© Strojniški vestnik 50(2004)10,446-461
ISSN 0039-2480
UDK 621.914:519.85
Izvirni znanstveni članek (1.01)

© Journal of Mechanical Engineering 50(2004)10,446-461
ISSN 0039-2480
UDC 621.914:519.85
Original scientific paper (1.01)

Sistem za spremljanje in optimiranje postopka frezanja z uporabo genetskih algoritmov

A System for Monitoring and Optimizing the Milling Process with Genetic Algorithms

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V prispevku je predstavljen sistem za spremljanje in optimiranje postopka frezanja z oblikovnim krogelnim frezalom. Sistem združuje različne metode in tehnologije, to so: evolucijske metode, tehnologija obdelave, merilna in nadzorna tehnologija, inteligentna postopkovna tehnologija s podporo ustrezne programske in strojne opreme.

Sistem za spremljanje in optimiranje postopka frezanja združuje sistem za spremljanje postopka frezanja in model optimiranja. Sistem za spremljanje postopka frezanja je namenjen spremljanju in zbiranju veličin odrezovalnega postopka z uporabo zaznaval in spremembo teh podatkov v numerične vrednosti, ki so izhodišče za optimiranje postopka frezanja z oblikovnim krogelnim frezalom. Z modelom optimiranja določamo rezalne parametre pri postopku frezanja na podlagi analitičnega modela rezalnih sil ter modela obstojnosti orodja z genetskim algoritmom. Sistem uporabimo za napovedovanje rezalnih sil, optimiranje rezalnih parametrov, zmanjšanje celotnega časa obdelave, povečanje natančnosti, zanesljivosti, produktivnosti in zmanjšanje stroškov obdelave.

(Ključne besede: optimiranje odrezovanja, sile rezanja, parametri rezanja, frezala oblikovna krogelna, algoritmi genetski)

This paper presents a system for monitoring and optimizing the ball-end milling process. The system combines different methods and technologies, like evolutionary methods, manufacturing technology, measuring and control technology and intelligent process technology with the appropriate hardware and software support.

The system for monitoring and optimizing the ball-end milling process combines the process monitoring system of the ball-end milling process and the optimization model. The monitoring system is designed for monitoring and collecting the variables of the milling process by means of sensors and the transformation of those data into numerical values, which are the starting point for the optimization of the ball-end milling process. The optimization model is used for the optimization of the milling parameters with genetic algorithms. The optimization is based on the analytical cutting-force model and the tool-wear model. The developed methods can be used for the cutting-force estimation and the optimization of the cutting parameters. The integration of the proposed system will lead to a reduction in the production costs and production time, flexibility in machining-parameter selection, and an improvement in product quality.

(Keywords: optimization, cutting forces, cutting parameters, ball-end mill, genetic algorithms)

0 UVOD

V prispevku je predstavljen razvoj sistema za spremljanje in optimiranje postopka odrezovanja, ki je prikazan na postopku odrezovanja materiala (jekel) z oblikovnim krogelnim frezalom. Postopek frezanja je eden izmed najpomembnejših in vsestranskih postopkov obdelave materiala, s katerim lahko obdelujemo zapletene površine in oblike izdelkov. Z združitvijo

0 INTRODUCTION

This paper presents a system for monitoring and optimizing the machining process, which is shown in detail in the process of machining steels with ball-end milling. The milling process has become a very important and useful procedure for the manufacture of 3D surfaces of different shapes. Due to the widespread use of highly autosodobnih večosnih, frezalnih strojev z velikimi hitrostmi pa se je v proizvodnji pojavila zahteva po spremljanju in optimiranju postopka odrezavanja.

Namen je razviti inteligentni sistem za spremljanje in optimiranje postopka frezanja, ki bo zbiral podatke med samim postopkom odrezovanja ter s pomočjo teh postopek optimiral. Z uporabo sodobnih metod umetne inteligence smo razvili model za optimiranje rezalnih parametrov na osnovi izmerjenih vhodnih parametrov. Sistem za spremljanje in optimiranje postopka frezanja z oblikovnim krogelnim frezalom temelji na vrednostih izmerjenih rezalnih sil z dinamometrom, analitičnemu modelu rezalnih sil, modelu obstojnosti orodja ter optimiranju rezalnih parametrov z genetskim algoritmom (GA). Sistem bo namenjen inžinerjem za določevanje optimalnih rezalnih parametrov z najmanjšim številom preizkusov ter za zagotavljanje največjih zmogljivosti izbranih opravil na obdelovalnem stroju.

1 PREDSTAVITEV SISTEMA

V zadnjem obdobju se je pojavila zahteva po vrhunski kakovosti izdelkov. Zaradi tega se inženirji srečujejo s težkimi nalogami - kako izboljšati produktivnost in ohraniti kakovost izdelkov. S povečevanjem rezalne hitrosti z namenom, da bi povečali produktivnost, se poslabša stabilnost sistema, kar vodi do preobremenitve stroja in zaradi tega do loma orodja. Pri tem je pomemben ustrezen nadzor obdelovalnega postopka s sistemom za spremljanje in optimiranje postopka odrezovanja. Z združitvijo obdelovalnih sistemov z veliko stopnjo avtomatizacije in prilagodljivosti v proizvodnji zagotovimo zanesljivost, natančnost in kakovost izdelka. Zahtevana velika prilagodljivost obdelovalnega postopka zahteva povečanje rezalnih parametrov. Rešitev tega problema je v razvoju sistemov za spremljanje in optimiranje postopka odrezovanja, ki temeljijo na metodah umetne inteligence.

Cilj raziskave je razvoj prilagodljivega in zanesljivega **sistema za spremljanje in optimiranje postopka odrezovanja** (**SOPO**), ki je predstavljen na postopku frezanja z oblikovnim krogelnim frezalom (sl. 1). Sistem je razdeljen na naslednje dele:

- tehnološki parametri,
- sistem za spremljanje postopka frezanja,
- model optimiranja rezalnih parametrov,
- modul za posredovanje optimalnih rezalnih parametrov obdelovalnemu stroju.

Sistem za spremljanje in optimiranje postopka odrezovanja je namenjen optimiranju postopka frezanja z genetskim algoritmom, s katerim optimiramo rezalne parametre ob vsaki spremembi rezalnih sil. S sistemom lahko prej napovemo vse pomembne veličine odrezovalnega postopka, ki se bodo kasneje dejansko pojavljale pri samem postopku obdelave.

mated machine tools in industry, manufacturing requires reliable monitoring and optimization models and methods.

The main objective of this paper is to develop an intelligent online monitoring and optimization system for the ball-end milling process. By exploring the advantages of artificial intelligence methods, the optimization model is developed. The system for monitoring and optimizing the ball-end milling process is based on the measured cutting forces, the analytical cutting-force model, the tool-wear model and the optimization of cutting parameters with the genetic algorithm (GA). The developed system will be applied to the manufacturing process for the determination of the optimum cutting parameters with the fewest number of experiments and the maximum cutting power on the tool machine.

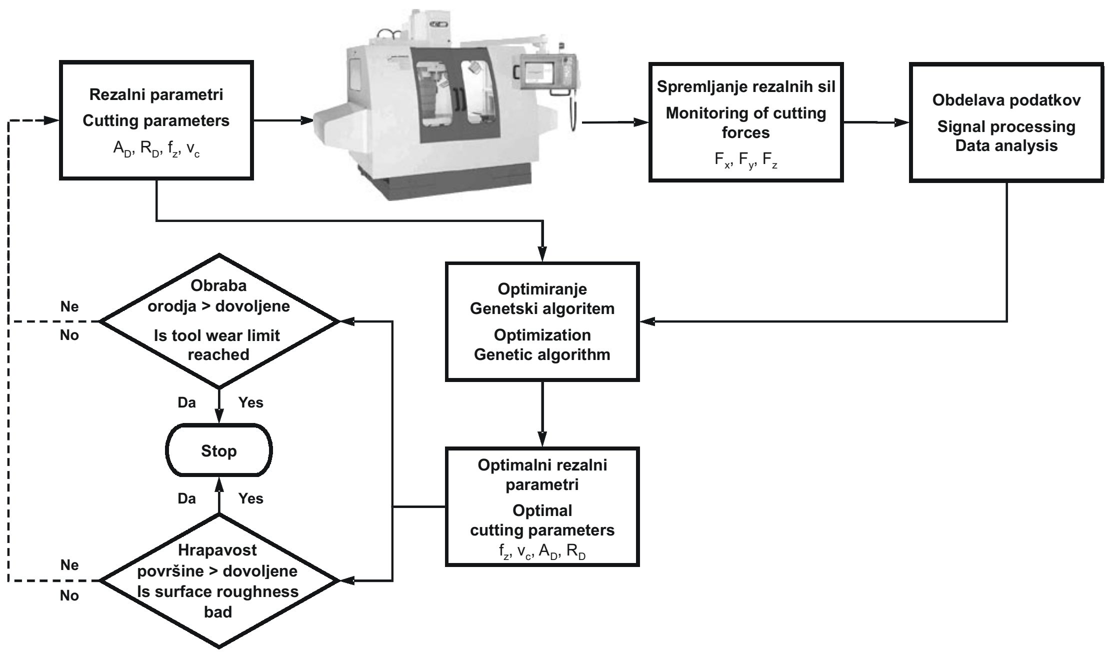
1 PRESENTATION OF THE SYSTEM

In recent years there has been an increase in the demand for high-quality products. Consequently, manufacturing engineers are faced with the difficult task of improving productivity without comprising quality. The use of high machining speeds to increase productivity exacerbates the stability problems and might even lead to tool breakages in certain situations. This emphasizes the proper control of the machining process through an online monitoring and optimization system. The success of manufacturing systems with a high level of automation and flexibility is the capability to strictly control the quality of the products, to guarantee working processes with a known reliability, and the availability of the whole system. The high flexibility required for the manufacturing process also involves increasing the severity of the operating parameters. The solution to this problem is in the development of systems for monitoring and optimizing the cutting process based on artificial intelligence.

