in the aluminium die-casting process a Six Sigma improvement project was begun. The main project goals were related to a reduction in the amount of scrap during pressure die casting, which on average amounted to 4.12%, as well as a reduction in the amount of scrap during machining, which on average equals 11.43%. The Six Sigma project goals were a reduction of scrap during the die-casting process to less than 2%, and scrap during machining to less than 4%.

In accordance with the *DMAIC* methodology the first step was to measure the current scrap level and to determine the percentage of each type of scrap in the total. Porosity was selected as a major scrap type in die-castings that contributes more than 80% to the total amount of scrap (Fig. 1).

The machining-scrap analysis revealed that the scrap caused by mould spraying and the type of scrap



Sl. 1. *Materialni izmeček za izbrana izdelka*
Fig. 1. *Material scrap for selected types of products*



Sl. 2. *Obdelovalni izmeček za izbrana izdelka*
Fig. 2. *Machining scrap for selected types of products*

izmeček, imenovan *"hladni strel"*, najbolj opazni vrsti izmečkov pri tlačnem litju (sl. 2).

called *cold shut* represented the two most influenced types of scrap observed during die-casting (Fig. 2).

1 ANALIZA PROCESA IN IZBOLJŠAVE

Postopek tlačnega litja je ponazorjen s shemo na sliki 3.

V postopek vstopa surovi material, kateremu je dodan tudi povratni material iz livarne ali obdelovalnice za ponovno pretaljevanje. Po taljenju se raztaljeni material nalije v lonec za litje in prenese v stroj za tlačno litje. Pred nalivanjem v stroj se raztaljeni material izpostavi procesu odplinjevanja, da bi se zmanjšal delež plinov v talini in s tem zmanjšal pojav poroznosti pri litju. Na vsakem stroju za tlačno litje se raztaljeni material nalije v peč, ki omogoča litje pri ustrezni temperaturi. Po tlačnem litju sledi ločevanje dolivkov, nadzor in raziglanje. Po tem so deli pripravljeni za prevoz za nadaljnjo obdelavo.

1 PROCESS ANALYSIS AND IMPROVEMENTS

The die-casting process is represented by the process map shown in Figure 3.

The process involves raw material, to which is added material that is returned from the process to be melted again. After melting, the melted material is poured into the casting vessel and transported to the casting machines. Before pouring into the die-casting machines, the melted material is subjected to a process of out-gassing to reduce the amount of gas in the materials and to prevent the appearance of porosity in the castings. On each die-casting machine melted material is poured into the furnace; this enables casting at the appropriate temperature. After the die-casting, the parts are subjected to trimming, control and deburring. At this point the parts are ready to be transported for further machining.

Kakor je razvidno, določena vrsta izmečka nastane med tlačnim litjem in le manjši del med procesom ločevanja dolivkov. Številni parametri lahko vplivajo na raven izmečka. Razvrščeni so v pet glavnih kategorij: material, osebje, stroji, meritve in okolje ter analizirani z diagramom vzrok – posledica (sl. 4).

Skupine material, osebje in stroji, s podskupino kalupi, so analizirani posebej, medtem ko je skupina meritve analizirana skupaj s skupino osebje, skupina okolje pa skupaj s skupino stroji.

1.1 Material

Da bi zagotovili celoten nadzor nad materialom, so izvedli podrobno analizo sestave in ravnanja s talino med prevozom, odplinjevanja in segrevanja na temperaturo litja. Opravljene dejavnosti izboljšanja, ki se nanašajo na pripravo raztaljenega materiala, so naslednje:

- Zaradi neustrezne čistoče talilne peči sta bila izvedena potrebno popravilo in čiščenje, skladno z ustrezno specifikacijo delovnega postopka; višja raven nadzora in pregleda snažnosti sta definirana.
- Po čiščenju se je delovna zmogljivost peči povečala, kar je pripeljalo do izboljšanja učinkovitosti izrabe energije v peči.

