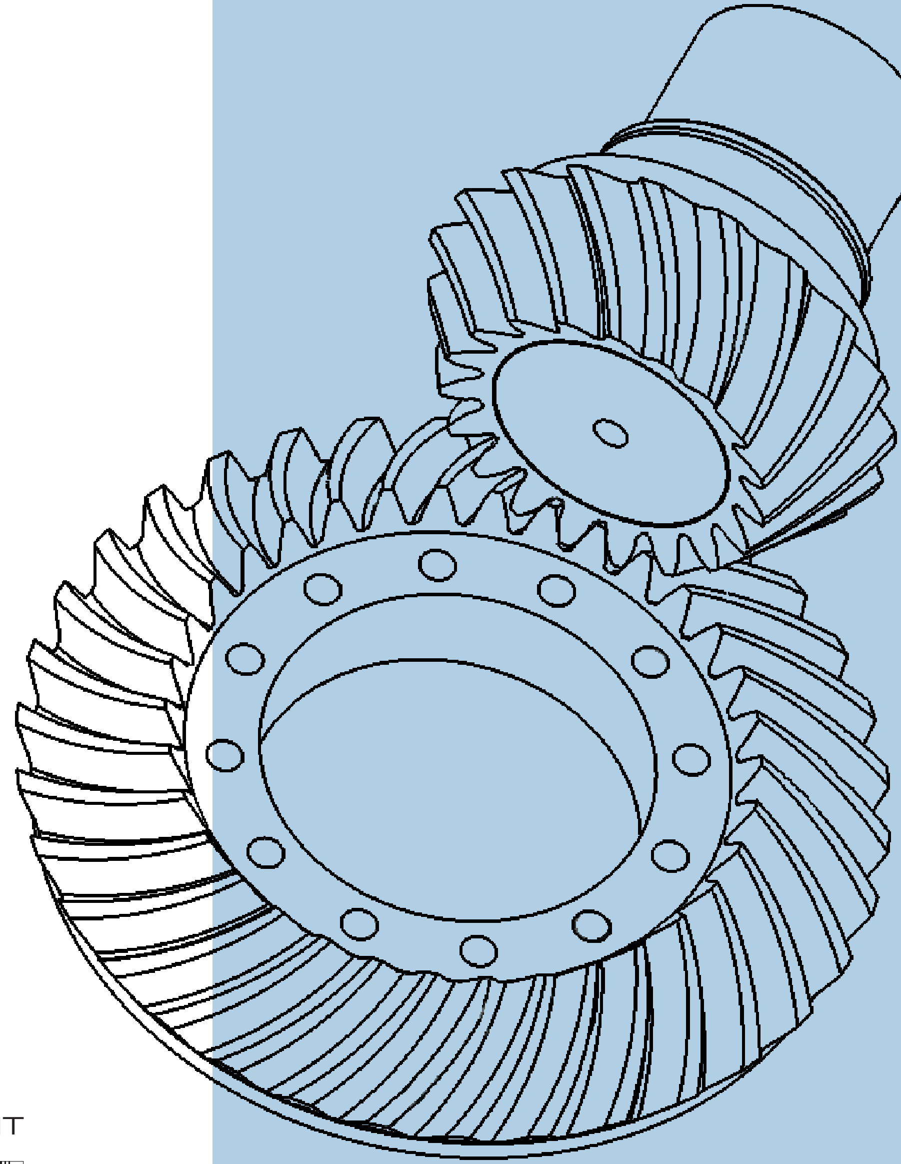
letnik/volume **52** - št./no. **11/06** - str./pp. **703-782**
Ljubljana, nov./Nov. 2006, zvezek/issue **499**

STROJNIŠKI VESTNIK

JOURNAL OF MECHANICAL ENGINEERING



cena 800 SIT

9 770039 248001

ISSN 0039-2480

Vsebina - Contents

Strojniški vestnik - Journal of Mechanical Engineering
letnik - volume 52, (2006), številka - number 11
Ljubljana, november - November 2006
ISSN 0039-2480

Izhaja mesečno - Published monthly

Uvodnik		**Editorial**
Kopač J.	704	Kopač J.
Razprave		**Papers**
Pušavec, F., Krajnik, P., Kopač, J.: Odrezovanje mehkih materialov z velikimi hitrostmi	706	Pušavec, F., Krajnik, P., Kopač, J.: High-Speed Cutting of Soft Materials
Stoić, A., Lucić, M., Kopač, J.: Vrednotenje stabilnosti pri struženju v trdo	723	Stoić, A., Lucić, M., Kopač, J.: Evaluation of the Stability During Hard Turning
Dolinšek, S., Panjan, P., Syvanen, T., Ramovš, J.: Lasersko sintranje orodja za tlačno litje aluminija	738	Dolinšek, S., Panjan, P., Syvanen, T., Ramovš, J.: Laser-Sintered Tools for the Die-casting of Aluminum
Cedilnik, M., Soković, M., Jurkovič, J.: Umerjanje in preverjanje geometrijske natančnosti računalniško krmiljenih obdelovalnih strojev	752	Cedilnik, M., Soković, M., Jurkovič, J.: Calibration and Checking the Geometrical Accuracy of a CNC Machine-Tool
Antić, A., Hodolič, J., Soković, M.: Razvoj sistema za nadzor obrabe orodja pri struženju na temelju nevronskih mrež	763	Antić, A., Hodolič, J., Soković, M.: Development of a Neural-Networks Tool-Wear Monitoring System for a Turning Process
Osebne vesti		**Personal Events**
Akademik profesor dr. Janez Peklenik 80-letnik, zaslužni profesor Univerze v Ljubljani	777	80th Anniversary of Professor Dr. Janez Peklenik, Academician and Professor Emeritus of the University of Ljubljana
Magisterij, specializacije in diplome	778	Master's, Specialisation's and Diploma Degrees
Navodila avtorjem	781	**Instructions for Authors**

Uvodnik - Editorial

Raziskovalna skupina, ki deluje v okviru Laboratorija za odrezavanje - LABOD - na Fakulteti za strojništvo v Ljubljani, vsaki dve leti napravi izvleček nekaj raziskovalnih poročil s področja analize rezalnih postopkov in hitrih tehnologij, da jih predstavi širši slovenski in tudi svetovni znanstveno strokovni javnosti. V številki, ki je pred nami, je predstavljeno pet prispevkov, ki obsegajo trenutno pomembne teme, to je odrezovanje z velikimi hitrostmi v trdo in mehko, kakor tudi spremljajoče analize dinamike odrezovalnega postopka. Spremljajoče strategije za doseganje zelo natančne in kakovostne obdelave so predstavljene v okviru nadzora obdelovalnega postopka v povezavi z nevronskimi mrežami, ki omogočajo hitro prepoznavanje dogodkov na rezalnem robu. Za uspešno delo, tako raziskovalno kakor tudi v proizvodni sferi, je potreben izhodiščni kriterij, to je poznavanje natančnosti stroja. Kajti znano je pravilo, da mora biti stroj vedno za en kakovostni razred boljši od zahtev za izdelek. S področja hitrih tehnologij in proizvodenj pa je zajeto področje lasersko sintranih trirazsežnih orodij, ki so namenjena praktični uporabi za litje izdelkov iz aluminija. Napredek v kakovosti tako izdelanih orodij je tolikšen, da že dosegajo smotrno uporabnost v proizvodnji.

V vse splošnem hitrem napredku različnih dejavnosti s področja proizvodnih tehnologij so zajeti sodobni obdelovalni stroji, ki prehajajo od tri- na petosne, medtem ko krmiljenje le-teh omogočajo že osebni računalniki. Zaradi zapletenosti obdelovalnih strojev se sicer cena modernih obdelovalnih strojev povečuje, povečuje pa se tudi možna količina izdelkov v časovni enoti kakor tudi njihova natančnost. Med zapletene stroje lahko štejemo dvovretenske stružnice z več revolverji, pri katerih so nameščena številna gnana orodja. Tak stroj omogoča obdelavo izdelkov zahtevnih oblik, za katere po običajni tehnologiji velja potreba obdelave na petih do sedmih različnih strojih z dodatno vmesno logistiko, položajenjem in vpenjanjem. Taki izdelki, kljub temu da so izdelani na stroju, ki mu komaj še lahko rečemo stružnica, so tako raznolikih oblik s številnimi ploščatimi površinami in trirazsežnimi gravurami, da bi laik pripisal, da so bili izdelani na frezalnem stroju. Moderni frezalni stroji z oznako "DCG" imajo

The research team from the Metal Cutting Department at the Faculty for Mechanical Engineering, University of Ljubljana, prepares a review of their work and achievements every second year. This represents part of the research work from the field of cutting processes and high-speed machining analysis. The aim is to show our work, results and achievements to the Slovenian public as well as to the world's scientific and industrial community. This current issue consists of five up-to-date scientific papers on the subject of what is called high-tech machining, like high-speed hard/soft cutting, the analysis of cutting-process dynamics, etc. These high-tech strategies, which allow high precision and surface quality to be achieved, are presented through process monitoring connected with a neural network platform that enables rapid process behavior identification at the cutting-tool edge. The clue to success in research and industrial work are the appropriate boundary conditions, represented by machine-tool accuracy, which leads to the consequence that machining-tool accuracy has to be one level higher than the requirements to the product. Another very interesting topic from the field of advanced production technologies are the 3D laser-sintering tools used in the aluminum-alloy molding industries. Improvements in this field are so great that the process can already be implemented as a common manufacturing procedure.

Rapid innovations and developments in production technologies are closely connected with modern machining tools, where three-axes machines are replaced by five-axes machines, and where the controllers are on PC platforms. It is true that the costs of machine tools are increasing with their complexity but, on the other hand, it is necessary to take into account the higher production rates and the better machined-surface quality. These "complex" machines are, for example, two-spindle lathes with several turrets, where in addition to classic tools there are also self-powered tools. Such machine tools enable machining of highly complex shapes, for which five to seven different conventional machining tools should be needed, with additional logistics, positioning and clamping of the machined parts. Products made on such machines - it is hard to call them lathes - can be of very different shapes with many straight surfaces and 3D engravings. As a consequence, a layman could easily make a mistake and recognize the piece as a product of milling. In modern milling machines there are special prigrajena hitro vrteča vretena z vrtilno frekvenco od 20 do 50 tisoč na minuto, obdelava pa poteka v težišču stroja, kar močno zmanjša tako vibracije kakor tudi njihove amplitude. S takim strojem dosegamo ob normalni tehnologiji in strategiji natančne obdelave za en kakovostni razred boljše izdelke, kar je posebej pomembno pri obdelavi v trdo za trirazsežna orodja. S tem dosegamo konkurenčnost izdelka, v prvi vrsti s krajšim časom izdelave kakor tudi z boljšo kakovostjo in nižjo ceno. Z novim letom 2007 bo tak stroj postavljen na Fakulteti za strojništvo - v LABOD-u - v Ljubljani. Podjetje BTS-Company Ljubljana se je namreč odločilo, da s postavitvijo takega stroja na fakulteto, in to v lastnem stroškovnem okviru, pripomore k hitrejšemu uvajanju modernih odrezovalnih postopkov v slovenski prostor.

machines called "DCG" that allow high-speed cutting with 20 to 50 thousand revolutions per minute, and with cutting in the center of gravity of the machine tool. This leads to lower vibration amplitudes. On such a machine using the same technology and fine milling, products are made that are one level higher in quality. This is especially important in 3D hard machining. So with faster production, better quality and lower costs a competitive position of the product has been achieved. At the start of 2007 this kind of a modern milling machine will be available at our Faculty for Mechanical Engineering in Ljubljana in the Laboratory for Metal Cutting - LABOD. The Slovenian BTS-Company, Ljubljana has decided to locate the machine on the faculty. The aim of the cooperation set up is to spread interest and get Slovenian industry familiar with these modern, advanced manufacturing technologies.

V zadnjih letih so bili v Sloveniji storjeni številni koraki za čim hitrejšem posodobljenju proizvodnje in to od tako imenovanih povezav v grozde TCS in ACS, kakor tudi tehnoloških platform in podobno. Sodobne slovenske revije, kakršne so IRT 3000, Euroteh, Ventil itn., so postale zanimive in prodorne za širok krog strokovnjakov - tehnikov in inženirjev - s področja tehnologij. Prinašajo informacije o sodobnih strojih, orodjih, računalniških programih pa tudi posameznih sodobnih tehnologijah, ki v slovenskem prostoru marsikomu še niso poznane. Strojniški vestnik pa še vedno ostaja zanimiv za vse tiste, ki jih zanimajo rezultati raziskav. Raziskave so namreč tiste, ki v prvi vrsti analizirajo vzroke za neuspešno obdelavo in slabo kakovost izdelkov. Menimo, da nam je tudi s to številko, ki je pred vami, uspelo za bralce zbrati in posredovati kar nekaj koristnih ugotovitev.

Prof. dr. Janez Kopač

Recently, in Slovenia, a lot has happened in the field of production modernization through the connection of industries to the TCS and ACS clusters as well as to technological platforms, etc. Slovenian high-tech journals, like IRT 3000, Euroteh, Ventil, etc., have become very popular and useful for a large number of specialists, e.g., technicians and engineers from the field of technology. These journals provide information about machine tools, tools, computer software and machining technologies, for the benefit of Slovenian industry. But the Journal of Mechanical Engineering remains interesting for those who are involved in research, because research gives answers to the problems of poor machinability and low product quality. We also believe that with this issue we have succeeded in collecting together and publishing some good results, conclusions and achievements for our readers.

Prof. Dr. Janez Kopač

Strojniški vestnik - Journal of Mechanical Engineering 52(2006)11, 706-722
UDK - UDC 621.9.02:621.91
Izvirni znanstveni članek - Original scientific paper (1.01)

Odrezovanje mehkih materialov z velikimi hitrostmi

High-Speed Cutting of Soft Materials

Franci Pušavec - Peter Krajnik - Janez Kopač
(Fakulteta za strojništvo, Ljubljana)

Široko uporabljan material, kakršen je mehka siva litina, je velika obremenitev rezalnih orodij pri suhem odrezovanju z velikimi hitrostmi (OVH). Vzrok zapletenosti obdelave so edinstvene kombinacije lastnosti obdelovanega materiala, to so: trdnost, trdota, trdi vključki in kemična obrabna obstojnost. Take lastnosti so sicer potrebne za izpolnjevanje zahtev izdelka, vendar pa lahko pri velikih temperaturnih in mehanskih obremenitvah negativno vplivajo na kakovost obdelane površine, sposobnost postopka in storilnosti. Te obremenitve se na orodju med drugim kažejo kot hitra in prekomerna obraba. Zato je namen prispevka predstaviti smernice za povečanje obdelovalnosti mehke sive litine pri OVH. Izboljšanje obdelovalnosti je lahko doseženo s pravo kombinacijo materiala rezalnega orodja in tehnologijo odrezovanja prilagojeno kupčevim zahtevam.

(Ključne besede: odrezovanje z velikimi hitrostmi, litina siva, obraba orodij, bornitrid kubični (CBN), nastanek igle)

Commonly used materials like soft grey cast iron represent a serious load for cutting-tool materials during dry high-speed cutting (HSC) due to the material's unique combination of properties, such as high toughness, ductility, hard inclusions and chemical wear resistance. Although these properties are desirable design requirements, they pose a great challenge to machining due to the high temperatures and stresses generated during the cutting to ensure high surface quality, process capability and productivity. This loading reduces the bonding strength of the tool substrate, thereby accelerating the tool wear. This paper provides guidelines for increasing soft grey cast iron's machinability during HSC. The improved machinability of such grey cast iron during HSC can be achieved by combining the appropriate tool material and machining technology adjusted to the part requirements defined by a customer.

(Keywords: high-speed cutting, grey cast iron, tool wear, CBN (cubic boron nitride), burr)

0 UVOD

Hiter razvoj in napredek v znanosti in tehnologiji materialov je privedel do velikega števila kakovostnih materialov z izboljšanimi mehanskimi lastnostmi za namensko uporabo. To so materiali s specifičnimi lastnostmi, ki zagotavljajo potrebe končnega izdelka. Omenjene posebne značilnosti so lahko: veliko razmerje med odpornostjo in težo, trdnostjo pri višjih temperaturah, odlično obrabno odpornostjo itn. Take posebne značilnosti izdelkov so lahko tudi majhne geometrijske tolerance brez izrazitih mehanskih obremenitev. V takih primerih je najpomembnejši ekonomski vidik izbire materiala obdelovanca. Zato so taki izdelki običajno narejeni iz mehke sive litine.

Siva litina ponuja široke možnosti izdelave geometrijsko zahtevnih konstrukcij izdelkov. Na

0 INTRODUCTION

Rapid developments in the science and technology of materials are resulting in the emergence of a wide range of advanced engineering materials with specific properties for new applications. These are materials with special characteristics that meet a product's requirements. The remarkable technological characteristics include a high strength-to-weight ratio, high strength at elevated temperatures, excellent wear resistance, etc. Special product tolerances also include low geometrical specifications without explicit mechanical loads. In this case the economics has to be considered. Therefore, such products are usually made of soft grey cast iron.

These materials offer attractive options for engineers working on component design. Unfortužalost so materialne lastnosti, zahtevane za zagotovitev mehanskih lastnosti izdelka v nasprotju z njegovimi tehnološkimi lastnostmi obdelovalnosti. Zato je obdelava takšnih materialov zelo zahtevna. Pomanjkanje primernih tehnologij obdelave je glavni zadržek pri izkoriščanju teh specifičnih materialov. Kljub naprednim vrhunskim tehnološkim lastnostim materialov pa je v avtomobilski industriji, z vidika tehnologije odrezovanja, uporaba gospodarne sive litine še vedno problem [1].

Pri končni obdelavi delov za avtomobilsko industrijo sta najpomembnejši zahtevi kupca: kakovost obdelane površine in zagotovitev toleranc. Izraz kakovosti obdelane površine sta nastanek igle in hrapavost obdelane površine. Obe zahtevi sta funkciji sistemskih parametrov, to so geometrijska oblika orodja (npr. polmer rezalnega robu, geometrijska oblika robu, cepilni kot itn.) in pogojev odrezovanja (podajanje, rezalna hitrost, globina itn.). Pri finem struženju, kot dodaten vpliv na kakovost obdelane površine in prisotnost igle na obdelovancu, vpliva obraba orodja [2]. V industrijski študiji hrapavost obdelane površine ni bila kritična. Zato prispevek obravnava le kritični pojav igle na robu obdelovanca.

Statistične raziskave kažejo, da sta v dejanskih odrezovalnih postopkih struženja v industriji uporabljena prava geometrijska oblika orodja in ustrezni obdelovalni parametri v manj ko polovici primerov in da se orodje uporablja do svojih mejnih zmogljivosti le v tretjini primerov [3]. Namen tega prispevka je tako predstaviti možnosti izboljšanja strategije obdelave OVH mehke sive litine na podlagi optimalne določitve kombinacije:

- materiala obdelovanca s specifičnim lastnostmi,
- odrezovalnega orodja ter
- odrezovalnega postopka.

1 OBDELOVALNOST MEHKE SIVE LITINE

Obdelovalnost je definirana kot zahtevnost obdelave materiala pod določenimi pogoji, vključno z rezalno hitrostjo, podajanjem in globino rezanja. Definirana je lahko tudi kot mera odziva materiala obdelovanca v stiku z določenim materialom rezalnega orodja. In sicer kot kombinacija še sprejemljive obrabe orodja ob hkratnem zagotavljanju ustrezne kakovosti obdelane površine ter delovnih lastnosti obdelovanca [4]. Stopnja obdelovalnosti določenega materiala se običajno ovrednoti z merjenjem obrabe rezalnega orodja, hrapavosti obdelane površine ali komponent rezalne sile med postopkom rezanja.

nately, the same material properties responsible for superior product performance render the transformation of such materials into useful products by traditional machining processes very difficult. The lack of an appropriate machining technology is thus a major obstacle to exploiting these advanced materials. Within the framework of high-tech materials in the automotive sector, the need for cost-effective grey cast iron still brings up problems related to machining technologies [1].

When machining automotive parts, surface quality and tolerances are the most specified customer requirements. The surface quality of machined parts refers to the following: the appearance of burrs and surface roughness. Both properties are mainly the result of system parameters such as tool geometry (i.e., nose radius, edge geometry, rake angle, etc.) and the cutting conditions (feed rate, cutting speed, depth of cut, etc.). During finish turning, tool wear becomes an additional parameter affecting the surface quality and the appearance of burrs on finished parts [2]. In our case study surface roughness is not critical. Therefore, we deal just with burr appearance on the products.

From statistical research it is known that in turning practice, industry chooses the correct tool geometry less than half of the time, uses the proper machining parameters only about half of the time, and uses the cutting tools to their full life capability only for one third of the time [3]. The objective of this paper is therefore to design improved manufacturing HSC strategies for soft grey cast iron machining by selecting an appropriate combination of:

- workpiece materials with specific characteristics,
- cutting tools,
- cutting process.

1 MACHINABILITY OF SOFT GREY CAST IRON

Machinability is defined as the ease with which a material can be machined under a given set of operating conditions, including cutting speed, feed rate and depth of cut. It can also be described as a measure of the response of a material to be machined with a given tool material, resulting in an acceptable tool life and at the same time providing a good surface finish and acceptable functional characteristics of the workpiece [4]. The machinability of a material is mainly assessed by measuring the tool life, the generated surface finish or the components of the cutting force during machining.

1.1 Vplivi na poslabšanje obdelovalnosti mehke sive litine

Litina, pri kateri se pri strjevanju izloča grafit, se imenuje siva litina ker je barva ulitka zaradi izločenega lamelarnega grafita siva. Je zmes z 2 do 3,5-odstotnim deležem ogljika in 1 do 3-odstotnim deležem silicija. V splošnem je eden od najbolj uporabljenih obdelovalnih železnih materialov. Tipična mikrostruktura je prikazana na sliki 1a. V sivi litini se prosti grafit izloči v lamelni obliki različnih velikosti in razporejenosti. Cementita je od 1 do 2 odstotka, kar je posledica hitrega ohlajevanja zmesi. V primeru počasnega ohlajanja z velikim deležem C in Si, pa pride do strukture z velikim deležem prostega ferita in velikih lamel grafita.

Za izdelovanje izdelkov iz mehke sive litine se uporabljajo natančni postopki litja. Kljub temu litje takih zahtevnih izdelkov ni preprosto. Zato se uporabljajo dodatne končne obdelave. Običajno so to odrezovalni postopki, ki zagotovijo izdelavo zapletenih kakovostnih izdelkov ob upravičenih stroških. Slaba obdelovalnost mehke sive litine je posledica njenih naravnih lastnosti, ki jih predstavljajo naslednji dejavniki:

- OVH neutrjene sive litine, z negativno geometrijsko obliko rezalnega orodja, vodi do močne plastifikacije odrezovalnega materiala pred rezalnim robom. To privede do visokih toplotnih in mehanskih obremenitev rezalnega robu orodja;
- velika koncentracija prostega ferita povzroča močno podvrženost orodja kemični obrabi [5];
- prisotnost trdih in abrazivnih vključkov v strukturi materiala obdelovanca povzroča oziroma pospešuje abrazivno obrabo orodja [6];

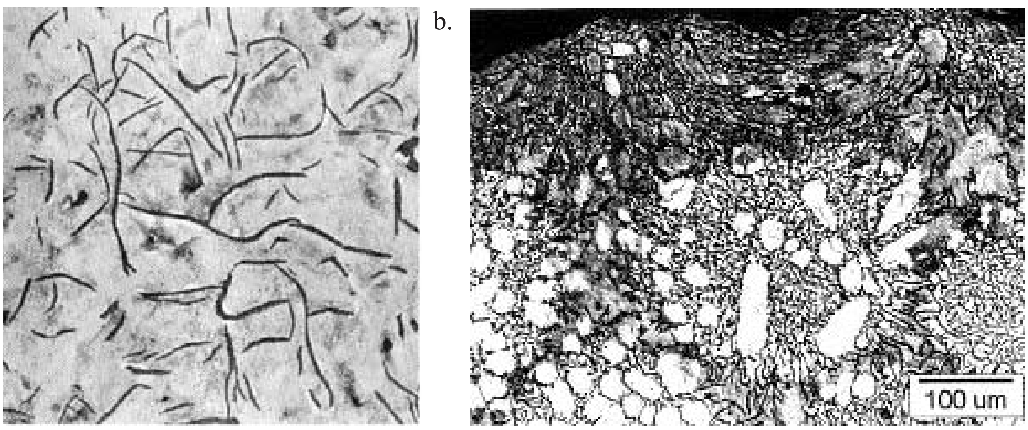
1.1 Properties impairing the machinability of soft grey cast iron

Cast iron that solidifies with the separation of graphite is called grey cast iron because the fracture surfaces appear grey because of the exposed free graphite. Cast iron is in fact an alloy with 2 to 3.5% carbon and 1 to 3% silicon content, and is one of the most widely used free machining ferrous materials. A typical microstructure is presented in Fig. 1a. In all grey cast iron grades free graphite is present in the form of various sized flakes and distributions. Grey cast iron includes 1 to 2% of cementite, which is the caused by the rapid cooling of the alloy. In contrast, the slow cooling of grey iron with a high content of carbon and silicon will yield a matrix with a high content of free ferrite and large flakes of graphite.

The precision casting process is used to manufacture components from soft grey cast iron. However, complex components cannot be easily produced using this process; hence finishing operations are employed to produce complex quality parts at a reasonable cost. The poor machinability of soft grey cast iron is related to its inherent characteristics, which include the following:

- the HSC of unhardened grey cast iron with a negative cutting-tool geometry results in high material plastification in front of the cutting edge. The plastification causes high thermal and mechanical loads on the tool tip,
- the high content of free ferrite causes rapid chemical wear of the cutting tool [5],
- the presence of hard abrasive inclusions in the microstructure increases the amount of abrasion-related tool failure [6],

a. b.



Sl. 1. *a. Grafitne lamele v perlitni osnovi, b. Mikrostruktura uporabljene sive litine ob površini*

Fig. 1. *a. Graphite flakes in a pearlite matrix, b. microstructure of grey cast iron near the surface*

- slaba toplotna prevodnost, povzroča visoke temperature (nad 1000°C) na rezalnem robu orodja in
- zvarjanje materiala obdelovanca na rezalni rob orodja in oblikovanje nestabilnega nalepka (NL - BUE), prav tako negativno vplivata na kakovost obdelane površine in rezalno orodje.

Napredek v tehnologiji izdelave rezalnih orodij je pripeljal do razvitja kakovostnih rezalnih orodij z izboljšanimi tribološkimi lastnostmi ter velikimi toplotnimi in kemičnimi obstojnostmi z namenom povečanja obdelovalnosti. Taka rezalna orodja so npr. karbidna trdina, keramika in kubični borov nitrid (CBN).

1.2 Rezalna orodja za OVH mehke sive litine

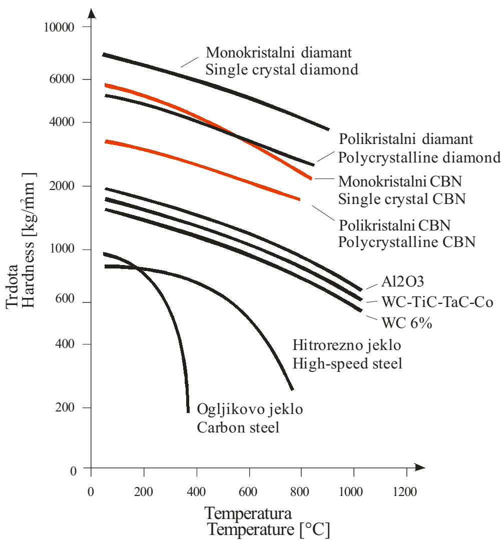
Slaba obdelovalnost mehke sive litine je vzrok izpostavljenosti materiala rezalnega orodja skrajnim toplotnim in mehanskim obremenitvam v okolici rezalnega robu. To povzroča plastifikacijo materiala in pospešeno obrabo orodja. Tipični mehanizmi obrabe pri odrezovanju mehke sive litine so: zareze na rezalnem robu, obraba proste ploskve, krušenje ali celo lom rezalnega robu. Rezalna orodja, primerna za odrezovanje sive litine, morajo tako imeti in obdržati veliko trdnost tudi pri višjih temperaturah, prisotnih pri OVH. V takih razmerah večina materialov orodij izgubi trdoto in se pospešeno obrablja. Slika 2 prikazuje spreminjanje trdote materialov orodij s temperaturo.

- a low thermal conductivity, which leads to the localization of cutting temperatures (over 1000°C) at the tool tips,
- the welding of the workpiece material on the tool's cutting edge and the formation of an unstable build-up edge (BUE), which deteriorates the machined surface as well as the cutting tool.

Developments in cutting-tool technology have led to the development of advance cutting tools with high lubrication properties and high thermal and chemical stability that can improve the machinability. These cutting-tool materials include coated carbides, ceramic tools, and cubic boron nitride (CBN).

1.2 Cutting tools used for HSC of soft grey cast iron

The poor machinability of soft grey cast iron subjects the cutting-tool materials to extreme thermal and mechanical loads close to the cutting edge, which often lead to plastic deformation and accelerated tool wear. Typical failure modes observed during the machining of soft grey cast iron are tool-nose notching, flank wear, crater wear, chipping or even tool-edge breakage. Cutting tools used for the machining of soft grey cast iron should have an adequate hot hardness to withstand the elevated temperatures generated during high-speed conditions. Under these conditions most tool materials lose their hardness, resulting in the weakening of the inter-particle bond strength and in an acceleration of the tool wear. Fig. 2 shows the variation of tool hardness with temperature.



Sl. 2. *Tipične značilnice trdote materialov pri povišanih temperaturah ([7] in [8])*
Fig. 2. *Typical hot hardness characteristics of some tool materials at higher temperatures ([7] and [8])*

Primerna izbira za OVH mehke sive litine je rezalno orodje iz CBN, v nasprotju z običajnimi materiali, ki so primerni za odrezovanje pri nižjih rezalnih hitrostih.

Učinkovitost tehnologije odrezovanja mehke sive litine je odvisna od izbire rezalne hitrosti → materiala rezalnega orodja → geometrijske oblike orodja → poti orodja. Tehnologija odrezovanja mora biti ustrezno izbrana z namenom zmanjšanja časa obdelave, ob zagotavljanju kakovosti površine ([9] in [10]). V obravnavanem primeru je kakovost površine čim manjša verjetnost pojavitve igle na robu obdelovanca (s tako rešitvijo se je moč izogniti dodatnim opravilom obdelave).

1.3 Geometrijska oblika rezalnega orodja

Kljub odličnim materialnim lastnostim mora imeti tudi material rezalnega orodja iz CBN primerno geometrijsko obliko. Na račun trdote je trdnost CBN manjša kakor pri drugih rezalnih orodjih, zato so orodja bolj občutljiva na krušenje. Zaradi tega je običajno potrebna uporaba negativne geometrijske oblike in ustrezna priprava rezalnega robu, z namenom povečanja odpornosti in doseganja ustrezne kakovosti obdelanih površin (sl. 3).

Geometrijska oblika rezalnega robu orodja iz CBN ima močan vpliv tudi na kakovost obdelane površine [5]. Posnet rezalni rob orodja iz CBN močno poveča dobo trajanja orodja. Na drugi strani pa ima posnetje rezalnega robu negativni vpliv na kakovost površine. Kakovost je večja pri honanem robu rezalnega orodja. Študija [11] se ukvarja s primerjavo treh različnih priprav rezalnega robu pri finem struženje z orodjem iz CBN (sl. 3). V prispevku je predstavljena ugotovitev, da ima honan rezalni rob (c) slabšo odpornost kakor ostali dve pripravi rezalnega robu. Tako ima geometrijska oblika rezalnega orodja pomemben vpliv na obrabo rezalnega orodja, kar neposredno vpliva na kakovost površine obdelovanca.

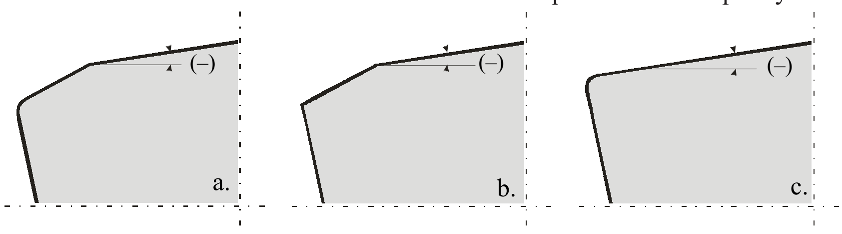
An appropriate choice for the HSC of soft grey cast iron is the CBN/pCBN tool material, while other conventional tools are employed for low-speed machining conditions.

The efficiency of soft grey cast iron machining depends on the selection of cutting speed machining → tool material → tool geometry → tool path. The cutting technology has to be carefully designed to reduce the machining time while maintaining an acceptable surface quality ([9] and [10]). In the case study the surface quality refers to the minimization of the appearance of burrs on the workpiece edge (such a solution excludes an additional machining operation).

1.3 Cutting-tool geometry

Despite good material performance, CBN cutting tools demand a suitable design of the tool geometry. CBN has a lower toughness than other common tool materials, thus chipping is more likely. Therefore, negative tool geometry and proper edge preparation is required to increase the strength of the cutting edge and to attain a favourable surface quality on the finished machined parts (Fig. 3).

The edge geometry of the CBN tool is an important factor affecting the surface quality [5]. The chamfered cutting edge of CBN tools results in a significantly increased tool life, but it is unfavourable in terms of attainable surface finish compared to honed or sharp cutting edges. The case study [11] employs tests for three different edge preparations when finish turning with CBN cutting tools (Fig. 3). The results indicate that the honed cutting edge has a worse performance than the other two, from the point of view of cutting-tool flank wear. Therefore, the cutting-edge geometry has an important influence on tool wear, which directly affects the workpiece's surface quality.



Sl. 3. *Različno pripravljeni rezalni robovi orodij iz CBN (a. posnet in honan, b. samo posnet in c. le honan)*

Fig. 3. *Cutting with CBN tools of various edge geometries (a. chamfer and hone, b. chamfer only and c. hone only)*

1.4 Verjetnost nastanka igle

Obsežnost in pomembnost problema pojavljanja igle v industriji je razvidna tudi iz dejstva, da obstaja veliko znanih metod raziglanja. Mehanske metode raziglanja, kot so brušenje, krtačenje in valjanje, so običajno cenejše; ampak tveganje za poškodbo obdelovanca je veliko. Ko pa se poveča zapletenost in zahteve obdelovanca, dodatne obdelave postanejo bolj zahtevne in dražje, kar velja tudi za postopek raziglanja.

Avtomobilska industrija daje velik pomen odrezovalnim postopkom brez igle na robovih obdelovanca. Ker se zahteve po tolerancah in kakovosti obdelane površine izdelka tesno izkazujejo na stroških, mora biti možna verjetnost nastanka igle obravnavana preventivno in ne z dodatnim obdelovalnim opravilom. Saj lahko igla v kasnejšem stanju med obratovanjem povzroči resno in nepričakovano poškodbo na napravi ali sistemu, če se odlomi od komponente.