The main objective of this research is to develop flexible and reliable **system for monitoring and optimization** (**SOPO**), which is shown on the ball-end milling process. (Fig. 1). The system is divided into:

- technological parameters,
- monitoring system,
- optimization model,
- response module.

The system for monitoring and optimizing of the cutting process has been developed for the optimization with a genetic algorithm at various obtained cutting forces. The system can show all the important cutting process variables, which will later actually appear in the machining process itself.



Sl. 1. *Sistem za spremljanje in optimiranje postopka odrezovanja*
Fig. 1. *System for monitoring and optimizing the of machining process*

2 REZALNE SILE PRI OBLIKOVNEM KROGELNEM FREZALU

Frezanje z oblikovnim krogelnim frezalom je zelo pogost postopek obdelave, posebej v avtomobilski, letalski in preoblikovalni industriji [1]. Uporablja se za obdelavo prosto oblikovanih površin, kot so npr. utopi, matrice, votlice, kalupi, turbine, propelerji in letalski sestavni deli. Zaradi različnih vzrokov, kakor so konstrukcijski (strukturni), optimirani ali estetski videz, postajajo geometrijske oblike izdelkov vedno bolj zahtevne. Z uporabo RPN/RPI sistemov in RNK obdelovalnih centrov lahko izdelamo zelo zahtevne oblike površin z oblikovnim krogelnim frezanjem.

Napovedovanje rezalnih sil pri frezanju z oblikovnim krogelnim frezalom je zelo pomembno. V fazi načrtovanja rezalnega postopka znanje o rezalnih silah pomaga tehnologu pri določevanju rezalnih parametrov za obdelavo. Napovedovanje rezalnih sil je v podporo pri načrtovanju postopka, izbiri primernih rezalnih razmer za zmanjšanje obrabe, deformacije in loma orodja, ter pri konstruiranju boljših vpenjalnih priprav, kar izboljša kakovost izdelka. Model rezalnih sil pri frezanju z oblikovnim krogelnim frezalom [2] je del združenega sistema SOPO pri frezanju z oblikovnim krogelnim frezalom.

2.1. Geometrijska oblika oblikovnega krogelnega frezala

Geometrijska oblika frezala ima pomemben vpliv na karakteristiko rezalne sile pri frezanju z oblikovnim krogelnim frezalom. Pri oblikovnem krogelnem frezalu poteka rezalni rob orodja po

2 CUTTING FORCES IN BALL-END MILLING

Ball-end milling is a very common machining process, especially in the automobile, aerospace, die and mould industries [1]. It is used for machining freely shaped surfaces such as dies, moulds, turbines, propellers, and for aircraft structural elements. For various reasons, such as the structural, optimization or esthetic points of view, nowadays, most industrial part geometries are becoming more and more complicated. The recent advances in CAD/CAM systems and CNC machining centers allows us to supply this demand for machining very complex sculpture surfaces by ball-end milling.

The importance of predicting the cutting forces in ball-end milling is evident. In the process-planning stage, knowledge of the cutting forces helps the process engineers to select "appropriate values" for the process parameters. The prediction of cutting forces gives support in the planning of the process, in selecting suitable cutting parameters for the reduction of excessive wear, the deformation and breakage of the tool, and helps to design better fixtures that increase the quality of the parts. The cutting force model for ball-end milling [2] can be utilized in an intelligent system for monitoring and optimization in the ball-end milling process.

2.1 Geometry of a ball-end milling cutter

Cutting-edge geometry plays a very important role in the cutting force characteristics in the ball-end milling process, whereas the straight-end mill, ball-end mill cutting-edge geometry varies locally in the ball površini krogle. Prav tako kakor se spreminja lokalni kot vijačnice, se spreminja tudi polmer frezala *R*, ki vpliva na rezalne sile in rezalno hitrost. Amplituda in potek rezalne sile pri frezanju z oblikovnim krogelnim frezalom sta odvisna od: vrste in geometrijske oblike frezala, rezalnih parametrov ter materiala obdelovanca.

Geometrijska oblika in rezalne sile pri oblikovnem krogelnem frezalu so prikazane na sliki 2. Rezalni rob frezala leži na površini poloble in je določen z nespremenljivim kotom vijačnice. Rezalni robovi imajo kot vijačnice λ_b na prehodu iz polokroglega dela frezala na valjasti del. Glede na zmanjšanje polmera frezala v ravnini *X-Y* proti konici frezala v smeri *Z* se spreminja kot vijačnice - lokalni kot vijačnice. Enačba ovojnice na polkrožnem delu frezala se glasi:

part. For example, as well as varying the local helix angle, varying the radius *R* directly affects the cutting forces through its effect on the cutting velocity. The selection of the proper cutter/cutting-edge geometry, as well as other process factors, is very important over the amplitude and waveform of the generated cutting forces during the machining.

The geometry and the cutting forces on the ball-end milling cutter are shown in Figure 2. The cutting edge of the milling cutter lies on the hemisphere surface and is determined with the constant helix angle. The cutting edges have the helix angle λ_b at the transition from the hemispherical part of the milling cutter into the cylindrical part. With respect to the reduction of the milling cutter radius in the *X-Y* plane towards the milling cutter tip in the *Z* direction the helix angle - the local helix angle changes. The expression for the envelope of the ball part is given by:

$$x^2+y^2+\left(R_0-z\right)^2=R_0^{\;2} \qquad (1)$$

koordinata točke *z*, ki leži na rezalnem robu frezala, je:

The *z* - coordinate of the point located on the cutting edge of the milling cutter is:

$$z=\frac{R_0\cdot\psi}{\tan\lambda_b} \qquad (2),$$

R_0 - polmer polkrožnega dela frezala,
ψ - kot med konico rezalnega roba pri z=0 in vzdolžno lego z,
λ_b - kot vijačnice rezalnega roba frezala.

Za frezala z nespremenljivo dolžino se lokalni kot vijačnice spreminja glede na polmer frezala in ga izračunamo po enačbi:

R_0 - radius of the hemispherical part of the milling cutter
ψ - angle between the cutting edge tip in case of z=0 and the axial position z.
λ_b - helix angle of the cutting edge of the milling cutter

For the milling cutters of constant length the local helix angle changes with respect to the milling cutter radius and it is calculated according to the equation:

$$\tan\lambda_b\left(\psi\right)=\frac{R\left(\psi\right)}{R_0}\cdot\tan\lambda_b \qquad (3),$$

R(ψ) - polmer orodja v ravnini *X-Y* glede na kot κ.