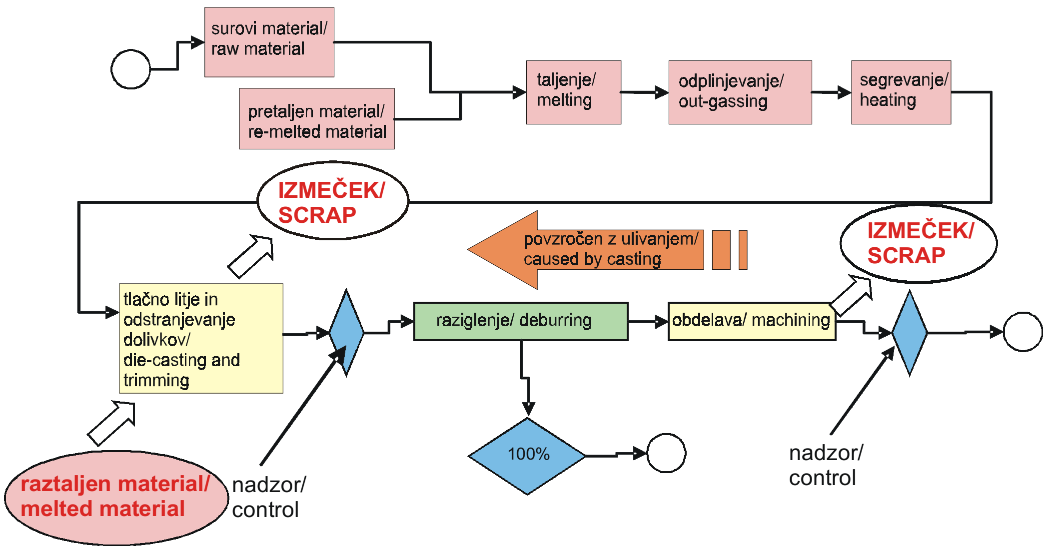
Obviously, scrap is produced during the die-casting and to a smaller extent during the trimming process. There are a large number of parameters that can influence the level of scrap. The parameters are grouped into five main categories: Material, Personnel, Machines, Measurements and Environment, and these are analyzed with a cause-and-effect diagram (Fig. 4).

The groups Material, Personnel and Machines, with the subgroup Moulds, are separately analyzed, while the group Measurement is analyzed together with the group Personnel, and the group Environment is analyzed together with the group Machines.

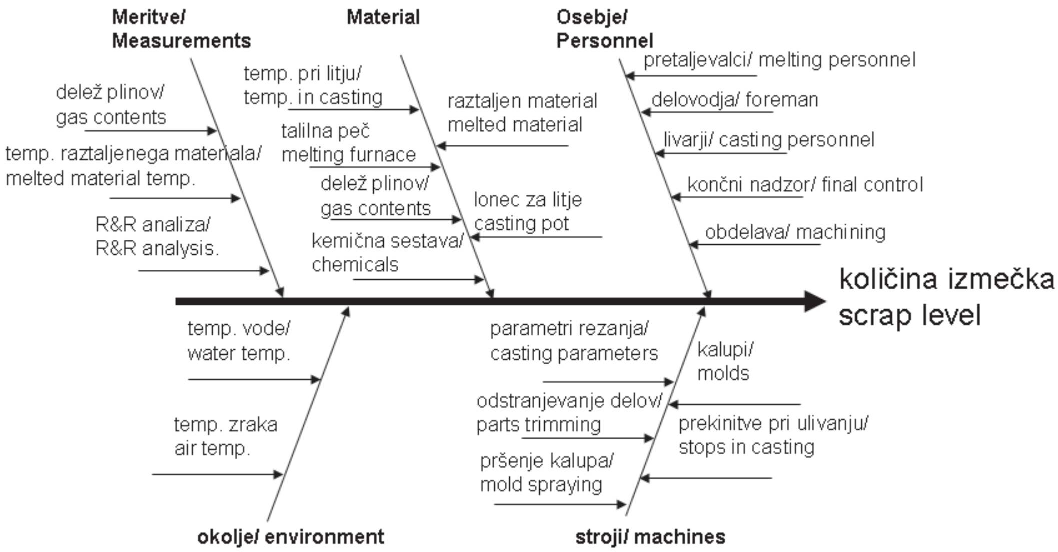
1.1 Material

To ensure that the material is completely under control, a detailed analysis of the composition and the handling with melted material during transportation, out-gassing and heating at the casting temperature, was carried out. The implemented improvement activities that concern the preparation and handling of the melted material are as follows:

- Due to the unsatisfactory cleanliness of the melting furnace, necessary repair and cleaning are carried out and, in accordance with appropriate operating procedure specification, a higher level of control and cleanliness inspections are defined.
- After cleaning, the operating capacity of the furnace is increased, resulting in an improved energy efficiency of the furnace.