Glavni mehanizem nastajanja igle sestoji iz štirih faz: (1) začetek, (2) začetno oblikovanje, (3) točka upogibanja in (4) končno oblikovanje igle (sl. 6). Začetno stanje predstavlja fazo, ko se pojavi področje plastifikacije na robu obdelovanca. V začetnem oblikovanju se pojavi še izrazit premik materiala. Ta mehanizem se kaže kot začetek upogibanja materiala. V fazi upogibne točke se pojavi točka vrtišča in nestabilnost narinjenega materiala na robu obdelovanca. Od tega stanja naprej sledi izrazito upogibanje neodrezanega odrezka na robu obdelovanca. V zadnji fazi se oblikuje končna igla skozi negativno deformacijsko območje, ki je posledica strižne deformacije. Tako sta plastično deformiranje in vpliv strižnih deformacij prevladujoča mehanizma oblikovanja igle. Odvisno od odrezovalnih pogojev in lastnosti materiala obdelovanca na koncu skozi negativno deformacijsko območje lahko pride do loma nastale igle.

Iglo se običajno označi z njeno višino in debelino (sl. 4). Težava pa je v tem, da je merjenje igle lahko dolgotrajno in zahtevno opravilo. V odrezovalnem postopku je pojavitev igle na obdelovancu večinoma vzrok uporabe istosmerne metode podajanja orodja (sl. 5). In sicer, ko rezalno orodje pride čez rob obdelovanca, se odrezek ne odlomi popolnoma od roba obdelovanca. Ta neodlomljeni del je igla. Poleg tehnologije na pojav pozitivno vpliva tudi krhkost materiala. Problem je lahko izboljšan z uporabo protismerne tehnologije

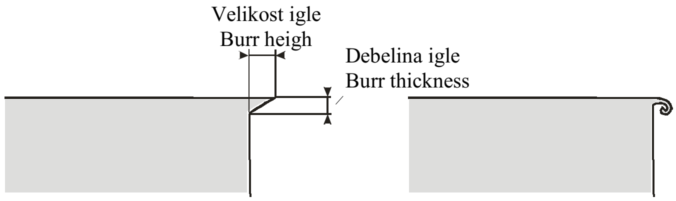
1.4 Probability of the appearance of burrs

The extent and importance of the burr-related problem for industry is underlined by the fact that there are many types of deburring methods. Mechanical deburring methods, such as brushing/buffing and rolling, are generally more cost effective, but the risk of workpiece damage is high. As parts continue to increase in complexity and demands, specifications become more demanding and the deburring processes become more complex and expensive.

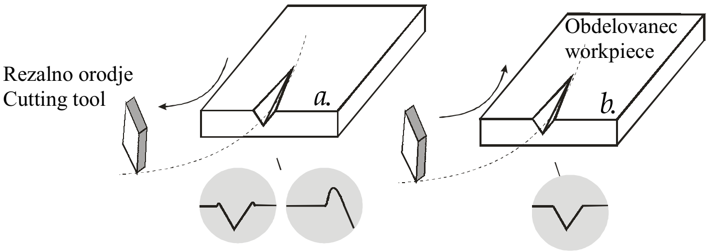
Burr avoidance in the manufacturing processes for the automotive industry has received a great deal of attention. As the demand for component tolerances and surface quality, which are in this industry more stringent in the relation with costs, the burr issues need to be addressed at the point of prevention rather than the removal operation. Burrs, when loosened from the component at a later stage, can cause major damage to the device or the system.

The basic burr-formation mechanism consists of four stages: (1) initiation, (2) initial formation, (3) pivoting point and (4) final formation (Fig. 6). The initiation stage represents the point where the plastically deformed region appears on the edge of the workpiece. In the initial development stage, significant deflection of the workpiece edge occurs. The mechanism involved in this stage is similar to the bending deformation. The pivoting-point stage represents the point where material instability occurs at the workpiece edge. From this stage on, bending at the workpiece edge occurs. In the final formation stage, a burr is further developed with the influence of the negative deformation zone formed by a shearing process. Hence, plastic bending and shearing are the dominant mechanisms during this stage. Depending on the cutting conditions and the material properties, through the negative deformation zone, edge breakout can occur.

Burrs are normally characterized by their height and thickness (Fig. 4). But the problem is that a burr-size measurement is a tedious task. In the process of cutting the cause of the burr is largely attributable to the use of the up-cut method in the tool feed (Fig. 5). As the cutting tool returns from the workpiece the chip does not break off clearly from the edge of the workpiece. The result is a residual burr. Also, the ductility of the workpiece material is likely to reinforce this phenomenon. The problem can be resolved with the use of a down-cut tool feed



Sl. 4. *Merjenje velikosti igle in zahtevnost določitve*
Fig. 4. *Burr-size measurement and the difficulty of the characterisation*



Sl. 5. *Pomembnost smeri odrezovanja z vidika nastajanja igle (a. isto-smerno, b. proti-smerno)*
Fig. 5. *The importance of feed direction in the way the burr forms (a. up-cutting, b. down-cutting)*

podajanja orodja (sl. 5). Poudariti je treba, da ta rešitev dejansko ne odpravi igle, pač pa iglo prestavi (mogoče v manjši meri) na drug rob obdelovanca, ki morda ni tako kritičen.

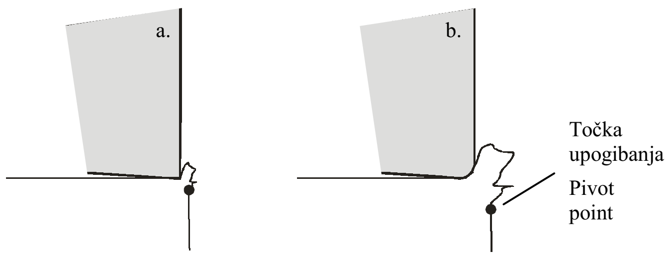
Dodatna dejavnika, ki vplivata na nastanek igle, sta geometrijska oblika in ostrina rezalnega robu. Ko je orodje ostro, je točka upogibanja blizu roba obdelovanca (sl. 6). Z obrabljanjem orodja se ta točka upogibanja materiala pomika v nasprotni smeri od roba obdelovanca. To oddaljevanje točke upogibanja pomeni povečanje igle.

Ker se vedno ni mogoče izogniti nastanku igle, nekaj pozornosti namenimo načrtovanju in izvajanju, ki lahko močno izboljšata obdelovalnost. Obdelovalnost je lahko izboljšana z vidika zmanjšanja stroškov ter časa in truda, potrebnega za dodatna opravila raziglanja. Če se nastanku igle ne da izogniti, jo je običajno moč odriniti na nekritična področja ali vsaj na področja, kjer je raziglanje bolj dostopno.

(Fig. 5). But here it is important to mention that with this solution we did not avoid the burr; the burr was just removed to another workpiece edge, which is probably not so critical.

Another factor that has an impact on burr formation is the sharpness of the cutting tool's edge. When the tool is sharp the "pivot" point of the tool is located close to the workpiece edge (Fig. 6). When the tool is worn, the pivot point is located further away from the workpiece edge. This results in the formation of larger burrs.

While it is not always possible to avoid the appearance of burrs completely, some attention taken at the planning and execution stages of the technology can provide significant cost reduction, deburring time and effort during post-machining operations. So, burrs should be kept in places that are not critical or are easier to access for removing operations.



Sl. 6. *Vpliv obrabe orodja na nastanek (a. ostro orodje, b. obrabljeno orodje)*
Fig. 6. *Effect of tool sharpness on burr formation (a. sharp tool tip, b. blunt tool tip)*

2 EKSPERIMENTALNO DELO

Preizkusi obdelovalnosti sive litine so bili izvedeni z dvema različnima geometrijskima oblikama rezalnega orodja iz CBN pri odrezovalnem postopku finega struženja. Spremljana je bila obraba orodij pri treh različnih tehnologijah odrezovanja. Namen je bil določitev različnih obrabnih karakteristik in mehanizmov. Poleg obrabe je bila izvedena tudi analiza nastajanja odrezka pri hipni ustavitvi postopka odrezovanja.

2.1 Material obdelovanca

Najbolj pomembna lastnost materiala obdelovanca je trdota, zato je bila trdota uporabljene sive litine tudi izmerjena. Izvedeno je bilo več meritev na več kosih in na več mestih vsakega kosa. Povprečna trdota po Vickersu je bila 210 ± 15 HV1.

Mikrostruktura sive litine ima perlitno osnovo z lamelarnim grafitom. Grafit v uporabljeni litini GG20 je pretežno tipa A. Na površini je mikrostruktura na nekaterih mestih močno feritna, prav tako globlje v ulitku (sl. 1b). Feritna mesta so v perlitni osnovi v obliki otokov. Tako je na nekaterih delih koncentracija ferita večja od 5%, lokalno tudi več ko 10% do skoraj 100% (sl. 1b). Kemična struktura uporabljenega materiala, ki jo je podala livarna, je predstavljena v preglednici 1.

2.2 Geometrijska oblika rezalnega orodja

Obe geometrijski obliki rezalnih orodij, uporabljeni pri preizkusih, sta negativni s honanim rezalnim robom in sta predstavljeni na sliki 8. Razlikujeta se le v velikosti posnetja robu.

Ker uporabljena siva litina ni utrjena, a ima dobre obrabno-odpornostne karakteristike, pomeni veliko abrazivnost rezalnega orodja. Ti vplivi in velika globina odrezovanja povzročajo veliko obremenitev rezalnega robu, kar ima za posledico hitro obrabo rezalnega orodja. Uporabljeni material

2 EXPERIMENTAL WORK

Grey cast iron machinability tests were performed with two different CBN cutting-tool geometries with the aim of analysing the different wear characteristics. The tests were carried out during the finish turning process. Tool wear was investigated with three different cutting technologies. Beside tool wear, a chip-formation mechanisms analysis was also carried out with interruption of the cutting process – Quick Stop Device (QSD).

2.1 Workpiece material

The most important characteristic of the workpiece material is its hardness. For this reason, the hardness of the grey cast iron was measured. Measurements were made on different casts and on different parts of the casts. The average hardness using the Vickers method was 210 ± 15 HV1.

Grey cast iron has a pearlite structure with lamellar graphite. The graphite in the cast iron GG20 is mostly A type. On the surfaces the microstructure at some parts is mostly ferrite and it is the same in depth (Fig. 1b). The ferrite is located in pearlite-like island areas. So on such a part the concentration of ferrite is more than 5%, locally more than 10% to almost 100% (Fig. 1b). The chemical structure of the material that was provided by the foundry is presented in Table 1.

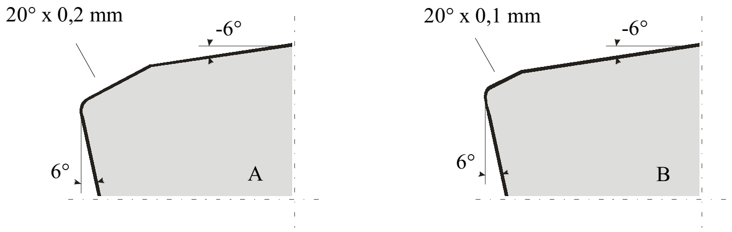
2.2 Cutting-tool geometries

Both the cutting-tool geometries used in the experimental tests were negative with a honed cutting edge and are compared in Fig. 8. The difference is just in the cutting-edge chamfer.

Because the grey cast iron material used here is not particularly hard, but exhibits a good wear-resistance characteristic, this makes it very abrasive to cutting-tool materials. These circumstances and the larger depth of cut mean much more load on the cutting edge, which leads to a high cutting-tool wear

Preglednica 1. *Kemična sestava uporabljene sive litine*
Table 1. *Chemical structure of the grey cast iron*

DIN 1691	CE [%]	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cr [%]	Sn [%]
GG20	x	x	2,2	0,55	0,025	0,05	0,08	0,007
	Cu [%]	Mo [%]	Ni [%]	V [%]	W [%]	Sc [%]	Rm [MPa]	HBN
	x	0,01	0,06	0,01	0,012	0,96	220	190



Sl. 8. *Primerjava testiranih geometrijskih oblik rezalnih orodij*
Fig. 8. *Comparison of the tested cutting-tool geometries*

rezalnega orodja je bil trden CBN z 90-odstotnim deležem CBN. Posnetje rezalnega robu rezalnemu orodju iz CBN poveča trdnost in tako zagotovi največjo dobo trajanja [12].

2.3 Tehnologija odrezovanja

Preizkusi so bili izvedeni s tremi različnimi odrezovalnimi tehnologijami, ki so dejansko uporabljene v avtomobilski industriji. Rezalna hitrost je bila enaka v vseh treh primerih, 1200m/min. To zagotovo predstavlja OVH [13]. Odrezovanje je bilo suho. Podajalne hitrosti za vse tri tehnologije *X*, *Y* in *Z* so bile f_X=0,35, f_Y=0,2 in f_Z=0,1mm/vrt. Pri globinah odrezovanja a_X=2, a_Y=0,3 in a_Z=1,5mm.

3 VREDNOTENJE REZULTATOV OBRABE

Obraba proste ploskve je bila spremljana z orodjarskim merilnim mikroskopom (MITUTOYO TM-505). Rezultati obrabe so predstavljeni na sliki 9, kot obraba proste ploskve (VB) v odvisnosti od števila obdelanih kosov. Ker je tehnologija odrezovanja *Z* najbolj kritična, so na sliki 10 predstavljeni samo posnetki obrabe rezalnega orodja pri tehnologiji *Z*.

Iz rezultatov je razvidno hitro začetno obrabljanje. Sledi mu ustaljeno območje linearnega naraščanja obrabe. Opazen je tudi močan toplotni vpliv. Po 100 (pri orodju A) in 140 (pri orodju B) obdelanih kosih, se je pojavila igla na obdelovancu in rezalni rob je moral biti zamenjan. Tako je bil kriterij dobe trajanja orodja pojav igle in ne neposredno obraba. Kljub temu je bila obraba uporabljena za meritev dobe trajanja in analizo obrabljanja posameznih geometrijskih oblik robu rezalnih orodij.

Iz rezultatov je moč merila dobe trajanja rezalnega orodja razdeliti v dve skupini glede na tehnologije odrezovanja. Prva skupina predstavlja tehnologija *Z*, pri kateri obraba VB ni kritična, ampak

rate. The cutting-tool material was solid CBN, where the CBN content was 90%. The chamfering of the insert strengthens the CBN cutting-tool edge, so ensuring the maximum tool life [12].

2.3 Cutting technology

Tests were conducted with three different cutting technologies that are used in the automotive industry. The cutting speed was constant for all three cases, i.e., 1200 m/min. So we are certainly dealing with HSC [13]. Dry cutting was performed, and the performed feed rates for all three technologies *X*, *Y* and *Z* were f_X=0.35, f_Y=0.2, f_Z=0.1mm/rev. The depths of the cutting were a_X=2, a_Y=0.3 and a_Z=1.5mm.

3 EVALUATION OF TOOL-WEAR RESULTS

The flank wear was observed with a tool maker's microscope (MITUTOYO TM-505). The results of the wear are presented in (Fig. 9) as flank wear (VB) versus the number of machined parts. Because the cutting technology *Z* is the most critical, just captured pictures of the cutting technology *Z* tool wear are presented (Fig.10).

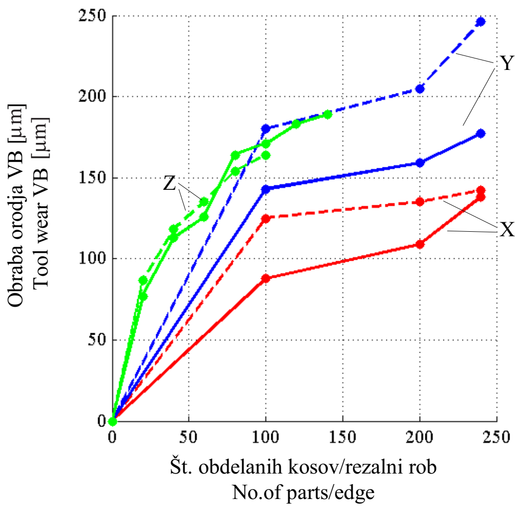
From these results one can see a rapid increase in the wear at the beginning, followed by an area of steady linearly increasing wear. A large thermal influence can also be recognized. After 100 machined workpieces (for tool A) and 140 (for tool B), the burr appeared and the tool edge had to be changed. So, the criterion for tool life is burr appearance and not directly the magnitude of the flank wear. Despite this, the flank wear VB was the main parameter used to measure the tool life and also to classify tool wear in the investigated cases of different cutting-tool edge preparations.

From the results, the criteria for tool life can be classified into two distinct groups, according to the cutting technology. The first group represents *Z* se pojavi igla. Zato je igla merilo za zamenjavo rezalnega robu. Preostali dve tehnologiji (*X*, *Y*) predstavljata drugo skupino, pri katerih nastanek igle ni mogoč in je tako merilo dobe trajanja rezalnega orodja neposredno obraba.

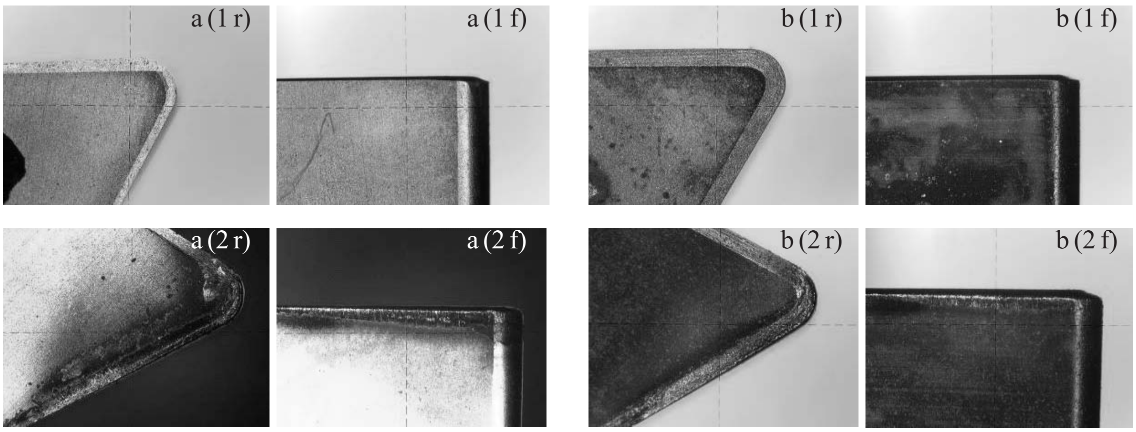
Prosta in cepilna ploskev orodja z rezalnim robom sta podvrženi veliko obrabnim mehanizmom, ki jih je moč določiti z orodjarskim mikroskopom. V začetnem stanju odrezovanja, sta bila prisotna mehanizma hitre začetne zaokrožitve in obraba proste ploskve, ki se je hitro povečevala. Nato obraba proste ploskve postane stabilna. Iz rezultatov (sl. 10) so razvidne raze, oblikovane v smeri rezalne hitrosti. Te raze so posledica močne abrazivne obrabe. Raze na

technology, where the tool wear VB is not critical, but the burr appearance is the criterion for tool or cutting-edge changing. The other two technologies represent the second group, where it is not possible for the burr to occur, and so the tool-life criterion is tool flank wear.

The tool rake faces, flank faces and also the cutting edges show many wear mechanisms that can be observed with an optical microscope. During the early stage of cutting, an initial breakdown in the cutting edge with edge rounding was observed, together with flank wear, which increased rapidly. After this the flank wear becomes stable. From worn tool images (Fig. 10) it is possible to see grooves, which were formed in the cutting-speed direction. These grooves seem to be



Sl. 9. *Obraba proste ploskve pri različnih geometrijah orodja (– – A, – B) za različne tehnologije (X, Y, Z)*
Fig. 9. *Flank wear for different cutting tools (– – A, – B) in three different cutting operations (X, Y, Z)*



Sl. 10. *Primerjava obrabe orodij (1 – novo, 2 – na koncu dobe trajanja), na cepilni (r) in prosti (f) ploskvi za dve različni geometrijski obliki orodij (a – B, b – A)*
Fig. 10. *Comparison of T6B tool wear (1 – new, 2 – at end of tool life), on rake (r) and flake (f) face for two different tool geometries (a – B, b – A)*

prosti ploskvi se pojavijo takoj na začetku odrezovanja in nikoli ne izginejo. Na cepilni ploskvi je razviden tudi mehanizem kotanjaste obrabe.

Kotanjasta obraba je posledica trdih vključkov v materialu obdelovanca, velike rezalne hitrosti ali velike rezalne hitrosti v kombinaciji z nalepkom (NL). Velika rezalna hitrost v kombinaciji z NL povzroča velike temperaturne vplive v rezalni coni in s tem pospešeno obrabo rezalnega orodja ([14] in [15]).

To izredno hitro obrabljanje orodja kaže na preveliko koncentracijo ferita. Delež prostega ferita v sivi litini je pomemben dejavnik pri odrezovanju z orodjem iz CBN. Delež ferita mora biti manjši od 10% za zagotavljanje najboljših odrezovalnih razmer [16]. Tako ima obravnavana siva litina lokalno prevelik delež ferita. Siva litina z deležem več ko 10% ferita, povzroča kemično obrabo orodja iz CBN. Na kemično obrabo zaradi prevelikega deleža ferita, poleg hitre obrabe proste ploskve, kažejo tudi navpične raze na obrabljenem rezalnem robu (prosta ploskev).

Drug vzrok za tako hitro obrabljanje pri tehnologiji *Z* je premajhno podajanje ([17] in [18]). Praktično je podajanje manjše od dolžine posnetja rezalnega robu (0,2 ali 0,1 mm). Tako je dejanski cepilni kot še bolj negativen $\gamma = -26°$.

Vendar pa so okoliščine od primera do primera različne (rezalne hitrosti, podajanje, različne serije litja itn.). Zato je za podaljšanje dobe trajanja rezalnega orodja treba analizirati nastajanje odrezka.

4 ANALIZA NASTANKA ODREZKA

Odrezovalni parametri in geometrijska oblika orodja imajo močan vpliv na rezalne sile. Zato lahko analiza mehanizma nastajanja odrezka pripomore k povečanju obdelovalnosti. Ena od metod za določitev mehanizma odrezovanja je "zamrznitev" odrezovanja med dejanskim odrezovalnim postopkom. Medtem odrezek ne sme biti deformiran. Za tako ustavitev postopka se uporablja posebna hitra prekinitvena naprava (HPN - QSD). HPN mora izpolnjevati tri pomembne specifikacije, ko se testni obdelovanec vrti in je orodje hipoma odmaknjeno iz odrezovalne cone:
- hitrost odmaknitve rezalnega robu mora biti hitrejša od rezalne hitrosti,
- zagotoviti mora prosto pot orodju pri odmikanju iz rezalnega območja in
- ohraniti mora nepoškodovan odrezek med zmanjševanjem hitrosti obdelovanca kot zadnji fazi testa.

the result of extensive abrasion wear. The grooves on the flank surface appear at the beginning of the machining and they never disappear. On the rake face, slight crater wear can also be seen.

Crater wear is a consequence of hard workpiece-material particles, high cutting speed or a combination of a high cutting speed with the presence of BUE. The latter has an influence at high temperature, which contributes to the acceleration of tool wear ([14] and [15]).

This rapid tool wear is due to the presence of free ferrite. The free ferrite content of the grey cast iron is an important factor when machining with CBN. The free ferrite content must be below 10% in order to achieve optimum performance [16]. So, a locally used workpiece material has a free ferrite content that is too high. Iron with a free ferrite content above 10% leads to a chemical attack of the CBN, which in turn will result in a greatly reduced tool life. Examination of the flank wear on the used worn tools and the presence of vertical striations on the wear scar is an indication of chemical wear as a result of the free ferrite contact.

Another cause of rapid tool wear during critical technology *Z* is a feed rate that is too small ([17] and [18]). In practise the feed rate is smaller than the tool chamfering length (0.2 or 0.1mm), so the tool rake angle in this case is even more negative, reaching $\gamma = -26°$.

But the circumstances could be different from case to case (cutting speeds, feed rates, different moulding series, etc.). So, to increase cutting-tool life it is necessary to perform a chip-formation analysis.

4 CHIP-FORMATION ANALYSIS

The cutting conditions and tool geometry have a major effect on the cutting force, so it seems interesting to analyze the chip-formation mechanisms, with aim to increase the machinability. So, the process has to be frozen during the real cutting conditions and without cutting the chips from the workpiece material. For this kind of experiments a quick stop device (QSD) was used. The QSD needs to meet the following three specifications when the workpiece is rotating and the tool is clamped:
- to remove the tool edge from the cutting zone faster than the cutting speed,
- to preserve the free way of the cutting edge from the cutting zone,
- to conserve the chip contact during the decrease in velocity and after stopping.

Prekinitveni testi so bili izvedeni le za najbolj kritično tehnologijo *Z*, zaradi zapletenosti take analize. Rezultat je prikazan na sliki 11. Razvidno je, da je pred posnetjem rezalnega robu območje velikih plastičnih deformacij materiala obdelovanca. Velike plastične deformacije materiala povzročajo velike toplotne in tlačne obremenitve rezalnega orodja. V takih razmerah postane odrezek lepljiv, zato se poveča verjetnost lepljenja odrezka na cepilno ploskev (NL). Deformacije in tok materiala so še posebej razločljivi iz usmeritve grafitnih lamel.

Zaradi negativne geometrijske oblike rezalnega orodja pri obdelovanju mehke sive litine rezalno orodje velik del materiala dobesedno potiska pred seboj. To močno poveča rezalne sile. V skrajnih primerih, ko ta deformacija materiala povzroči zelo velike mehanske in toplotne obremenitve, lahko pride celo do loma orodja. Močne deformacije v rezalni coni povzročajo tudi močno nagnjenje k pojavitvi igle in slabi kakovosti obdelane površine. Največji del deformacijske cone se pojavi pred posnetjem rezalnega robu, ker je podajanje premajhno in je tako dejanski cepilni kot preveč negativen (namesto -6° je -26°). Iz teh rezultatov lahko povzamemo, da:

- mora biti posnetje rezalnega robu zmanjšano ali celo odstranjeno. Kljub temu mora biti rezalni rob honan za dosego kakovostne obdelane površine, ali
- uporabiti pozitivno geometrijsko obliko rezalnega roba.

Material je takoj pred rezalnim robom ločen in se začne upogibati navzgor po rezalnem robu. V področju strižne ravnine, po kateri se material premika, se poleg strižnih napetosti pojavijo tudi visoke tlačne obremenitve, kar je razvidno tudi s slike 11. Za večino analiz je lahko strižno področje poenostavljeno v strižno ravnino. Ob pomikanju orodja naprej se material giblje po tej ravnini. Če je material plastičen, se ne bo lomil, tako bo odrezek nepretrgan. V primeru krhkega materiala pa se material periodično lomi in tvori kratke odrezke. V obravnavanem primeru je siva litina dokaj mehka, zato dopušča večje plastične deformacije in so odrezki nekoliko daljši.

Razliko med globino odrezovanja in debelino odrezka predstavlja koeficient nakrčenja $\lambda = h_c/h$. Vrednost koeficienta nakrčenja je v obravnavanem primeru $\lambda = 2$, medtem ko je kot strižne ravnine $\varphi = 20°$. Kot strižne ravnine in koeficient nakrčenja sta v obratni soodvisnosti. S povečevanjem rezalne

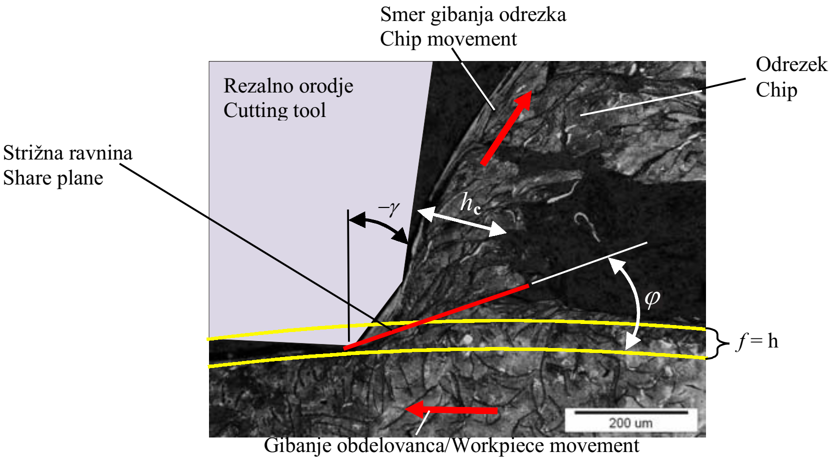
The QSD test was performed only for the most critical cutting technology, *Z*, because of its complexity. The result is presented in Fig. 11. It is possible to recognize that in front of the cutting-tool chamfer, there is a zone of high deformation of the cutting material. This large workpiece-material deformation causes high thermal and mechanical loads on the cutting tool, which are very hard to identify. Under these conditions the chips become gummy and tend to smear and stick to the insert flank (BUE). The deformations and material flow are easy to observe, especially due to orientation of the graphite flakes.

Because of the negative cutting-tool geometry and the tough grey cast material, a "push away material" process appears, which leads to an increase of the cutting forces. At the extreme point, where this material deformation causes very high mechanical and thermal loads on the cutting-tool edge, premature edge breakdown can occur, and there can even be a catastrophic insert breakage. The effect also has a major influence on the burr's appearance and the quality of the machined surface. The main part of the plastification process is localised in front of the cutting-tool chamfer, because of a feed rate that is too small, and so the real rake angle is even more negative (instead of -6° it is -26°). Based on this result it is possible to conclude that:

- the cutting-tool edge chamfer must be decreased or even eliminated. In spite of that, the cutting edge still must be honed, to reach the machined surface quality,
- a positive cutting-tool geometry should be employed.

The material close to the front of the tool is shared and bent upward and is compressed in a narrow zone of shear, i.e., the shear plane that is shown in (Fig. 11). For most analyses, this shear area can be simplified to a plane. As the tool moves forward, the material ahead of the tool passes through this shear plane. If the material is ductile, fracture will not occur and the chip will be in the form of a continuous ribbon. If the material is brittle, however, the chip will periodically fracture and separate chips will be formed. In the case of grey cast iron the material is not so brittle, so the chip is more continuous.

The difference between the uncut and the cut chip thickness is described by the chip-compression coefficient, $\lambda = h_c/h$. The value of the chip-compression coefficient in this case is $\lambda = 2$, while the shear plane angle is $\varphi = 20°$. The shear plane angle increases if the chip-compression coefficient



Sl. 11. *Mikrostruktura korena odrezka z lastnostmi oblikovanega odrezka (h_c - debelina odrezka, h - globina odrezovanja, φ - kot strižne ravnine, γ - cepilni kot)*

Fig. 11 *Microstructure of chip root, with characterized chip-formation mechanism properties (h_c - chip thickness, h - uncut chip thickness, φ - shear plane angle, γ - rake angle)*

hitrosti in podajanja se poveča tudi kot strižne ravnine. Kot strižne ravnine se poveča tudi v primeru povečanja cepilnega kota. Ker se zmanjšanje velikosti strižne površine kaže v manjših rezalnih silah in temperaturah v rezalni coni, je treba čim bolj povečati kot strižne ravnine ([19] in [20]). Te ugotovitve bodo natančneje predstavljene v naslednjem poglavju.

is decreased. With an increase of the cutting speed and the feed rate, the shear plane angle increases. The shear plane angle is also increasing with an increase of the rake angle. So it is important to decrease the shear plane, because this leads to a reduction of the cutting forces and the temperatures in the cutting zone ([19] and [20]). These remarks will be presented in the next section in greater detail.

5 OPTIMIRANJE ODREZOVALNIH POGOJEV

Iz predstavljenih preizkusov je moč povzeti, da je glavni vzrok slabe obdelovalnosti, prevelika obraba rezalnega orodja. Dejstvu se ni moč izogniti, orodja za vrhunsko storilno tehnologijo se prav tako kakor običajna obrabljajo [21].

Kotanjasta obraba in obraba proste ploskve se razvijeta med obratovanjem pri vseh obdelovalnih orodjih. Poznavanje nastanka obrabe z zelo pomembnim nastajanjem igle in mehanizmov pomaga pri izboljšanju obdelovalnosti sive litine. Obdelovalnost obravnavane sive litine je moč izboljšati na treh področjih: (1) geometrijski obliki orodja, (2) odrezovalnih parametrih in (3) poti rezalnega orodja.

5.1 Geometrijska oblika orodja

Na podlagi lastnosti obravnavane sive litine (sl. 1b in pregl. 1) je razvidno dejstvo, da je delež ferita nad 10 odstotki. Trdota ferita je približno 90 HBN, tako da imamo opravka z razmeroma mehko

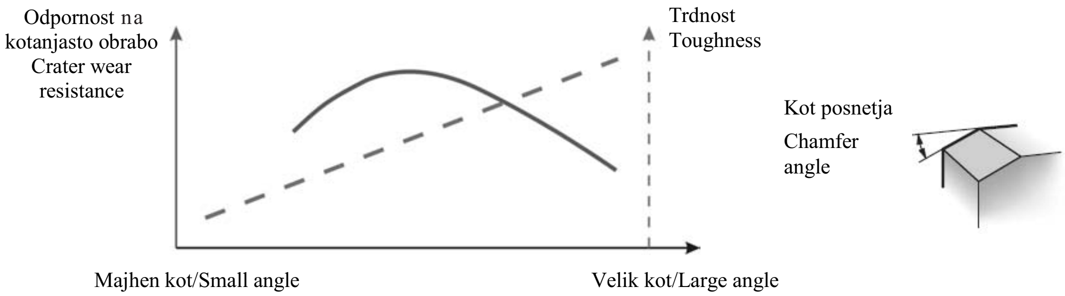
5 IMPROVEMENT OF THE CUTTING CONDITIONS

From the conducted experiments it is possible to conclude that the main reason for the low machinability is a wear rate that is too high for the tool. One cannot avoid this fact, tools for high production technology are just like all others – they wear out as well [21].

Crater and flank wear are being developed during the life cycle of all high production technology tools. Knowing how they are wearing, how burring appears and how they affect the surface quality, will nevertheless help to maximise the productivity benefits of grey cast iron finish turning. To increase the machinability of the used grey cast iron, one can optimise the appropriate combination of (1) tool geometry, (2) cutting parameters and (3) cutting-tool path.

5.1 Tool geometry

From the material properties (Fig. 1b and Table 1) one can see that the content of free ferrite in the grey cast iron is above 10%. The hardness of the free ferrite is about 90 HBN, hence we have to deal



Sl. 12. *Vpliv kota posnetja rezalnega robu na obrabo in trdnost orodja [22]*
Fig. 12. *Influence of chamfer angle on tool wear and tool toughness [22]*

sivo litino. Zato ni potrebe po zelo veliki trdnosti rezalnega orodja. Na račun pomanjšanja trdnosti lahko povečamo kot strižne ravnine s povečanim cepilnim kotom orodja. Poleg tega pa lahko zmanjšamo tudi posnetje rezalnega robu.