Kotna lega κ v smeri osi *Z* od središča polkrožnega dela do točke na rezalnem robu je:

R(ψ) - tool radius in *X-Y* plane with respect to angle κ

The angular position κ in the direction of the *Z* axis from the center of the hemispherical part to the point on the cutting edge:

$$\kappa=\arcsin\frac{R\left(\psi\right)}{R_0} \qquad (4).$$

Polmer rezalnega roba v ravnini *X-Y*, ki se dotika točke na spiralnem in krogelnem rezalnem robu pri kotu ψ, določimo:

The radius of the cutting edge in the *X-Y* plane, which touches the point on the helical and spherical cutting edge with angle ψ, is determined as follows:

$$R\left(\psi\right)=\sqrt{1-\left(\psi\cdot\cot\lambda_b-1\right)^2}\cdot R_0 \qquad (5).$$

Kotni razmik med rezalnimi robovi na frezalu:

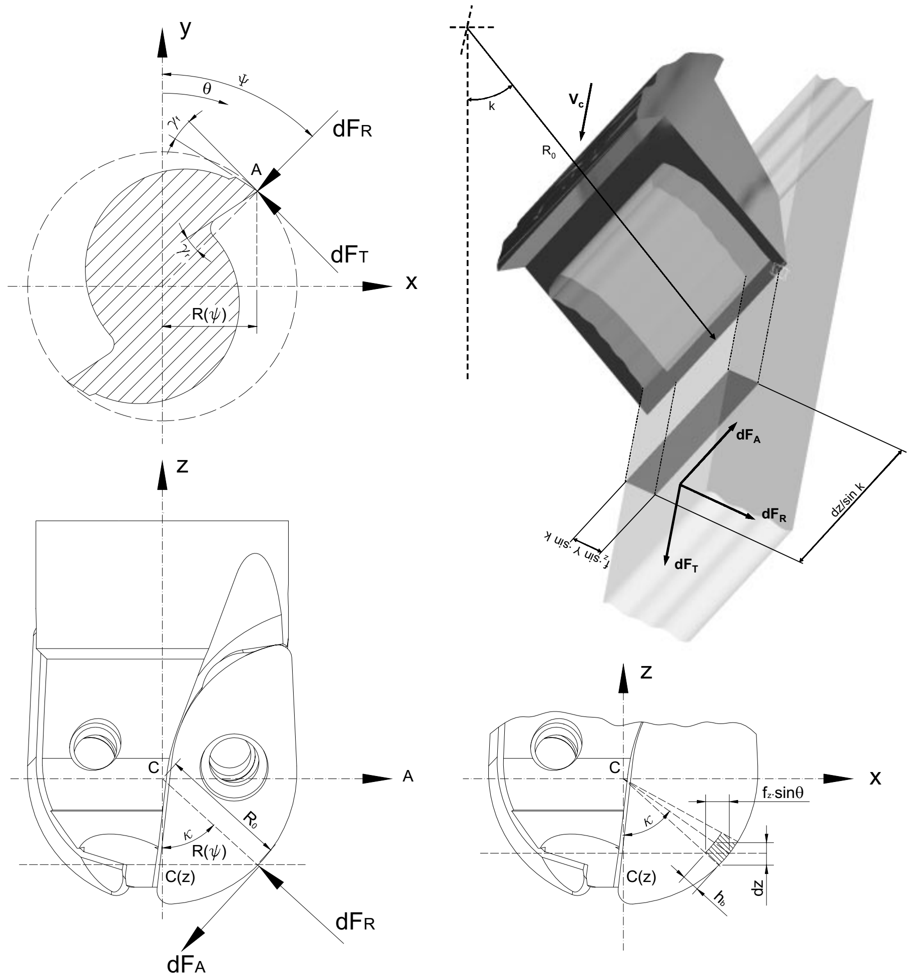
Angular spacing between the cutting edge on the milling cutter:

$$\phi_P=\frac{360^\circ}{N_f} \qquad (6),$$

N_f - število rezalnih robov.
Kotna lega rezalnega roba:

N_f - number of cutting edges
Angular position of the cutting edge:

$$\theta\left(j\right)=j\left(\frac{\phi_p}{N_\theta}\right) \qquad j=1,2,\ldots,N_\theta \qquad (7),$$



Sl. 2. *Rezalne sile in geometrijska oblika pri oblikovnem krogelnem frezalu*
Fig. 2. *Cutting forces and geometry in the case of ball-end milling cutter*

$N\theta$ - število kotnih leg,
$\theta(j)$ - kotna lega rezalnega roba,
ϕ_P - kotni razmik med rezalnimi robovi.

Debelina vzdolžnih delov na rezalnem robu frezala:

$N\theta$ - number of angular positions
$\theta(j)$ - angular position of cutting edges
ϕ_P - angular spacing between cutting edges

Thickness of axial differential elements on the cutting edge of the milling cutter:

$$dz(i) = i\left(\frac{A_D}{N_z}\right) \qquad i = 1, 2, ..., N_z \qquad (8),$$

A_D - vzdolžna globina reza,
N_z - število vzdolžnih delov na rezalnem robu frezala.

Kotna lega rezalnega roba pri odrezovanju $\Psi(i,j,k)$:

A_D - axial depth of cut
N_z - number of axial differential elements on the cutting edge of the milling cutter

Angular position of the cutting edge during cutting $\Psi(i,j,k)$:

$$\Psi(i,j,k) = \theta(j) + \phi_P(k-1) - \frac{z}{R_0} \cdot \tan\lambda_b \qquad (9).$$

Nedeformirano debelino odrezka lahko zapišemo z enačbo:

The undeformed chip thickness is determined as follows:

$$h_b = f_z \cdot \sin\Psi \qquad (10),$$

f_z - podajanje na zob.

Debelina odrezka h_b je funkcija prečnega in vzdolžnega kota:

f_z - feeding per tooth

The chip thickness h_b in the function of the radial and axial angle :

$$h_b = f_z \cdot \sin\Psi \cdot \sin\kappa \qquad (11),$$

Ψ - kotna lega rezalnega roba pri odrezovanju v smeri vrtenja frezala,
κ - kotna lega v smeri osi z od središča polkrožnega dela do točke na rezalnem robu.

Generalizirana enačba za debelino odrezka se glasi:

Ψ - angular position of cutting edge during cutting in the direction of rotation of the milling cutter
κ - angular position in the direction of *Z* axis from the center of the hemispherical part to the point on the cutting edge

The generalized equation for the chip thickness is as follows:

$$h_b\left(i,j,k\right) = f_z \cdot \sin\left[\Psi\left(i,j,k\right)\right] \cdot \sin\left[\kappa\left(i\right)\right] \qquad (12).$$

Napaka v enačbi (12) za debelino odrezka se pojavi le v območju konice frezala [3].

Geometrijsko obliko oblikovnega krogelnega frezala in usmeritev rezalnega roba uporabimo v enačbah za določitev rezalnih sil.

The error in Equation (12) for chip thickness is significant only in areas around the ball tip [3].

The geometry of the ball-end milling cutter and the orientation of the cutting edge are used in the equation for the determination of the cutting forces.

2.2 Določitev rezalnih sil za oblikovno krogelno frezalo

2.2 Determination of the cutting forcess during ball-end milling

Enačbe za delno obodno dF_T, prečno dF_R in vzdolžno dF_A rezalno silo so:

The equations for the differential tangential dF_T, radial dF_R and axial dF_A cutting forces are:

$$\begin{aligned} dF_T &= K_T \cdot h_b \cdot db = K_T \cdot f_z \cdot \sin\Psi \cdot \sin\kappa \cdot db \\ dF_R &= K_R \cdot h_b \cdot db = K_R \cdot f_z \cdot \sin\Psi \cdot \sin\kappa \cdot db \\ dF_A &= K_A \cdot h_b \cdot db = K_A \cdot f_z \cdot \sin\Psi \cdot \sin\kappa \cdot db \end{aligned} \qquad (13),$$

K_T - obodni koeficient materiala
K_R - prečni koeficient materiala
K_A - vzdolžni koeficient materiala
db - delna dolžina rezalnega roba,
če namesto *db* vstavimo:

K_T - tangential coefficient of material
K_R - radial coefficient of material
K_A - axial coefficient of material
db - differential length of cutting edge
if instead of *db* we enter:

$$db = \frac{dz}{\sin\kappa} \qquad (14),$$

dobimo:

we obtain:

$$\begin{aligned} dF_T &= K_T \cdot f_z \cdot \sin\Psi \cdot dz \\ dF_R &= K_R \cdot f_z \cdot \sin\Psi \cdot dz \\ dF_A &= K_A \cdot f_z \cdot \sin\Psi \cdot dz \end{aligned} \qquad (15).$$

Posplošena enačba za obodno, prečno in vzdolžno rezalno silo se glasi:

The generalized equation for the tangential, radial and axial cutting force is:

$$\begin{aligned} dF_T\left(i,j,k\right) &= K_T \cdot f_z \cdot \sin\left[\Psi\left(i,j,k\right)\right] \cdot dz \\ dF_R\left(i,j,k\right) &= K_R \cdot f_z \cdot \sin\left[\Psi\left(i,j,k\right)\right] \cdot dz \\ dF_A\left(i,j,k\right) &= K_A \cdot f_z \cdot \sin\left[\Psi\left(i,j,k\right)\right] \cdot dz \end{aligned} \qquad (16)$$

in velja, če je kot $\Psi(i,j,k)$:

$\varphi_{EX} \le \Psi\left(i,j,k\right) \le \varphi_{EN}$ za protismerno frezanje, če je

$\varphi_{EX} = 0$ in $\varphi_{EN} = \arccos\left[1-\left(\frac{R_D}{R}\right)\right]$,

$\varphi_{EN} \le \Psi\left(i,j,k\right) \le \varphi_{EX}$ za istosmerno frezanje, če je

$\varphi_{EN} = 0$ in $\varphi_{EX} = \arccos\left[1-\left(\frac{R_D}{R}\right)\right]$,

if the angle $\Psi(i,j,k)$ is:

$\varphi_{EX} \le \Psi\left(i,j,k\right) \le \varphi_{EN}$ for down milling, if

$\varphi_{EX} = 0$ and $\varphi_{EN} = \arccos\left[1-\left(\frac{R_D}{R}\right)\right]$,

$\varphi_{EN} \le \Psi\left(i,j,k\right) \le \varphi_{EX}$ for up milling, if

$\varphi_{EN} = 0$ and $\varphi_{EX} = \arccos\left[1-\left(\frac{R_D}{R}\right)\right]$,

φ_{EX} - kot, pod katerim rezalni rob zapusti material,
φ_{EN} - kot, pod katerim rezalni rob začne rezati,
R_D - prečna globina reza.