Sl. 3. *Poenostavljena shema postopka tlačnega litja*
Fig. 3. *Simplified die-casting process map*



Sl. 4. *Diagram vzrok - posledica za parametre, ki vplivajo na količino izmečka*
Fig. 4. *Cause-and-effect diagram of parameters that influence scrap level*

- Osebje je dodatno usposabljano za izvajanje ustreznega čiščenja povratnega materiala iz procesa tlačnega litja pred taljenjem.
- Sedanja izolacija lonca za litje je zamenjana z izolacijo, ki ima manjšo toplotno prevodnost, kar povzroča neznatno ohlajanje raztaljenega materiala med prevozom. Neposredni rezultat te izboljšave je, da se je temperatura segrevanja v peči za litje lahko znižala za približno 45 °C.
- Metoda "Poka-yoke" je uporabljena na stroju za odplinjevanje, da bi preprečili odplinjevanje s tlakom plina, nižjim od dovoljenega.
- Metoda "Poka-yoke" je tudi uporabljena na strojih za tlačno litje, da bi preprečili litje pri temperaturi raztaljenega materiala zunaj določenega delovnega področja.

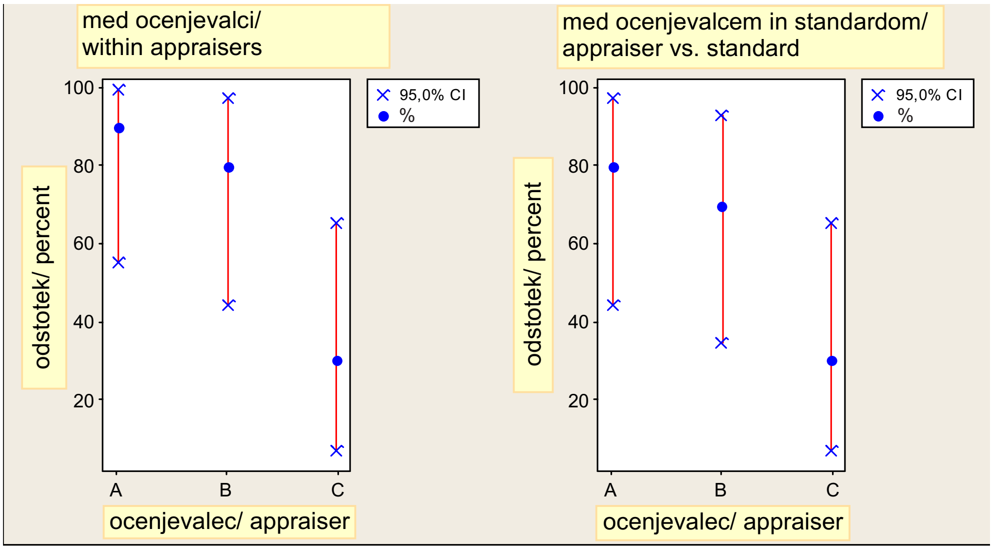
1.2 Osebje

Naslednji pomembni parameter, ki močno vpliva na raven izmečka, je osebje. Ugotovljeno je, da naj bi bil operater, kot dejavni udeleženec v procesu litja, ustrezno usposobljen za čimprejšnje prepoznavanje izmečka in ustrezno ukrepanje. Po tej poti bi lahko preprečili ali se izognili velikim nihanjem procesa, ki se jih včasih odkrije prepozno. Za oceno ravni prepoznavanja izmečka osebja se izvaja analiza R&R. Doseženi rezultati kažejo, da bi morali izpeljati naslednje usposabljanje osebja (sl. 5).

- Personnel are additionally trained to provide adequate cleanliness of the material that is returned from the die-casting process to melting.
- The existing casting vessel's insulation was replaced with insulation that has less thermal conductivity, which results in significantly less cooling of the melted material during the transportation. As a direct result of that improvement, the heating temperature in the melting furnace can be decreased by approximately 45°C.
- A Poka-yoke is applied to the out-gassing machine to prevent out-gassing with a gas pressure lower than that which is allowed.
- A Poka-yoke is also applied on the die-casting machines to prevent casting with a melted-material temperature outside the defined operating window.

1.2 Personnel

The next important parameter that strongly influences the level of scrap is the personnel. We concluded that the operator, as an active participator in the casting process, should be adequately trained to recognize scrap as soon as possible, and to react appropriately. In such a way scrap can be prevented and we can avoid major process discontinuities that are sometimes recognized too late. To assess the level of personnel scrap recognition, an R&R analysis was conducted. The results show that further personnel training should be carried out (Fig. 5).