Dejansko imajo vsa rezalna orodja za veliko storilnost posnet rezalni rob, kar je potrebno za zagotavljanje njihovih trdnostnih lastnosti [23]. Posnet rezalni rob je manj občutljiv za krušenje in se obnaša bolj čvrsto (sl. 12), medtem ko honan rezalni rob povzroča manjše rezalne sile ([24] in [25]). Obremenitve v smeri rezalne hitrosti so na rezalnem robu in na površini odrezka večje v primeru posnetega rezalnega robu. Temu je vzrok večja površina stika med orodjem in obdelovancem.

Povečanje cepilnega kota posledično poveča kot strižne ravnine in tako lahko izboljša tok odrezka po cepilni ploskvi orodja. S tem se rezalne sile zmanjšajo in raven energije, porabljene v odrezovalnem postopku, je bistveno nižja. Rezultat tega je nižja temperatura v rezalnem območju in podaljšanje dobe trajanja orodja zaradi manjše oziroma počasnejše obrabe proste ploskve. Zmanjšanje rezalnih sil in temperatur zmanjša tudi kemični odziv materiala rezalnega orodja. Poleg teh prednosti je moč pričakovati tudi boljšo kakovost obdelane površine zaradi izboljšanega toka odrezka. Na podlagi tega, mora biti za povečanje obdelovalnosti uporabljena pozitivna geometrijska oblika rezalnega orodja. Taka geometrijska oblika je zagotovljena s cepilnim kotom $\gamma = +6°$. Tudi z ekonomskega vidika je mogoče izdelati tako orodje iz CBN s postopkom brušenja in tako izdelati geometrijsko obliko rezalnega orodja z več rezilnimi robovi na eni rezalni ploščici iz CBN.

5.2 Parametri odrezovanja

Drugo mogočo izboljšavo obdelovalnosti pomenijo spremenjeni odrezovalni parametri. Glavni vzrok hitre obrabe pri najbolj kritični tehnologiji *Z* je

with a relatively soft grey cast iron and a high tool toughness is not necessary. As a consequence of this, the rake angle can be increased and the chamfer angle of the tool edge can be decreased.

Actually, all high production technology inserts have a chamfer, which is essential for controlling their performance [23]. In addition, a chamfered edge is less sensitive to chipping and generally performs more consistently (Fig. 12). From the point of view of ([24] and [25]), the honed tool gives a low resultant force as compared to the chamfered tool; the cutting-direction stresses are higher at the tool tip, and on the chip surface for the chamfered tool due to a larger workpiece, i.e., tool contact area.

An increase of the cutting rake angle causes an increase in the shear angle and an improved chip flow over the insert. This leads to lower cutting forces and thus decreases the levels of transferred energy, which results in a lower temperature in the cutting zone and improves tool life through reduced flank wear. Reductions in both the cutting temperature and load lead to a reduction in chemical attack of the cutting edge, thereby increasing tool life. In addition, the improvement in the surface finish due to the improved chip flow can also be expected. From this point of view, a positive cutting-tool geometry has to be used to improve the machinability. This tool geometry is reached with a $\gamma = +6°$ rake angle. Also, from the economic point of view it is possible to manufacture a positive tool geometry with the grinding of a multi-cutting-edge solid CBN insert.

5.2 Cutting parameters

The second improvement in machinability could be reached by adapting the cutting parameters. The source of a high tool-wear rate in the critical tech-premajhno podajanje (f = 0,08 mm/vrt). Povečanje podajanja ne bi povečalo le dobe trajanja orodja, ampak zmanjšalo tudi verjetnost za nastanek igle na robu obdelovanca. Saj je znano, da večje ko je podajanje, manjša je verjetnost za plastično deformiranje materiala.

5.3 Pot orodja

Tretja izboljšava je lahko dosežena s primernejšo izbiro poti orodja. Namen je povečanje obdelovalnosti z zmanjšanjem verjetnosti nastanka igle. V odrezovalnih postopkih je že pri načrtovanju treba paziti na možnost nastanka igle na robu obdelovanca [26]. Igla na določenih kritičnih mestih lahko močno poslabša delovanje izdelka. Za zmanjšanje tega vpliva je treba, ob načrtovanju geometrijske oblike upoštevati vpliv oblike roba izdelka na njegove lastnosti v kombinaciji s primerno spremembo strategije odrezovanja, kar je prikazano na sliki 13.

6 SKLEPI

V avtomobilski industriji so izbrani ali izdelani materiali, ki zagotavljajo delovanje v določenih pričakovanih mehanskih in toplotnih razmerah. Poleg tega morajo zagotavljati obdelovalnostne kriterije za zagotovitev ekonomskega vidika uporabe takega materiala. Obdelovalnost mehke sive litine, ki je obravnavana v tem prispevku, privede do visokih temperatur na rezalnem robu. To negativno vpliva na lastnosti materiala rezalnega orodja. Tržno dostopna rezalna orodja so običajno uporabna za odrezovanje pri majhnih rezalnih hitrostih. Napredni material orodja kakršen je CBN, je namenjen za odrezovanje tehnološko zahtevnih izdelkov z OVH. Prav tako kakor pri drugih rezalnih orodjih je tudi njihova doba trajanja omejena z mejnimi temperaturnimi in mehanskimi obremenitvami. Ker vsa orodja izgubljajo trdoto v zahtevnejših

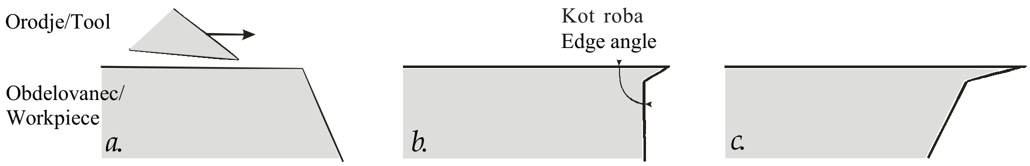
nology Z refers to a low feed rate (f = 0.08 mm/rev). Increasing the rate will not just increase the tool life, but it will also diminish the probability of a burr-formation possibility on the workpiece edge, because it is known that the higher the feed rate, the smaller the possibility for plastic deformation of the material.

5.3 Tool path

The third improvement to increase machinability is related to the cutting strategy, by reducing the probability of burr appearance. In the cutting process, part designers need to pay attention to the burr-formation potential on the workpiece edges [26]. A burr at a certain location on the edge can drastically affect the part's performance. The designer should be aware of the impact of the edge finish on the part's performance. To diminish the possibility of a burr appearing, the cutting strategy can be changed, following some practical solutions like those presented in Fig. 13.

6 CONCLUSIONS

In the automotive industry, part materials are chosen or developed to be able to operate under specific mechanical and thermal conditions encountered in the working environment, and at the same time, to maintain their machinability characteristics, and to ensure an economic efficiency. The machining of soft grey cast iron generates high temperatures at the cutting edge, which impair the performance of cutting-tool materials. Commercially available cutting-tool materials can only be used in moderate-speed conditions. Advanced tool materials, such as CBN, are capable of producing high-quality components at higher cutting speeds. Like all tool materials their tool life is limited by the extreme temperature and the mechanical load generated at the cutting interface. Since all tool materials lose their hardness under tougher cutting conditions, there is



Sl. 13. *Vpliv nagiba roba na nastanek igle: (a. velik kot roba – majhna igla, b. in c. majhen kot roba – velika igla)*

Fig. 13. *Effect of part's edge angle on burr formation: (a. large edge angle – smaller burr, b. and c. small edge angle – larger burr)*

odrezovalnih razmerah, je treba tehnologijo prilagoditi specifičnostim obravnavanega postopka. To je moč narediti z zmanjšanjem nastale temperature na stiku orodje – obdelovanec in orodje – odrezek. Seveda morajo biti pri taki optimizaciji tehnologije upoštevane zahteve kupca izdelka. Pri odrezovanju za avtomobilsko industrijo so kakovost obdelane površine, tolerance in storilnost najbolj izpostavljene zahteve kupca. Pri kakovosti obdelane površine sta najpomembnejša hrapavost in odprava nastanka igle.

Na kratko, prispevek predstavlja alternative za izboljšanje obdelovalnosti mehke sive litine s sedanjimi rezalnimi orodji kakor tudi z optimiranjem tehnologije odrezovanja. To lahko v kombinaciji močno izboljša obdelovalnost široko uporabljene mehke sive litine. V prihodnosti je obdelovalnost pri velikih hitrostih take mehke sive litine lahko izboljšana z določitvijo kombinacije primernega materiala orodja, tehnologije odrezovanja in izbiro primerne geometrijske oblike rezalnega orodja.

a genuine need to harness technologies specifically tailored to minimise the temperature generated at the tool–workpiece and the tool–chip interfaces. During machining-technology optimization, the customer requirements for the machined parts must be taken into account. When machining automotive parts, the surface quality, the tolerances and the productivity are the most specified customer requirements, where the major indicators of surface quality for the machined parts are the surface roughness and the appearance of burrs.

Briefly, the paper presents recommendations and inexpensive solutions for improving the performance of available cutting tools, as well as introducing improved cutting technology, which in combination can significantly improve the soft grey cast iron HSC's machinability. The machining of grey cast iron at higher speeds can therefore be improved by a combination of the appropriate tool material, the machining strategy and the choice of a suitable cutting-tool geometry.

8 LITERATURA
8 REFERENCES

[1] U. Župerl, F. Čuš (2004) A determination of the characteristic technological and economic parameters during metal cutting, *Journal of Mechanical Engineering*, 50(2004)5, 252-266.

[2] J. Kopač (2005) Cutting-tool wear during high-speed cutting, *Journal of Mechanical Engineering*, 50(2004)4, 195-205.

[3] T.Ozel, Y.Karpat (2005) Predictive modelling of surface roughness and tool wear in hard turning using regression and neutral networks, *International Journal of Machine Tools & Manufacture*, 45, 2005, 467-479.

[4] D.Julean (2004) A method for assessment of steels grindability, *Proceedings of 9th CIRP International Workshop on Modeling of Machining operations*, pp.303-306.

[5] (2004) SECO, Technical Guide 2004, *Seco Tools AB*, Sweden.

[6] A. K. Srivastava, M. E. Finn (2001) Machinability of cast iron, *TechSolve - The Manufacturing Solutions Centre*, Cincinnati, Ohio.

[7] E. A. Amond (1981) Towards improved tests based on fundamental properties, *Proceedings of the International Conference on Improved Performance of Tool Material*s, The National Laboratory and the Metals Society, Teddington, Middlesex, 28-29 April, 1981, pp. 161-169.

[8] K.Y.Benyounis, O.M.A.Fakron, J.H.Abbowd, A.G.Olabi, M.J.S.Hashmi (2005) Surface melting of nodular cast iron by Nd-YAG laser and TIG, *Journal of Materials Processing Technology*, 2005, vol.170, n.1-2, pp.127-132.

[9] U.Župerl, F.Čuš, E.Kiker (2006) Intelligent adaptive cutting force control in end-milling, *Tehnički vijestnik*, 2006, vol.13, n.1-2, pp.15-22.

[10] J.Balič (2006) Model of automated computer aided NC machine tools programming, *Journal of Achievements in Materials and Manufacturing Engineering*, 2006, vol.17, n.1-2, pp.309-312.

[11] Y. K. Chou, C. J. Evans (1997) Tool wear mechanism in continuous cutting of hardened tool steels, *Wear* 212, 1997, 59-65.

[12] G. Poulachon, A. Moisan, I. S. Jawahir (2001) Tool-wear mechanisms in hard turning with polycrystalline cubic boron nitride tools, *Elsevier Science - Wear*, 576-586.

[13] S. Ekinović, S. Dolinšek, J. Kopač, M. Godec (2002) The transition from the conventional to the high-speed cutting region and a chip-formation analysis, *Journal of Mechanical Engineering*, 48(2002)3, 133-142.
[14] J.Kopač (1991) Cutting processes, *Faculty of Mechanical Engineering Ljubljana*, Slovenia (in Slovenian).
[15] Y. Altintas (2000) Manufacture automation: Metal cutting mechanics, machine tool vibrations, and CNC design, *Cambridge University Press*.
[16] G. Dawson, T. R. Kurfess: Wear trends of PCBN cutting tools in hard turning, *Georgia Institute of Technology*, Atlanta, USA.
[17] M. Hamiuddin, Q. Murtaza (2001) Machinability of phosphorous containing sintered steels, *Mater. Chem. Phys.* 67, 2001, 78-84.
[18] G. Poulachon, B. P. Bandyopadhyay, I. S. Jawahir, S. Pheulpin, E. Seguin (2004) Wear behaviour of CBN tools while turning various hardened steels, *ENSAM, LaBoMaP*, France.
[19] J. Kopač (2002) Cutting forces and their influence on the economics of machining, *Journal of Mechanical Engineering*, 48(2002)3, 121-132.
[20] M. Milfelner, F. Cus (2001) An analysis of temperatures and thermal energy during cutting, *Journal of Mechanical Engineering*, 47(2001)1, 45-52.
[21] S. Thamizhmanii, S. Hasan (2006) Analyses of roughness, forces and wear in turning grey cast iron, *Journal of Achievements in Materials and Manufacturing Engineering*.
[22] J. Kopač, A. Stoić, M. Lucić (2006) Dynamics instability of the hard turning process, *Journal of Achievements in Materials and Manufacturing Engineering*.
[23] U. Umer, L. J. Xie, X. B. Wang (2006) Modeling the effect of tool edge preparation by ALE method, *9th CIRP International Workshop on Modeling of Machining Operations*, 525-532.
[24] L. A. Dobrzanski, K. Golombek, J. Mikula, D. Pakula (2006) Cutting ability improvement of coated tool materials, *Journal of Achievements in Materials and Manufacturing Engineering*.
[25] (2005) AB Sandvik Coromant, Switch to hard-part turning, Technical guide.
[26] J. Hassamontr, D. A. Dornfeld (1999) Review of burr minimization approaches, *King Mongkut's Institute of Technology*, North Bangkok.

Naslov avtorjev: Franci Pušavec
Peter Krajnik
prof.dr. Janez Kopač
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
franci.pusavec@fs.uni-lj.si
peter.krajnik@fs.uni-lj.si
janez.kopac@fs.uni-lj.si

Author's Address: Franci Pušavec
Peter Krajnik
Prof. Dr. Janez Kopač
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
1000 Ljubljana, Slovenia
franci.pusavec@fs.uni-lj.si
peter.krajnik@fs.uni-lj.si
janez.kopac@fs.uni-lj.si

Prejeto: / Received: 25.7.2006
Sprejeto: / Accepted: 25.10.2006
Odprto za diskusijo: 1 leto
Open for discussion: 1 year

Strojniški vestnik - Journal of Mechanical Engineering 52(2006)11, 723-737
UDK - UDC 621.941:531.3
Izvirni znanstveni članek - Original scientific paper (1.01)

Vrednotenje stabilnosti pri struženju v trdo

Evaluation of the Stability During Hard Turning

Antun Stoić[1] - Mirjana Lucić[1] - Janez Kopač[2]
([1]University of Osijek, Croatia; [1]Fakulteta za strojništvo, Ljubljana)

Prispevek obravnava vrednotenje stabilnosti pri struženju v trdo. Nestabilnosti se pojavijo zaradi spreminjanja globine odrezovanja, neprimernega razmerja sil Fc/Fp, premajhnega polmera konice orodja in neenakomernih porazdelitev napetosti v materialu na območju stika orodja z obdelovancem. Ta področja nestabilnosti je moč določiti s spremljanjem postopka, npr.: sile, pospeškov, merjenja zvočne intenzivnosti itn., ali po končanem obdelovalnem postopku z merjenjem hrapavosti, temperature, obrabe itn. V primeru nestabilnega odrezovalnega postopka se sile pri odrezovanju povečajo. Poveča se hitrost obrabljanja orodja, kar neposredno vodi do slabše kakovosti obdelane površine. Zato se je treba izogibati nestabilnemu postopku odrezovanja. Za določevanje oz. ocenjevanje stopnje nestabilnosti so bile v delu izvedeni numerični izračuni in pripadajoči preizkusni testi z uporabo in primerjavo različnih zaznaval spremljanja postopka in tehnike zbiranja podatkov na podlagi osebnega računalnika.

V prispevku je prikazano, da se globina odrezovanja med postopkom spreminja za 60 odstotkov v primeru analize geometrijske oblike orodje-obdelovanec. Pri merjenju odrivne sile Fp pa se to nihanje še poveča v primeru premajhne togosti odrezovalnega orodja.

Dosežki in ugotovitve tega prispevka so predstavljeni kakovostno in se lahko rahlo razlikujejo pri drugačnih odrezovalnih razmerah (npr.: pri uporabi rezalnega orodja Wiper). Pri odrezovanju v trdo ne glede na to, ali gre za pol fino ali fino obdelavo, ima kakovost obdelane površine izreden pomen. Kakovost obdelane površine je neposredna posledica stabilnosti postopka in neperiodičnosti obremenitve na stiku obdelovanca in orodja. Rezultati prispevka tako pomenijo določitev optimalne globine odrezovanja pri zadnjem prehodu orodja za zagotovitev najmanjše hrapavosti obdelane površine, kar pa je izredno pomembno za določitev optimalnega režima obdelovanja.

(Ključne besede: struženje, stabilnost, lastnosti dinamične, globina rezanja)

This paper deals with the lack of cutting stability during hard turning (appearing due to cutting-depth variation, unfavorable ratio of forces, Fc/Fp, a small tool-nose radius, and a non-uniform stress distribution over the tool/workpiece contact), which is possible to evaluate with process sensing (e.g., forces, vibrations, sound measurements) or after the process has finished (e.g., roughness, wear measurements). If the cutting process is unstable, the cutting force can become large and the machined surface quality can be poor or the tool can quickly become broken. Therefore, it is desirable to avoid unstable cutting conditions. Numerical calculations and experimental tests were made to evaluate the rate of cutting instability while using and comparing different process monitoring sensors and acquisition techniques based on the PC platform.

It was found that the cutting depth varies by a value of some 60% if the tool/workpiece (T/W) contact geometry is analyzed, and even more if the Fp force signal is analyzed when the machine tool has inadequate stiffness.

The results and findings presented in this paper are qualitative and might be slightly different under other cutting condition (e.g., if wiper inserts are used). Assuming that the hard turning is a semi-finishing or finishing process, the surface finish is very relevant, because it is a direct consequence of both the cutting stability and of the tool/workpiece non-uniform loading distribution. The results of the test indicate an optimum cutting depth for the final pass when the minimum surface roughness can be achieved, which can be valuable for the cutting-regime determination.

(Keywords: turning, stability, dynamic properties, cutting depths)

0 UVOD

Določevanje optimalnih obdelovalnih razmer pri odrezovanju, s tako imenovanimi mejno stabilnostnimi diagrami za vsako od kombinacij orodje - držalo - stroj - material obdelovanca, je običajno zelo neprimerno. Zato so potrebe in interesi industrije določitev območij stabilnosti z uporabo metod, ki ne potrebujejo širokega znanja teorije vibracij. Določevanje stabilnosti s spremljanjem odrezovalnega postopka je v današnjih časih precej preprosto z uporabo hitre Fourierjeve transformacije (HFT) zajetega signala v časovnem prostoru. V preteklosti je bila preizkušena tudi možnost določitve stabilnosti z uporabo variance signala [1] in drugimi preizkusi določitve vpliva geometrijskih lastnosti na stabilnost odrezovalnega postopka. Med drugim tudi vpliv polmera konice rezalnega orodja ([2] in [3]), prostega in cepilnega kota ([2] in [4]) ter usmeritve odrezovanja ([2] in [5]). Pomembnost stabilnosti odrezovalnega postopka je bila v preteklosti predvsem označena s frezanjem, pojavlja pa se tudi pri "prekinjenem" struženju, obdelavi v trdo itn.

Postopek struženja obdelovancev z veliko površinsko trdoto materiala, pri katerem so uporabljene manjše odrezovalne hitrosti in površine odrezkov (v primerjavi s struženjem v mehko), lahko dobro nadomesti dodatni postopek brušenja. To zagotavljanje velike kakovosti obdelane površine vodi do bistveno večje storilnosti pri manjšem obremenjevanju okolja z uporabo manjših količin hladilno-mazalnih tekočin. Poleg vseh teh prednosti tehnologije so opazne tudi negativne lastnosti. Struženje v trdo je nepretrgan postopek odrezovanja in posledično tudi nepretrgan postopek obrabljanja orodja. Obrabljanje je odvisno od mehanskih in toplotnih obremenitev orodja [22]. Tako kakor odrezovanje je tudi obrabljanje orodja dinamično, kar je pričakovano zaradi take dinamike spreminjanja globine odrezovanja. Pri zunanjem struženju spreminjanje globine odrezovanja, zaradi geometrijskih lastnosti obdelovanca in spreminjanja globine odrezovanja (GO) glede na predhodno valovitost obdelane površine, podajanja, rezalne hitrosti in dejanskega nastavnega kota po opravljeni "poti" orodja, lahko povzročajo močno dinamiko rezalnih sil, ki neposredno vplivajo na stabilnost postopka. Poleg vseh teh vplivnih parametrov na stabilnost negativno vpliva tudi izsrednost vpetja obdelovanca, kar se kaže kot samovzbujajoče nihanje katere koli komponente odrezovalnega orodja. Prisotnost takih nihanj se lahko kaže kot nepravilna geometrijska oblika obdelane površine ali celo poškodba obdelovanca.

0 INTRODUCTION

The calculation of the optimum cutting conditions using stability-lobes diagrams for each tool/holder/spindle/machine/material combination on the shop floor is not convenient. The need for rapid identification of the stability behavior using methods that do not require an extensive background in vibration theory increases. A stability-testing technique performed with process sensing is nowadays a rapid job that calculates the fast Fourier transform (FFT) of the time-based signal collected during cutting. There was an attempt [1] in the past to evaluate the instability with signal data variance and other attempts that have been geared towards including the effects of real process-geometry parameters into the stability solution, including tool-nose radius ([2] and [3]), feed rate and lead angle ([2] and [4]), and cutting-mode orientation ([2] and [5]). The importance of the instable behavior of cutting was in previous years associated with milling, but also with interrupt cutting, hard machining, etc.

The turning of parts with a high surface hardness, where small values of cutting speed and chip area in the cross section (compared with soft turning) can be applied, has appeared in the past few decades as a process that substitutes grinding very successfully. This substitution enables higher-productivity machining and reduces the environmental impact (lowering the coolant consumption). However, in addition to these positive effects there are a few negative effects. Hard turning is a continuous process of chip removal according to the tool engagement and thermal loads, but also the dynamic undertaking the uncut chip area and the depth of cutting in particular [22]. In contour or outer diameter turning, the workpiece's geometric variations, and the variations in the depth of cut (DOC) as a result of a prior pass valley, the feed rate, the cutting velocity and the effective lead angle, along the tool path produce large dynamic force variations, which induce variations in the process stability. Besides those already mentioned, cutting instability is also associated with the eccentricity of the workpieces, which might lead to self-exited vibration in any component of the machine tool. The presence of this kind of vibration can lead to irregularity of the machined shape as well as to surface damage of the machined workpiece. The

Vpliv se poveča z večanjem rezalne hitrosti do obdelave z velikimi hitrostmi (OVH). Saj je dejstvo, da so se v zadnjih petdesetih letih odrezovalne hitrosti podvojile. To pomeni, da se je vpliv izsrednih sil v enaki časovni dobi povečal za faktor štiri, kar povzroča izrazitejše probleme z vibracijami.

Veliko je vplivnih parametrov, ki vplivajo na storilnost in natančnost obdelovanja. Najbolj vplivna med njimi so samovzbujajoča nihanja. Poleg tega nihanja, povzročajo hitro obrabo orodja ali celo lom orodja. Velik polmer konice odrezovalnega robu zagotavlja kakovostnejšo obdelano površino na račun povečane specifične energije odrezovanja [6] s povečanjem rezalnih sil.

Za zmanjšanje ali celo odpravo samovzbujajočih nihanj so običajno globine odrezovanja in podajanja manjše, ali je spremenjena celo geometrijska oblika orodja. Te spremembe pomenijo omejitve postopka in s tem slabši izkoristek. Zato je zelo pomembno poznati dinamiko odrezovalnega postopka in biti zmožen določitve obdelovalnih pogojev in parametrov, pri katerih se bodo pojavila ta nihanja. Ob poznavanju vzrokov in mejnih točk, kjer se ta nihanja pojavijo, je to moč izkoristiti za povečanje izkoristka odrezovalnega postopka.

Primerljiv postopek odrezovanja kakor je stružilno frezanje, sicer poveča storilnost, še vedno pa ne odpravi problema nihanj, ki nastajajo zaradi spreminjanja kinematike postopka glede na površino odrezka. Dinamičnost kinematike je najmočnejša zaradi vhodov in izhodov posameznega rezalnega robu v odrezovanje in iz njega [7].

Nestabilnosti postopka so vzrok premiku ali deformaciji posameznih delov obdelovalnega sistema (stroj - orodje - obdelovanec) [8]. Vzrokov za odklanjanje je lahko več: lastnosti odrezovalnega stroja, lastnosti rezalnega orodja in lastnosti obdelovanca [23].

1 NAČINI IN PREDPOSTAVKE VREDNOTENJA

Hitrost tvorjenja odrezka pri struženju v trdo in presek neodrezanega odrezka sta v območju A_c = 5 do 90 · 10^3 µm^2 (a_p = 0,05 do 0,3 mm; f = 0,1 do 0,3 mm). Tak prerez odrezka je zagotovljen z ustrezno geometrijsko obliko orodja, podajanjem itn.

Kakor je prikazano na sliki 1, je stik med orodjem in obdelovancem običajno le na območju polmera rezalnega robu. Tako odrezovanje popisuje razmerje:

problem becomes increasingly important due to the trend for developing high-speed machinery. It is estimated that the speed of operation of machinery has doubled during the past 50 years. This means that the level of unbalance forces may have quadrupled during the same period, causing more serious vibration problems.

A lot of factors can affect the precision and productivity of machining and one of the most affecting is self-exited vibration. On the other hand, vibrations can lead to increased tool wearing and tool breakage as well. A large tool-nose radius offers a finer surface finish, but also an increased specific cutting energy [6], which means higher forces.

In order to reduce or remove the presence of self-exited vibration it is the usual procedure to lower the cutting width and the cutting feed rate or to modify the tool geometry. These limitations imply a lower efficiency of the machining process. As a result, it is of great importance to become familiar with the dynamic behavior of machining and to be able to determine under which working conditions and parameters the vibrations will occur. If the causes are known, as is when they occur, it is possible to maximize the efficiency of the machining process itself.

Turn-milling as a competitive process, which reaches a higher productive removal rate, still cannot overcome the occurrence of vibrations as a result of the process of kinematics variations in the chip cross-section, and especially with the entry-exit condition [7].

Process instabilities are caused by deflections in the machining system (machine-tool-workpiece) [8]. The sources of deformations and deflection can be one or more of the following [9]: machine-tool parameters, cutting-tool parameters, workpiece parameters [23].

1 APPROACH AND ASSUMPTIONS IN THE EVALUATION

The chip-removal rate in the hard turning process and the appropriate uncut chip area is in the range of A_c = 5 to 90 · 10^3 µm^2 (a_p = 0.05 to 0.3 mm; f = 0.1 to 0.3 mm). The above uncut-chip area is provided in terms of the tool geometry and the true feed, after the first few revolutions.

As shown in Fig. 1, the tool/workpiece contact is mostly within the tool-nose radius. This condition is derived using:

$$a_p \leq r_\varepsilon (1 - \cos \kappa_r) \quad (1).$$

Pri konkretnem primeru preizkusov je bilo uporabljeno orodje CNMA in držalo rezalnega orodja PCLNR (κ_r= 97°), kar pomeni da mora biti globina odrezovanja (a_{max}) manjša od vrednosti predstavljenih v preglednici 1.

V primeru razmeroma globokih odrezovanj, pri katerih je razmerje med globino odrezovanja in polmerom konice orodja veliko (večje od 5), je dejanski nastavni kot približno enak nastavnemu kotu orodja κ_r. V primerih manjših globin (fina obdelava v trdo), dejanski nastavni kot popisuje razmerje [10]:

Which for the turning condition where the CNMA geometry of the insert and the PCLNR geometry of the holder (while κ_r= 97°) are applied, means that the depth of cutting (a_{max}) is smaller than the value given in Table 1.

For relatively deep cuts in which the depth-of-cut/tool-nose-radius ratio is large (e.g., larger than 5), the effective lead angle is approximately equal to the lead angle κ_r. Otherwise, in finishing cuts (hard turning), the effective lead angle is given as in [10]:

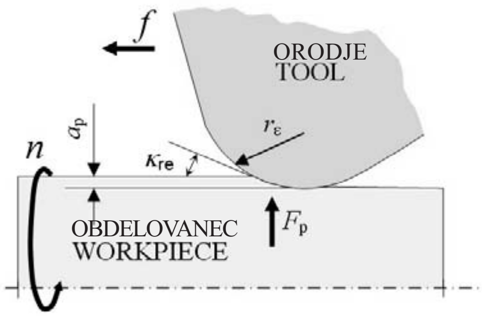
$$\tan \kappa_{re} = 0{,}5053 \tan \kappa_r + 1{,}0473\,(f / r_\varepsilon) + 0{,}4654\,(r_\varepsilon / a_p) \quad (2).$$

Poudariti pa je treba, da se spreminjata globina odrezovanja med samim postopkom, pa tudi dejanski nastavni kot, kakor je prikazano na sliki 2.

Z zmanjšanjem globine (GO) se zmanjša tudi sila odrezovanja. S tem se pomanjša tudi nastavni kot, kar poveča prečno komponento sile odrezovanja. Teoretično je tak postopek zahtevnejši za popis zaradi dodatne odrivne sile ali prečne komponente sile odrezovanja. Ta učinek vpliva na kakovost obdelane površine po Brammerzu [11]. Hrapavost obdelane površine (R_{th}) je lahko opredeljena kot korak med R_t in R_{tB}.

If a variation of the depth of cut during cutting exists, the effective lead angle will vary too, Fig.2.

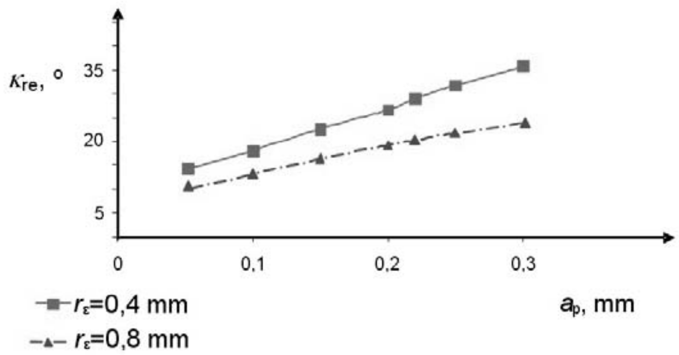
With lowering the depth of cut, the lead angle will decrease (Fig. 2) and the passive force increases. With decreasing the depth of cut, the uncut-chip thickness decreases, as do the forces. This theoretical consideration is more complicated because of the push-off effect (Fig.3) derived by Brammertz [11] in terms of the surface roughness. The surface roughness (R_{th}) is therefore within R_t and R_{tB}.



Sl. 1. *Skica geometriskje oblike stika orodja in obdelovanca*
Fig. 1 *Schematic representation of the tool/workpiece contact geometry*

Preglednica 1. *Pogoji obdelave, kjer odrezovanje opravlja le polmer konice rezalnega robu*
Table 1. *Conditions when the turning is conducted over the tool-nose radius*

r_ε [mm]	a_{max} [mm]
0,4	0,434843
0,8	0,869686
1,2	1,304528



Sl. 2. *Spreminjanje dejanskega nastavnega kota v odvisnosti od globine odrezovanja*
Fig. 2 *Influence of DOC on the effective lead angle*

$$R_{tB} = \frac{f^2}{8 \cdot r_\varepsilon} + \frac{h_{\min}}{2}(1 + \frac{r_\varepsilon \cdot h_{\min}}{2}) \quad (3),$$

kjer h_{min} pomeni najmanjšo globino odrezovanja brez izrazitejšega učinka odrivne sile.

Kot posledica spreminjanja globine odrezovanja, ki je odvisna od geometrijske oblike obdelane površine v prejšnjem vrtljaju, se pojavi tudi spreminjanje sile odrezovanja. Velikost amplitude odrezovalne sile se spreminja s približevanjem postopka podkritični nestabilnosti zaradi večanja podajalne hitrosti [12].

Hua [13] na primeru finega odrezovanja opozori na nastanek površinskih napetosti, ki so posledica različnih geometrijskih oblik odrezovalnega orodja.

where h_{min} is the minimum chip thickness for push-off-free cutting.

The variation of the uncut-chip thickness during the turning process depends on the previous cut profile. If that variation is significant, the amplitude of the cutting force can increase to a nearly sub-critical instability [12].

Hua at al. [13] suggest that the effect of the finishing process on the subsurface residual stress profile is related to the cutting-edge geometry.

2 REZULTATI VREDNOTENJA STABILNOSTI

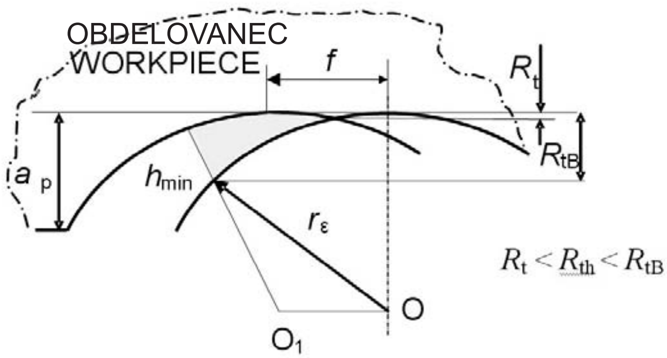
2.1 Vpliv globine odrezovanja na stabilnost postopka

Za vrednotenje spreminjanja globine odrezovanja je bil izdelan model orodje/obdelovanec (sl. 4) in določeno spreminjanje globine $a_{min}<a<a_{max}$ glede na valovitost obdelane površine iz prejšnjega vrtljaja (obdelane površine) ($p \geq 0$). S slike 5 je

2 RESULTS OF THE STABILITY EVALUATION

2.1 Importance of the DOC value for cutting stability

To check the DOC variation, a tool/workpiece model interface was made (valley shown in Fig.4), and the DOC $a_{min}<a<a_{max}$ computed in a different valley position according to previous tool passes and different displacement values ($p \geq 0$). Fig 5 shows that



Sl. 3. *Hrapavost površine skladno z Brammertzem*
Fig. 3 *Surface roughness in accordance with Brammertz*

razvidno, da je spreminjanje globine odrezovanja okoli 60%, medtem ko je ta vrednost pri struženju mehkega materiala okoli 10%. 60 odstotkov pomeni, da je spreminjanje globine odrezovanja pri nastavljeni globini 0,3 mm, približno ± 0,1 mm.