Sile, izražene v kartezičnem koordinatnem sistemu, dobimo, če vpeljemo spreminjevalno matriko [T]:

φ_{EX} - angle at which cutter exits the cut
φ_{EN} - angle at which cutter enters the cut
R_D - radial depth of cut

The forces expressed in the Cartesian coordinate system are obtained if the transformation matrix [T] is inserted:

$$\left\{dF_{X,Y,Z}\right\}=\left[T\right]\left\{dF_{R,T,A}\right\} \quad (17).$$

Delne rezalne sile izračunamo po enačbi:

The differential cutting forces are determined by the equation:

$$\begin{bmatrix} dF_X \\ dF_Y \\ dF_Z \end{bmatrix}=\begin{bmatrix} -\sin\kappa\sin\Psi & -\cos\Psi & -\cos\kappa\sin\Psi \\ -\sin\kappa\cos\Psi & \sin\Psi & -\cos\kappa\cos\Psi \\ \cos\kappa & 0 & -\sin\kappa \end{bmatrix}\begin{bmatrix} dF_R \\ dF_T \\ dF_A \end{bmatrix} \quad (18)$$

$$\left[T\right](i,j,k)=\begin{bmatrix} -\sin\kappa(i)\sin\Psi(i,j,k) & -\cos\Psi(i,j,k) & -\cos\kappa(i)\sin\Psi(i,j,k) \\ -\sin\kappa(i)\cos\Psi(i,j,k) & \sin\Psi(i,j,k) & -\cos\kappa(i)\cos\Psi(i,j,k) \\ \cos\kappa(i) & 0 & -\sin\kappa(i) \end{bmatrix} \quad (19)$$

$$\begin{bmatrix} dF_X(i,j) \\ dF_Y(i,j) \\ dF_Z(i,j) \end{bmatrix}=\sum_{k=1}^{N_f}\left[T\right](i,j,k)\begin{bmatrix} K_R \\ K_T \\ K_A \end{bmatrix}\cdot f_z\cdot\sin\left[\Psi(i,j,k)\right]\cdot dz \quad (20).$$

Celotna sila na rezalnem robu pri j-ti legi je:

The total force on the cutting edge in the case of the j-th position is:

$$\begin{bmatrix} F_X(j) \\ F_Y(j) \\ F_Z(j) \end{bmatrix}=\sum_{i=1}^{N_z}\sum_{k=1}^{N_f}\left[T\right](i,j,k)\begin{bmatrix} K_R \\ K_T \\ K_A \end{bmatrix}\cdot f_z\cdot\sin\left[\Psi(i,j,k)\right]\cdot dz \quad (21).$$

Povprečna rezalna sila je:

The average cutting force is:

$$\begin{bmatrix} \bar{F}_X \\ \bar{F}_Y \\ \bar{F}_Z \end{bmatrix}=\left\{\sum_{i=1}^{N_z}\sum_{j=1}^{N_\theta}\sum_{k=1}^{N_f}\left[T\right](i,j,k)\begin{bmatrix} K_R \\ K_T \\ K_A \end{bmatrix}\cdot f_z\cdot\sin\left[\Psi(i,j,k)\right]\cdot dz\right\}\Big/ N_\theta \quad (22).$$

3 OPTIMIRANJE Z GENETSKIMI ALGORITMI

Modeliranje in optimiranje postopka odrezovanja sta pomembna elementa v proizvodnem postopku. Proizvodni postopek je ovrednoten z dinamičnimi in med seboj povezanimi spremenljivkami [4]. Zahteva po natančnosti, kakovosti, učinkovitosti in gospodarnosti v proizvodnem postopku je vedno večja. Glede na to je zelo pomembna izbira optimalnih rezalnih parametrov. Optimiranje rezalnih parametrov ne poveča samo zmogljivosti obdelovalnega postopka, ampak tudi kakovost proizvodov [4].

Optimiranje rezalnih parametrov z uporabo umetne inteligence je nova metoda za modeliranje in optimiranje postopkov na področju strojništva [5]. Iz tega razloga smo za optimiranje rezalnih parametrov izbrali model na podlagi genetskih algoritmov [6], ki temelji na načelu naravne biološke evolucije. V primerjavi z običajnimi metodami optimiranja so genetski algoritmi bolj robustni in splošni ter jih je

3 OPTIMIZATION BY GENETIC ALGORITHMS

Cutting-process modelling and optimization are two important issues in manufacturing. The manufacturing process is characterized by a multiplicity of dynamically interacting process variables [4]. Greater attention is given to accuracy, quality, effectiveness and economy of product by industry these days. To ensure these requirements, it is very important to select the optimum machining parameters. The optimization of machining parameters not only increases the utility for the machining process, but also the product quality to a great extent [4].

Artificial-intelligence-based optimization is a new trend in modelling and optimization for machining operations [5]. Genetic algorithms [6], based on the principles of natural biological evolution, were selected for the optimization of the cutting parameters. Compared to traditional optimisation methods, a genetic algorithm is robust, global and can be apmogoče uporabiti na vseh raziskovalnih področjih. Niso namenjeni samo za optimiranje splošnih problemov, lahko se jih namreč uporabi tudi za optimiranje neopredeljenih in konkavnih problemov. Uporabljajo se tudi na področju strojnega učenja, optimiranja funkcij in modeliranja ([7] in [8]). V razpravi je predstavljen genetski algoritem za optimiranje rezalnih parametrov pri frezanju z oblikovnim krogelnim frezalom.

4 SISTEM ZA SPREMLJANJE IN OPTIMIRANJE POSTOPKA FREZANJA Z OBLIKOVNIM KROGELNIM FREZALOM

4.1 Spremljanje postopka frezanja (SPF)

Razvoj sistema za spremljanje postopka frezanja temelji na predhodnih raziskavah in izhodiščih iz prakse, pri čemer se je zaznavalo za merjenje rezalnih sil (dinamometer) izkazal za najbolj uporabnega. Zaznavalo omogoča zanesljivo spremljanje postopka frezanja in prepoznavo obremenitve na ležaju glavnega vretena. Iz opravljenih raziskav je razvidno, da lahko obstojnost [9] in lom orodja glede na druge metode najbolj natančno določimo z uporabo analize rezalnih sil.

Največja rezalna sila F_{max} pri postopku frezanja z oblikovnim krogelnim frezalom je osnova za optimiranje rezalnih parametrov ter določitve obstojnosti in loma orodja. Obstojnost orodja določimo z uporabo genetskih metod. Z računalniškim programom, s katerim sproti spremljamo potek meritev rezalnih sil med postopkom odrezovanja, posredujemo vsako spremembo izmerjenih vrednosti modelu optimiranja.

4.2 Zgradba sistema za spremljanje postopka frezanja

S sistemom SPF zbiramo vrednosti rezalnih sil (F_x, F_y in F_z) pri postopku frezanja z oblikovnim krogelnim frezalom. Zgradba sistema SPF je prikazana na sliki 3.

Sistem SPF je sestavljen iz:
- obdelovalnega stroja (RNK frezalni center **MORI SEIKI FRONTIER - M**),
- orodja (oblikovno krogelno frezalo tip **R216.44-10030-040-AL10G**, iz materiala **GC 1010**),
- vpenjalne priprave,
- obdelovanca (material: **Ck45**, **Ck45 (XM)**, **16MnCr5** in **16MnCr5 (XM)**),
- merilne plošče (**KISTLER 9259A)**,
- ojačevala (**KISTLER 5001)**,
- A/D pretvornika (**PC-MIO-16E-4**.),
- računalnika (PII 350MHz s programsko opremo Windows 2000) in
- programskega paketa LabVIEW.

4.3 Model optimiranja

Običajno priporočene rezalne parametre, dobljene iz priročnikov in katalogov prilagodimo v bolj

plied generally without recourse to domain-specific heuristics. It can be used not only for general optimisation problems, but also in indifferent optimisation problems and unconvex optimisation problems, etc. Genetic algorithms are widely used for machine learning, function optimising and system modelling ([7] and [8]). In this research, a genetic algorithm is used for the optimisation of cutting parameters in ball-end milling.