Sl. 5. *Rezultati R&R analize pri prepoznavanju izmečka pri obdelavi*
Fig. 5. *Results of the R&R analysis for scrap recognition during machining*

Vodeno usposabljanje osebja vpliva na boljše prepoznavanje izmečka pri litju; omogoča uporabo nadzornih načrtov, s katerimi se da zelo zgodaj prepoznati posebne vzroke za spremembe procesa.

1.3 Stroji

V analizi vpliva stroja na raven izmečka, je bil glavni poudarek podan znižanju ravni izmečka zaradi potrebnega pršenja kalupa z oljem. Pri sedanji tehnološki rešitvi je prvi uliti del po pršenju vedno izmeček. Številne tehnološke rešitve so bile analizirane in najbolj obetajoča je bila uporaba avtomatskega pršenja kalupa z različnimi vrstami olja. Po začetnih preizkusih in poskusih je bil nameščen sistem za avtomatsko pršenje kalupa na vseh strojih za tlačno litje. Na sliki 6 so prikazane šobe za pršenje kalupov z oljem.

Analiza vpliva stroja za tlačno litje na količino izmečka je bila izpeljana v številnih smereh. Tako so bili med projektom nadzorovani številni delovni parametri, zamenjani neustrezno delujoči elementi strojev za tlačno litje ipd.

Posebna pozornost je bila namenjena analizi nihanj pri delovanju stroja za tlačno litje ali zaustavitvam. Izkazalo se je, da je bilo veliko število nezabeleženih kratkih prekinitev med delovanjem stroja za tlačno litje. Nihanje pri delovanju stroja za tlačno litje povzroča nepotrebno in

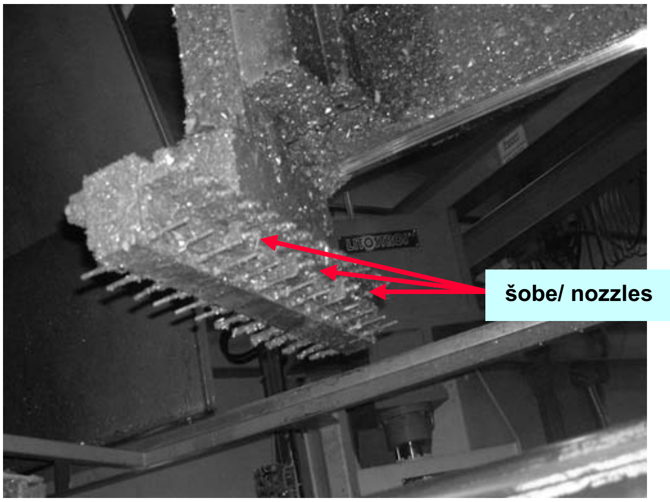
The personnel training resulted in better scrap recognition during casting, enabling the application of control charts, by which special causes of variation in the process are recognized as early as possible.

1.3 Machines

In the analysis of the machine's influence on scrap level, the main focus was on decreasing the level of scrap due to the necessary mould spraying. With the existing technological solution, the first part cast after spraying is always scrapped. Several technological solutions were analyzed, and the most promising was the use of automated mould spraying with different types of oil. After the initial experiments and tests, automated mould spraying was installed on all the die-casting machines in the process. Figure 6 shows the nozzles for spraying the mould with oil.

An analysis of the influence of the die-casting machine on the level of scrap was carried out in several directions. This means that during the work on the project, several operating parameters were controlled, and malfunctioning die-casting machine parts were replaced, etc.

Special attention was given to an analysis of the die-casting machine's operating discontinuities or stops. It was shown that large numbers of undocumented short stops take place during the die-casting machine's operation. The die-casting machine's operating discontinuities cause



Sl. 6. *Šobe za razprševanje olja v kalupu*
Fig. 6. *Nozzles for oil spraying the mould*

nepričakovano ohlajanje kalupov, ki neposredno vpliva na količino izmečka.

Opazovanje stroja za tlačno litje prek krmilne enote stroja in postavljanje doseženih podatkov v povezavo z količino izmečka za določene krajše odmore, pokaže močno povezavo med količino izmečka in številom prekinitev pri delovanju stroja (sl. 7). Zato je treba ločeno analizirati nihanja pri delovanju strojev za tlačno litje, da bi jih zmanjšali na minimum.

unnecessary and unwanted cooling of the moulds, which directly influence the level of scrap.