Spreminjanje globine odrezovanja pri struženju v trdo je lahko zmanjšano za 25 do 30% z večjim polmerom konice rezalnega orodja in zmanjšanim podajanjem. Poveča pa se z od nič različno vrednostjo parametra p za 10 do 15%.

Na račun spreminjanja geometrijske oblike po poti rezalnega orodja izraz za površino odrezka pri struženju [14] vsebuje tudi nelinearno funkcijo globine odrezovanja in podajanja v časovni odvisnosti. Natančni popis dinamike spreminjanja površine odrezka lahko glede na različne vrednosti globine odrezovanja v prejšnjem in trenutnem obratu, podajanju v prečni in vzdolžni smeri, polmera konice rezalnega orodja in nastavnega kota orodja, privede do različnih dinamik. To spreminjanje globine odrezovanja posredno vpliva tudi na silo odrezovanja. Na sliki 6, je prikazan potek odrivne sile F_p, ki se izkaže za najbolj občutljivo za spreminjanje globine odrezovanja. S slike 7a, je razvidno spreminjanje odrivne sile za več ko 70 odstotkov. Ta vrednost je zelo blizu predhodni napovedi (60-odstotno spreminjanje globine odrezovanja) in potrjuje predpostavljeno dinamiko globine odrezovanja.

Odrivna komponenta sile odrezovanja F_p (sl. 7b) v frekvenčnem prostoru (dobljenega iz časovnega poteka sl. 6) prikazuje izrazite amplitude frekvenčnega spektra v območju pod 2 kHz (spremljano je bilo območje do 40 kHz) in veliko amplitudo moči pri frekvenci, ki je frekvenca prečkanja orodja doline/vrha na površini obdelovanca iz prejšnjega vrtljaja.

Pri merjenju pospeškov (merjenih v enaki smeri kakor deluje odrivna sila) se frekvence izrazitih amplitud v frekvenčnem spektru signala pomaknejo v višje

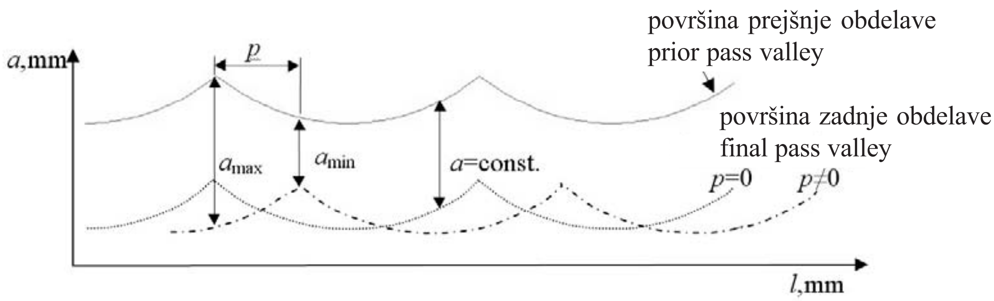
the variation in the DOC is in the range of 60%, while in soft-steel turning this value is about 10%. With a settled DOC of 0.3 mm, this 60% means roughly ± 0.1 mm.

The DOC variation during hard turning could be slightly lower, 25 to 30% (for a higher nose radius of a prior tool pass, and for a smaller feed rate), and slightly higher, 10 to 15% (for valley-displacement values, marked with $p \geq 0$ in Fig.4).

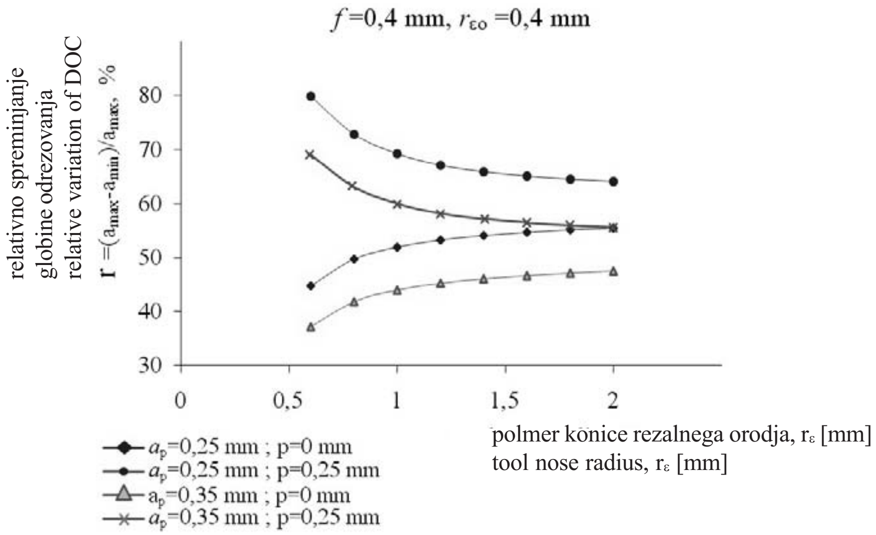
Due to the geometrical variations along the tool path, the chip-area expressions during turning [14] include non-linear functions of the depth of cut and the feed rate vs. time. Determining the dynamic chip-area variations with the exact expressions involves several cases, depending upon the values of the depth of cut in the current and previous tool positions, the feed rates along the axial and radial directions, the tool-nose radius, and the tool lead angle. This DOC variation can also be recorded using a force measurement. Tests were performed on steel for work at high temperatures, 40 CrMnMo7. The specimen was heat treated with hardening at 880°C (100 min) and tempered at a temperature of 440°C. The test sample was a bar with a diameter of 200 mm and a length of 60 mm. The average hardness of the test specimen was 45–47 HRC. As shown in Fig. 6, the passive force, F_p, is the most sensitive to DOC variation and as a result the F_p force variation over 70% can be established (Figure 7a). This value is close to the previous consideration (a 60% variation of the DOC) and confirms the assumed facts about the dynamic behavior of the depth of cutting.

The force-signal data of the F_p component (Fig 7b) in the frequency domain (derived from time-signal data shown in Fig. 6) shows peaks only in the range below 2 kHz (the observed range was up to 40 kHz), and a high power peak at the frequency that corresponds to the frequency when the tool is passing over the valley peaks of the previous pass.

On the accelerometer signal (the sensor was oriented in the same direction as the passive force)



Sl. 4. *Parametri postavitve modela orodje/obdelovanec in izračun globine odrezovanja*
Fig. 4 *Parameters for tool/workpiece interface modelling and DOC computing*



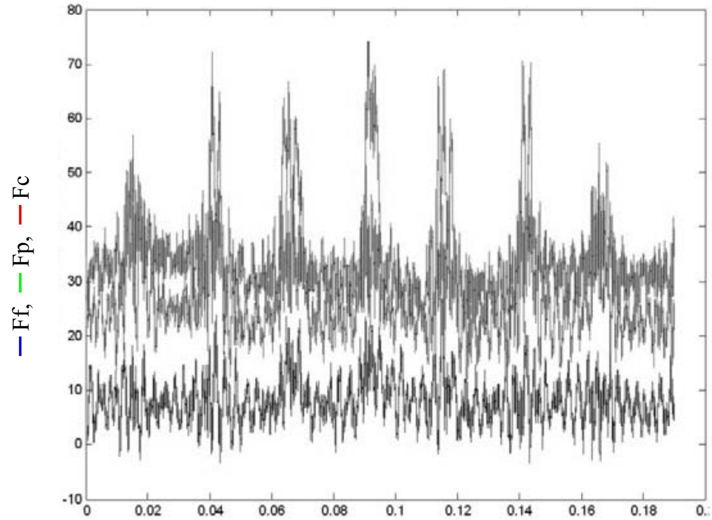
Sl. 5. *Spreminjanje globine odrezovanja pri struženju v trdo*
Fig. 5 *Variation of the DOC during hard turning*

frekvenčno območje, 5 do 45 kHz, z ne prav izrazitima amplitudnima vrhovoma pri frekvencah 17 in 31 kHz. Ta premik frekvenčnega območja je močno povezan z rezalno hitrostjo, nastajanjem odrezka in lomom odrezka [15].

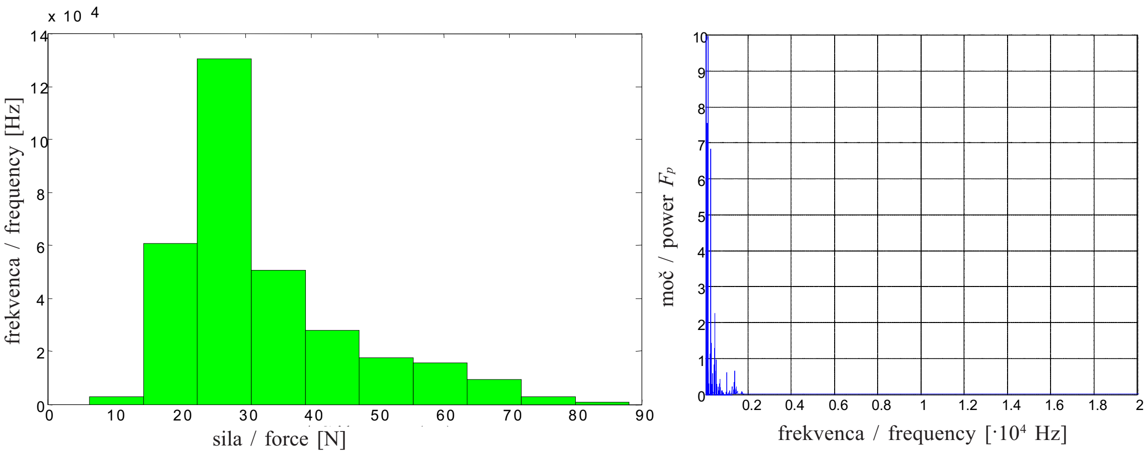
Na sliki 8 sta prikazana frekvenčna spektra signala odrivne sile Fp in pospeškov v tej smeri. Razvidne so izrazite amplitude pri nekaterih frekvencah. Frekvenca prve amplitude se ujema z lastno frekvenco obdelovanca. Tako ima ta vrednost velik vpliv na dinamiko obnašanja obdelovalnega postopka.

the frequency peaks are spread over the range 5 to 45 kHz (with not so high dominant peaks at 17 and 31 kHz). This spread is influenced by the cutting speed as well as the chip form and segmentation [15].

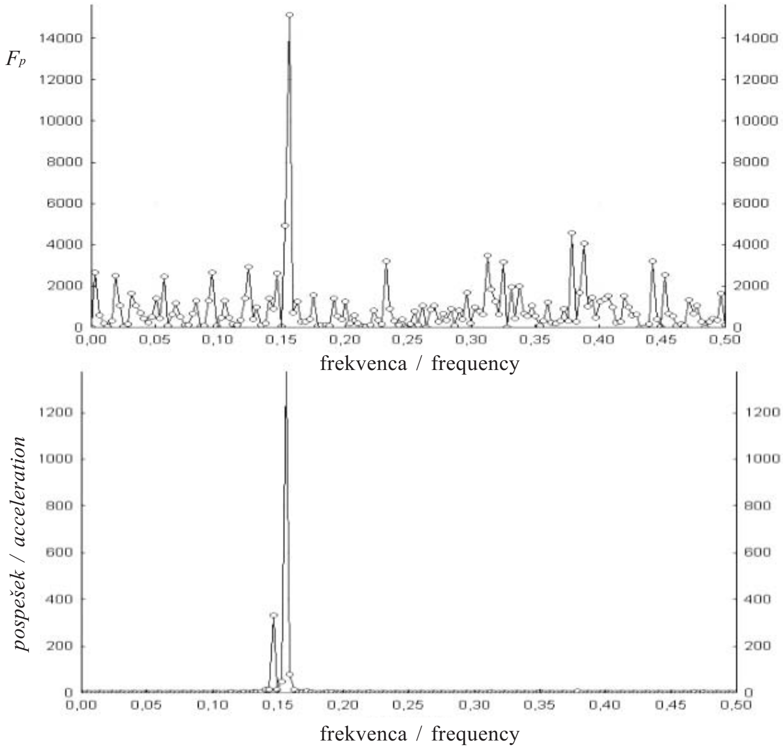
Fig. 8. shows the cutting data signals from the force sensors and accelerometers with prominent peaks at certain frequencies. The first peak correlates with the natural frequencies of the workpiece, and this value has a dominant effect on the dynamic behavior during machining.



Sl. 6. *Signal odrezovalne sile (časovno območje). Pogoji: material 40 CrMnMo7; orodje CBN25 CNMA 120412TN3; suho;* v_c*=500 m/min,* r_c*=1,2 mm,* a_p*=0,2 mm/rev,* f_{old}*=0,2 mm*
Fig. 6 *Cutting-force signal (time domain). Conditions: Material 40 CrMnMo7; Tool CBN25 CNMA 120412TN3; dry;* v_c*=500 m/min,* r_c*=1.2 mm,* a_p*=0.2 mm/rev,* f_{old}*=0.2 mm.*



Sl. 7. *Analiza komponente rezalne sile F_p(levo- histogram; desno: frekvenčni spekter)*
Fig. 7. *Force component F_p data analysis (left- histogram view; right: frequency domain)*



Sl. 8. *Signala odrivne sile in pospeška po HFT transformaciji (frekvenca v kHz)*
Fig.8. *Signals from accelerometers and force sensors after FFT (frequency in kHz)*

2.2 Merjenje dinamičnih parametrov sistema

Povečanje stabilnosti postopka je mogoče doseči z ustreznim razumevanjem odvisnosti med dinamičnimi lastnostmi obdelovalnega stroja, orodja in obdelovanca. Vse te značilnosti sklopa je mogoče določiti pred obdelovanjem. Poleg tega so običajno periodične in jih lahko statistično ovrednotimo in

2.2 Results of the dynamic parameter measurements

Enhancement of the turning-process stability is achievable with appropriate understanding of the interactions between the dynamic characteristics of the machine tool, the tool material and the workpiece material. The dynamic behavior of the machine-tool components can be determined before the cutting process starts določimo na podlagi spremljanja postopka (nihanja, pomiki itn.). Analize so lahko izvedene z različno natančnostjo in različnimi spremenljivkami, ki jih spremljamo [16].

V raziskavi so bile uporabljene različne metode za določitev stabilnosti/nestabilnosti postopka z analizo izmerjenih signalov (HFT) in opazovanjem kakovosti obdelane površine (hrapavost). Za analiziranje obnašanja postopka so bile merjene sile in pospeški.

Za razpoznavo pojava, ki je vzrok izraziti nepravilnosti na obdelovancu, so bile izvedene meritve dinamičnih parametrov obdelovalnega sistema pri vzbujanju z udarnim kladivom. Tipični signal, zajet pri udarnem vzbujanju je prikazan na sliki 9a. Ena od metod za določitev koeficienta dušenja ξ je določitev koeficienta neposredno iz hitrosti zmanjševanja amplitude po številu vrhov n in je prikazana na sliki 9b z upoštevanjem razmerja:

(idle runs of machines) and mostly have a cyclic nature that can be statistically analyzed using appropriate data acquisition (vibration, displacement, etc.). The analysis can be performed with different levels of measuring precision and parameters to be controlled [16].

Various methods have been used to decide upon the process stability/instability, including signal analysis (fast Fourier transforms - FFT), and observation of the workpiece's surface finish. Force and accelerometer data were analyzed in our tests. As parts of the machining system: the workpiece, tool, headstock, slideways, compound rest saddle, and carriage were analyzed.

To be able to identify the phenomenon that causes an emphasized irregularity on the workpiece, measurements of the dynamic parameters of the machining system were performed by impact hammer testing. A typical signal form obtained after the hammer test is shown in Fig. 9a. An approximation of the damping percentage ξ is directly given by the decrease of n consecutive maxima, as shown in Figure 9b:

$$\xi = \frac{1}{2 \cdot n \cdot \pi} \cdot \ln\left(\frac{X_1}{X_n}\right) \tag{4}$$

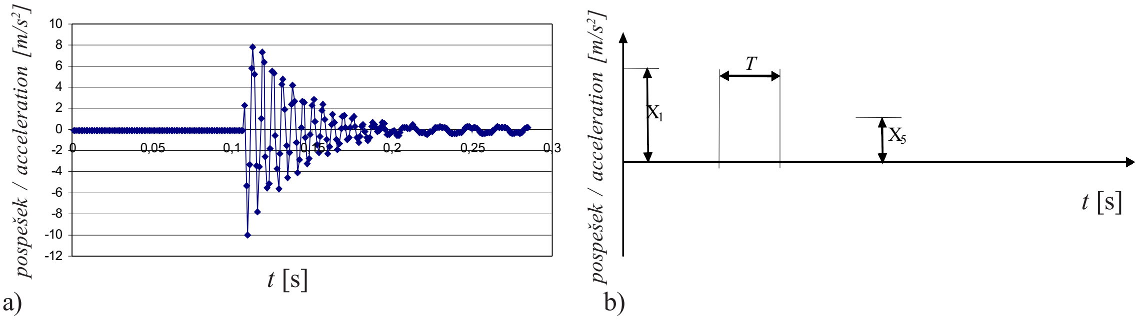
Iz periode prostega nihanja je moč določiti lastno frekvenco dušenega nihanja ω_d sistema, $\omega_d = 2\pi/T$. Iz te pa lahko določimo lastno frekvenco nedušenega nihanja na podlagi razmerja:

The period T of the free oscillations allows one to determine the damped self-frequency ω_d of the structure $\omega_d = 2\pi/T$. The natural self-frequency was then computed using:

$$w_s = \frac{w_d}{\sqrt{1-\xi^2}} \tag{5}$$

Zaznavanje dinamičnih parametrov (lastnih frekvenc in dušenja) je bilo izvedeno z uporabo merilnika pospeškov Hottinger in Baldwin Messtechnik model B12. Uporabljeni ojačevalnik signala je bil HBM CWS-3082A, A/D pretvornik pa PCI120428-3A. Preizkusi so bili izvedeni na obdelovancu - okrogli konzoli s premerom 40 mm. Celotna razdalja med konjičkom in stružilno glavo je bila 765 mm. Nepravilnost v geometrijski obliki

The sensing of the dynamic parameters (natural frequencies and damping) was made by using a Hottinger and Baldwin Messtechnik model B12 accelerometer. The signal amplifier was an HBM CWS-3082A, and a PCI20428-3A was used as the A/D converter. Tests were applied on a bar-shaped workpiece with a diameter of 40 mm. The total distance from the tailstock to the headstock was 765 mm, and shape irregularities on the machined surface



Sl. 9. *Rezultati vzbujanja z udarnim kladivom; a) vhodni podatki, b) značilni parametri*
Fig. 9. *Impact hammer testing results; a) input data, b) characteristic parameters*

Preglednica 2. *Lastne frekvence komponent stružnice*
Table 2. *Natural frequencies of the lathe components*

Del Object	Frekvenca Frequency Hz	Dušenje Damping
glava/ chuck	315	0,065
konjiček/ tailstock	277	0,064
bočna vodila/ slideways	163	0,187
sedlo/ saddle	226	0,132
vodila glave/ headstock	326	0,0708

obdelovanca in obdelani površini so bile zaznane na razdalji 190 mm od stružilne glave, kjer je dobro razviden pojav drdranja.

Vsi zbrani podatki so bili analizirani s programskim paketom MATLAB. Rezultati so predstavljeni v preglednici 2. Ko je rezalno orodje v stiku z obdelovancem na točno določenem mestu in se lastne frekvence vodil in obdelovanca ujemajo, pride do pojava resonance. To specifično področje pojave resonance se točno ujema z mestom pojave nepravilnosti geometrijske oblike na obdelani površini.

Zelo izrazite amplitude zajetih signalov v frekvenčnem spektru blizu lastnih frekvenc sistema so bile zaznane tudi v delu [19], čeprav je tam resonanca obravnavana le s spreminjanjem frekvence vrtenja obdelovanca.

Do podobnih rezultatov lastnih frekvenc in resonančnih področij je prišel tudi Khanfir [18]. Za vrednotenje preizkusnih rezultatov je bil izveden numerični preračun z metodo končnih elementov, s programskim paketom ANSYS, kakor v primeru [19]. Obdelovanec je bil obravnavan kot konzolni nosilnik, rezalno orodje pa je bilo predstavljeno kot sklop elementov, ki vključujejo togosti in dušenje [20]. Obe podpori sta bili predpostavljeni kot togi v prvem delu analize. V drugem pa je stružilna glava predpostavljena kot elastična podpora z veliko togostjo za zmožnost upoštevanja zračnosti v glavi. Na podlagi izračunane togosti rezalnega orodja so bile določene lastne frekvence pri različnih legah orodja glede na stik z obdelovancem. Ti rezultati in rezultati obdelovanca, ko ta ni v stiku z orodjem, so prikazani v preglednici 3. Lastne frekvence v primeru, ko je obravnavana ena elastična podpora z upoštevanim stikom obdelovanec - orodje (osenčeni del v pregl. 3) se ujemajo s

were detected at a distance of 190 mm from the chuck – chattering was clearly audible.

Raw real-time measured data acquired from the accelerometers were analyzed with MATLAB software (the results are shown in Table 2). If the cutting tool is in contact with the workpiece at a specific place, and the natural frequencies of the slideways and the workpiece are the same, resonance appears. That specific place of resonance is in the same place where the emphasized irregularities are observed after machining.

Very large amplitudes of signals in the frequency domain, close to the natural frequency of the dominant mode were also derived in [17], while this resonance is linked only with the frequency of revolution.

Similar findings for the natural-frequency data and resonance were pointed out by Khanfir at al. [18]. In order to validate the experimental results, a finite-element analysis was performed, and as in [19], ANSYS software was used. The workpiece was modeled as a beam element, and the cutting tool was represented with combined elements that include spring rigidity and damping [20]. Both supports are considered rigid in the first analysis, while in the second analysis the chuck was considered as an elastic support with high rigidity, to be able to predict the backlash in the chuck. Using the calculated rigidity of the cutting tool, the results of the natural frequencies for different locations of cutting tool in contact with the workpiece were obtained. These results and the results for the workpiece without any contact with the cutting tool are shown in Table 3. The natural-frequency data for one elastic support, including contact with the cutting tool, corresponds (shadowed cell in Table 3) with frequency

Preglednica 3. *Analitično določene lastne frekvence obdelovanca z metodo končnih elementov*
Table 3. *Natural frequencies of the workpiece obtained by finite-element analysis*

	Toga podpora brez stika z orodjem/ Rigid supports, without contact	Ena podpora elastična brez stika/ One elastic support, without contact	Ena podpora elastična s stikom/ One elastic support, in contact
1. lastna frekvenca/ natural frequency [Hz]	30,6	29,5	30,8
2. lastna frekvenca/ natural frequency [Hz]	185,8	149,5	165,8
3. lastna frekvenca/ natural frequency [Hz]	327	224,4	224,4
4. lastna frekvenca/ natural frequency [Hz]	652	439,7	445
5. lastna frekvenca/ natural frequency [Hz]	977	726,1	728,4

frekvencami izrazitih amplitud v frekvenčnem spektru na sliki 8. Katerim lastnim oblikam rezalnega orodja pripadajo lastne frekvence, pa obravnava Mahdavinejad [21].

2.3 Vpliv polmera konice rezalnega orodja na stabilnost odrezovalnega postopka

Kakor je omenjeno, ima polmer konice rezalnega orodja velik vpliv na spreminjanje globine odrezovanja (GO) in na dejanski nastavni kot, kar privede do nestabilnosti postopka. Zato je treba določiti vpliv polmera konice rezalnega orodja na dinamiko odrezovanja v frekvenčnem prostoru.

Preizkusi so bili izvedeni pri struženju žarjenega jekla (Č1431 HRN C.B9.021 ali Ck 35 DIN ali C35E EN WNr1.118; trdota HRC=50 ± 2) z rezalnim orodjem (CBN, geometrijska oblika CNMA 1204 TN3), z merjenjem pospeška rezalnega orodja v smeri x (sl. 10).

Zasnova in razporeditev meritev sta prikazani na sliki 10, iz katere je razvidna smer merjenja pospeška. Ta se ujema s smerjo odrivne sile - smer x. Opaziti je moč tudi, da ima uporabljena stružnica z RŠK (Mori Seiki SL-153) razmeroma veliko revolversko glavo, kjer je vpeto držalo z merilnikom pospeškov na eni in rezalno orodje na drugi strani.

Kakor je prikazano na sliki 10 je bila dejanska dolžina obdelovanja obdelovanca pri preizkusih 350 mm. Ta dolžina je bila razdeljena na več področij v enakih obdelovanih razmerah (enakih parametrih odrezovanja). Za vsako od področij je bilo zbranih po deset signalov

periodogram peaks shown in Fig. 8. Mahdavinejad in [21] reports which natural-frequency mode is related to a certain machine-tool structure component.

2.3 Correlation with the obtained results of the tool-nose radius' influence on the cutting stability

The tool-nose radius has, as mentioned above, a strong influence on the DOC variation, and on the lead angle, which suggests cutting instability. It seems reasonable to verify the influence of the nose radius on the cutting dynamic in the frequency domain.

The evaluation was made by turning some heat-treatable steel (Č1431 HRN C.B9.021 or Ck 35 DIN or C35E EN WNr1.118; hardness HRC=50 ± 2) with cutting inserts (CBN, geometry CNMA 1204 TN3), while the acceleration of the tool holder in the x-axis was measured.

The concept and arrangement of the measurements is shown in Fig.10. One can see from Fig. 10 that the direction of the accelerometer sensitivity coincides with the direction of the passive force in the x-axis. It is also evident that the applied CNC lathe (Mori Seiki SL-153) has a relatively large revolver head, where our experimental tool holder with an accelerometer at one end and with a cutting insert (geometry CNMA 1204 TN3) at the other end was fixed.

As shown in Fig. 10, the useful length of a test workpiece (heat-treatable steel Ck35 E) was slightly less than 350 millimeters. This length was divided into several sections, and for each two neighboring sections the machining was performed under the same conditions (the same cutting parameters). For each section 10 single pospeškov v smeri x. Signali so bili povprečeni in preoblikovani v frekvenčni prostor. Tako so predstavljeni rezultati povprečni frekvenčni spektri, dobljeni z diskretno hitro Fourierjevo transformacijo (HFT). Frekvenca vzorčenja postopka je bila 100 kHz ob 8192 diskretizacijskih točkah. Na podlagi razmerja frekvence vzorčenja, števila diskretizacijskih točk in periode zbiranja signala, je ločljivost časovne periode 0,08192 s. To pomeni frekvenčno ločljivost povprečnega frekvenčnega spektra 12.207 Hz.

Slika 11 prikazuje vpliv polmera konice rezalnega orodja (r_ε) na merjene pospeške v smeri *x*. V splošnem manjši ko je polmer r_ε, večje so amplitude pospeška. Tudi iz analize je razvidno, da je amplituda pospeškov v frekvenčnem prostoru pri frekvenci 4 kHz obratno sorazmerna s polmerom r_ε. Na podlagi tega je moč sklepati, da je amplituda pospeška pri frekvenci 4 kHz ustrezna cenilka polmera rezalnega orodja. Poleg amplitude pri 4 kHz je izrazita tudi amplituda pri 10 kHz (sl. 11). Vendar pa se ta amplituda povečuje z večanjem polmera rezalnega orodja. To pa je v nasprotju s prvo določeno cenilko. Tako je moč upravičeno sklepati, da ima le prvi resonančni vrh v frekvenčnem prostoru smiselno fizikalno ozadje: manjši polmer konice vodi do večje nestabilnosti držala orodja (nihanj z večjimi amplitudami) pri tej frekvenci v primerjavi z večjim polmerom konice orodja.

signals for acceleration in the x-axis were recorded, and after that transformed and averaged in the frequency domain. Thus, the presented results are the average spectra of 10 single spectra, obtained with a discrete FFT. The sampling frequency during the signal recording was 100 kHz and number of discrete points was 8192. According to the relations between the sampling frequency, the number of discrete points and the time of recording, the latter was 0.08192 s. This means that the frequency resolution of the average frequency spectra was approximately 12.207 Hz.

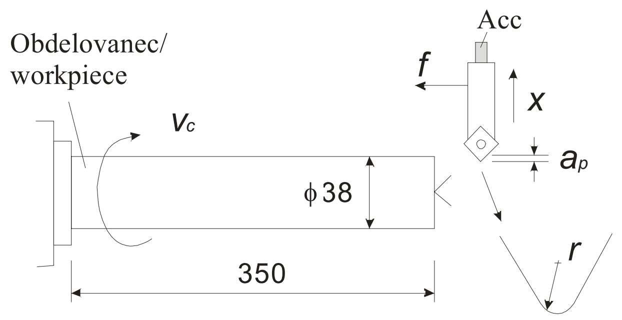
Fig. 11 shows the effect of the nose radius (r_ε) on the accelerometer's data signal. One can see that a smaller r_ε means higher amplitudes, in general. The analysis of the effect of the nose radius shows that the amplitude peak at 4 kHz is inversely proportional to the nose radius r_ε. Therefore, one can conclude that the amplitude peak at 4 kHz is a reliable criterion for the identification of the cutting-nose radius. From Fig. 11 one can see that there is an additional prominent peak at 10 kHz; however, its amplitude is higher for a larger nose radius, which is not in agreement with the conclusions from the first amplitude peak (see above). Therefore, it is reasonable to conclude that only the first resonant peak has a physically logical meaning: a smaller nose radius results in a reduced tool-holder stability (stronger vibrations) at this frequency in comparison to a larger nose radius.

3 SKLEP

Splošne ugotovitve oziroma sklepi analize odrezovanja v trdo (struženja) so:
- Analitično dobljen delež spreminjanja globine odrezovanja - GO je bil 60%. Določen je bil na

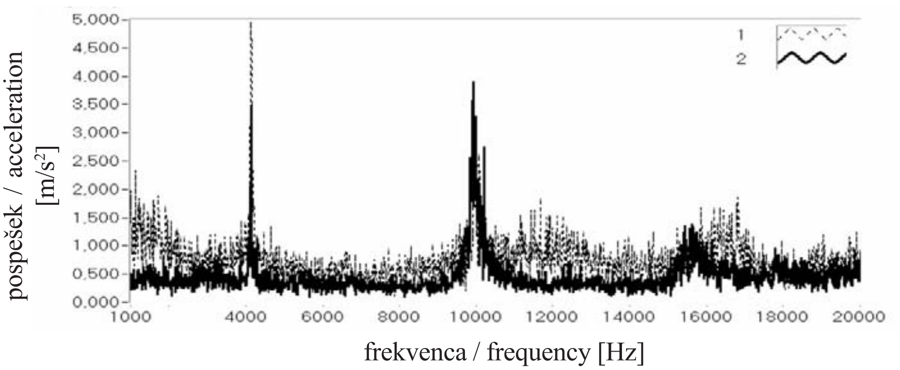
3 CONCLUSION

The general results provided during the hard-turning stability evaluation are:
- it was found that the DOC variation was 60%, with the tool/workpiece interface modeling, and



Sl. 10. *Testiranje vplivnosti polmera rezilnega orodja (f-podajanje, v_c-rezalna hitrost, r-polmer rezalnega orodja, Acc-merilnik pospeškov)*

Fig. 10. *Setup for testing the significance of the nose radius (f-feed rate, v_c-cutting speed, r-insert radius, Acc-accelerometer)*



Sl. 11. *Vpliv polmera rezalnega robu orodja na pospeške v smeri x, v_c = 450 m/min, a_p =0,2 mm, f =0,2 mm/vrt (1- r_ε =0,4 mm, 2 – r_ε =1,2 mm)*

Fig. 11. *The influence of tool-nose radius on the acceleration data, v_c = 450 m/min, a_p =0.2 mm, f =0.2 mm/rev (1- r_ε =0.4 mm, 2 – r_ε =1.2 mm)*

podlagi modeliranja stika orodje - obdelovanec. Analitično modeliranje je bilo potrjeno z meritvami odrivne komponente sile odrezovanja. Izmerjeni delež spreminjanja sile je bil rahlo večji 70%, zaradi tako imenovanega učinka odrivanja.

- Lastne frekvence posameznih delov stružnice so bile določene na različnih mestih obdelane površine kakor tudi različnih resonančnih področjih.
- Te resonančne frekvence in lege resonančnih območij so potrjene z analizo MKE (metodo končnih elementov), pri katerih je bil obdelovanec modeliran kot nosilnik, medtem ko je bilo orodje modelirano kot sklop elementov togosti in dušenja.
- Analitično določene lastne frekvence obdelovanca, določene z metodo končnih elementov se zelo dobro ujemajo. V primeru predpostavke elastičnega vpetja obdelovanca glavo z visoko togostjo in upoštevanjem stika med obdelovancem in orodjem, je odstopanje približno en odstotek.
- Izrazite amplitude odrivne komponente rezalne sile v frekvenčnem prostoru se pojavljajo le v področju pod 2 kHz (merjeno do 40 kHz). Največja moč spektra je bila določena pri frekvenci, ki se ujema s frekvenco prečkanja orodja doline ali vrha obdelane površine iz prejšnje obdelave.
- Vpliv polmera konice rezalnega robu orodja (r_ε) na pospeške orodja je lahko posplošen, npr.: manjši ko je polmer konice rezalnega robu, r_ε večje so amplitude pospeška.
- Pod obravnavanimi pogoji je amplituda pospeškov v frekvenčnem spektru pri frekvenci 4 kHz ugodna cenilka vplivanja rezalnega robu orodja. Velikost amplitude pri tej frekvenci je v obratnem razmerju s polmerom konice rezalnega robu r_ε.

confirmed with the passive force measurement, where variation is slightly higher (70%), probably because of the influence of the “push off” effect,

- the natural frequencies of the lathe components are determined at different locations in the work area and the resonant frequency as well,
- this resonance frequency and the location of the resonance was confirmed by a FEM analysis, where the workpiece was modeled as a beam element, and the cutting tool was represented by combined elements that include spring rigidity and damping,
- the natural frequencies of the workpiece obtained with the finite-element analysis match well (1% difference) with the experimental data if the chuck is considered as an elastic support with high rigidity and the tool is in contact,
- significant passive-force component (F_p) peaks in the frequency domain are only in the range below 2 kHz (the observed range was up to 40 kHz), and the high-power peak is estimated at the frequency which corresponds to the frequency when the tool is passing over the valley peaks of the previous pass,
- the effect of nose radius (r_ε) on the accelerometer data signal can be generalized by the conclusion in which the smaller r_ε means higher amplitudes,
- under the given circumstances the amplitude peak at 4 kHz is a reliable criterion for the identification of the cutting-nose radius influence, and the acceleration amplitude at this frequency was inversely proportional to the tool-nose radius r_ε,

- Skleniti je moč, da je možnost izboljšati storilnost z določitvijo primernih odrezovalnih pogojev in geometrijsko obliko orodja in/ali spreminjanjem hitrosti odrezovanja.