4 SYSTEM FOR MONITORING AND OPTIMIZING THE BALL-END MILLING PROCESS

4.1 Monitoring of the milling process (SPF)

The system for the monitoring of the milling process is based on preliminary researches and tests. The piezoelectric dynamometer is widely used for cutting-force monitoring. The dynamometer is a very successful and reliable tool in establishing inter-relationships between the secondary machining parameters and the cutting force. In this study the cutting forces are used to explain the tool wear [9] and tool breakage.

The maximum cutting force, $F_{max,}$ in the ball-end milling process is used for the optimization of the cutting parameters and the tool-wear estimation. Tool wear is estimated with a genetic algorithm. The online monitoring system delivers the measured values to the optimization model.

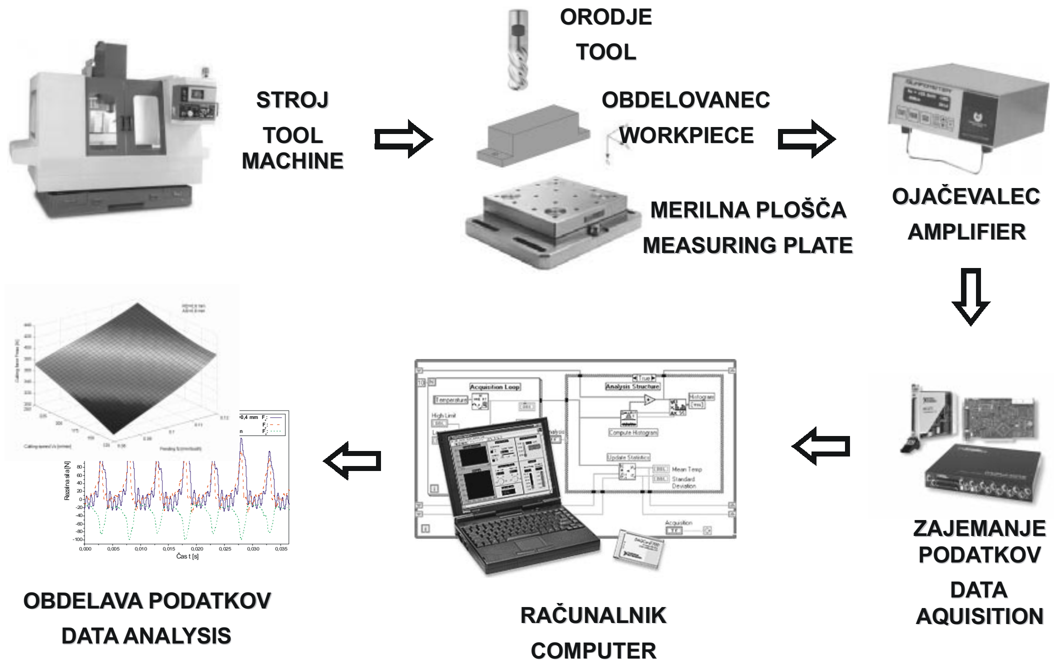
4.2 System for monitoring the milling process

The system SPF is designed for cutting-force monitoring (F_x, F_y and F_z) in the ball-end milling process. The system SPF is presented in Figure 3.

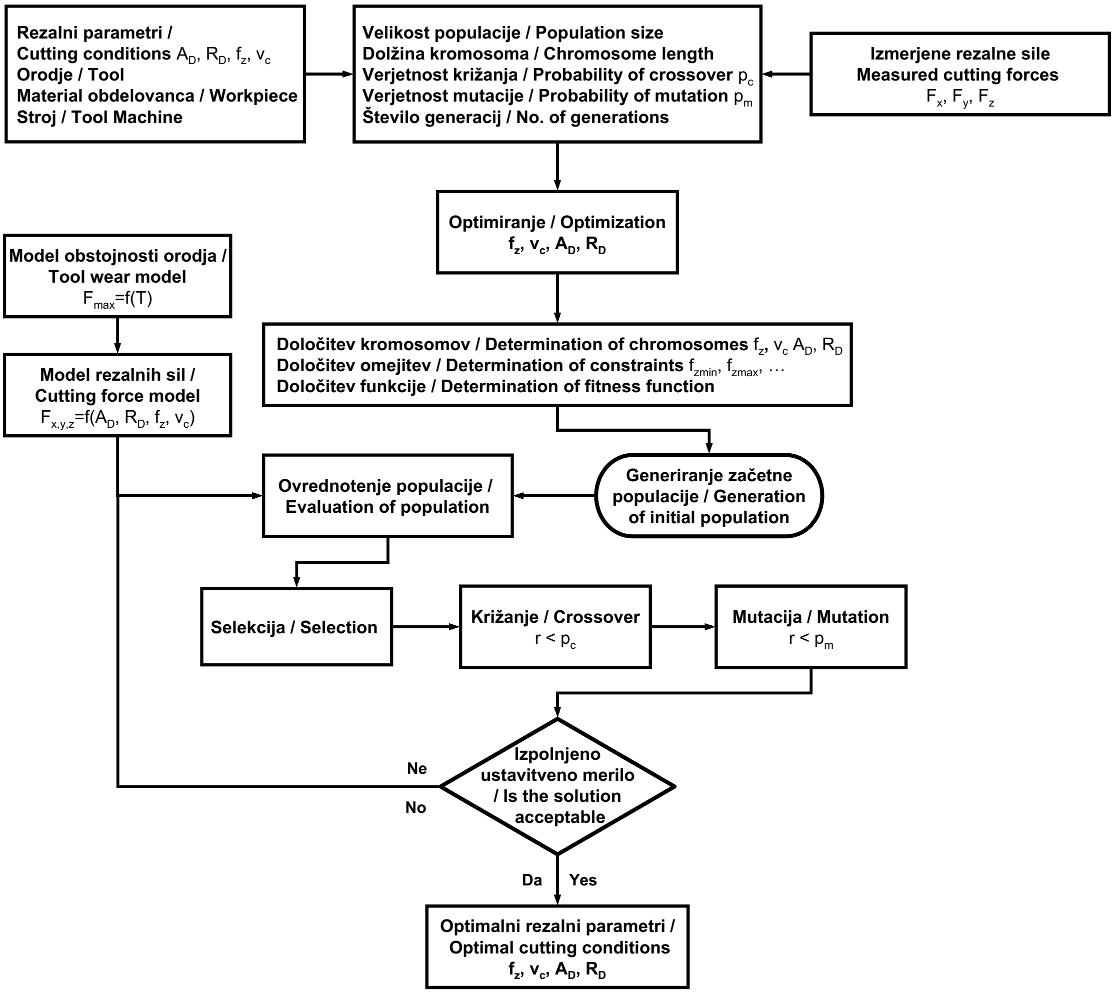
The system SPF consists of:
- tool machine (CNC milling machine **MORI SEIKI FRONTIER - M**),
- tool (solid ball-end milling cutter type **R216.44-10030-040-AL10G**, tool material **GC 1010**),
- clamping device,
- workpiece (material: **Ck45**, **Ck45 (XM)**, **16MnCr5** and **16MnCr5 (XM)**),
- piezoelectric dynamometer (**KISTLER 9259A)**,
- amplifier (**KISTLER 5001)**,
- A/D interface board (**PC-MIO-16E-4**.),
- computer (PII 350MHz with Windows 2000 software),
- programe package LabVIEW.

4.3 Optimization model

The usually recommended cutting parameters, selected according to handbooks or cata-



Sl. 3. *Zgradba sistema za spremljanje postopka frezanja*
Fig. 3. *System for milling-process monitoring*



Sl. 4. *Optimiranje rezalnih parametrov z genetskim algoritmom*
Fig. 4. *Optimization of cutting parameters with the genetic algorithm*

učinkovite rezalne parametre z uporabo hevrističnih metod. Zelo težko je razložiti logično povezavo med rezalnimi veličinami, ker so te odvisne od rezalnih parametrov (rezalne hitrosti V_c, podajanja f_z, globine frezanja A_D in širine frezanja R_D). Iz tega razloga za določevanje in optimiranje rezalnih parametrov uporabimo genetske algoritme. Pri optimiranju rezalnih parametrov upoštevamo vse vplivne dejavnike, ki se pojavljajo pri postopku frezanja.

Ob upoštevanju vseh naštetih predpostavk smo razvili model optimiranja na temelju genetskih algoritmov, ki je namenjen določevanju optimalnih rezalnih parametrov pri postopku frezanja z oblikovnim krogelnim frezalom. Model temelji na sprotnem optimiranju rezalnih parametrov, na podlagi rezalnih sil, zajetih s sistemom za spremljanje postopka frezanja. Optimiranje rezalnih parametrov (rezalne hitrosti V_c, podajanja f_z, globine frezanja A_D in širine frezanja R_D) z genetskim algoritmom temelji na vrednostih rezalnih sil F_X, F_Y in F_Z izmerjenih s sistemom za spremljanje postopka frezanja, analitičnemu modelu rezalnih sil in izkustvenem modelu obstojnosti orodja (sl. 4).