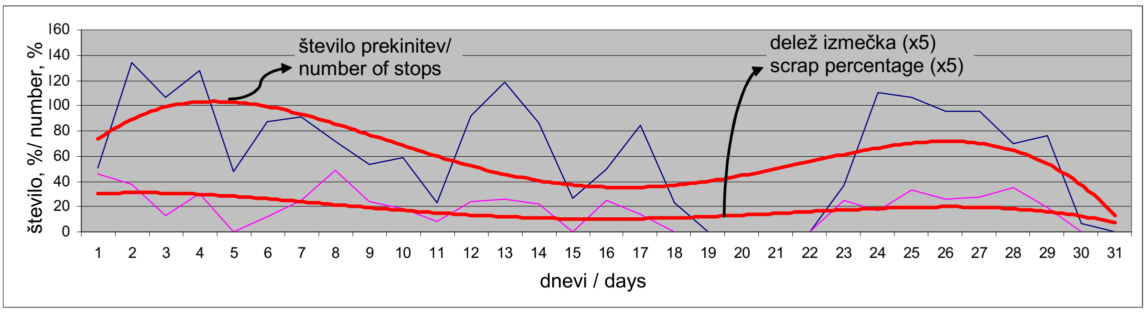
Monitoring the die-casting machine via a machine control unit, and putting the obtained data in correlation with the scrap level for certain shorter intervals showed the strong correlation between the scrap level and the number of stops when a machine is in operation (Fig. 7). Therefore, it is necessary to separately analyze the casting machine's operating discontinuities in order to reduce them to a minimum.

1.4 Kalupi

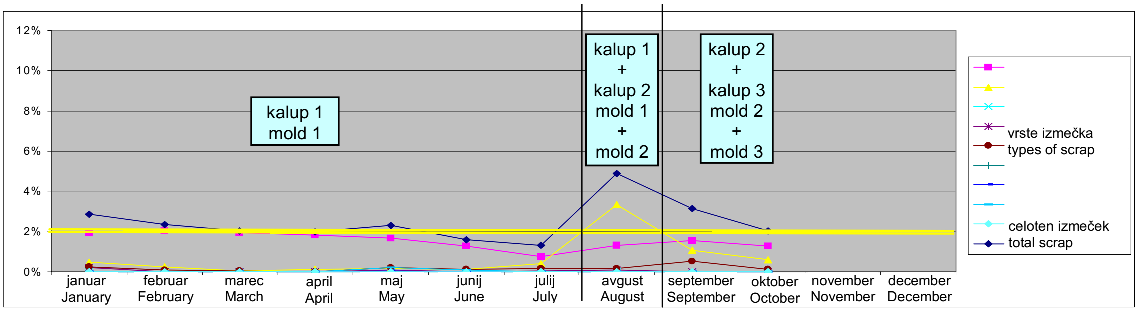
Osrednja karakteristika opazovanega procesa tlačnega litja je hitro spreminjanje. Med projektom so uporabili precejšnje število novih kalupov. Ta usmeritev se nadaljuje. Vsak nov kalup pri procesu je nov vir sprememb. Poseben problem je bilo uvajanje novega kalupa za sedanji liti del. V

1.4 Moulds

The main characteristic of the observed die-casting process is rapid changing. During the project a significant number of new moulds was introduced, and this trend is continuing. Each new mould in the process represents a new source of variability. A particular problem was the introduction of a new mould for the



Sl. 7. *Analiza količine izmečka ter prekinitev tlačnega litja na stroju, krajših kot 10 minut*
Fig. 7. *Analysis of the level of scrap and the die-casting machine's operating stops that are shorter than 10 minutes*



Sl. 8. *Količina izmečka za del H, za obdobje 10 mesecev*
Fig. 8. *Scrap level for part H, for a 10-month period*

nekaj primerih drugi ali tretji kalup, za enako vrsto litega dela, ni bil dobavljen z uporabljenimi izboljšavami glede na prvi kalup, kar je jasno pri uporabi drugega ali tretjega kalupa povzročilo veliko količino izmečka v procesu. Primer je prikazan na sliki 8.

2 SKLEP

Količina obdelovalnega izmečka, ki je bil na začetku projekta v povprečju 11,43 %, je zmanjšan na povprečje 7,51 %. Upoštevajoč stroške ulitega dela, stroške surovega povratnega materiala, ki se vrača na taljenje, in načrtovanega števila ulitih delov v naslednjem opazovanem obdobju, lahko izračunamo znatne prihranke.