- the findings can be applied to increase productivity by guiding the correct choice of cutting conditions and tooling geometry, and/or by regulating the spindle speed.

4 LITERATURA
4 REFERENCES

[1] T. L. Schmitz (2003) Chatter recognition by a statistical evaluation of the synchronously sampled audio signal, *Journal of Sound and Vibration*, Vol. 262, Issue 3(2003), 721-730

[2] O. B. Ozdoganlar, and W.J. Endres (1998) An analytical stability solution for the turning process with depth-direction dynamics and corner-radiused tooling, *Symp. on Advances in Modeling, Monitoring, and Control of Machining Systems*, Vol. DCS-64, 511-518.

[3] T. Moriwaki, and K. Iwata (1976) In-process analysis of machine tool structure dynamics and prediction of machining chatter, *ASME J. Eng. Ind.*, 98, (1976) 301-305.

[4] S.A. Jensen, and Y.C. Shin (1999) Stability analysis in face milling operations, Part 1: Theory of stability lobe predictions, *ASME J. Manuf. Sci. Eng.*, 121(4) (1999), 600-605.

[5] O.B. Ozdoganlar (1999) Stability of single and parallel process machining including geometry of corner-radiused tooling, PhD thesis, *University of Michigan*.

[6] R. Pavel, I. Marinescu, M. Deis, J. Pillar (2005) Effect of tool wear on surface finish for a case of continuous and interrupted hard turning, *Journal of Materials Processing Technology*, 170 (2005), 341-349.

[7] M. Pogačnik, J. Kopač (2000) Dynamic stabilization of the turn-milling process by parameter optimization, *Proc Instn Mech Engrs*, Vol 214 Part B, ImechE, 127-135.

[8] H. Schulz, A. Stoić, A. Sahm (2001) Improvement of cutting process in accordance with process disturbances, *7th International conference on production engineering CIM2001*, HUPS Zagreb, I123-I131.

[9] J.L. Andreasen, L.De Chifre (1993) Automatic chip-breaking detection in turning by frequency analysis of cutting force, *Annals of CIRP*, Vol 42/1/1993 (1993) 45-48.

[10] X. Li (2001) Real-time prediction of workpiece errors for a CNC turning centre, Part 3: Cutting force estimation using current sensors, *International Journal of Advanced Manufacturing Technology*, 17 (2001) 659-664.

[11] P. Brammertz (1961) Die Entstehung der Oberflächenrauheit beim Feindrehen, *Industrie-Anzeiger*, 83/2, (1961), 25-32.

[12] N.K. Chandiramani, T. Pothala (2006) Dynamics of 2-dof regenerative chatter during turning, *Journal of Sound and Vibration*, 290 (2006) 448-464.

[13] J. Hua, D. Umbrello, R. Shivpuri (2006) Investigation of cutting conditions and cutting edge preparations for enhanced compressive subsurface residual stress in the hard turning of bearing steel, *Journal of Materials Processing Technology*, 171 (2006), 180-187.

[14] R.G. Reddy, S.G. Kapoor, and R.E. DeVor (2000) A mechanistic force model for contour turning, *ASME J. Manuf. Sci. Erg.,* 123 (2000) 3.

[15] S. Dolinšek, S. Ekinović, J. Kopač (2004) A contribution to the understanding of chip formation mechanism in high-speed cutting of hardened steel, *Journal of Materials Processing Technology*, 157-158 (2004) 485-490.

[16] Y. Lee; D.A. Dornfeld (1998) Application of open architecture control system in precision machining. *31st CIRP International Seminar on Manufacturing Systems*, Berkeley CA May 1998, 436-441.

[17] J. Kopač, S. Šali (2001) Tool wear monitoring during the turning process, *Journal of Materials Processing Technology*, 113 (2001), 312-316.

[18] H. Khanfir, M. Bonis, P. Revel (2005) Improving waviness in ultra precision turning by optimizing he dynamic behavior of a spindle with magnetic bearings, *International Journal of Machine Tools & Manufacture*, 45 (2005), 841-848.

[19] M. C. Cakir, Y. Isik (2005) Finite element analysis of cutting tools prior to fracture in hard turning operations, *Materials and Design*, 26 (2005), 105-112.
[20] T. Ergić, A. Stoić, P. Konjatić (2005) Dynamic analysis of machine and workpiece instability in turning, *Proceedings of the 4th DAAAM International Conference ATD*C, Slavonski Brod, 497-502.
[21] R. Mahdavinejad (2005) Finite element analysis of machine and workpiece instability in turning, *International Journal of Machine Tools & Manufacture*, 45 (2005), 753-760.
[22] L.A. Dobrzanski, K. Golombek, J. Mikula, D. Pakula (2006) Cutting ability improvement of coated tool materials, *Journal of Achievements in Materials and Manufacturing Engineering*, 17(2006)1-2, 41-44.
[23] J. Krawczyk, J. Pacund (2006) Effect of tool microstructure on the white layer formation, *Journal of Achievements in Materials and Manufacturing Engineering*, 17(2006)1-2, 93-96.

Authors' Addresses: Prof. Dr. Antun Stoić
Mirjana Lucić
Univerza v Osijeku
Fakulteta za strojništvo
Trg Ivane Brlić-Mažuranić 18
35000 Slavonski Brod, Hrvatska
astoic@sfsb.hr
mlucic@sfsb.hr

Prof. Dr. Janez Kopač
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
janez.kopac@fs.uni-lj.si

Authors' Addresses: Prof. Dr. Antun Stoić
Mirjana Lucić
University of Osijek
Faculty of Mechanical Eng.
Trg Ivane Brlić-Mažuranić 18
35000 Slavonski Brod, Croatia
astoic@sfsb.hr
mlucic@sfsb.hr

Prof. Dr. Janez Kopač
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
1000 Ljubljana, Slovenia
janez.kopac@fs.uni-lj.si

Prejeto:
Received: 24.7.2006

Sprejeto:
Accepted: 25.10.2006

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

Strojniški vestnik - Journal of Mechanical Engineering 52(2006)11, 738-751
UDK - UDC 621.753.5.001.41:621.74.043
Pregledni znanstveni članek - Preview scientific paper (1.02)

Lasersko sintranje orodja za tlačno litje aluminija

Laser-Sintered Tools for the Die-casting of Aluminum

Slavko Dolinšek[1] - Peter Panjan[2] - Tatu Syvanen[3] - Jože Ramovš[4]
([1]Fakulteta za strojništvo, Ljubljana; [2]Inštitut Jožef Stefan, Ljubljana; [3]EOS Finland Oy;
[4]TCG Unitech Lth-ol d.o.o, Škofja Loka)

V prispevku so prikazani rezultati uporabe neposrednega laserskega sintranja kovinskih prahov (NLSK) kot postopka hitre izdelave orodij za tlačno litje aluminija. Za izvedbo raziskave smo izbrali za izdelek navijalnik varnostnega pasu (uporaba v avtomobilski industriji). Skladno z zahtevami glede izdelave prototipnih orodij smo sedanjo konstrukcijo običajnega orodja ustrezno prilagodili in naredili nekatere izboljšave materiala za sintranje kakor tudi postopka sintranja. Primerjalna vrednostna analiza med običajno izdelavo orodij in NLSK je pokazala, da je z NLSK čas izdelave dosti krajši. Končne raziskave so bile usmerjene v industrijsko testiranje orodja izdelanega z NLSK in analizo njegove obstojnosti za potrditev postavljenega raziskovalnega cilja, tj. izdelati 5.000 praktičnih izdelkov v industrijskem okolju.

(Ključne besede: izdelava orodij hitra, sintranje lasersko, litje aluminija, litje tlačno)

In this paper some results from using a DMLS (direct metal laser sintering) rapid-tooling solution for aluminum die-casting are presented. The product chosen for the investigation was a car safety-belt strap winder (an application for the automotive industry), and according to the requirements of the prototype tools, we have adapted the construction of the classic tools and made some improvements to the material and the sintering process. The comparative-value analysis with classical tooling has shown that the time of production with the DMLS process is considerably shorter. The final investigation was focused on the industrial testing of the DMLS, followed by the tool analysis after die-casting to confirm the research goal, i.e., 5,000 practical parts produced.

(Keywords: rapid tooling, laser sintering, aluminium castings, pressure die casting)

0 UVOD

Kakor opisuje svoji objavi Gideon [1], so postopki hitre izdelave prototipov v zadnjem desetletju že dosegli široko uporabo, vendar je trg za hitro izdelana orodja (kot ene prvih uporab hitre proizvodnje za neposredno izdelavo orodij za tlačno litje) še vedno zelo omejen. Čeprav so izdelovalci opreme in prahov za sintranje zelo napredovali (na primer EOS ([2] do [4])) in čeprav ni dvoma o tem, da se lahko sintrana orodja brez težav uporablja za brizganje plastičnih izdelkov v serijah preko 100.000 kosov, ni veliko potrditev glede uporabe teh orodij v praksi.

Vendar so potrebe po izdelavi majhnih serij različnih komponent, izdelanih s postopki tlačnega litja, v zadnjem času čedalje večje. Tudi splošne težnje po skrajšanju dobavnih časov in zmanjševanju

0 INTRODUCTION

According to Gideon [1], rapid prototyping has gained very wide acceptance over the past decade, but the market for rapid tooling (as a first application of rapid manufacturing for the direct and fast production of tools for injection molding) remains limited. Even producers of the equipment and the powder materials have made significant progress (e.g., EOS ([2] to [4])), and there is no doubt that tools can be used for series up to 100,000 shots for injection-molding applications, but there are no results to confirm this in practice.

The need for small-series production for die-cast components has arisen during recent years. The general development trend to speed-up tooling times has forced tooling companies to intensify mold stroškov sili orodjarje v večanje učinkovitosti razvoja in izdelave orodij. Zato je zanimanje za nove tehnološke rešitve tudi vse večje. Doslej ni bilo na voljo hitrih in ekonomsko upravičenih postopkov za izdelavo orodij, ki bi jih lahko uporabili za majhne serije tlačno litih izdelkov. Orodja je bilo treba izdelati iz ustrezno trdih orodnih materialov z običajnimi postopki frezanja in elektro erozijsko obdelavo (EDM), saj je tlačno litje veliko bolj zahteven in obremenilen postopek (visoke temperature taline in s tem velike toplotne obremenitve taline na orodja). Kratki časovni krogi in dodatno hitro ohlajanje odlitkov povzroča tudi toplotne razpoke v orodjih, zato je obstojnostne čase teh orodij mogoče napovedovati le približno.

Glede na to orodjarji za izdelavo orodij za tlačno litje aluminija vse bolj zahtevajo hitre in cenovno sprejemljive rešitve, ki jim bodo omogočale hitrejšo povrnitev vlaganj v orodja. Za veliko primerov je že dovolj, da so orodja primerna za litje do 1.000 odlitkov, za tehnične prototipe celo v količini do 100 odlitkov. Vendar je za hitro izdelavo orodij trenutno na voljo le nekaj rešitev, saj se v primeru tlačnega litja aluminija in podobnih barvnih kovin postavljajo skrajne zahteve glede visokih temperatur in tlakov [5]. V povezavi s to problematiko in glede na vpeljavo opreme za NLSK so bile narejene določene temeljne raziskave značilnosti postopka neposrednega laserskega sintranja, pa tudi pregled mogočih uporab te tehnologije v slovenski orodjarski industriji [6].

Preizkusni rezultati so tesno povezani s praktičnimi orodjarskimi uporabami ([7] in [8]); izdelanih je bilo veliko število orodij za potrebe brizganja plastičnih izdelkov, nekaj jih je bilo tudi uporabljenih za izdelavo orodij za tlačno litje zlitin cinka in drugih barvnih kovin. Poleg tega je bilo NLSK uspešno uporabljeno za neposredno izdelavo končnih izdelkov zapletenih oblik (primeri vključujejo zahtevne izdelke za smučarske vezi, plezalno opremo). Raziskave so bile tudi usmerjene v mikro-strukturno in mehansko ovrednotenje izdelkov na osnovi NLSK za določitev ustrezne površinske obdelave in prevlek za izboljšanje toplotnih in obrabnih značilnosti lasersko sintranih izdelkov ([9] in [10]).

V tem prispevku so prikazani nekateri zadnji raziskovalni rezultati in izkušnje, pridobljene z uporabo NLSK za izdelavo orodij za tlačno litje aluminija. V povezavi z dejavnostmi projekta Eureka [11] smo raziskovali: kako oblikovati vložke orodij pri uporabi postopka laserskega sintranja, kakšni so ustrezni prahovi za sintranje, kakšne postopke

manufacturing, and therefore the overall interests for new technological solutions is very high. In the past there were no fast and economical tooling solutions for small-series production in die-casting because the molds had to be made by milling and EDM (Electrical Discharge Machining) in hard steels. Die casting is a much more vigorous process than injection molding, mainly due to the high processing temperatures and the high heat loads of the casting metals. The comparatively short cycle times and the rapid cooling of the cast products induce continuous thermal fatigue in the tooling and so only approximate life times can be predicted for the molds.

For these reasons, the toolmakers for high-pressure die-casting urgently require rapid tooling solutions that will give them a faster return on a tool. For such tools, as few as 1000 castings are required for short-run tooling, and for technical prototypes this figure can be as low as 100 castings. For pressure die-casting applications, only a few rapid-tooling solutions exist due to the high temperatures and pressure loads (see Dolinšek, [5]). Following this problem and in relation to the introduction of DMLS equipment some basic research on the characteristics of the direct metal laser sintering (DMLS) process and the applications of this technology in the Slovenian tool-making industry have been performed [6].

Our experimental results are closely related to practical tool-making applications ([7] and [8]); a number of tools were produced for injection-molding applications, and some of them were used in the production of tools for zinc alloy and aluminum die casting. Additionally, DMLS has been used for the direct production of parts with complicated shapes (examples include demanding sintered parts for ski bindings and equipment for climbers). Research has also been focused on microstructural and morphological analyses of the metal powders and the subsequent chemical, microstructural and mechanical characterizations of DMLS products, with the aim to find the proper surface finishing and coatings to improve the thermal and wear characteristics of the laser-sintered products ([9] and [10]).

In this paper some recent research results and experiences using a DMLS tooling solution for aluminum die-casting are presented. According to the activities within a Eureka project [11] we investigated how to design suitable inserts for the direct laser sintering of metal powders, determine a proper poznejše obdelave in prevleke orodij potrebujemo, kakšni so delovni parametri za tlačno litje aluminija in ali je tržno upravičeno uporabljati NLSK za izdelavo orodij za tlačno litje aluminija.

1 POSTOPEK TLAČNEGA LITJA ALUMINIJA IN UPORABA HITRE IZDELAVE ORODIJ

Tlačno litje aluminija je zelo pomemben postopek pri masovni proizvodnji komponent skoraj končnih izmer in je še vedno glavna usmeritev za izdelavo litih lahkih in obremenjenih komponent v avtomobilski industriji. Postopek je stroškovno sprejemljiv le v primeru litja zadostnih količin izdelkov, saj so zaradi zapletenih oblik in vrhunskih zahtev po ustrezni dobi trajanja potrebna velika investicijska vlaganja v orodja.

Pri tlačnem litju aluminija so temperaturne razlike med litim izdelkom in talino tudi čez 500 °C, temperaturni gradient je še posebej velik v bližini različnih votlin in prehodov. Talina, ki z visokim tlakom (tudi čez 800 bar) vstopa v orodje, povzroča velike mehanske obremenitve oziroma napetosti v orodjih. To pa pomeni, da želimo sintrane vložke uporabljati v najbolj kritičnih delih orodij, kjer so toplotne in mehanske obremenitve največje. Za doseganje uspešnih rezultatov je pri uporabi NLSK vložkov za tlačno litje treba upoštevati nekatere omejitve in opozorila. To se nanaša na praškasti material, na oblikovanje izdelkov in orodij, na sam postopek sintranja ter na končno obdelavo vložkov orodij.

Nekateri začetni preizkusi na področju tlačnega litja so že pokazali, da je mogoče NLSK uporabiti kot zelo primerljiv postopek za izdelavo orodij. V nekaterih primerih lahko NLSK primerjamo z izdelovalnimi rešitvami, pri katerih so uporabljene tehnologije odrezovanja (poročilo EOS [12]). Za manjše količine brizganih izdelkov so cilji običajno naslednji: obstojnost vložkov orodij do 1.000 tlačno litih kosov in sprejemljiva kakovost izdelkov brez pojava razpok (za najbolj uporabljane postopke tlačnega litja, npr. aluminij, magnezij, cink). Pri cinku in magneziju so te zahteve že izpolnjene, pri tlačnem litju aluminija pa obstaja še vedno nekaj težav, ki zahtevajo nadaljnji razvoj postopka NLSK.

Glede na vse te postavljene zahteve smo prve raziskave že opravili. Za testiranje NLSK orodij za tlačno litje aluminija v industrijskem okolju smo oblikovali poseben testni izdelek (material AlSi9Cu3, temperatura taline 690 °C, tlak 780 barov, hitrost taline na vstopu v orodje 50 m/s). Različni sintrani vložki iz DirectSteel 20 so bili ustrezno obdelani in površinsko

powder material, define suitable post-processing and coatings, and also some operating conditions for die casting are proposed with a commercial justification for using DMLS for die casting.

1 THE ALUMINUM DIE-CASTING PROCESS AND RAPID-TOOLING APPLICATIONS

Aluminum die-casting is an important technique for the mass production of near-net-shape components, and is still the major automotive casting route for lightweight components used in stressed areas. The high-pressure die-casting process produces the lowest cost-per-part for the castings but requires the highest level of capital investment due to the complexity and longevity of the tooling.

In die casting the temperature difference between the molten metal and the mold can be over 500ºC, and the temperature gradient is highest in the mold cavity areas. Molten material with a high pressure of up to 800 bars also induces high mechanical stresses in the tool inserts, particularly at the entrance of the mold flow. This means that sintered inserts need to be used in the critical areas, where the most demanding thermal and pressure conditions exist. Therefore, when using DMLS inserts in die-casting tooling applications some precautions related to the powder material, the product and tool design, and the sintering and post-processing methods should be taken to ensure successful results.

Some early experiments in die-casting have already indicated that DMLS can also be used as a highly competitive process and in some cases it can be compared to machining technologies (EOS report [12]). The short-term target in die-casting is as follows: durability up to 1000 parts, acceptable crack-free quality for the main die-casting metals (aluminum, magnesium and zinc). For zinc and magnesium the demands have already been met, but in aluminum casting there are still some problems and further development needs to be done.

According to all known preconditions a special testing part was designed and suitable tooling inserts were prepared according to different post-processing methods for pressure die-casting in an industrial environment (material, $AlSi_9Cu_3$; temperature of the molten material, 690ºC; pressure, 780 bar; speed at the entrance to the mold, 50 m/s), using DirectSteel 20 material. Due to a problem caused zaščiteni. Zaradi pojava poroznosti sintranega materiala in s tem povezane slabe oprijemljivosti prevleke pri tej raziskavi prevleka ni pokazala pričakovanih prednosti [13].

S počasnejšim sintranjem na površini izdelka oblikujemo dodatno staljeni zunanji sloj, s tem se zmanjša poroznost sintranca in izboljšajo površinske značilnosti vložka orodja. Rezultati litja (število kosov) so v tem primeru povsem enaki kakor pri uporabi prevleke. V obeh primerih je bilo brez razpok narejenih več ko 210 kosov, prve vidne razpoke so se pojavile šele po 250 kosih. Obstojnostno merilo vložkov je bilo postavljeno glede na pojav prvih razpok na izdelku, razpoke so se pojavile na najbolj obremenjenih delih orodja (na ovirah pri vstopu taline v orodje zaradi posebne konstrukcije testnega izdelka [14]).

Raziskave so torej potrdile, da je mogoče odliti dovolj kosov, če pri sintranju uporabljamo postopek zunanjega zataljenega sloja in ustrezno prevleko. Zaradi visokih tlakov pri litju aluminija je treba sintrane vložke tudi dodatno pripraviti in obdelati (postopek, ki vključuje udarjanje s keramičnimi kroglicami, poliranje orodja za izboljšanje poroznosti in površinske hrapavosti pod 1 μm ter nanos dodatne prevleke za izboljšanje površinske trdote [15]). Zaradi najnovejšega razvoja prašnih materialov, še posebej pa možnosti uporabe trdih prevlek, so rezultati vse boljši, kar podpira nadaljnji razvoj v smeri obrabnih in temperaturnih izboljšav značilnosti sintranih vložkov orodij [16].

by the porosity of the sintered material and the subsequent poor deposition of the coatings, the coatings did not show great potential for die-casting applications [13].

With the application of the up-skin layer the surface porosities can be reduced and the surface characteristics can be improved; inserts have shown almost the same characteristics as when using coating. There were 210 parts produced without cracks, the first visible cracks appeared after 250 shots. The life criteria of the inserts were set in relation to the first visible cracks on the parts; however, due to the special design of the part with the barriers at the entrance to the mold flow, the cracks actually appeared near those barriers [14].

Observations, therefore, confirmed that more parts can be produced using an up-skin approach and subsequent coatings. Due to the high loads during the casting of the aluminum some necessary machining and post processing after the sintering needed to be done (up-skin technology including shot peening and polishing to improve the porosity and surface roughness below 1 μm and an additional hard coating with different layers to improve the surface hardness) [15]. The recent development of powder materials and particularly the application of hard coatings have, therefore, given good prospects for the further improvement of the wear and temperature resistance of tool inserts for die-casting applications [16].

2 RAZISKOVALNI CILJI IN METODOLOGIJA

Z uporabo novega prahu za sintranje DirectSteel H20, ki od vseh razpoložljivih materialov omogoča največjo trdnost, trdoto, obrabno odpornost in površinsko gostoto, je treba po postopku NLSK izdelati prototipno maloserijsko orodje za tlačno litje aluminijeve zlitine. Postavljeni raziskovalni cilji so:

(1) razvoj NLSK orodij in ustrezne površinske obdelave za tlačno litje aluminija v industrijskem okolju,
(2) dokazati, da lahko z NLSK vložki uspešno izdelamo 5.000 tlačno litih zapletenih izdelkov iz aluminija,
(3) izdelek in/ali geometrična oblika orodja morata biti takšna, da bo mogoče izrabiti vse prednosti NLSK (zahtevna geometrijska oblika in notranje hlajenje orodja).

Ustrezen izdelek za raziskavo in testiranje orodja je bil navijalnik avtomobilskih varnostnih

2 RESEARCH GOALS AND METHODOLOGY

Using the new sintering material DirectSteel H20, which offers the highest strength, hardness, wear resistance and surface density of all available materials, it is necessary to produce prototype small-series tools for the pressure casting of aluminum alloy with the DMLS process. The research goals were defined as follows:

(1) Development of the DMLS tools and a suitable surface treatment for the die casting of aluminum applications in a practical industrial environment,
(2) To prove that sintered DMLS inserts can successfully produce at least 5000 complex parts in aluminum die casting,
(3) The product and/or tool geometry must be such that the advantages of the DMLS process can be utilized (complex geometries and internal cooling channels etc.).

A suitable product for the investigation and the tool-testing was a car's safety-belt strap winder, a pasov, tržni izdelek, kjer se velikokrat zahteva prototipe v količini nekaj tisoč kosov. Izdelek ustreza poglavitni zahtevi, je dovolj zahteven, hkrati pa ne presega izmer, ki jih lahko izdelamo s sintranjem (omejitev stroja).

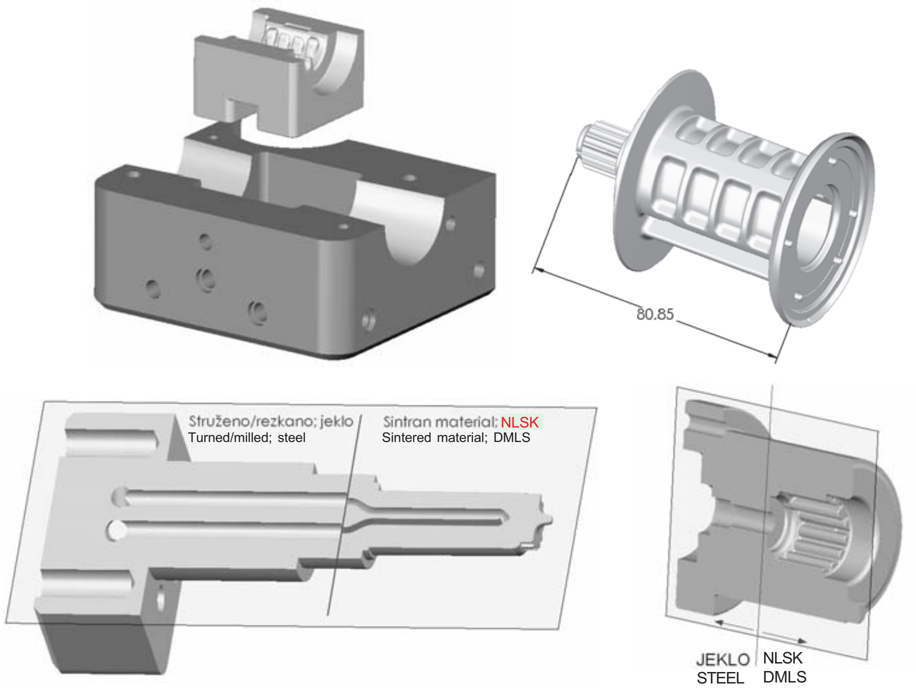
Zaradi specifičnosti NLSK je bilo potrebno konstrukcijo orodja ustrezno prilagoditi. Novo orodje je takšno, da so uporabljeni sintrani vložki orodja tam, kjer so zapletene gravure. S kombinacijo hitrejših in cenejših običajnih postopkov za izdelavo ogrodja orodja smo dosegli optimalno kakovost in ceno (sl. 1). Ogrevni sistem in vsi potrebni priključki so postavljeni na zunanji del orodja. Zaradi modulne zasnove orodja je mogoče oblikovne vložke zamenjavati in z najmanjšim stroškom izdelati orodje, ko se pojavi nov tip izdelka. Dodatno je bilo izdelano tudi notranje hlajenje daljših stranskih jeder (trnov), ta možnost obstaja edino pri uporabi NLSK.

Sestavljeno orodje in njegova notranjost s ogrevnim sistemom je prikazana na sliki 2. Za preprečevanje temperaturnih skokov in posledičnega pokanja gravur vložkov orodja ogrevni kanali niso nameščeni v neposredni bližini gravur. Bistvo ogrevanja je v vzdrževanju ustrezne temperature orodja in ne v lokalnem hlajenju gravur.

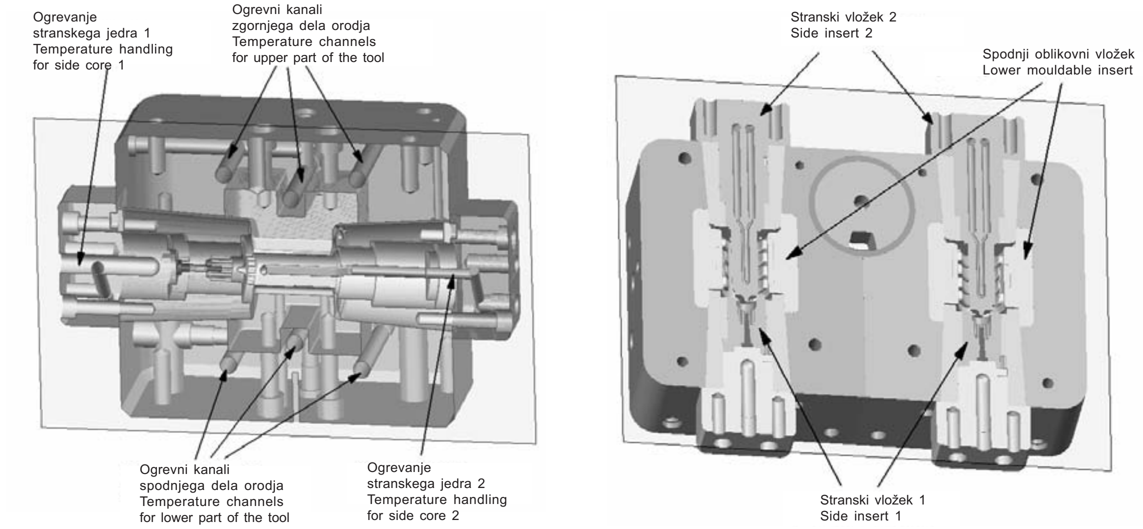
marketable product, where prototypes in a series of up to a few thousand pieces are commonly demanded. The product meets the basic requirement, i.e., it was complex enough, and at the same time its dimensions did not exceed the limits set by the sintering machine.

Due to the specifics of the DMLS procedure the construction of the tools was properly modified. The new construction required sintering only the tool parts with complicated engravings. Therefore, with the combination of faster and cheaper classic cutting processes for making a tool base we ensured the optimal quality and the price of the tool (Fig. 1). The temperature handling system and all the necessary connectors were placed on the exterior part of the tool. Due to the modular design, the approach of using changeable tool inserts resulted in a fast switch to the new type of product with minimum expenses. Additionally, conformal cooling was designed within the long side core (kernel); such an approach is only possible when using the DMLS process.

The assembled tool and the internal view with the temperature handling system are shown in Figure 2. To prevent temperature shocks and consequent cracks, the temperature channels are not placed close to the engravings. The essence of handling temperature is to maintain the proper temperature of the tool rather than local cooling of the engraving.



Sl. 1. *Modularna zgradba orodja: vložek, stranska jedra in izdelek (navijalnik avtomobilskih varnostnih pasov)*
Fig. 1. *Modular tool design: insert, side cores and the product (safety-belt strap winder)*



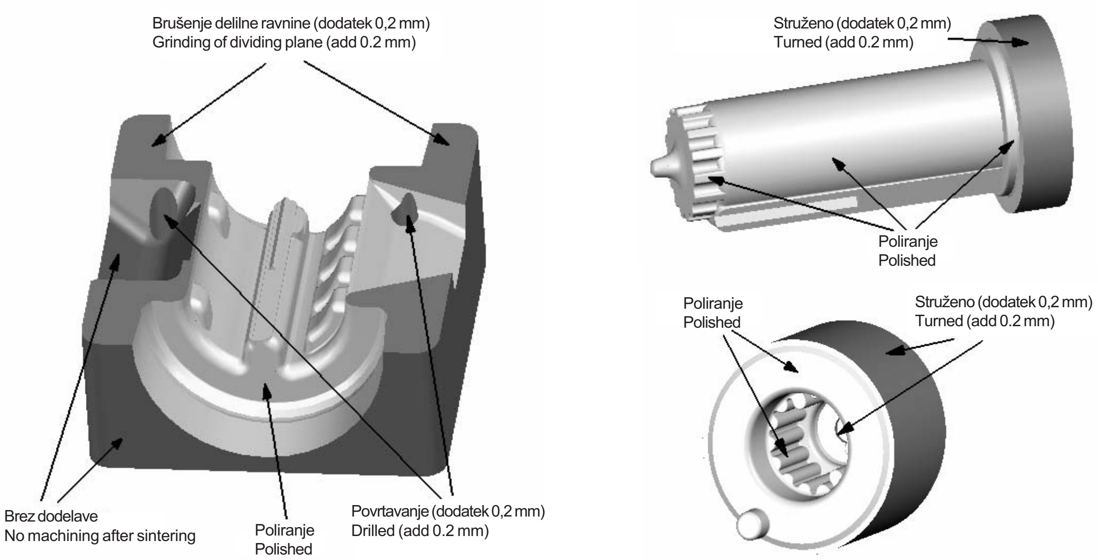
Sl. 2. *Sestavljeno orodje, lega ogrevnih kanalov ter stranskih jeder*
Fig. 2. *Assembled tool with the position of the temperature channels and side cores*

Za izdelavo vložkov orodij iz materiala DSH20 (za brizganje plastičnih izdelkov) se običajno uporablja tako imenovana strategija "dvojnega sloja - jedro": zunanji sloj sintramo z uporabo visoke vstopne toplote in razmeroma majhnimi hitrostmi gibanja laserskega žarka (hitrost gibanja žarka 80 mm/s in podajalni premik 0,25 mm). Zato je zunanji sloj zelo gost in ima najboljše mehanske značilnosti (trdota 380 do 420 HV). Notranji sloj je področje v notranjosti vložka, običajno ga sintramo z velikimi hitrostmi gibanja žarka (hitrost gibanja žarka 200 mm/s in podajalni premik 0,25 mm), zaradi česar se pojavi določena poroznost v materialu (trdota 340 do 380 HV). Poroznost notranjosti je običajno ~ 5%. Parametri "dvojni sloj - jedro" so dali dobre rezultate pri uporabi sintranih orodij v serijski proizvodnji, v načelu bi morala biti enaka strategija ustrezna tudi za sintranje orodij za tlačno litje aluminija. Glavna razlika je v delovni temperaturi litja in visoki krožni temperaturni obremenitvi taline aluminija, ki orodje izrazito toplotno obremenjuje. Za lasersko sintranje vložkov orodij so za to potrebni posebna pozornost in določene spremembe parametrov sintranja, poleg tega so bila za doseganje večje trdnosti dolga stranska jedra izdelana le z uporabo parametrov zunanjega sloja.

Pred končnim sestavljanjem orodja je za zagotavljanje boljše kakovost orodij in izdelkov treba gravure vložkov ustrezno polirati in nekatere površine tudi dodatno mehansko obdelati. Delilne površine vložkov orodij in kanale za vgradnjo stranskih jeder je treba brusiti (zaradi ustreznih

The standard approach to sintering injection-molding tools from DSH20 material has been called the "double-skin–core" strategy: the "outer skin" is built using a high heat input and relatively slow scanning parameters (scanning speed 80 mm/s with hatch distance 0.25 mm). Therefore, this outer skin is very dense and has the highest mechanical properties (hardness 380 to 420 HV). The "inner skin" is the inside area, which is normally sintered at a higher speed (scanning speed 200 mm/s with hatch distance 0.25 mm), so resulting in some porosity inside the material (hardness approximately 340 to 380 HV). The porosity of the inner skin is typically ~ 5%. These "double-skin–core" parameters have given good results for injection molding, even for serial production, and in principle the same strategy should also work for aluminum die casting. The main difference is the operating temperature of the molding process and the higher cyclic heat input that is transferred into the tool by the molten aluminum. Therefore, some extra precaution and changes have been decided on for the laser sintering of tool inserts, and also long side cores were built-up using only the "outer skin" parameters to make them stronger.

Before the final assembly of the tool, the engravings of the inserts need to be polished and some surfaces also machined to ensure the better quality of the tool or products. The parting surfaces of the tool inserts and the hollows for the side cores need to be grinded to ensure suitable fitting and the



Sl. 3. *Potrebna dodatna obdelava sintranih kosov orodja*
Fig. 3. *Required post-machining of the sintered parts*

prilegov in toleranc), stranska jedra pa postružiti (sl. 3).