5 ANALIZA REZULTATOV

Za potrditev sistema za spremljanje postopka frezanja in modela optimiranja smo opravili obsežno število preizkusov na NK frezalnem stroju, pri različnih parametrih frezanja. V tem poglavju so predstavljeni rezultati preizkusov ter primerjava in analiza rezalnih sil, v odvisnosti od rezalnih parametrov.

5.1 Uporabljena preizkusna oprema

Razviti analitični model rezalnih sil za oblikovno krogelno frezalo uporabimo za napovedovanje rezalnih sil in optimiranje rezalnih parametrov.

Za preizkuse smo uporabili:

- RNK frezalni stroj **MORI SEIKI FRONTIER - M**,
- merilno ploščo **KISTLER 9259A**,
- material obdelovanca **Ck45**,
- oblikovno krogelno frezalo tip **R216.44-10030-040-AL10G - GC 1010** s premerom 10 mm, kotom vijačnice 30° in štirimi rezalnimi robovi.

5.2 Povezava med rezalno silo in rezalnimi parametri

Rezalna sila F_{max} in rezalna hitrost V_c sta glavni vplivni veličini obdelovalnega postopka. Zmnožek rezalne sile in hitrosti je sorazmeren rezalni moči obdelovalnega stroja. Količina odvzetega materiala je glavno kazalo produktivnosti postopka odrezovanja.

Velikost rezalne sile med odrezovanjem je odvisna od rezalnih parametrov (rezalne hitrosti V_c, podajanja f_z, globine frezanja A_D in širine frezanja R_D). Povečanje rezalne hitrosti je prednost, ker povečuje

logues, were optimized by heuristic methods. The formulation of the relations between the cutting quantities is very difficult because they depend on the cutting parameters (cutting speed V_c, feeding f_z, axial depth A_D, radial depth R_D). For this reason the genetic algorithm was used for the optimization of the cutting parameters. All the influencing factors that appear in the ball-end milling process were considered.

By taking into account all the influencing factors the genetic algorithm optimization model for ball-end milling was developed. The online optimization of the cutting parameters is based on the cutting forces collected by the monitoring system. The optimization of the cutting parameters (cutting speed V_c, feeding f_z, axial depth A_D, radial depth R_D) is based on the measured cutting forces F_X, F_Y and F_Z, the analytical cutting-force model and the empirical tool-wear model. (Fig. 4).

5 ANALYSIS OF THE RESULTS

An extensive number of tests were made on the milling machine to confirm the monitoring system and the optimization model with different cutting parameters. This chapter presents the results of the experiments and the comparison and analysis of cutting forces depending on the cutting parameters.

5.1 Experimental setup

The developed analytical cutting-force model for ball-end milling is applied for the cutting-force estimation and the optimization of the cutting parameters.

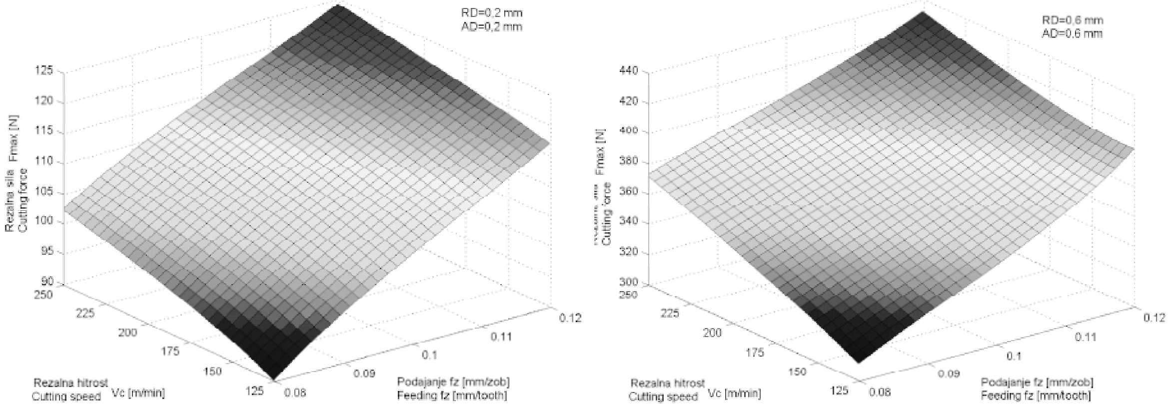
The experimental model consists of:

- CNC milling machine **MORI SEIKI FRONTIER - M**,
- piezoelectric dynamometer **KISTLER 9259A**,
- workpiece material **Ck45**,
- solid ball-end milling cutter type **R216.44-10030-040-AL10G - GC 1010** with four cutting edges, of 10 mm diameter and 30° helix angle,

5.2 Relationship between the cutting force and the cutting parameters

The cutting force, F_{max}, and the cutting speed, V_c, are the two main quantities for an efficient machining operation. Their product is proportional to the cutting power of the milling machine. The metal removal rate is the main indicator of the productivity of the cutting process.

The cutting force developed during the machining can be controlled by varying the cutting parameters (cutting speed V_c, feeding f_z, axial depth A_D, radial depth R_D). An increase of the cutting speed



Sl. 5. *Največje rezalne sile v odvisnosti od rezalne hitrosti in podajanja*
Fig. 5. *Relationship between the maximum cutting force, the cutting speed and the feeding*

količino odvzetega materiala. Rezalno hitrost je smiselno povečati do vrednosti, pri kateri največja rezalna sila ne preseže kritične vrednosti, ker to vodi do deformacije orodja, obdelovalnega stroja in obdelovanca.

Na sliki 5 je prikazana vrednost največje rezalne sile F_{max} za frezalo **R216.44-10030-040-AL10G** v odvisnosti rezalne hitrosti V_c, podajanja f_z, globine frezanja A_D.

5.3 Določitev obstojnosti orodja z genetskim algoritmom

Za določitev obstojnosti orodja v odvisnosti od največje rezalne sile F_{max} smo razvili izkustveni model obstojnosti. Izkustveni model je predstavljen v naslednji obliki:

is an advantage; however, an the increase in cutting force is a disadvantage because no increase in the metal removal rate results from it, but rather larger deformations of the machine and workpiece occur.

Figure 5 presents the maximum cutting force, F_{max}, for the cutter **R216.44-10030-040-AL10G,** according to cutting speed V_c, feeding f_z, and axial depth A_D.

5.3 Estimation of tool wear using the genetic algorithm

Based on the tool wear and the maximum cutting force, F_{max}, a relationship for the empirical tool wear model is developed. It is proposed in the following format:

$$F_{\max} = K_1 + \left(K_2 \cdot T\right)^{K_3} \tag{23}$$

F_{max} - največja rezalna sila,
T - obstojnost orodja v mm,
K_1, K_2, K_3 - koeficienti obstojnosti.

V izkustvenem modelu za določitev obstojnosti orodja imajo največji vpliv koeficienti obstojnosti. K_1 je stopnja rezalne sile in je odvisen od rezalnih parametrov pri frezanju z oblikovnim krogelnim frezalom. K_2 je gradient obstojnosti orodja, ki je odvisen od rezalnih parametrov, rezalnega orodja in materiala obdelovanca. Če je vrednost K_2 majhna, potem se obraba orodja počasi zvečuje in nasprotno. Koeficient K_3 pove, kako hitro se bo pojavil lom orodja, ko se rezalna sila poveča čez kritično vrednost. Vrednost koeficienta K_3 je tem večja, čim trši je material obdelovanca oz. pri neprimernih rezalnih parametrih.

Iz preizkusnih vrednosti največje rezalne sile F_{max}, zajete s sistemom za spremljanje postopka frezanja, lahko z uporabo genetskega algoritma določimo koeficiente obstojnosti. Program za določitev koeficientov obstojnosti je napravljen v programskem paketu MATLAB. Z genetskim

F_{max} - maximum cutting force
T - tool life [mm]
K_1, K_2, K_3 - tool-wear coefficients.

In the empirical tool-wear model, the tool-wear coefficients have their physical meaning. K_1 is the cutting-force level, which depends on the cutting parameters of the ball-end milling operations. K_2 is the tool-wear gradient, which depends on the cutting parameters, the tool and the workpiece materials. A small K_2 indicates slow progress of the wear. K_3 represents how fast the tool is broken when the cutting force is above a critical level. The harder the workpiece material is or the more uncomfortable cutting parameters the tool has, the larger K_3 is.