Prihranki so doseženi tudi pri taljenju z večjo učinkovitostjo talilne peči kakor tudi pri procesu tlačnega litja zaradi večje učinkovitosti in izkoristka strojev za tlačno litje.

Čeprav so bili doseženi znatni prihranki in izboljšave je treba povedati, da na začetku postavljeni cilji procesa niso povsem doseženi. Razlogov za to je kar nekaj: npr. velika dinamika proizvodnje, uvajanje velikega števila novih kalupov v proces ipd. Zato je treba predlagati smernice za nadaljnje delo pri stalnem izboljšanju kakovosti procesa tlačnega litja.

Te smernice so:

- stalno izboljšanje discipline pri postopku,
- stalno usposabljanje osebja,
- uvedli naj bi preventivno vzdrževanje kalupov.

Posebno pozornost naj bi posvetili prekinitvam delovnega procesa tlačnega litja, še posebej skozi novi projekt Šest sigem.

Na koncu je v preglednici 1 podana še skupna količina izmečka za določene dele v procesu tlačnega litja aluminija.

existing cast parts. In several cases, the second or the third mould for the same kind of cast part was not delivered with the applied improvement from the first mould. This means that the introduction of the second or the third mould also introduces a higher level of scrap in the process. An example is shown in Figure 8.

2 CONCLUSION

The machining scrap level, which at the beginning of the project was on average 11.43%, was reduced by an average of 7.51%. Taking into account the price of the part, the price of the raw material that is returned during melting, and the planned number of parts in a subsequent control period, significant savings can be achieved.

Savings were also achieved during melting, due to the higher efficiency of the melting furnace and, in the die-casting process, also due to the higher efficiency and utilization of the die-casting machines.

Although significant savings and improvements are achieved, it should be said that the initial process goals were not completely met. There are several reasons for this; for example, the high dynamics of the production, the introduction of a large number of new moulds in the process, etc. For this reason it is necessary to suggest directions for further work in continuous quality improvement in the die-casting process.

These directions are:

- the discipline in the process should be continuously improved,
- the personnel should be continuously trained,
- preventive mould maintenance should be introduced.

Special attention should be given to the die-casting process' operating discontinuities, which are possible with a new Six Sigma project.

In conclusion, a summary of the scrap level for certain parts in the pressure die-casting process and the results of the aluminium die-casting process are shown in Table 1.

Preglednica 1. *Količina izmečka na začetku in na koncu projekta*
Table 1. *Scrap level at the beginning and at the end of the project*

	izmeček zaradi pršenja kalupa scrap due mould spraying	**hladni strel cold shut**
količina izmečka na začetku projekta scrap level at the beginning of the project	1,92 %	5,75 %
količina izmečka na koncu projekta scrap level at the end of the project	0,55 %	2,89 %
izboljšanje improvement	**1,37 %**	**2,86 %**

3 LITERATURA
3 REFERENCES

[1] Pavletić, D., Soković, M. (2002) Six Sigma: a complex quality initiative, *Journal of Mech. Eng.*, Vol. 48, No. 3, 2002.
[2] Pavletić, D., Fakin, S., Soković, M. (2004) Six Sigma in process design, *Journal of Mech. Eng.*, Vol. 50, No. 3, 2004.
[3] Soković, M., Pavletić, D., Fakin, S. (2005) Application of Six Sigma methodology for process design, *Journal of Mater. Process. Techn.*, Vol. 162/163, 2005.
[4] Soković, M., Pavletić, D., Matković, R. (2005) Measuring system analysis for quality assurance in a Six-Sigma process, *Journal of Mech. Eng.*, Vol. 51, No. 9, 2005.
[5] Breyfogle III, F. W., et al. (2001) Managing Six Sigma, *John Wiley & Sons*, Inc., New York.
[6] Pyzdek, T. (1999) The Six Sigma revolution, *Quality America Inc*.
[7] Sistemska navodila podjetja Cimos, *PS Cimos*, Koper, 1999-2001.
[8] Delovna navodila PS CIMOS, *PC BUZET, PS Cimos*, 1999-2001.

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Magisteriji in diplome - Master's and Diploma Degrees

MAGISTERIJI

Na Fakulteti za strojništvo Univerze v Mariboru so z uspehom zagovarjali svoja magistrska dela:

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