Primerjalna vrednostna analiza med orodjem, izdelanim z običajnimi metodami in z uporabo NLSK, je pokazala, da je predvsem čas izdelave pri NLSK precej krajši. Razlika je večja, čim večji je delež EDM (potopna erozija). Zato je tudi sintranje stranskih jeder stroškovno bolj ugodno od izdelave oblikovnih vložkov (zgornji in spodnji del orodja), še posebej, če jih lahko skoraj v celoti izdelamo s frezanjem. V primeru, ko je ogrodje orodja narejeno za večje število prototipov in ko menjujemo le vložke orodja, pa je NLSK hitrejše in tudi cenejše od običajnega postopka izdelave orodij.

Tribološke lastnosti lasersko sintranega orodja za tlačno litje aluminija lahko bistveno izboljšamo, če ga zaščitimo z ustrezno trdo prevleko PVD (fizikalno naparjanje v parni fazi). Ta mora biti abrazijsko obstojna in mora imeti veliko trdoto, hkrati pa mora biti kemijsko inertna in oksidacijsko obstojna. Tem merilom najbolj ustrezata prevleki CrN in TiAlN PVD. Glede na to, da je standardno lasersko sintrano jeklo preveč porozno (DirectSteel 20 [13]) in zaradi premajhne nosilnosti (zaradi majhne trdote), smo preizkusili kombinacijo kemijsko nanesenega trdega niklja (Ni-P) in trde PVD prevleke. Ugotovili smo, da breztokovno naneseni trdi nikelj dobro zapolni pore na površini orodja, če je njegova debelina primerljiva z izmerami por (10 do 20 μm). Tako debela plast Ni-P bistveno izboljša nosilnost lasersko sintranega vložka.

required tolerances, and the side cores also need to be machined by turning (Fig. 3).

The cost analysis between the classical production of the tools compared to DMLS showed that the time of production when using DMLS is considerably shorter. The difference in relation to the classical method depends on the extent of the EDM. Therefore, the sintering of the side cores is much more cost-effective than the production of tool inserts (the upper and lower parts of the tool), particularly when they can be made just by milling. However, if the base of the tool is made for several prototypes and only the inserts are changed, the DMLS approach is faster, and can also be cheaper than the classic methods.

The tribological characteristics of a laser-sintered tool for aluminum die-casting can be significantly improved by the deposition of suitable PVD (Physical Vapour Deposition) hard coatings, which have to be abrasive resistant (and with a high hardness), and at the same time as chemically inert and resistant to oxidation as possible. Based on these preconditions CrN and TiAlN PVD coatings can meet the demands. Due to the problem of the porosity of standard laser-sintered steel (DirectSteel 20 [13]), and due to its lower load capacity (low hardness), a combination of hard nickel (Ni-P) and hard PVD coatings has been investigated. It was found that electroless coatings are suitable for filling the pores on the tool surface; however, with the precondition that the thickness of the coatings is higher than the dimensions of the pores (10 to 20 μm). Such a layer of Ni-P can, therefore, improve the load capacity of the laser-sintered tools.

Alternativa temu hibridnemu postopku zaščite je nanos samo prevleke PVD. Vendar je v tem primeru treba izdelati orodje tako, da je hitrost sintranja vrhnje plasti orodja (do globine približno 1 mm) čim manjša, da dobimo majhno poroznost. Površino je treba predhodno tudi utrditi z obstreljevanjem z jeklenimi kroglicami, da zagotovimo ustrezno nosilnost razmeroma krhki trdi prevleki. Kakovost nanosa prevleke je mogoče določiti z uporabo testa razenja. Merilo za oprijemljivost prevleke je nastanek mikrorazpok, ki ga spremlja pojav zvočne emisije in naglo povečanje sile razenja (ko se v razi začne prevleka luščiti). Kakor vidimo iz spodnjega posnetka SEM (sl. 4), se je prevleka CrN pričela luščiti pri sili razenja okrog 65 N, kar pomeni, da je oprijemljivost s tehnološkega vidika dobra.

Primerjava mehanskih lastnosti CrN in TiAlN trdih prevlek PVD je pokazala, da je oprijemljivost obeh prevlek primerljiva, medtem ko je mikrotrdota TiAlN znatno večja. Zato smo se odločili, da bomo za zaščito lasersko sintranega orodja za tlačno litje aluminijevih zlitin uporabili prevleko TiAlN.

The alternative to such a hybrid coating process is the deposition of just a PVD coating. A basic precondition for such a deposition is the tool shape, where the speed of sintering of the upper layer of the tool (depth of 1 mm) is as low as possible to obtain minimal porosity. The surface has to be additionally hardened before the deposition, a shot-peening process is used to ensure the proper load capacity demanded for the deposition of brittle and hard coatings. The quality of the deposition can be investigated using a scratch test. The appearance of acoustic emission and the rapid increase in the scratching force when the coating starts to delaminate are a measure of the adhesion of the coating. As we can see from the SEM picture (Fig. 4), the CrN coating starts to delaminate at a scratch force of 65 N, which from the technological point of view indicates that adhesion of the coating is good enough.

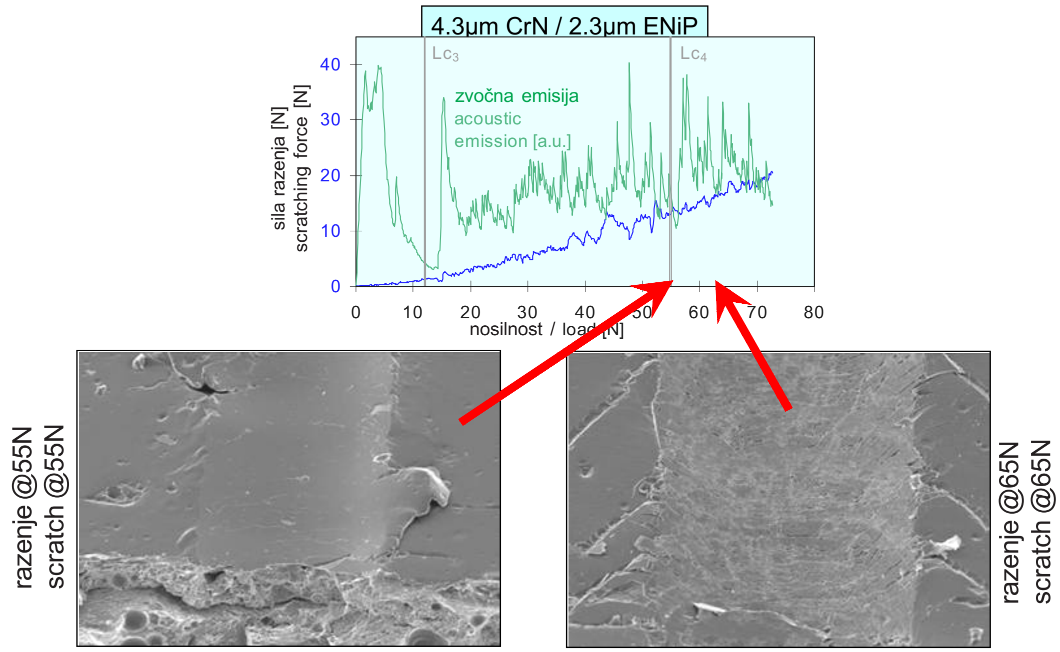
A comparison of the characteristics of the CrN and TiAlN hard PVD coatings has shown that the adhesion of both coatings is comparable; however, the microhardness of the TiAlN is much higher. Therefore, the TiAlN prevailed as the best choice for the deposition of hard coatings on the laser-sintered tool.

3 PREIZKUSNI REZULTATI IN RAZPRAVA

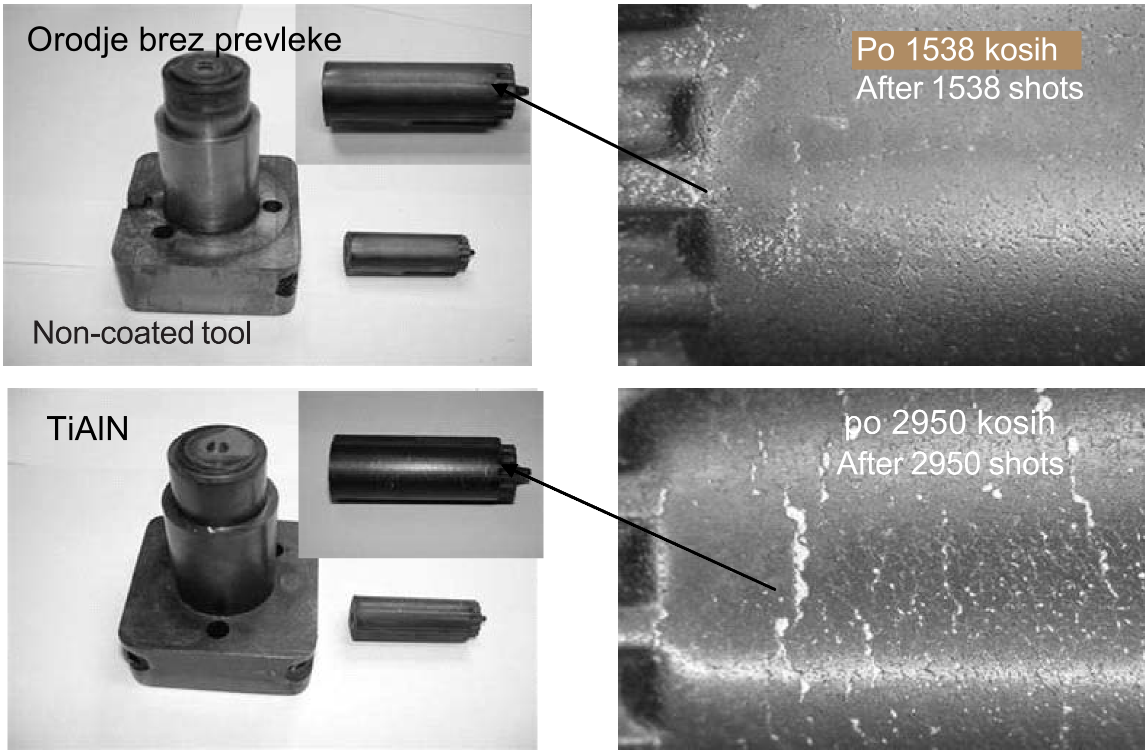
Testiranje NLSK orodij se je pričelo v industrijski livarni avgusta leta 2005. Izbrano je bilo

3 EXPERIMENTAL RESULTS AND DISCUSSION

The DMLS tool testing began at the industrial die-casting company in August 2005. A double-



Sl. 4. *Test razenja po nanosu prevleke iz kemijsko nanesenega niklja in trde prevleke PVD*
Fig. 4. *Scratch test after deposition of chemical nickel and the hard CrN coating*



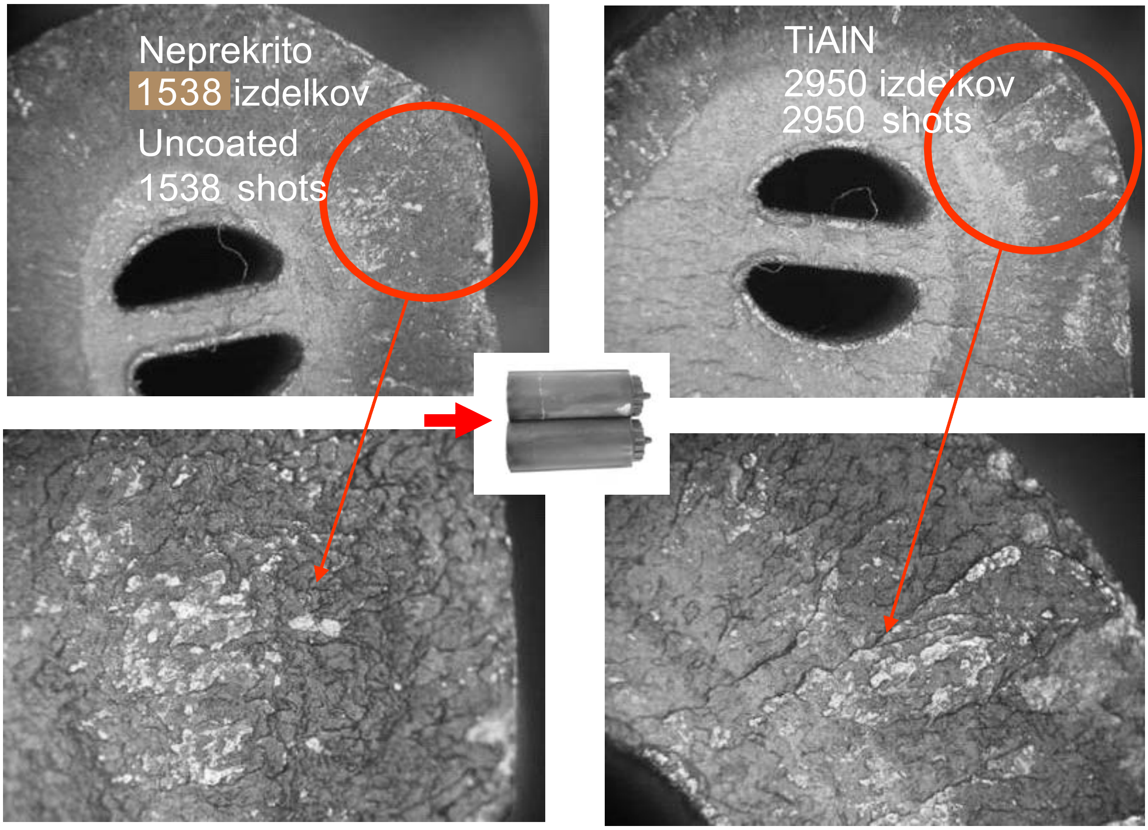
Sl. 5. *Stransko jedro – lom neprevlečenega in prevlečenega orodja*
Fig. 5. *Side cores – brakeage of the uncoated and coated tool*

dvognezdno orodje, vsako gnezdo je vsebovalo štiri sintrane vložke. Uporabili smo stroj za tlačno litje BÜHLER H-160B in standardni aluminij $AlSi_9Cu_3$. Prametri testiranja so bili naslednji: predgrevanje 130 do 215 °C, temperature litja 690 °C, tlak na vstopu taline 600 bar, čas trajanja litja 35 sekund, vsa predhodna opravila in predgrevanje orodja je bilo izvedeno glede na bogate izkušnje strokovnjakov s področja tlačnega litja. Obstojnostni kriterij je bil izbran v obliki loma orodja ali kot pojav prvih vidnih razpok na orodju. Preverjanje je bilo narejeno na podlagi optičnega opazovanja postopka litja in odlitih izdelkov. Ugotovljeno je bilo, da se je neprevlečeno daljše jedro orodja zlomilo pri 1538. brizgu, medtem ko je daljše, s TiAlN prevlečeno jedro zdržalo 2950 brizgov (sl. 5).

Glavni vzrok za lom stranskega jedra je bila upogibna sila na jedro, ki nastane med postopkom polnjenja orodja in ob sprostitvi pri odpiranju orodja. Mogoč vzrok za večjo obstojnost prevlečenega orodja je lahko v tem, da je bilo to orodje med vakuumskim postopkom nanašanja prevleke popuščeno na 450 °C. Primerjava optično-mikroskopskih posnetkov površine neprekritega in

cavity tool was chosen; each cavity was composed of four sintered inserts. A BÜHLER H-160B die-casting machine was used and standard $AlSi_9Cu_3$ aluminum material. The testing parameters were: preheating 130–215ºC, casting temperature 690ºC, melt pressure 600 bars cycle time 35 seconds, and all the preliminary tasks and the machine pre-heating and settings were carried in accordance with the experiences of die-casting specialists. A tool-life criterion has been chosen as a tool breakage or first significant signs of cracks. Therefore an optical observation of the casting process and the parts produced was made during the testing. It was found that the uncoated long side core of the tool broke during the 1538th injection; however, the TiAlN coated long side core withstood die-casting until the 2950th injection (Fig. 5).

The main reason for the breakage of the core was the bending forces during the filling cycle and the relaxation during the opening cycle of the tool. A possible reason for the longer tool life for the coated core could be the fact that during the vacuum-coating process at 450ºC a yielding process occurred. A comparison of the optical microscope photographs



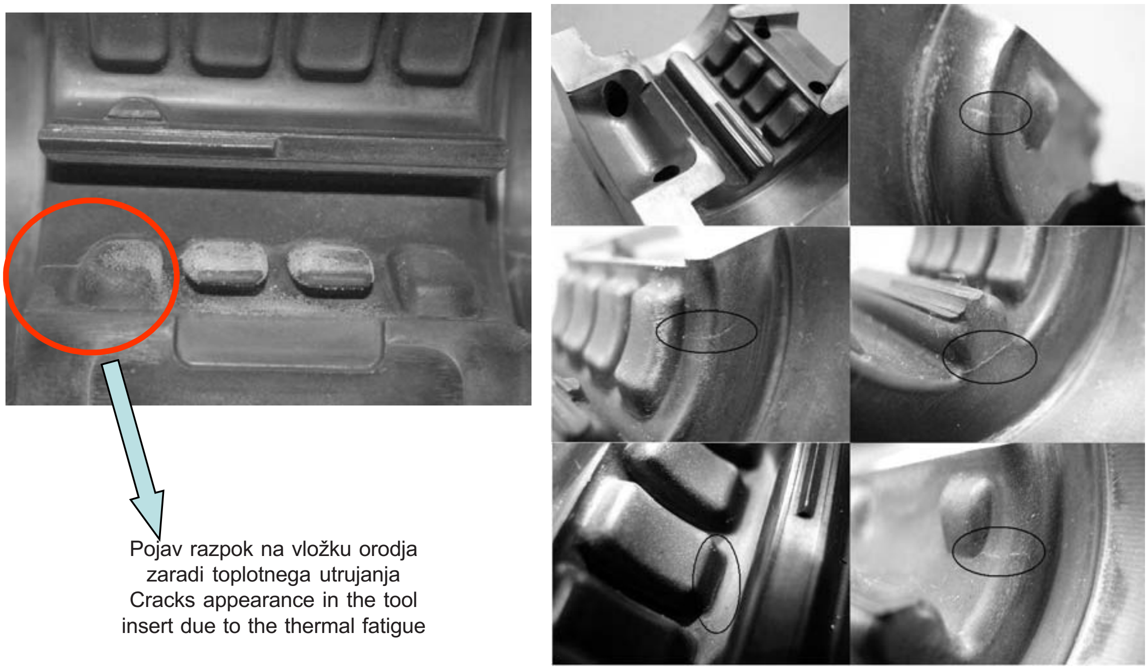
Sl. 6. *Stranska jedra – mehanska utrujenost*
Fig. 6. *Side cores – mechanical fatigue*

prekritega orodja kaže, da je poškodb na prekritem orodju bistveno manj (sl. 6). To pa pomeni, da prevleka izboljša toplotne in tribološke značilnosti vložkov orodij. Vendar pa je večji problem obstojnosti orodja v neustreznem razmerju med trdoto in žilavostjo materiala za izdelavo stranskih jeder (zaradi upogibne sile in posledične mehanske utrujenosti materiala).

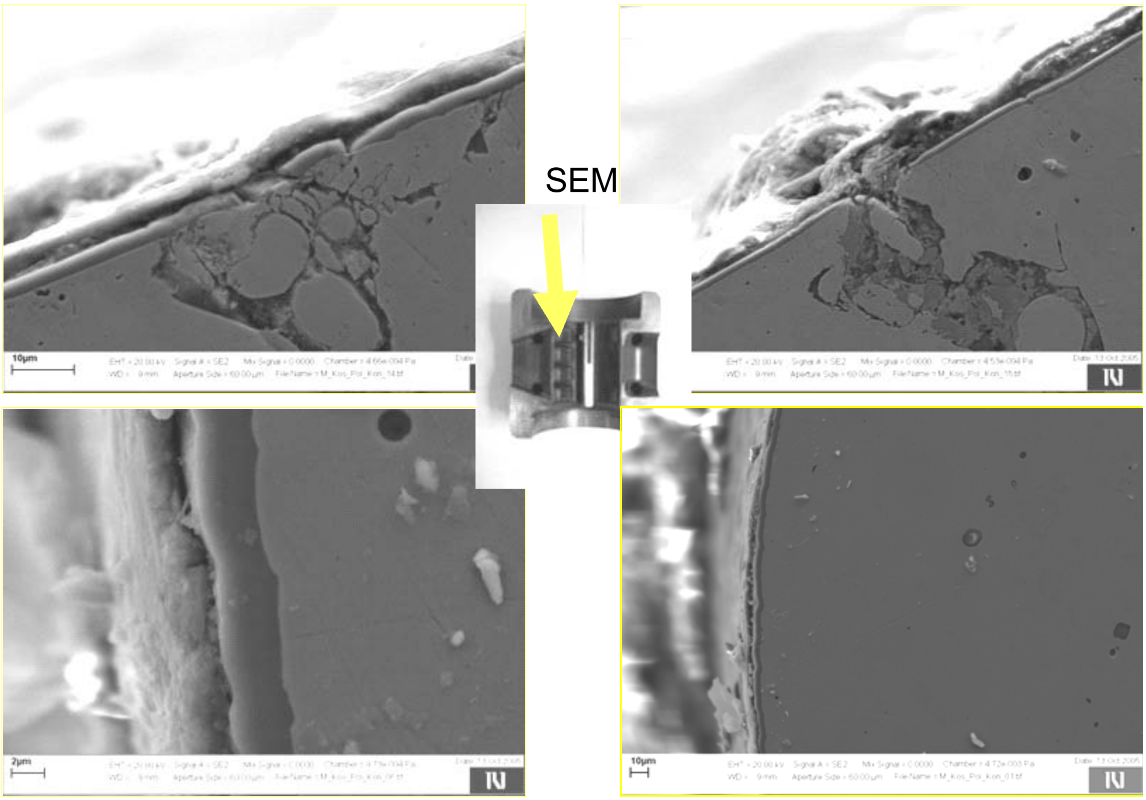
Po pregledovanju izdelkov so bile ugotovljene tudi nekatere vidne razpoke, nastajale so hkrati na obeh vložkih orodja in stranskih jedrih. Vzrok za nastanek razpok je v toplotni obremenitvi orodja (pojav je podoben kakor pri uporabi klasičnih orodij); makroskopske poškodbe in razpoke so vidne na sliki 7. Analiza z vrstično elektronsko mikroskopijo (SEM) toplotno najbolj obremenjenih delov orodja je tudi pokazala, da je prevleka še vedno nepoškodovana na celotni površini vložkov orodij, razen v področjih, kjer so določene poškodbe ali pore (sl. 8). Nekatere od teh so lahko že bile v orodju pred nanosom prevleke, nekatere pa so lahko posledica toplotnih

of the surfaces of un-coated and coated tools shows that there is less damage to the coated tool (Fig. 6). Coatings therefore improved the thermal and the tribological characteristics of the tool inserts; however, the main problem is a proper ratio for the hardness/toughness of the material for side cores (due to the bending forces and the consequent mechanical fatigue).

On basis of a visual inspection of the products it was also found that some cracks are already visible, and they appeared simultaneously in both inserts and side cores. The main problem of cracks is related to the thermal loads (a similar situation can also be found in classical steel materials); macroscopic defects and cracks in the structure are evident in Figure 7. An SEM (Scanning Electron Microscopy) analysis of the main thermally loaded parts of the tool has also shown that the coating still remains un-damaged over the whole surface of the tool, with the exception of the locations where some damage has occurred or pores are present (Fig. 8). Some of them may exist in the tool before the deposition; some of them can be the consequence of



Sl. 7. *Neprikrit vložek po končanem testiranju (po 2950 litih izdelkih)*
Fig. 7. *Uncoated insert at the end of the testing (2950 injections)*



Sl. 8. *Analiza SEM s TiAlN prekritega orodja po 2950 izdelanih kosih*
Fig. 8. *SEM analysis of the TiAlN coated tool after 2950 shots*

obremenitev. Meritve hrapavosti so prav tako pokazale, da površina orodja ni bila optimalno polirana, še posebej v področju kavitacij, ki jih je težko doseči.

Čeprav raziskovalni cilj – tlačno odliti 5.000 kosov v vsakem gnezdu orodja – ni bil dosežen, pa so rezultati vseeno zelo spodbudni. Glede na to, da je bilo testiranje končano, ko se je stransko jedro zlomilo, ne moremo vedeti, koliko dodatnih izdelkov bi bilo mogoče odliti. Po strokovnem pregledu orodja mnenje industrijskih strokovnjakov potrjuje, da je to vsekakor dosegljiva tehnološka meja, če bi izboljšali značilnosti materiala za izdelavo stranskih jeder. Kakorkoli, doslej ni bilo potrditve, da je mogoče NLSK ali druge metode za hitro izdelavo orodij tako uporabiti za uporabo tlačnega litja aluminija v majhnih serijah izdelkov.

5 SKLEP

Predstavljene raziskave in praktične rešitve so del rezultatov projekta Eureka, kjer je bil eden od najpomembnejših ciljev v prenosu temeljnega raziskovalnega znanja v industrijo, ki bodo ustrezale industrijskim zahtevam za prototipno orodje (za izdelavo tržnega izdelka) za tlačno litje aluminija. Na temelju eksperimentalne analize so bili predstavljeni obrabni pojavi in strukturne spremembe na orodju DMLS, pa tudi pričakovanja glede prihodnosti hitre izdelave orodij za potrebe industrije tlačnega litja aluminija.

Dokazano je bilo, da NLSK orodja lahko uporabimo za izdelavo najmanj 2950 tlačno litih kosov v industrijskem okolju, vendar obstaja problem žilavosti in trdote materiala ter posledičnega loma daljšega stranskega jedra. Pomembne so predvsem lastnosti sintranega prahu, zato mora biti razvoj usmerjen bolj na metalurške vidike, saj bomo lahko le tako zadostili zahtevam po izdelavi serijskih orodij za tlačna litja aluminija.

Začetni načrt je bil izdelati sintrano orodje za tlačno litje s strojem EOSINT M250 Xtended in uporabiti najnovejši material DirectSteel H20. Sedaj, dve leti po začetku projekta, ko je le ta v končni fazi, pa začetna izbira materiala in stroja ne predstavlja več najnovejših dosežkov na tem področju. To zato, ker je bil v tem obdobju narejen od EOS tako razvoj NLSK opreme in materiala. Nova zasnova stroja EOS M270 dandanes predstavlja najnovejše dosežke strojne opreme, prav tako so bili razviti novi materiali. Intenzivni razvoj materiala bo omogočal

the thermal loads. The roughness measurement also indicates that the surface of the tool has not been optimally polished, particularly for the cavities that are more difficult to reach.

Although the goal of 5,000 casting parts from each cavity was not achieved, the results are still very promising. As the tests of the tool ended when the coated side core was broken, we cannot say how many additional products could be produced. On the basis of after-tests professional tool examination, the opinion from the industrial experiences confirmed that this will be a reachable technological limit if some material characteristics for the side cores can be improved. However there is also no evidence that the DMLS or a similar rapid-tooling solution has been successfully until now applied for a small series of aluminum die-casting applications in such a way.

5 CONCLUSION

The presented research and the practical solution is part of a Eureka project, where the main goal is to transform basic scientific knowledge to applications that will meet industrial demands for building a prototype tool (on the basis of a practical marketable product) for the die-casting of aluminum. With an experimental analysis the wear and structural changes to the DMLS tool were presented, and the prospects of a rapid-tooling solution for the aluminum die-casting industry have been discussed.

It has been shown that we can use DMLS tools for producing 2950 die-casting parts in an industrial environment; however, there is a problem related to the toughness and the hardness of the material, and consequently the breakage of the movable core parts. Therefore the material properties play a more important role for die casting, and the development focus has to be even more on metallurgy to fulfill the serial tool requirements in aluminum die casting.

The initial plan was to produce the die casting tools with the EOSINT M250 Xtended machine using the current state-of-the-art material DirectSteel H20. Now, two years later, the project is in the final stage and the original selection of the material and machine does not quite represent the state-of-the-art status anymore. This is due to the development work done both in the DMLS hardware and the DMLS materials at EOS. Today, the new machine platform EOS M270 represents the state-of-the-art on the hardware side and new materials izdelavo novih izdelkov tudi na področju orodjarstva, ti bodo spremenili tako tehnične značilnosti orodij kakor tudi samo učinkovitost izdelave orodij.

Dodatni raziskovalni in razvojni rezultati projekta so: zasnova oblikovanja orodij za potrebe NLSK, znanje o postopku sintranja, izkušnje glede dodatne obdelave in ocena ekonomske upravičenosti. Najbolj zanimiv del orodja je stransko jedro, kjer so bili oblikovani notranji hladilni kanali. Tovrstne rešitve dajejo nove zanimive značilnosti, ki jih je mogoče doseči z uporabo laserskega sintranja. S takšnim načinom oblikovanja orodij in z uporabo svobode, ki jo omogoča tehnologija z dodajanjem materiala, bo mogoče najti mnogo boljše izdelovalne rešitve. Dolga jedra bo mogoče učinkoviteje hladiti, kar je zelo zanimivo za uporabo tlačnega litja. Na podlagi bogatih pridobljenih izkušenj opisanega industrijskega testiranja orodij obstajajo velike možnosti za nadaljevanje raziskav (kar je potrjeno od izdelovalca opreme in uporabnika rezultatov).

have also been released for this platform. Intensive material development work will result in the new product(s) also in the tooling areas, which will change not only the technical performance of the tools but also the cost efficiency of the tooling.

Additional research-and-development results are as follows: the tool design for the DMLS, the sintering know-how, the post-machining experiences, the economic justification. The most interesting part in the tool design was the core pin where an internal cooling channel was designed. These kinds of solutions are the most interesting features that can be used in laser sintered tool parts. By designing die casting tools in a modern way and by utilizing the freedom of additive manufacturing technology better solutions will become possible. Long cores and pins can be cooled more efficiently and this should be very interesting for die casting application. Therefore there is great potential for further research according to the rich experiences obtained on the basis of industrial testing (this was also confirmed by EOS-Finland and TCG Unitech).

6 LITERATURA
6 REFERENCES

[1] N. L. Gideon, R. Schindel, J.P. Kruth (2003) Rapid manufacturing and rapid tooling with layer manufacturing technologies, state of the art and future perspectives, *CIRP* 52 (2003) 1-21.

[2] EOS Electro Optical Systems (2001) DMLS moves from rapid tooling to rapid manufacturing, *Metal Powder Report*, 56 (2001) 1-6.

[3] S. Syrjala (2002) DMLS for injection molding and die casting applications, *Proceedings of Special EuroMold Event*, Frankfurt.

[4] J. Kotila, J. Hanninen, T. Syvanen, O. Nyrhila (2004) Direct metal laser sintering – from rapid tooling to series production, *PMTEC Conference*.

[5] S. Dolinšek (2003) DMLS technology for making industrial tools for casting aluminium, *7th International research/Expert Conference TMT 2003*, Lloret de Mar, Barcelona, Spain.

[6] S. Dolinšek, J. Kopač (2003) DMLS Technology – from the Prototyping to the Rapid Manufacturing, *6th International Conference of Innovative Technologies, MIT 2003*, Piran, Slovenia, 203-210.

[7] S. Dolinšek, J. Kopač (2005) Industrial applications with DMLS rapid tooling. *International Manufacturing Leaders Forum*, Adelaide, Australia, March 2005,

[8] S. Dolinšek (2005) Some investigations into improvement of laser sintered tools. *TMT 2005*, Antalya, Turkey, September, 2005.

[9] S. Dolinšek (2004) Investigation of direct metal laser sintering process, *Journal of Mechanical Engineering*, 50 (2004) 229-238.

[10] B. Sustaršič, et.all. (2005) Bulk and surface characterisation of metal powders for direct laser sintering. *Vacuum*, 80 (2005), No. 1/3, p. 29-34.

[11] S. Dolinšek (2004) Laser sintered aluminium die casting tools: *EUREKA project - project documentation*, Hrastnik.

[12] Syvanen T (2001) Behavior of DMLS steel inserts in die casting, *EOS appl. notes*, EOS Finland.

[13] P. Panjan, et all. (2003) Deposition and characterization of TiAlN/CrN multilayer coatings sputtered at low temperature. *Material technologies*, 37 (2003) 123-127.

[14] S. Dolinšek (2004) Applications of different coatings for improvement of the characteristics of DMLS Tools, *EOS International user Meeting*, Fulschlsee, Austria.
[15] S. Dolinšek, et. all. (2005) Some latest development of laser sintered tools for die casting of aluminium. *Euro-u Rapid 2005*, Leipzig, Germany, May 2005.
[16] S. Dolinšek (2005) Wear characteristics of laser sintered molding tools. *Wear*, Vol. 259 (2005), No. 7/12, p. 1241-1247.

Naslovi avtorjev: dr. Slavko Dolinšek
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
slavko.dolinsek@fs.uni-lj.si

dr. Peter Panjan
Inštitut Jožef Stefan
Jamova 39
1000 Ljubljana
peter.panjan@ijs.si

Tatu Syvanen
EOS Finland Oy
Finska

Jože Ramovš
TCG Unitech Lth-ol d.o.o.
Vincarje 2
4220 Škofja Loka

Authors' Addresses: Dr. Slavko Dolinšek
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
1000 Ljubljana, Slovenia
slavko.dolinsek@fs.uni-lj.si

Dr. Peter Panjan
Institute Jožef Stefan
Jamova 39
1000 Ljubljana, Slovenia
peter.panjan@ijs.si

Tatu Syvanen
EOS Finland Oy
Finland

Jože Ramovš
TCG Unitech Lth-ol d.o.o.
Vincarje 2
4220 Škofja Loka, Slovenia

Prejeto:
Received: 24.9.2006

Sprejeto:
Accepted: 25.10.2006

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

Strojniški vestnik - Journal of Mechanical Engineering 52(2006)11, 752-762
UDK - UDC 621.9-52:004.45
Kratki znanstveni prispevek - Short scientific paper (1.03)

Umerjanje in preverjanje geometrijske natančnosti računalniško krmiljenih obdelovalnih strojev

Calibration and Checking the Geometrical Accuracy of a CNC Machine-Tool

Marko Cedilnik - Mirko Soković - Jože Jurkovič
(Fakulteta za strojništvo, Ljubljana)

Nenehen razvoj računalniške opreme je v postopek nastajanja izdelkov vnesel ostre zahteve po izmerni primernosti izdelkov. Natančni izdelki namreč kažejo na geometrijsko natančnost računalniško krmiljenega (RK) obdelovalnega stroja. Hitro preverjanje geometrijske natančnosti strojev poteka z uporabo naprave Ballbar QC10, natančno umerjanje oz. popravo parametrov v krmilniku pa poteka na podlagi rezultatov meritev natančne laserske naprave ML10. V prispevku je prikazano osnovno načelo delovanja naprave Ballbar QC10. Nekateri parametri, ki neposredno vplivajo na natančnost RK obdelovalnega stroja, pa so tudi natančneje opisani.