From the experimental data of the maximum cutting force, F_{max}, the coefficients of the proposed tool-wear model can be found by using the genetic algorithm. The program for the determination of the tool-wear coefficients was made with the program package MATLAB. The genetic algorithm is used to algoritmom poiščemo optimalne koeficiente obstojnosti, ki jih uporabimo v modelu. Vsoto razlik rezalnih sil, dobljenih iz sistema za spremljanje postopka frezanja in rezalnih sil iz izkustvenega modela smo uporabili kot funkcijo uspešnosti. Funkcijo uspešnosti zapišemo kot:

search for the optimum tool-wear coefficients, which will be used in the model. The sum of the difference between the experimental cutting-force data and the cutting force obtained from the developed model is used as the optimum objective function. The objective function is:

$$Min(E)=\frac{1}{N}\sum_{i=1}^{N}\left|F_{\max(i)}^{model}-F_{\max(i)}^{eksperiment}\right| \qquad (24),$$

E - povprečna absolutna napaka
$F_{\max(i)}^{model}$ - največja rezalna sila, določena z modelom,
$F_{\max(i)}^{eksperiment}$ - največja rezalna sila, dobljena s preizkusom.

E – average absolute error
$F_{\max(i)}^{model}$ - estimated maximum cutting force
$F_{\max(i)}^{eksperiment}$ - experimental maximum cutting force

Preglednica 1. *Primerjava eksperimentalnih z izkustvenimi vrednostmi rezalne sile F_{max}*
Table 1. *The comparison of the experimental and empirical cutting forces F_{max}*

Obstojnost orodja Tool life mm	**F_{max} [N]**		**Napaka Error %**
	Preizkus Experiment	**Izkustveni model Empirical model**	
0	256,9	246,7	4,14
19250	260,7	260,7	0,01
38500	280,0	280,2	0,10
57750	290,8	302,6	3,92
77000	326,3	327,1	0,24
96250	355,3	353,3	0,58
115500	392,4	380,8	3,03
134750	429,3	409,6	4,81
173250	467,6	470,4	0,60
231000	536,4	568,3	5,62
Povprečna napaka Average error			**2,30**

Preglednica 2. *Optimalni koeficienti obstojnosti*
Table 2. *Optimum tool-wear coefficients*

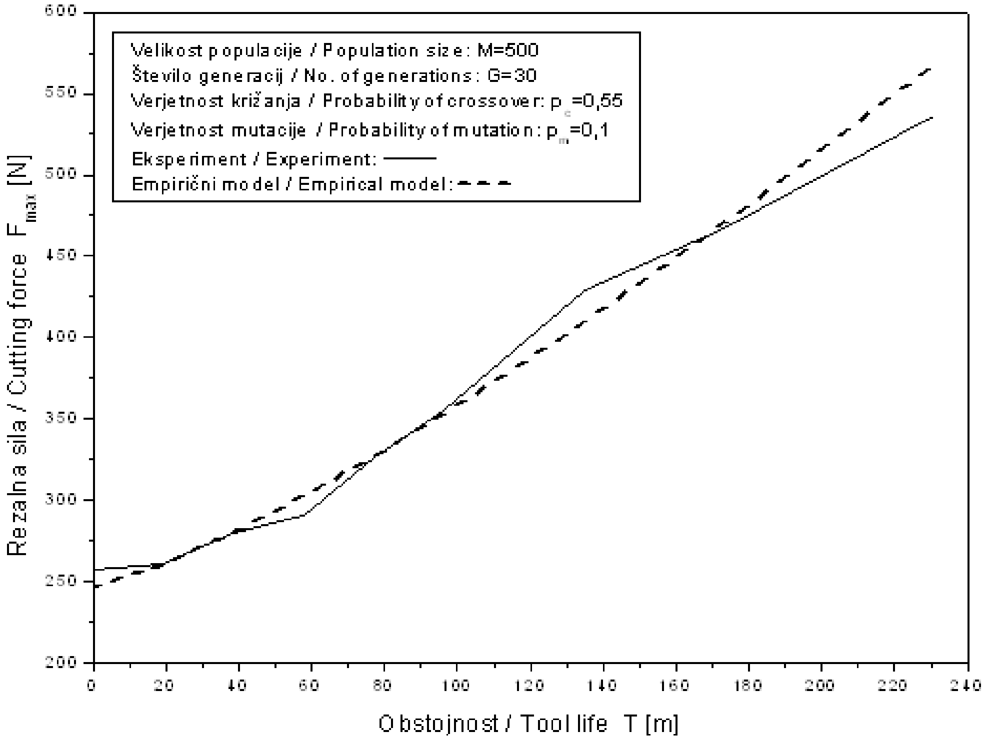
Koeficienti obstojnosti Tool-wear coefficients	**R216.44-10030-040-AL10G**
K_1	246,70577
K_2	0,0004
K_3	1,26198

Za določitev koeficientov obstojnosti pri frezanju s frezalom **R216.44-10030-040-AL10G** in rezalnimi parametri (širina frezanja R_D = 0,4 mm, globina frezanja A_D = 0,4 mm, podajanje f_z = 0,1 mm/zob, rezalna hitrost V_c = 188,5 m/min) smo izbrali naslednje vhodne parametre za delovanje genetskega algoritma. Velikost populacije 500 organizmov. Največje število generacij 30. Velikost posameznega kromosoma 10 bitov. Uporabili smo genetski operaciji križanje in mutacijo. Verjetnost križanja p_c = 0,55 in mutacije p_c = 0,1. Optimalne koeficiente obstojnosti je genetski algoritem našel v tretji generaciji s povprečno napako modela 2,30%.

Izkustveni model obstojnosti orodja je prikazan v diagramu (sl. 6).

For the determination of the tool-wear coefficients in ball-end milling the **R216.44-10030-040-AL10G** milling cutter and cutting parameters (radial depth R_D = 0.4 mm, axial depth A_D = 0.4 mm, feeding f_z = 0.1 mm/tooth, cutting speed V_c = 188.5 m/min) were used. The evolutionary parameters for the genetic algorithm were as follows: population size, 500; number of generations, 30; and number of genes for each chromosome, 10. The genetic operations known as crossover and mutation were used. The probability of crossover was p_c = 0.55 and the probability of mutation was p_c = 0.1. The optimum tool-wear coefficients were found in the 3rd generation with an average error of 2.30%.

The empirical tool-wear model is presented in the diagram (Fig. 6).



Sl. 6. *Izkustveni model obstojnosti orodja*
Fig. 6. *Empirical tool-wear model*

5.4 Optimiranje postopka frezanja z oblikovnim krogelnim frezalom

Za optimiranje rezalnih parametrov pri frezanju z oblikovnim krogelnim frezalom smo razvili model optimiranja na podlagi genetskega algoritma. Algoritem smo napravili v programskem okolju MATLAB. Z algoritmom smo dokazali, da informacijo, ki jo dobimo iz izmerjenih rezalnih sil, lahko prepoznamo s predlagano metodo. Rezalne sile, obstojnost orodja in rezalne parametre pri frezanju z oblikovnim krogelnim frezalom lahko napovemo z majhnim številom generacij in z zadovoljivo napako. Algoritem daje hitre in natančne rezultate, ki jih lahko vključimo v postopek sprotnega spremljanja postopka frezanja. Pri frezanju z oblikovnim krogelnim frezalom je zelo pomembna določitev optimalnih rezalnih parametrov. Zaradi velikih rezalnih hitrosti, trdih materialov in majhnih premerov orodja lahko zelo hitro pride do loma orodja. Z neprimerno izbranimi rezalnimi parametri podaljšamo čas obdelave in zmanjšamo obstojnost orodja. Za tehnologa je zelo težko izbrati optimalne rezalne parametre pri zelo velikem številu različnih orodij, materialih obdelovanca in načinih obdelave.

Rezalni parametri so optimirani glede na najmanjši obdelovalni čas, tako da poiščemo največje rezalne parametre, ki jih določimo glede na dobo trajanja orodja. Vsoto razlik največjih rezalnih sil, dobljenih iz analitičnega modela

5.4 Optimization of the ball-end milling process

For the optimization of the cutting parameters in ball-end milling the genetic algorithm optimization model was developed. The optimization algorithm was made in MATLAB. The present model has been proven to provide a reliable optimization of the cutting process for ball-end milling. The cutting forces, the tool life and the cutting parameters in ball-end milling can be estimated in a few evolution generations with an acceptable error. The algorithm has a fast reaction and accurate results that can be applied to the online monitoring of the milling process. In ball-end-milling operations it is important to select the tool's optimum cutting conditions. Because of the high cutting speeds and the hard materials the small tools are very easily broken. A conservative selection of cutting parameters would result in a longer machining time, and other unsuitable selections of cutting parameters would mean frequent tool changes, which also wastes machining time. It is very difficult for operators to select the optimum cutting parameters for so many different types of tools, workpieces and different machining tasks.

The cutting parameters were optimized based on the minimum machining time to find the maximum cutting parameters that are able to meet the tool-life requirements for a specific machining task. The genetic algorithm was used to optimize the tool cutting parameters with the analytical cutting-force model. The sum of the difference of the maximum rezalnih sil in rezalnih sil iz empiričnega modela, smo uporabili kot funkcijo uspešnosti. Zapišemo jo kot:

cutting forces, which were obtained from the analytical force model and the empirical model, were used for the objective function. The objective function is:

$$Min(E)=\frac{1}{3}\left(\left|F_{X\max}^{model}-F_{X\max}^{dovoljena}\right|+\left|F_{Y\max}^{model}-F_{Y\max}^{dovoljena}\right|+\left|F_{Z\max}^{model}-F_{Z\max}^{dovoljena}\right|\right) \tag{25}$$

oz.

or

$$Min(E)=\left|F_{\max}^{model}-F_{\max}^{dovoljena}\right| \tag{26}$$

ob upoštevanju pogojev:

$F_{X\max}^{model}\le F_{X\max}^{dovoljena}$, $F_{Y\max}^{model}\le F_{Y\max}^{dovoljena}$, $F_{Z\max}^{model}\le F_{Z\max}^{dovoljena}$, $F_{\max}^{model}\le F_{\max}^{dovoljena}$

E - absolutna napaka

$F_{X\max}^{model}$, $F_{Y\max}^{model}$, $F_{Z\max}^{model}$, $F_{\max}^{model}$ - največja rezalna sila, določena z analitičnim modelom,

$F_{X\max}^{dovoljena}$, $F_{Y\max}^{dovoljena}$, $F_{Z\max}^{dovoljena}$, $F_{\max}^{dovoljena}$ - dopustna največja rezalna sila glede na obstojnost

Za določitev optimalnih rezalnih parametrov smo izbrali optimiranje po dveh spremenljivkah (podajanju f_z in rezalni hitrosti V_c). Izbrali smo naslednje vhodne parametre: velikost populacije 500 organizmov, število generacij 15 in velikost posameznega kromosoma 10 bitov. Uporabili smo genetski opravil križanje in mutacijo. Verjetnost križanja $p_c = 0{,}65$ in mutacije $p_c = 0{,}1$.

Optimalne rezalne parametre je genetski algoritem našel v trinajsti generaciji z napako 0,28%. Evolucijski potek genetskega algoritma za določitev

Conditions:

$F_{X\max}^{model}\le F_{X\max}^{dovoljena}$, $F_{Y\max}^{model}\le F_{Y\max}^{dovoljena}$, $F_{Z\max}^{model}\le F_{Z\max}^{dovoljena}$, $F_{\max}^{model}\le F_{\max}^{dovoljena}$

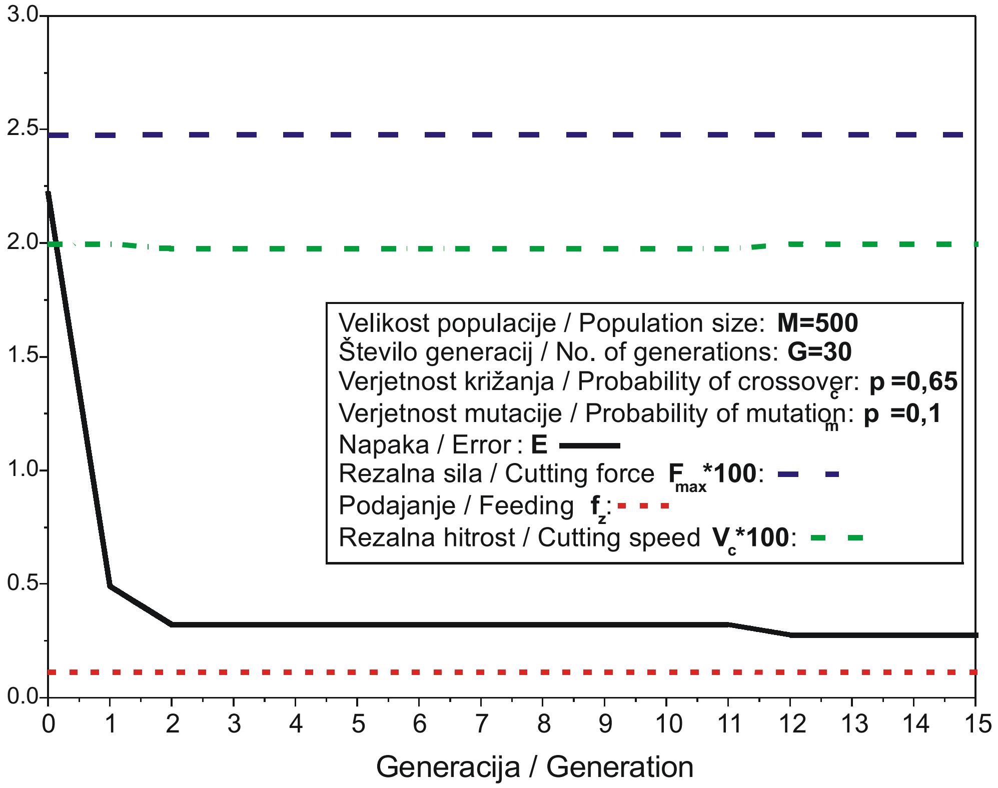
E - absolute error

$F_{X\max}^{model}$, $F_{Y\max}^{model}$, $F_{Z\max}^{model}$, $F_{\max}^{model}$ - maximum cutting forces calculated by the analytical cutting-force model

$F_{X\max}^{dovoljena}$, $F_{Y\max}^{dovoljena}$, $F_{Z\max}^{dovoljena}$, $F_{\max}^{dovoljena}$ - maximum cutting forces determined by the tool-life estimation

For the determination of the optimum cutting parameters the optimization of two variables (feeding f_z and cutting speed V_c) was used. The evolutionary parameters for the genetic algorithm were as follows: population size, 500; number of generations, 15; and number of genes of each chromosome, 10. The genetic operations crossover and mutation were used. Probability of crossover was $p_c = 0.65$ and the probability of mutation was $p_c = 0.1$.

The optimum cutting parameters were found in the 13th generation with an average error of 0.28%. The evolution of the genetic algorithm for the deter-



Sl. 7. *Evolucijski potek genetskega algoritma*
Fig. 7. *Evolution of the genetic algorithm*

Preglednica 3. *Optimalni rezalni parametri*
Table 3. *Optimum cutting parameters*

Rezalni parametri **Cutting parameters**	**Vhodni parametri** **Initial parameters**	**Optimalni parametri** **Optimum parameters**
F_{max}	247,60 N	247,61 N
R_D	0,4 mm	0,4 mm
A_D	0,4 mm	0,4 mm
f_z	0,1 mm/zob (mm/tooth)	0,11 mm/zob (mm/tooth)
V_c	188,5 m/min	199,5 m/min
l_m	100 mm	100 mm
T_c	2,5 s	2,1 s
Časovna razlika obdelave **Cutting time difference**		**16,4 %**

optimalnih rezalnih parametrov je prikazan v diagramu (sl. 7).

Iz dobljenih vrednosti vidimo, da se čas obdelave pri optimalnih rezalnih parametrih zmanjša za 16,4%.

6 SKLEP

V prispevku je predstavljen razvoj sistema za spremljanje in optimiranje postopka frezanja z oblikovnim krogelnim frezalom. Sistem je namenjen spremljanju postopka frezanja in je preizkušen z velikim številom preizkusov, z različnimi rezalnimi orodji, materiali obdelovancev in rezalnimi parametri. Za optimiranje rezalnih parametrov smo razvili računalniški program z metodo optimiranja genetskih algoritmov.

Sistem je namenjen spremljanju in napovedovanju rezalnih sil, obstojnosti orodja in optimiranju rezalnih parametrov. Osnovna zamisel, ki je opisana, je prikaz odnosov med orodjem in obdelovancem, določenim z analitičnim modelom rezalnih sil.

Rezultati prikazujejo, da lahko razvite metode, predstavljene v prispevku, uporabimo za napovedovanje obstojnosti orodja, rezalnih sil, optimiranje rezalnih parametrov, povečanje natančnosti, zanesljivosti, produktivnosti ter zmanjšanje stroškov in časa obdelave.

mination of the optimal cutting parameters is presented in Fig. 7.

With the optimum cutting parameters the machining time was reduced by 16.4 %.

6 CONCLUSION

This paper presents a system for monitoring and optimizing the ball-end milling process. An extensive number of tests with different cutting tools, workpieces and cutting parameters, were performed to confirm the monitoring system. For the optimization of the cutting parameters in ball-end milling the genetic algorithm optimization program was developed.

The system is intended for cutting-force monitoring and the prediction of cutting forces, tool wear and the optimization of the cutting parameters. The basic concept included in the paper is the representation of the relations between the tool and the workpiece, determined by the analytical cutting-force model. Experimental results show that the proposed model presented in the paper can be used for tool-wear and cutting-force estimations, optimization of the cutting parameters, improvements to product accuracy, reliability, productivity and a reduction in production costs and production time.

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Prejeto:
Received: 21.4.2004

Sprejeto:
Accepted: 30.9.2004

Odprto za diskusijo: 1 leto
Open for discussion: 1 year