(Ključne besede: natančnost geometrijska, RK obdelovalni stroji, analize preizkušanja)

Constant computer-hardware and software developments have resulted in enhanced requirements for the dimensional accuracy of products. An accurate product reflects the geometrical accuracy of the CNC machine-tool. A quick accuracy test of a CNC machine-tool can be performed with the Ballbar QC10 device; calibration and parameter correction on the CNC controller can be done with a test-result analysis from the very accurate ML10 laser device. In this paper a brief overview of the working principles of the Ballbar QC10 device is presented. Some of the parameters that are directly related to the accuracy level of the CNC machine-tool are described in detail.

(Keywords: geometrical accuracy, CNC machine-tool, test analysis)

0 UVOD

Zahteve po natančni izdelavi se vedno bolj povečujejo. Velike zahteve po natančnih izdelkih na eni strani "vrtijo kolo" razvoja računalniške in programske opreme, na drugi strani pa se nenehno povečuje natančnost strojev in orodij uporabljenih v postopku. Natančnost izdelkov je namreč neposredno povezana s sposobnostmi strojev uporabljenih v postopku. Smotrna proizvodnja v modernem podjetju in konkurenčni izdelki zahtevajo spremljanje in preverjanje natančnosti strojev. Geometrijska natančnost strojev je zato lahko podlaga za njihovo razvrščanje glede na zmožnosti. Na tak način se lahko zmanjša neobratovalni čas stroja, izmeček oz. izmerno neustrezne izdelke, obenem pa se s tem podaljša uporabna doba stroja. Izmerno nezahtevne izdelke lahko izdelujemo na zanje primernih strojih.

Po drugi strani lahko redna preverjanja natančnosti stroja in spremljanje velikosti odstopanj

0 INTRODUCTION

The accuracy requirements of machined products are constantly increasing. High standards for accurate products "spin the wheel" of constant computer software and hardware development, on the one hand, and accuracy improvements to machines and tools used in the process, on the other. The accuracy level of machined products is directly related to the performance of the machine(s) used in the production line. Competitive products and an effective production line in modern enterprises demand constant checking of machine-tool performance. Thus, the geometrical accuracy of CNC machine-tools can be the basis for rating CNC machine-tools according to their performance. With these measures machine downtime and scrap can be minimized, and at the same time the life-cycle of the machine-tools can be prolonged. Simple parts can, however, be machined on relatively inaccurate machines.

On the other hand, regular check-ups and the accompanying size of errors can dictate the narekujejo redna ali preprečevalna vzdrževalna dela, s čimer lahko še dodatno vplivamo na podaljšanje uporabne dobe obdelovalnega stroja ([1] do [5]).

1 NAPRAVA BALLBAR QC10

Zelo uspešna metoda za hitro ugotavljanje geometrijske natančnosti stroja temelji na krožnem testu z napravo Ballbar QC10, izdelovalca Renishaw iz Velike Britanije (sl. 1). Naprava Ballbar QC10 se uporablja za kratke 10-minutne teste geometrijske natančnosti obdelovalnih strojev. Osrčje naprave je induktivno dolžinsko zaznavalo (IDZ - LVDT), ki je postavljeno med dve jekleni kroglici (Ø =12,7 mm ± 2,5 µm) na vsakem koncu merilne palice. To se postavi v magnetna sedeža, ki ju pritrdimo na obdelovalno mizo (A) oz. vpnemo v vreteno stroja (B) (sl. 1). Prek serijskih vrat RS232 (COM) je IDZ povezano z računalnikom in ustreznim programom, ki med izvajanjem krožnega testa zajema majhne prečne pomike ene kroglice glede na drugo. Glede na omejitve in različne tipe obdelovalnih strojev lahko naredimo različne teste: krožne (360°), polkrožne (180°) ali četrtinske (90°) v ravninah XY, XZ in YZ ([1] in [6]).

Glede na vrsto in smer testa je treba napisati računalniški program, ki je zapis programirane idealne krožne poti vretena B okoli središča kroglice A. Polmer krožnega testa je mogoče prilagajati za različne velikosti obdelovalnih strojev. Osnovni polmer

regular or preventive maintenance of the machine parts, which again contributes to the extension of the machine-tool life-cycle time ([1] to [5]).

1 THE BALLBAR QC10 DEVICE

A very successful method for a quick check of the geometrical accuracy of a CNC machine-tool is based on a circular test with the Ballbar QC10 (**QC10 - Q**uick **C**heck **10** min) device from the Renishaw company in the UK, Fig.1. The Ballbar QC 10 device is used for a brief test to determine the geometrical accuracy of the machine. The Ballbar device consists of an LVDT (linear variable differential transformer) sensor, which is placed between two accurate steel balls (Ø =12.7 mm ± 2.5 µm) at each end of the bar. With two magnetic mounts the Ballbar is set-up on the machine bed (A) and in the spindle (B), Fig.1. Through an RS 232 port (COM), the LVDT sensor is connected with the computer and suitable software, which detect radial movements of one steel ball relative to the other, during a circular test. According to the limits of each machine and the different types of machines, various tests can be made: circular (360°), half-circular (180°) or one quarter of a circle test (90°) in the XY, XZ in YZ planes ([1] and [6]).

According to the type of test, an NC program should be written, which presents a record of the ideal circular path of the spindle B around the center of the steel ball A. The Ballbar radius can be adapted according to the size of the CNC machine-

Preglednica 1. *Podrobni popis naprave Ballbar QC10*
Table 1**.** *System specification of the Ballbar QC10 device*

ločljivost resolution	0,1 µm
natančnost induktivnega dolžinskega zaznavala LVDT sensor accuracy	± 0,5 µm (pri/at 20 °C)
najv. število zajetih podatkov max. sample rate	250 /s
imenska dolžina Ballbar naprave (± najv. pomik) Ballbar length (± max. move)	100 mm (med jeklenima kroglama/ between steel balls) (-1,25 mm to/do +1,75 mm)
podaljški merilne palice extension bars	50 mm, 150 mm, 300 mm
temp. območje delovanja operating temperature range	0 do/to 40 °C
natančnost umerjanja na stekleni plošči Zerodur (pri 20 °C) calibrator accuracies Zerodur-plate (at 20°C)	± 0,1 µm (za/for 100 mm) ± 0,1 µm (za/for 150 mm) ± 0,15 µm (za/for 300 mm)
poraba energije energy consumption	50 mA / 9V DC

Sl. 1. *Naprava Ballbar QC10*
Fig. 1. *Ballbar QC10 device*

Ballbar naprave je 100 mm, s podaljški pa je mogoče polmer povečati na 150, 300 oz. 600 mm. Če izvajamo polni krožni test (360°), je ta sestavljen iz dveh delov meritev:

- dve zavrtitvi vretena okoli središča kroglice A v *proti urni smeri,*
- dve zavrtitvi vretena okoli središča kroglica A v *urni smeri*.

Med menjavo smeri, zaradi pravilnega zajemanja podatkov, upoštevamo najmanj 3-sekundni premor. Tudi pri polkrožnem ali četrtinskem testu izvajamo gibanje v obe smeri. Med izvajanjem testa, računalnik prikazuje in zapisuje odstopanja dejanske poti vretena od idealne krožnice, ki je zapisana s programom.

Natančnost naprave Ballbar in plošče Zerodur (ki je del celote) je podana in overjena od izdelovalca naprave, podjetja Renishaw. Glede na temperaturi okolice in stroja z RK, se pred vsakim testom izvede temperaturno umerjanje naprave Ballbar. Temperaturno umerjanje se izvede na plošči Zerodur, ki ima zanemarljiv temperaturni razteznostni koeficient α v celotnem temperaturnem območju delovanja naprave Ballbar (pregl. 1).

Rezultati testa so prikazani in ovrednoteni grafično in pregledno in so skladni s standardi ISO 320-1, ANSI B5.54 in B5.57 ter JIS B6194 (sl. 5). Nekateri odstopki, so glede na velikost odstopanja in tudi glede na ostale odstopke, predstavljeni kot deleži od skupnega odstopanja na RK stroju. Velikost

tool. The basic radius of the Ballbar is 100 mm, but it can be extended with additional bars to 150, 300 or 600 mm. In the case of the circular (360°) test, the measurement is a combination of two movements:

- two rounds of the spindle around the center steel ball A in a *counter-clockwise* direction,
- two rounds of the spindle around the center steel ball A in a *clockwise* direction.

For an accurate measurement, at least 3 seconds should pass between changes of direction. The measurement consists of two movements of the Ballbar sensor in the half circular (180°) and the one quarter of a circle test (90°). During the test the computer shows and writes errors, which is the difference between the actual path of the spindle against the ideal path written in the NC program.

The accuracy of the Ballbar sensor and the Zerodur plate (which is in a kit) is stated and certified by the producer, i.e., Renishaw. Considering the working and surrounding temperature of the CNC machine-tool, the temperature calibration of the Ballbar device should be made before any test. The temperature calibration is made on the Zerodur plate, which has a very low temperature coefficient of extension, α, in the range of the Ballbar device's working temperature, Table 1.

The test results are presented and evaluated in graphical and tabular modes, and are in compliance with the ISO 320-1, ANSI B5.54, B5.57 and JIS B6194 standards, Fig. 5. Some errors are, according to their magnitude and in comparison to the other errors, posameznega odstopka ni neposredno povezana z geometrijsko natančnostjo RK stroja, temveč je povezava le posredno določena. Rezultate testa je s programom za pomoč mogoče razčleniti na več kot 20 različnih virov odstopanj. Prevladujoča oblika krožnega zapisa se navadno zelo hitro opazi in ima največji vpliv na geometrijsko nenatančnost RK stroja. Natančna razlaga preostalih manj vplivnih odstopanj in povezava z mogočimi vzroki zanje je po navadi zelo zahtevno delo, saj zahteva že kar nekaj izkušenj ter znanja o natančni zgradbi posameznih modulov RK stroja in njihovem delovanju. Pomoč pri razlagi rezultatov meritev nedvomno ponuja že omenjen program za pomoč, v katerem so za vsak značilni krožni zapis v grobem navedene neposredne posledice posameznih odstopanj in priporočila za njihovo zmanjšanje ali odpravo.

Programski paket, ki je dodan merilni napravi, shrani vsak test posebej, kar omogoča, da lahko v daljšem časovnem obdobju spremljamo spreminjanje vsakega posameznega parametra na RK stroju. Takšno spremljanje parametrov posledično narekuje potrebna vzdrževalna dela na stroju, s čimer se podaljša uporabna doba obdelovalnega stroja ([1] in [6]).

Zelo pomemben del programskega paketa Ballbar je t.i. simulator Ballbar, ki omogoča simuliranje fizičnih nastavitev obdelovalnega stroja in parametrov v krmilniku stroja. S takšno simulacijo lahko enostavno določimo vsak posamezen parameter, ki mora biti popravljen in za koliko morajo biti vrednosti drugačne, da se z najmanjšimi stroški in v čim krajšem času geometrijska natančnost RK stroja izboljša. Soodvisnost parametrov lahko včasih zamegli glavno težavo, ki vpliva na geometrijsko nenatančnost RK stroja [6].

1.1 Teorija merjenja z napravo Ballbar

Pri vsaki meritvi ali gibanju po poti se pojavijo odstopki. Odstopanja so posledica merilne negotovosti elementov v sistemu. Idealnih sistemov ni, kakor tudi ne idealnih RK strojev.

Središče kroglice, vpete v magnetni sedež A na obdelovalni mizi (sl. 1), je izhodiščna točka (0,0,0) v opazovanem primeru. Kroglica, ki kroži (B) pa ima v določenem časovnem trenutku (t_1) koordinate B (X,Y,Z) (sl. 3). R pomeni razdaljo med točkama A in B v opazovanem časovnem trenutku t_1. Sledi:

presented as a share of the total deviation on the CNC machine-tool. The magnitude of the error is not directly related to the general accuracy of the CNC machine-tool; however, there is an indirect connection. Test results can be classified with the "Help" program into 20 possible sources of errors. The prevailing test error is usually very noticeable, and has a relatively high impact on the general non-accuracy of the CNC machine-tool. The interpretation of other less-significant errors and related causes for it can be a very demanding task, which requires some extra knowledge of CNC machine-tool modules and their working principles. The above-mentioned Help program also offers assistance to determine the real cause of each error's origin and includes a recommendation to minimize or nullify a particular error.

Software embedded in the Ballbar device also keeps a record of each measurement, thus information about each parameter of the CNC machine-tool can be analyzed over the long term. Such activities dictate regular or preventive maintenance of the machine parts, which contributes to the extension of the machine-tool life-cycle.

A very important part of the Ballbar software is the Ballbar simulator, which can be used for a simulation of the physical corrections on CNC machine-tool modules as well as parameter corrections in the machine controller. With such a simulation we can easily determine which and for how much each parameter should be corrected in order to get as accurate a CNC machine-tool as possible, with minimum corrections and with minimal time and costs. Indirect interrelations among several parameters can sometimes "fog" the real cause of CNC machine-tool errors ([1] and [6]).

1.1 The Ballbar measuring theory

Errors originate from measurements or path movements. Root causes of the errors are related to the measurement uncertainty of the elements in the system. There are no ideal systems, as well as there is no ideal CNC machine-tool.

The center of the steel ball (A) placed on the machine bed (Fig. 1) can be set as the origin point (0,0,0) in our coordinate system. Moving the steel ball (B), which circulates around the origin point, has in time (t_1) position B (X,Y,Z), Fig 2. R is the distance between the points A and B in the time t_1. Thus:

$$R^2 = X^2 + Y^2 + Z^2 \quad (1).$$

Ko se vreteno premakne na lego B (X,Y,Z), se orodje zaradi odstopkov pravzaprav premakne v lego B'' (X'',Y'',Z'') (sl. 2). Zaradi tega lahko napako lege izrazimo takole:

When the spindle is moved to a point B (X,Y,Z), the real position of the spindle with an error will be B'' (X'',Y'',Z''), Fig. 2. Therefore, the positioning error of the spindle can be expressed as follows:

$$\begin{aligned} \vec{C} &= (\Delta X, \Delta Y, \Delta Z) \\ \Delta X &= X'' - X \\ \Delta Y &= Y'' - Y \\ \Delta Z &= Z'' - Z \end{aligned} \qquad (2).$$

Če vektor C upoštevamo v enačbi (1), dobimo:

If vector C is entered into Equation (1), we obtain :

$$(R+\Delta R)^2 = (X+\Delta X)^2 + (Y+\Delta Y)^2 + (Z+\Delta Z)^2 \qquad (3).$$

Če še upoštevamo enakost iz enačbe (1) in zanemarimo kvadratne člene odstopkov iz enačbe (4), dobimo enačbo (6):

Considering Equation (1) and neglecting the squared error elements from Equation (4), we obtain Equation (6):

$$R^2 + 2\cdot\Delta R\cdot R = X^2 + Y^2 + Z^2 + 2\cdot(X\cdot\Delta X + Y\cdot\Delta Y + Z\cdot\Delta Z) \qquad (4)$$

$$\Delta R = R'' - R \qquad (5)$$

$$\Delta R = \frac{1}{R}\cdot(X\cdot\Delta X + Y\cdot\Delta Y + Z\cdot\Delta Z) \qquad (6),$$

kjer je ΔR skupni odstopek v smeri polmera R. Enačba (6) daje odvisnost napake lege vretena B'' in izmerjenih podatkov z uporabo naprave Ballbar QC10 [2].

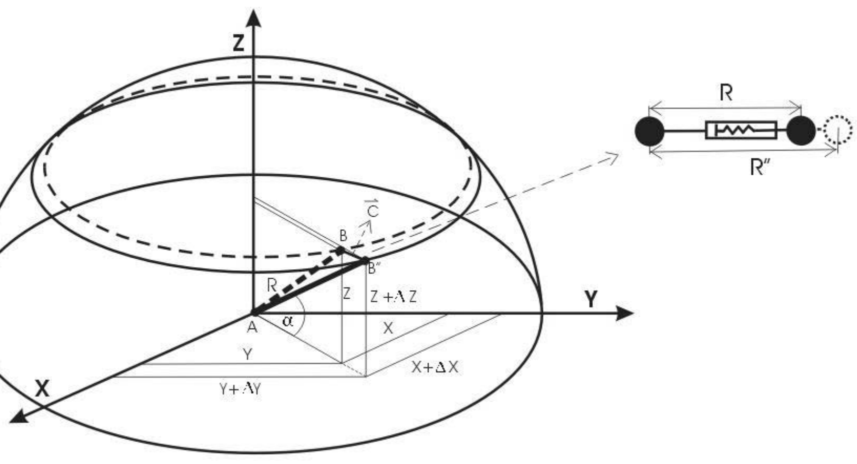
where ΔR is the length error along the radius R direction. Equation (6) shows the relation between the positioning error vector of the spindle B'' and the measuring data using the Ballbar QC10 device [2].

2 LASERSKA NAPRAVA ML10

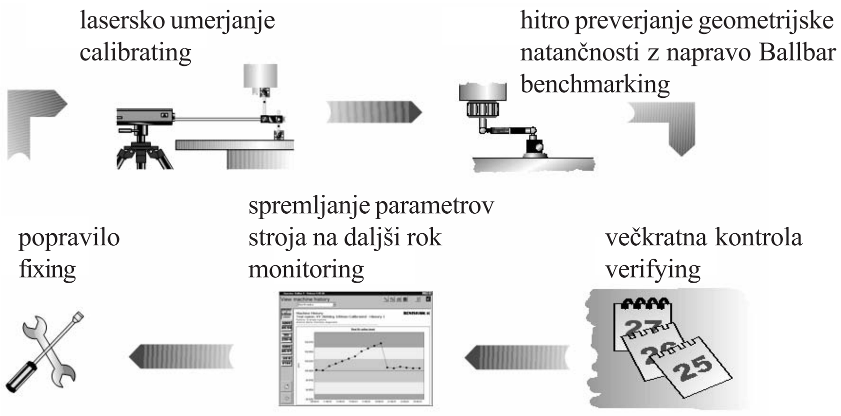
2 THE ML10 LASER SYSTEM

Laserski sistem ML10 Gold Standard je drugi način za vrhunsko preverjanje in umerjanje natančnosti obdelovalnih strojev ter tudi koordinatnih merilnih strojev (KMS - CMM). Z veliko

The ML10 Gold Standard laser system represents the second mode for top-level identification and the compensation of errors on CNC machine-tools and coordinate-measuring machines (CMM). With the



Sl. 2. *Izmerjena krožnica in idealna krožna pot naprave Ballbar pri kotu merilne palice α [°]*
Fig. 2. *Measuring circle and ideal circular path of the Ballbar device with a tilting angle α [°]*



Sl. 3. *Zaporedje aktivnosti za določanje geometrijske natančnosti RK stroja*
Fig. 3. *Sequence of actions to determine the geometrical accuracy of the CNC machine-tool*

natančnostjo laserskega vira lahko z nanometrsko ločljivostjo merimo velikost napak oz. odstopanj. S posebnimi pripomočki in z dodatnimi optičnimi elementi v merilni verigi lahko merimo: premi pomik, kotne zasuke, ravnosti, pravokotnosti, ploskovnosti, vrtenje osi itn.

Obe napravi (Ballbar QC10 in laserska naprava ML10) se lahko uporabljata za preverjanje geometrijske natančnosti RK strojev. Najboljša je vzajemna uporaba obeh naprav, kakor je prikazano na sliki 3. Na sliki je prikazano zaporedje dejavnosti pri preverjanju geometrijske natančnosti RK stroja. V tem primeru je laserska naprava uporabljena za umerjanje po večjih mehanskih posegih na RK stroju, med tem ko se naprava Ballbar QC10 uporablja za hitre in redne preglede natančnosti RK stroja. Takšna uporaba naprav lahko narekuje redna ali preprečevalna vzdrževalna dela na elementih, vgrajenih v RK stroj ([7] do [9]).

3 RAZVRŠČANJE ODSTOPKOV/NAPAK

Vzroke za nenatančnost obdelovalnih strojev je mogoče iskati v več kot 20 različnih virih odstopanj. Odstopanja lahko razdelimo v dve glavni skupini, in sicer glede na vzrok za njihov nastanek:

- Odstopanja od lege
  - geometrične odstopke
  - odstopanja na položajnih elementih
- Odstopanja zaradi gibanja (podajanja)

Vektor, ki označuje odstopanje od lege je odvisen od elementov v vodilih delovne mize, delovni mizi in vretenu. Odstopke, ki povzročajo odstopanje od položaja, lahko razdelimo v dve skupini: na

high accuracy of a laser beam, nanometric measurements can be executed. With special equipment and additional optical devices, several measurements on the CNC machine-tool can be performed: linear accuracy, angular pitch, straightness measurement, squareness measurement, flatness measurement, rotary-axes measurement, etc.

Both devices (the Ballbar QC10 and the ML10 laser system) can be used for accuracy identification of the CNC machine-tools. The best solution is the combined use of both devices, shown in Fig. 3. The figure presents the sequential actions to determine the geometrical accuracy of the CNC machine-tools. In this case the laser system is used for a calibration after a major mechanical intervention on the CNC machine-tool, in contrast the Ballbar QC10 device, which is used for quick and frequent check-ups of the accuracy of the CNC machine-tool. Such activities could dictate regular or preventive maintenance of the CNC machine-tool parts ([7] to [9]).

3 ERROR CLASSIFICATION

Causes for the non-accuracy of the CNC machine-tools can be classified into more than 20 possible sources. Motion errors and their origins can be divided into the following two groups:

- Position-dependent errors
  - geometrical errors
  - errors of the positioning system
- Feed-motion-dependent errors

The error vector of the position-dependent error is defined only by the sliders, the table and the saddle. The position-dependent error can be classified into two groups: the geometrical error of geometrijske odstopke in na odstopke zaradi nenatančnosti položajnih elementov. Geometrijski odstopki na stroju so posledica nenatančnosti vodil na delovni mizi, in sicer nepopolne medsebojne pravokotnosti med osema, odstopanja od ravnosti vodil ter nelinearnega (kotnega zasuka) gibanja drsnika.

Nenatančnost položajnih elementov obsega odstopke v natančnosti lestvice oz. pogonskega sklopa na krogelnih vretenih, odstopanja detektorja kotnih zasukov, napako lestvice, nepravilno izravnavo prostega giba in nepravilno izravnavo razdalje med dvema zajetima točkama. V primeru izravnave prostega giba, je vrednost vedno enaka, spreminja se le predznak, ki je odvisen od smeri gibanja.

Na drugi strani pa odstopanja zaradi gibanja (podajanja) vključujejo odstopke zaradi podajanja, lepljenja, zdrsnega učinka ter odstopke na povratni zvezi določanja natančne lege. Velikost odstopkov je v teh primerih vedno nespremenljiva ([10] in [11]).

4 TEST BALLBAR NA STROJU CNC

Test z napravo QC10 je bil izveden na 3-osnem, navpičnem RK-frezalnem stroju Mori Seiki Frontier M1 v Laboratoriju za odrezovanje na Fakulteti za strojništvo v Ljubljani. Po nekaj predhodnih testih je bil narejen polni krožni test (360 °) v ravnini XY. Zaradi večje natančnosti rezultatov je bil krožni test (ki zagotavlja tudi najboljšo "sliko" o natančnosti stroja) izveden na dveh legah na obdelovalni mizi (v ravnini XY) in pri dveh višinah (z_1 = 0 mm in z_2 = 200 mm) (sl. 4). Temperatura okolice je bila med izvajanjem testa nespremenjena (24 °C), kar smo upoštevali pri temperaturnem umerjanju naprave Ballbar QC10 pred izvajanjem testa. V preglednici 2 in na sliki 5 so podani značilni odstopki, ki v veliki meri vplivajo na rezultate

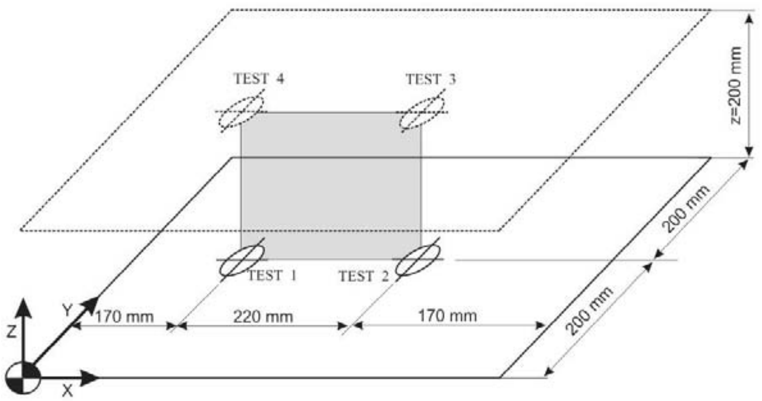
the machine-tool and the error of the positioning system. The machine's geometrical errors are caused by the guide way, such as the squareness error between two rectangular axes, the straightness error of the guide way and the angular motion of the slider.

The error of the positioning system consists of the error of the positioning scale or a ball screw driving system, the misalignment of the angle detector, the error of the position scale, the backlash compensation and the pitch-error compensation. In the case of the backlash compensation, the value is always constant, though the sign – plus or minus – may differ according to the feed direction.

On the other hand, the feed-motion-dependent error includes errors caused mainly by feed-rate, stick motion, slick slip, and mismatching of the position-loop gain. The amounts of these four types of errors are always constant ([10] and [11]).

4 BALLBAR TEST ON A CNC MACHINE-TOOL

The Ballbar test was made on a Mori Seiki Frontier M 3-axis vertical CNC machine-tool, used in the Laboratory for Cutting, Faculty of Mechanical Engineering, University of Ljubljana, Slovenia. After a few experimental Ballbar tests on the CNC machine-tool, a circular (360°) test on the XY-plane was performed. Due to more accurate results, circular tests (which provide the best "picture" of the machine's accuracy) were made at two test positions on the machine bed and at two heights (z_1 = 0 mm in z_2 = 200 mm), Fig. 4. During the tests, the surrounding temperature was 24°C, which was taken into consideration before the test, when the temperature calibration of the Ballbar QC10 device was made. In Table 2 and Fig. 5, characteristic errors, which



Sl. 4. *Lega jeklene kroglice A za posamezni test na RK stroju*
Fig. 4. *Position of steel ball A for each test on the CNC machine-tool*

Preglednica 2. *Primerjava najpomembnejših podatkov iz poročil Ballbar*
Table 2. *Comparison of the most important data from the Ballbar reports*

	obdelovalna miza (z_1= 0 mm) machine bed (z_1= 0 mm)		test na višini z_2 = 200 mm test on height z_2 = 200 mm	
	TEST 1	TEST 2	TEST 3	TEST 4
Kvadratnost [μm/m] **Squarness** [μm/m]	**-46,6**	**-38,9**	**-64,2**	**-72,0**
Neujemanje lestvice [μm] **Scaling mismatch** [μm]	**-13,7**	**-13,3**	**0,6**	**-1,0**
Najboljše ujemanje polmera [mm] **Best fit radius** [mm]	**149,9915**	**149,9935**	**149,9965**	**149,9958**
Napaka lestvice X [μm/m] Scaling error X [μm/m]	-79,2	-65,6	-22,1	-29,6
Napaka lestvice Y [μm/m] Scaling error Y [μm/m]	-33,5	-21,2	-24,0	-26,3
Zamik središča X [μm] Center offset X [μm]	-25,6	-29,2	21,3	2,6
Zamik središča Y [μm] Center offset Y [μm]	4,9	22,2	-11,5	43,5
Napaka lege [μm] Positional tolerance [μm]	58,9	47,8	43,8	49,8
Zaostali vrhovi X [μm] Reversal spikes X [μm]	-18,6	-17,8	-19,3	-17,6
Zaostali vrhovi Y [μm] Reversal spikes Y [μm]	-6,7	-6,4	-5,9	-7,7
Krožnost [μm] Circularity [μm]	29,5	29,9	27,6	26,6

meritev. Ti rezultati so tudi osnova za nadaljnjo podrobnejšo analizo rezultatov meritev, ki so predstavljeni v nadaljevanju.

4.1 Analiza rezultatov testa Ballbar

Iz podatkov predstavljenih v preglednici 2 in na sliki 5, je mogoče izpostaviti naslednje odstopke:

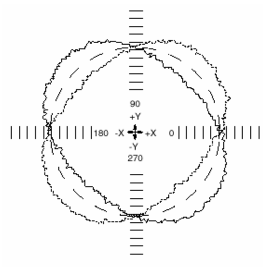
1. **Odstopek kvadratnosti,** ki neposredno opisuje pravokotnost vodil X in Y med seboj, kaže, da je kot med osema manjši od 90°, saj ima odstopek negativni predznak. Elipsa je prav tako nagnjena diagonalno za kot 45°. Iz testov lahko ugotovimo, da se odstopanje kvadratnosti povečuje z višino.
2. **Napaka lestvice** označuje razliko med izmerjenimi potmi na oseh. Negativna vrednost opisuje prehitevanje osi Y glede na os X. V našem primeru os Y prehiteva os X, pri čemer je prehitevanje na obdelovalni mizi (z_1 = 0 mm) izrazito večje kot na višini z_2 = 200 mm, kjer se prehitevanje komaj opazi.
3. **Najboljše ujemanje polmera** prikazuje najboljše ujemanje krožnice z zajetim krožnim podatkom. V

have a major influence on the test results, are presented. These results were also the basis for a detailed test analysis, presented later in the paper.

4.1 Ballbar test analysis

From the data presented in Table 2, and from Fig. 5, the following errors can be exposed:

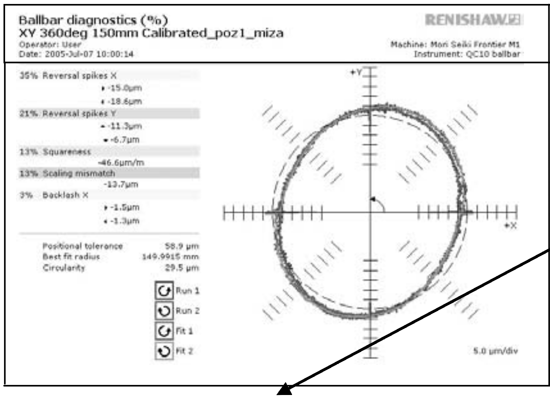
1. **The squareness error** directly describes the perpendicular position between the X- and Y-axis sliders, shows that the angle between the axes is less than 90°, because the value is negative. The oval shape is also distorted along the 45° diagonal. From the test we can find that the squareness error increases with the height.
2. **The scaling mismatch** error is the difference in the measured travels of the axes during the test. A negative value signifies that the Y-axis is over traveling the X-axis. In our case the Y-axis over traveled the X-axis; however, the over traveling on the machine bed (z_1 = 0 mm) is far more extensive than at the height z_2 = 200 mm, where the over traveling is hardly noticed.
3. **The best-fit radius** is the best circle that passes though the captured data. In our case the best-fit



Neujemanje podajanja servomotorjev / Servo mismatch

Slika ima obliko jajca ali lešnika, pri čemer sta kroga na diagonalah pod kotom 45° ali 135°. Odvisno od proti- ali urnega gibanja je odvisna tudi lega kroga (elipse). Večje odstopanje je navadno tudi odvisno od večjega podajanja. Neujemanje podajanja servomotorjev je tesno povezano z odstopanjem kvadratnosti. Odstopanje je podano v časovnih enotah, pri čemer opisuje, za koliko podajanje servomotorja ene osi prehiteva drugo os. Vrednost je lahko negativna oz. pozitivna, odvisno od smeri testa [6].

The plot has an oval or peanut shape, distorted along the 45° or 135° diagonal. The axis on which the plot is distorted switches if the feed changes from the clockwise direction to the counter-clockwise direction; both directions are shown on the plot. The amount of distortion usually increases with increasing feed-rate. This error is also connected to the squareness error. This value is the time in milliseconds by which one of the machines axis servos leads the other. The value is either positive or negative, depending on the axial direction of the test [6].



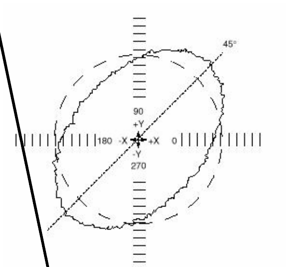
Ballbar diagnostics table
XY 360deg 150mm Calibrated_poz1_miza
Operator: User
Date: 2005-Jul-07 10:00:14
RENISHAW
Machine: Mori Seiki Frontier M1
Instrument: QC10 ballbar

Error	Magnitude		Independent circularity		Ranking
Backlash X	-1.5	-1.3 μm	1.5 μm	(3%)	(5)
Backlash Y	0.4	-0.3 μm	0.4 μm	(1%)	(9)
Reversal spikes X	-15.0	-18.6 μm	18.6 μm	(35%)	(1)
Reversal spikes Y	-11.3	-6.7 μm	11.3 μm	(21%)	(2)
Lateral play X	0.7	0.6 μm	0.6 μm	(1%)	(8)
Lateral play Y	-0.8	-0.5 μm	0.7 μm	(1%)	(7)
Cyclic error X	0.8	1.0 μm	1.0 μm	(2%)	(6)
Cyclic error Y	0.4	0.4 μm	0.4 μm	(1%)	(10)
Servo mismatch	-0.01 ms		0.1 μm	(0%)	(12)
Squareness	-46.6 μm/m		7.0 μm	(13%)	(3)
Straightness X	-0.3 μm		0.2 μm	(0%)	(11)
Straightness Y	0.2 μm		0.1 μm	(0%)	(13)
Scaling mismatch	-13.7 μm		6.8 μm	(13%)	(4)
Cyclic pitch X	2.5000 mm				
Cyclic pitch Y	20.0000 mm				
Scaling error X	-79.2 ppm				
Scaling error Y	-33.5 ppm				
Calculated feedrate	1000.5 mm/min				
Centre offset X	-25.6 μm				
Centre offset Y	4.9 μm				
Positional tolerance	58.9 μm				
Best fit radius	149.9915 mm				
Circularity	29.5 μm				

Kvadratnost/ Squareness

Slika ima obliko jajca ali lešnika. Oblika leži pod kotom 45° ali 135° pri protiurni in urni smeri vrtenja in je neodvisen od hitrosti podajanja. Odstopek kvadratnost opisuje pravokotnost med vodiloma X in Y. Pozitivno odstopanje kvadratnosti označuje, da kot med vodiloma presega 90°. Negativna vrednost odstopanja kvadratnosti pa označuje kot, ki je manjši od 90° [6].

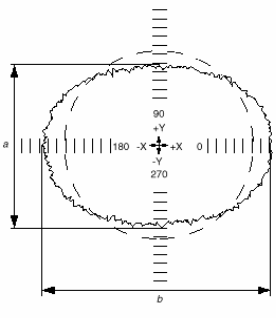
The plot has an oval or peanut shape, distorted along the 45° or 135° diagonal. The axis of distortion is the same for both clockwise and counter-clockwise directions, and is unaffected by feed-rate. The squareness error describes the perpendicular position between the X- and Y-axis slides. A positive squareness error indicates that the angle between the positive axes exceeds 90°. A negative squareness error (on a plot) indicates that the angle between the positive axes is less than 90° [6].



Napaka lestvice / Scaling error (mismatch)

Elipsa, ki nastane pri odstopanju lestvice, je lahko usmerjena v smeri 0° ali 90° in je neodvisna od smeri gibanja in navadno tudi neodvisna od podajanja. Napaka lestvice je razlika med opravljeno potjo v eni smeri glede na drugo. Na primer, če izvajamo krožni test XY mora biti vzdolžni premik v smereh X in Y povsem enak. Natančnost meritve je zelo odvisna od umerjenosti naprave Ballbar in od pravilne temperaturne izravnave. Odstopanje je podano v μm [6].

An oval shape distorted along the 0° or 90° axis is caused by a scaling error, which is unaffected by the direction of data capture, i.e., clockwise or counter-clockwise or federate. The scaling error is the difference in the measured travels of the axes during the test. For example, if the machine is performing a circle in the XY plane, the X and Y axes should move over exactly the same distance. The accuracy of the scaling error results depends heavily on the correct calibration of the Ballbar and on the correct application of thermal compensation. The scaling error is given in μm [6].



Sl. 5. *Rezultati testa na obdelovalni mizi (z_1 = 0 mm, lega 1); grafični in preglednični prikaz*
Fig. 5. *Test result on machine bed (z_1 = 0 mm, position 1), graphical and tabular presentation*

našem primeru se vrednost najboljšega ujemanja polmera povečuje z večanjem višine. To pomeni, da so vodila RK stroja v neobremenjen stanju izbočena.

Iz rezultatov testov je mogoče podati tudi natančnejšo oceno zmogljivosti RK stroja. Grobo sliko o geometrijski natančnosti stroja podajata prvi dve zgornji ugotovitvi. Na prvi pogled se odstopanja oz. združitev prve in druge ugotovitve izključujeta, toda natančnejša analiza pokaže zelo zanimiv rezultat. Druga ugotovitev, kot je bilo že omenjeno, označuje, da na obdelovalni mizi RK stroja os Y prehiteva os X. Na višini z_2 = 200 mm se prehitevanje komaj opazi.

Če upoštevamo drugo, prvo in tretjo ugotovitev, lahko podamo precej jasen sklep. Prehitevanje osi Y na obdelovalni mizi (z1) je na višini z_2 ***izravnano*** z nepravokotnostjo in ukrivljenostjo vodil. Iz rezultatov testov lahko sklepamo tudi, da je ukrivljenost vodila Y nekoliko večja kot je ukrivljenost vodila X. Ob teh ugotovitvah lahko podamo dokaj verjetno oceno, da bi dodatna obremenitev (masa) na obdelovalni mizi zmanjšala odstopanja na RK stroju, čeprav bi za dokončno potrditev te podmene morali narediti še kakšen dodaten test tudi pri različnih obremenitvah na obdelovalni mizi.

Najzahtevnejši del meritev z napravo Ballbar je analiza rezultatov. Zaradi velikega števila informacij, ki jih dobimo s testom je včasih težko razbrati vzroke za nenatančnost RK stroja. Za natančno analizo je potrebno pregledati in upoštevati vse podatke. Analiza mora upoštevati zgradbo in delovanje RK stroja. Zaradi tega analiza Ballbar zahteva človeka z izkušnjami pri uporabi naprave Ballbar in poznavanjem vseh mogočih odstopanj, ki se lahko pojavijo na RK stroju, kakor tudi dobro poznavanje njegovega delovanja.

5 SKLEP

V prispevku sta predstavljeni dve napravi Ballbar QC10 in laserski sistem ML10, s katerima lahko preverimo geometrijsko natančnost RK stroja. Najboljša je vzajemna uporaba obeh naprav. V tem primeru laserska naprava podaja absolutno natančne, a nekoliko počasno pridobljene meritve, za razliko od naprave Ballbar, ki poda hitre, a nekoliko manj točne rezultate o geometrijski natančnosti stroja. Pri analizi rezultatov iz testa Ballbar lahko nastanejo težave, toda laserska naprava ima tudi svoje pomanjkljivosti, še posebno pri ceni laserske opreme.

radius is getting larger with the increased height. Thus, the sliders in the unloaded situation have a convex shape on the CNC machine-tool.

From the test results, a more accurate evaluation of the performance of the CNC machine-tool can be made. A rough picture of the machine-tool accuracy is given in the first and second statements listed above. Although it seems that the first and second statements are contradictory, a closer look indicates a very interesting result. In statement 2 it was mentioned that the Y-axis over travels the X-axis on the machine bed. At height z_2 = 200 mm the over traveling is hardly noticed.

Considering statement 2 and statement 1 and 3, an evident conclusion can be made. The Y-axis over traveling on the machine bed (z_1) is, at the z_2 height, ***compensated*** with the perpendicularity and the slides' convexity. From the test results it can also be concluded that the Y-slide is more bent than the X-axis slide. Thus, a very credible estimation can be given. The extra load on the machine bed should lower the inaccuracy of the CNC machine-tool, although some extra tests with different loadings should be made on the CNC machine-tool for a full confirmation of this statement.

The Ballbar test-result analysis is the most demanding part of the measurements. Due to a large amount of information from the test results, it is sometimes difficult to identify real sources of inaccuracy of the CNC machine-tool. For an accurate interpretation a cross-sectional look over all of the data should be considered. The analysis should always correspond to the machine structure and its working principles. Thus, the Ballbar test analysis requires a person with experiences of using the Ballbar device, knowing the possible origins of the errors and knowledge about the working principles of CNC machine-tools.

5 CONCLUSION

In the paper we present two devices – the Ballbar QC10 and the ML10 laser system – which can determine the accuracy of a CNC machine-tool. The best solution is the use of both devices. In this case the laser device presents absolutely accurate and slow measurements, in contrast to the Ballbar device, which gives quick and a bit less accurate results, about the accuracy level of the CNC machine-tool. Some difficulties can occur when interpreting the Ballbar test results; however, the laser also has some disadvantages, especially the price of the laser equipment.

6 LITERATURA
6 REFERENCES

[1] Presentational CD for Ballbar device (2004) *Renishaw*, UK.

[2] E.-S. Lee, S.-H. Suh, Ch.-H. Shin (1985) Performance evaluation of NC controller using a Ball-bar, *Annals of CIRP*, Vol. 34/1/1985, pp. 402-407.

[3] Kopač J. (2003) Sočasno inženirstvo v teoriji in praksi = Concurrent engineering in theory and practice. *Strojniški Vestnik*, letnik. 49(2003)12, str. 566-574.

[4] Balic J. (2006) Model of computer aided NC machine tool programming. *Journal of Achievements in Materials and Manufacturing systems*, Volume 17, Issue 1-2, July-August 2006.

[5] Choi J.P., Minb B.K., Lee S.J. (2004) Reduction of machining errors of a three-axis machine tool by on-machine measurement and error compensation system. *Journal of Materials Processing Technology*, Vol. 155-156, Year 2004, pp. 2056-2064.

[6] »Help« program in Renishaw Ballbar software, version 5.06.17, *Renishaw*, UK.

[7] Presentational CD for Laser ML10 device (2004) *Renishaw*, UK.

[8] Okafor A.C., Ertekin Y.M. (2000) Vertical machining center accuracy characterization using laser interferometer, Part 1. Linear positional errors, *Journal of Materials Processing Technology*, Vol. 105, Year 2000, pp. 394-406.

[9] Iwasawa K., Iwamaa A., Mitsui K. (2004) Development of a measuring method for several types of programmed tool paths for NC machine tools using a laser displacement interferometer and a rotary encoder, *Precision Engineering*, Vol. 28, Year 2004, pp. 399-408.

[10] W. Knapp (1993) Test of the three-dimensional uncertainty of machine tools and measuring machines and its relation to the machine errors, *ETH Zurich*, pp. 459-464.

[11] Y. Kakino, Y. Ihara, Y. Nakatsu (1987) The measurement of motion errors of NC machine tools and diagnostics of their origins by using telescoping magnetic Ballbar method, *Annals of CIRP*, Vol. 36/1/1987, pp. 377-380.

Naslov avtorjev: Marko Cedilnik
prof. dr. Mirko Soković
dr. Jože Jurkovič
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
mirko.sokovic@fs.uni-lj.si
marko.cedilnik@fs.uni-lj.si
joze.jurkovic@fs.uni-lj.si

Authors' adress: Marko Cedilnik
Prof. Dr. Mirko Soković
Dr. Jože Jurkovič
University of Ljubljana
Faculty of Mechanical Engineering
Aškerčeva 6
1000 Ljubljana, Slovenia
mirko.sokovic@fs.uni-lj.si
marko.cedilnik@fs.uni-lj.si
joze.jurkovic@fs.uni-lj.si

Prejeto:
Received: 19.7.2006

Sprejeto:
Accepted: 25.10.2006

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

Strojniški vestnik - Journal of Mechanical Engineering 52(2006)11, 763-776
UDK - UDC 621.941:004.8
Kratki znanstveni prispevek - Short scientific paper (1.03)

Razvoj sistema za nadzor obrabe orodja pri struženju na temelju nevronskih mrež

Development of a Neural-Networks Tool-Wear Monitoring System for a Turning Process

Aco Antić[1] - Janko Hodolič[1] - Mirko Soković[2]
([1]University of Novi Sad, Serbia; [2]Fakulteta za strojništvo, Ljubljana)

Prispevek podaja rezultate razvoja sistema za nadzor obrabe orodja pri struženju v trdo, v laboratorijskih razmerah, z uporabo sodobnih metod umetne inteligence kakor so nevronske mreže. Eden od najbolj pomembnih dejavnikov, ki vplivajo na zanesljivost postopka struženja, je stanje orodja, zato je sistem za spremljanje stanja orodja razvit tako za laboratorijske kakor tudi razmere v praksi. Prispevek prikazuje raziskave, povezane z izbiro metod in strategije za določanje obrabe orodja po struženju, na podlagi serije laboratorijskih preizkusov. Nadzor stanja orodja je izvajan po posredni metodi na podlagi merjenja rezalnih sil, ki so najboljši pokazatelj stanja orodja med delovanjem, kombinirano z nevronskimi mrežami. Prav tako je predstavljena topologija nevronske mreže, uporabljene za struženje.

(Ključne besede: nadzor orodij, obraba orodij, struženje, sile rezanja, mreže nevronske)

This paper presents the results of developing a tool-wear monitoring system for hard turning in laboratory conditions. The system is based on modern artificial intelligence methods such as neural networks (NNs). One of the most dominant factors influencing the reliability of the turning process is the condition of the tool; thus, systems for monitoring tool conditions have been developed both in practice and in the laboratory. The paper describes research connected to the selection of methods and strategies for determining the tool-wear condition after turning on the basis of a set laboratory system model. The tool monitoring is performed by an indirect method on the basis of cutting force as one of best determiners of tool condition in the online working regime, combined with one of the artificial intelligence methods, i.e. neural networks. The paper also presents the topology of the neural network used for the training.

(Keywords: tool wear monitoring, turning, cutting forces, neural networks)

0 UVOD

Sodobni postopki izdelave zahtevajo zmanjševanje stroškov, ki pa jih lahko uresničimo takole: z ostrejšimi rezalnimi pogoji, s krajšimi časi izdelave in zmanjšanjem izmečka. Da bi vse to izpolnili v različnih izdelovalnih postopkih, je treba skrajno izkoristiti orodja in stroje. Stanje orodja med delom močno vpliva na zmanjšanje izmečka in zastojev v proizvodnji, ki se lahko vidijo neposredno skozi geometrijske, površinske in strukturne lastnosti obdelanih delov.

Povečevanje rezalnih sil je neposredno povezano z obrabo uporabljenega orodja, kar vodi k povečanju toplote in zato do sprememb strukture

0 INTRODUCTION

Modern procedures for part manufacturing impose cost reductions that can be realized in the following ways: increasing the turning regime, reducing the manufacturing time, and reducing the number of rejects. In order to accomplish this in various processing procedures, extreme efforts from tools and machines are required. The condition of the processing tool is very influential on reducing rejects and hold ups in manufacturing, which can directly be seen through the geometric, surface and structural properties and the characteristics of the processed part.

The increase in the cutting forces is directly linked to the wear condition of a processing tool, which obdelane površine in izmer obdelovanca. Ustrezen čas zamenjave orodja pomeni zelo pomembno sestavino v postopku obdelave, zato bo temu, na primeru struženja, posvečena posebna pozornost v tem prispevku. Številni avtorji so upoštevali mehanizme, ki vplivajo na pojav obrabe orodja pri struženju. Na primer Scheffer idr. [1] verjamejo da obstajata dve glavni značilnici, ki vplivata na zanesljivost pri struženju: rezalna hitrost in vrednost rezalne sile, ki se pojavi pri struženju. Raziskovalci, ki se ukvarjajo s to tematiko, so pokazali da, z vidika pričakovanja največje obstojnosti, večje spremembe hitrosti in rezalne sile niso dovoljene.

Iz izkušenj je znano, da obraba na prosti ploskvi neposredno vpliva na kakovost obdelane površine ter, da na porušitev rezalnega robu vpliva kotanjasta obraba cepilne ploskve, ki nastaja zaradi kemičnih, difuzijskih pojavov med rezanjem. Izkušnje govorijo tudi, da pojav obrabe orodja poteka nepretrgano in postopno, zato lahko določimo stopnjo obrabe orodja, ker pa se porušitev orodja pojavi trenutno, je izjemnega pomena nepretrgan nadzor orodja za zaznavo porušitve in pravočasno odzivanje. Sklenemo lahko, da druge metode uporabimo za nadzor porušitve orodja in navzkrižje v povezavi z nadzorom obrabe orodja.

0.1 Nadzor obrabe orodja

Sistemi za nadzor obrabe orodja tako stare kakor tudi nove generacije kot merno veličino uporabljajo postopkovne parametre, ki so posredno povezani z obrabo orodja in so lahko: sile ali vibracije, zvočna emisija (ZE) ipd. Na postopek tudi vplivajo razmere, pri katerih ta poteka, kot npr. geometrijska oblika orodja, material orodja in obdelovanca ipd. Za modeliranje nelinearnih odvisnosti, ki se lahko izločijo iz merilnih signalov postopkovnih razmer, obrabe orodja ali porušitve orodja se uporablja nevronske mreže, sisteme mehke logike ali kombinacijo obeh metod. Balazinski idr. [2] so dognali, da se inteligentne nevronske mreže in nevronske mehke tehnike močno preučujejo in pomenijo najbolj izbirano inteligenčno mrežo metod (umetna inteligenca - UI) za spojitev nadzorovanih značilnosti. Vendar, pri tržno dosegljivih sistemih prevladuje pristop "eno zaznavalo/eno orodje v postopku" in je uporaba metod UI redkokdaj uporabljana. V svojem preglednem članku Siek [3] trdi, da se je v preteklem času večina raziskovalcev ukvarjala z nalogami določanja obrabe ali porušitve. Obraba orodja je pojem, ki ni enotno definiran in ga je

leads to a heat increase and hence to a structure change of the processed surface of the workpiece and its dimensions. Timely and appropriate tool replacement represents a very important component in processing, and therefore in turning, to which significant attention will be given in this paper. Many authors have considered mechanisms influencing the tool-wear process during turning. For example, Scheffer et al. [1] believe there are two principal characteristics influencing the reliability of turning: cutting speed and the value of the force appearing during turning. Research dealing with this topic has shown that, from the point of view of the optimum tool-life expectancy, large variations in speed and cutting force are not allowed.

Based on experience, it is known that flank wear directly influences the quality of the processed surface, and that insert breakage is influenced by crater wear appearing because of a diffusion chemical reaction during processing. Experience says that the tool-wear process moves on continually and gradually, i.e., that the insert wear degree can be determined and one can react in time, while the breakage comes suddenly and continuous tool monitoring is essential for breakage detection. The conclusion is that other methods can be used for tool-breakage monitoring and collisions in relation to tool-wear monitoring.

0.1 Monitoring of tool wear

Systems for monitoring tool wear, both old and new generation, use process parameters that are indirectly linked to tool wear, i.e., force or vibration, acoustic emissions (AEs), etc. The process is also influenced by conditions under which the processing is taking place, like tool geometry, tool material and product, etc. For modelling non-linear dependencies that are separated from the measuring signal, processing conditions, tool wear or tool breakage, neural networks, fuzzy logic systems or a combination of both methods are used. Balazinski et al. [2] state that intelligent neural networks and neural fuzzy techniques are intensively studied and they present the most selected intelligence network (artificial inteligence - AI) methods for merging the monitored properties. However, with commercially available systems, the approach "one sensor/one tool per process" is dominant, and the application of the AI method can rarely be found. In his survey paper, Siek [3] established that, in the previous period, most researchers elaborated on the tasks of classifying wear or breakage. Tool wear is a term not uniformly defined and it has to be defined clearly before stating the treba jasno definirati pred izvajanjem nadzora. Porušitev orodja je vedno definirana in določena kot dve stanji: porušeno ali neporušeno (orodje). Določitev obrabe orodja mora uporabljati več ko dve stanji, da je mogoče nepretrgana ocena razmer pri obrabi ([4] in [5]).

Parametri za definiranje obrabe so povprečna in največja širina obrabe proste ploskve, pa tudi globina, dolžina in širina kotanje na cepilni ploskvi. Merilo, ki naj bi enolično definiralo obrabo, mora biti stalno, da bo predstavljalo stanje obrabe orodja. Če je obraba definirana v dveh skupinah (širina obrabe), to postane pogosto problem - lahko prepoznamo samo nova ter izrazito obrabljena orodja. Za nadziranje obrabe v praksi je treba postaviti več skupin obrabe, ki so praktično zelo obetajoča strategija nadzora. Lahko rečemo, da je obraba nepretrgan in monotono naraščajoči postopek, zato naj bi za nepretrgano ocenjevanje bilo najbolj ustrezno fizikalno postopanje.

Zadnja leta je opazno izrazito delo na uporabi metode umetne inteligence (UI) pri nadzoru obrabe orodja. Tako Balazinski idr. [2] primerjajo uporabo treh metod UI: nevronsko mrežo z veriženjem naprej, mehki sistem za podporo odločanju ter mehki sklepni sistem, ki temelji na umetni nevronski mreži. Žarišče ni samo na natančnosti napovedi obrabe orodja, temveč tudi na praktični uporabnosti predstavljenih metod. Ozel in Nadgir [6] predlagata uporabo nevronskih mrež za učenje z vzvratnim razširjanjem napake, za napovedovanje obrabe proste ploskve pri struženju v trdo. Merjenje sil, nastalih v rezalnih postopkih, je izvedeno z dinamometrom, ki omogoča merjenje treh komponent sile.

V tem primeru sta razmerje sil in razmere v postopku vključeni kot značilnosti vstopne ravni nevronske mreže; skrita raven ima 30 nevronov, izstopna raven pa sestoji iz osem nevronov, ki so bili binarna ponazoritev eksperimentalno merjene obrabe proste ploskve oziroma osem značilnic razmer pri obrabi orodja. Za napoved obrabe proste ploskve so bili zajeti dobri rezultati z uporabo te metode nevronske mreže.

Kothamasu in Huang [7] ter Scheffer idr. ([1] in [8]) tudi predlagajo drugo metodo, ki temelji na kombinaciji statičnih in dinamičnih nevronskih mrež.

1 PREDLOG MODELA SISTEMA ZA NADZOR

Predlagani model sistema za nadzor orodja je lahko v bistvu opazovan skozi štiri sklope

monitoring task. Tool breakage is always defined and classified by two states, broken or not broken. The tool-wear classification has to use more than two tool states, i.e., it should be a continual evaluation of the wear condition ([4] and [5]).

The parameters defining wear are the average and maximum width of the flank wear, as well as the depth, length and widths of the crater wear. Criteria that should define wear as uniform need to be fixed in order to present the state of the tool wear. If wear is defined in two groups (wear width), it becomes quite wide and one can recognize only new and significantly worn tools. To monitor wear in practice, it is necessary to establish several wear groups, which in practise represents a very promising monitoring strategy. It can be said that wear is a continual and monotonously increasing process; therefore, continual evaluation would suit the physical processing most appropriately.

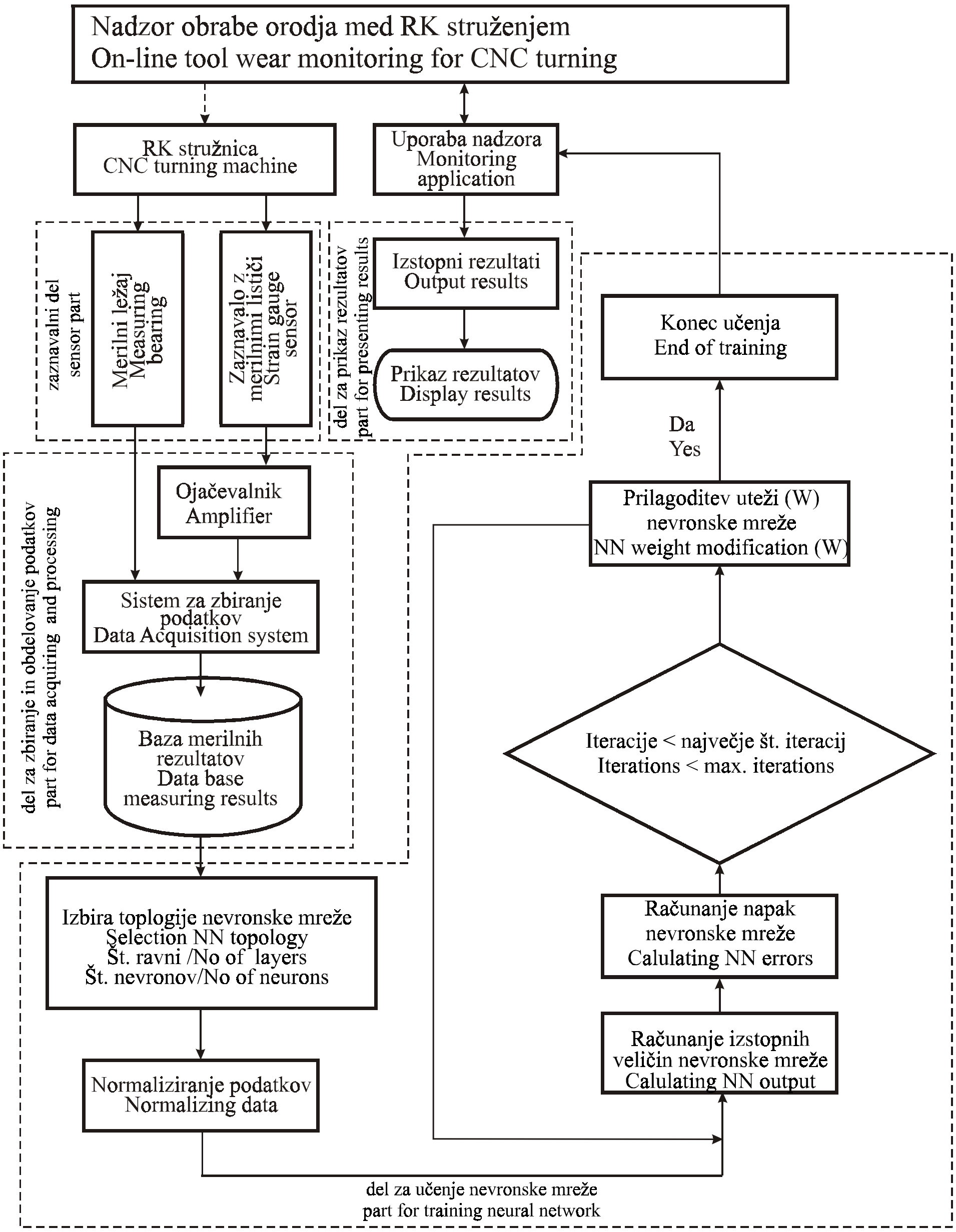
Recent years have seen intensive work to apply the artificial intelligence (AI) method for monitoring tool wear. Thus, Balazinski et al. [2] compare the application of three AI methods: a feed-forward back-propagation (FF-BP) neural network, a fuzzy-decision support system (FDSS) and an artificial-neural-network-based fuzzy-inference system (ANNBFIS). The focus is not only on the accuracy of the tool wear prediction, but also on the practical usability of the presented methods. Ozel and Nadgir [6] propose the use of back-propagation neural networks for predicting flank wear during hard turning. Force-measuring tests that appear during the cutting processes are performed using a dynamometer that could measure three force components.

In this case, the force ratio and the processing conditions are included as a characteristic of the neural-network input layer; the hidden layer had 30 neurons, and the output layer consisted of 8 neurons, which was a binary representation of the experimentally measured flank wear, i.e., 8 condition characteristics of tool wear. For flank-wear predictions, good results were acquired using this neural-network method.

Kothamasu and Huang [7] and Scheffer et al. ([1] and [8]) also propose another method based on a combination of static and dynamic neural networks.

1 PROPOSAL FOR A MONITORING SYSTEM MODEL

The proposed tool-monitoring system model can basically be observed through four segments



Sl. 1. *Potek razvitega sistema nadzora orodja, ki temelji na nevronskih mrežah*
Fig. 1. *Algorithm of the developed tool-monitoring system based on neural networks*

sestavljene v celoto, ki uporablja nevronsko mrežo za učenje z vzvratnim razširjanjem napake in je povezana s krmilno enoto stroja, kot je prikazano na sliki 1.

Posebni sklopi sistema so:
- zaznavalni del,
- del za zbiranje, obdelovanje in analizo podatkov,
- del za učenje nevronske mreže,
- del za predstavitev rezultatov.

united in a whole, i.e., using back propagation, connected with the machine-managing unit, as shown in Figure 1.

The special segments of the system are:
- the sensor part,
- the part for data acquisition, processing and analyzing,
- the part for training the neural network,
- the part for presenting the results.

Zaznavalni del obdelovalnega stroja je narejen iz merilnega ležaja, ki je nameščen na sprednjem delu glavnega vretena stroja. Poleg merilnega ležaja je tukaj tudi drugo zaznavalo, ki deluje na načelu merilnih lističev, nameščenih na uporabljeno držalo orodja in posebno oblikovanih za ta primer merjenja rezalnih sil, ki se pojavljajo na tem orodju.

Del za zbiranje, obdelovanje in analizo podatkov vsebuje standardno kartico A/D ED 300, ki sprejema vstopne podatke iz sedanjih zaznaval, pretvarja jih v digitalne informacije ter pošilja v računalnik z bazo podatkov. Za tok informacij je odgovorna programska oprema, imenovana ED LINK, ki dopušča možnost programiranja hitrosti prenosa in vrsto vstopnih podatkov ([9] do [11]).

Nevronska mreža, vgrajena v obravnavni sistem je mreža z več ravnmi zaznavanja, z razširjanjem signala v eni smeri in je ena od najbolj znanih vrst nepovratnih mrež (brez povratnih zvez). Mreža ima tri ravni: vstopna ravnina vsebuje tri nevrone, vmesna skrita ravnina vsebuje m nevronov, izstopna ravnina ima en nevron.

Sistem programske opreme je oblikovan, da zbira in obdeluje informacije med delovanjem in upravlja delovanje komponent strojne opreme, zato lahko temelji na seriji omejitev za izvajanje nadzora obrabe orodja. Za določitev stopnje obrabe orodja lahko uporabimo primerjalno analizo krivulj obrabe, dobljenih pri sistemu učenja z uporabo nevronskih mrež. Določanje preostalega časa obstojnosti orodja temelji na podlagi razvoja obrabe, pridobljenega s primerjalno analizo krivulje obrabe in realnih razmer.

2 NEVRONSKA MREŽA ZA NADZOR OBRABE ORODJA

2.1 Predhodna obdelava in učenje

Kakor je že navedeno, ima nevronska mreža tri vstope, ki usmerjajo vrednosti iz zaznavala na nosilniku orodja, izmerjene velikosti sil iz merilnega ležaja in rezalne hitrosti. Z uporabo teh treh vrednosti nevronska mreža na izstopu določa vrednost obrabe proste ploskve VB v istem trenutku.

Za potrebe postopka učenja je bila oblikovana serija, ki vsebuje 30.900 vstopnih vektorjev in enako število natančnih vrednosti izstopnih spremenljivk. Pri oblikovanju serije je bila posebna pozornost posvečena predstavniškim

The sensor part of the machine tool is made of a measuring bearing placed in the front bed of the machine tool's main spindle. In addition to the measuring bearing, there is also another sensor working on the principle of a measuring strain gauge, placed on the processing tool holder and designed specially for this case, for measuring the cutting forces appearing on the tool itself.

The part for data acquisition, processing and analyzing contains a standard A/D card ED 300, which receives input data from the existing sensors, converts them to digital information, and sends them to a computer database. For information flow, the composite software named ED LINK is responsible, allowing the possibility for programming the conditioning speed and the type of input data ([9] to [11]).

The neural network built into the system is a multi-layer perception network with signal spreading in one direction (feed-forward topology), and one of the best-known types of feed-forward neural networks. The network has three layers: the input layer contains three neurons, the intermediate hidden layer contains m neurons, and the output layer has one neuron.

The software system is designed to acquire and process the information in an online work regime and to manage the work of hardware components, so it can be based on set limitations for the monitor processing and the tool wear. To establish the degree of tool wear we can utilize comparative analysis of the wear curves obtained by system training using neural networks. Determining the leftover tool duration is set on the basis of the wear trend gained by a comparative analysis with the wear curve and real conditions.

2 NEURAL NETWORK FOR TOOL-WEAR MONITORING

2.1 Pre-processing and training set

As already stated, the neural network has three inputs to which the force values from the sensor on the tool holder, the measured force size from the measuring bearing, and the cutting speed are directed. Using these three values, the neural network at its output evaluates the values of flank wear VB in the same time moment.

For the requirements of the training process, a set was formed containing 30,900 input vectors and the same number of precise values of output variable. In creating the set, special attention was podatkom, tako da so izbrani podatki pokrili celotno območje mogočih vrednosti vstopnih parametrov in ustrezali dejanskim spremembam razmer. Serija za učenje je oblikovana tako, da zagotovi, da nevronska mreža pravilno oceni odvisnost vstopnih vrednosti in izstopne spremenljivke na celotnem območju vstopnih veličin.

Zato da bi imeli učinkovito učenje so bile vse veličine v seriji za učenje poprej normalizirane. Normaliziranje je bilo izvedeno tako, da je vsaka vstopna in izstopna veličina v seriji za učenje imela povprečno vrednost enako nič in je bil standardni odmik omejen na enotno vrednost. Za i-to vrednost vstopnega vektorja, iz spremenljivk, zaznanih z merilnim ležajem FRprom, lahko zapišemo enačbo za normalizacijo v naslednji obliki:

given to data representatives, i.e., data were selected to cover all the intervals of possible values of input variables and to be appropriate for the real change conditions. The training set formed in such a manner ensured that the neural network correctly approximated the dependence of input values and output variables on the whole range of input sizes.

In order to have efficient training, all the sizes in the training set were previously normalized. Normalization was performed in such a way that every input and output size in the training set had an average value equal to zero, and a standard deviation reduced to the unit value. For the i-th value of the input vector from the variable registered by the measuring bearing FRprom, normalization formula can be written in the following way:

$$\hat{p}_i = \frac{p_i - p_{sr}}{s_p} \quad (1),$$

kjer je: / where:

$$p_{sr} = \frac{1}{N}\sum_{i=1}^{N} p_i \quad (2)$$

srednja vrednost in: / is an average value, and:

$$s_p = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(p_i - p_{sr})^2} \quad (3)$$

standardni odmik vstopnega vektorja, določenega prek celotne serije za učenje (N = 30.900). Enačbe za preostale spremenljivke v seriji za učenje bi lahko zapisali podobno.

Pred postopkom učenja, ne glede na normaliziranje podatkov, je bilo treba izpeljati izbiro topologije nevronske mreže. Ker so vrednosti izstopne spremenljivke VB odvisne edino od trenutnih vrednosti vstopnih spremenljivk, je bila večravenska zaznavna mreža z razširjanjem signala v eni smeri izbrana kot topologija mreže. Poleg tega teorija navaja, da je funkcija, ki jo mora nevronska mreža oceniti, izrazito nelinearna; zato je bila za prožilno funkcijo nevronov v skriti ravnini izbrana sigmasta funkcija ([12] in [13]):

is a standard deviation of the promess variable input vector defined over the whole training set (N = 30,900). The formulas for other variables in the training set can be written similarly.

Before the training process, apart from data normalization, it was necessary to select the neural-network topology. Since the values of the output variable VB depend solely on the momentary values of the input variables, a multi-layer perception network with a signal spreading in one direction (feed-forward topology) was selected for the network topology. In addition, the theory stated that the function that the resultant neural network had to approximate was distinctly non-linear; hence, for the output function of the neurons in the hidden layer a sigmoid function ([12] and [13]) was selected:

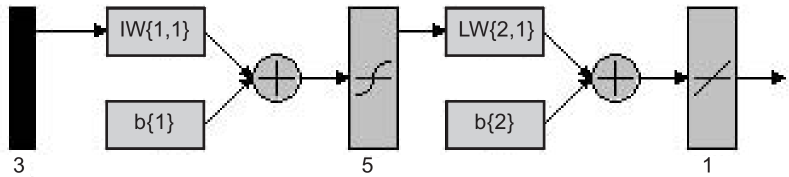
$$y(net_i) = \frac{2}{1+e^{-net_i}} - 1 \quad (4),$$

kjer je: / where:

$$net_i = \sum_{j=1}^{M} w_{ji} x_j - b_i, \quad (5)$$

vsota vrednosti vstopne mreže, pomnožena z ustreznimi koeficienti uteži nevrona.

is the sum of the input network sizes multiplied by the appropriate neuron weight coefficients.



Sl. 2. *Topologija nevronske mreže*
Fig. 2. *Neural-network topology*

Uporabljena mreža ima tri ravni: vstopno, skrito in izstopno, kar je prikazano na sliki 2; predstavlja zadostno število ravni za problem, ki ga obravnava, upoštevajoč dejstvo, da več ravensko zaznavanje z eno skrito ravnino lahko oceni poljubno dejansko zvezno funkcijo.

V vstopni kakor tudi izstopni ravnini je bilo število nevronov določeno s številom vstopnih veličin, tako je vstopna ravnina vsebovala tri nevrone, ki ustrezajo vstopnim spremenljivkam (FRtool, FRprom, Vm/min), izstopna ravnina pa je vsebovala en nevron, katerega izstopna veličina je imela vrednost ocenjene velikosti obrabe proste ploskve VB.

Število nevronov v skriti ravnini je bilo določeno s preizkusi, s primerjanjem lastnosti mreže z različnimi števili nevronov v skriti ravnini. Med preizkusi je bila mreža testirana z dvema do sedmimi nevroni v skriti ravnini in za vsako topologijo so bile izvedene številne ponovitve z enakimi serijami za učenje mreže, tako da so bile značilnosti vsake topologije določene kar se da primerno. Mreže z majhnim številom nevronov (dvema ali tremi nevroni) v skriti ravnini niso pokazale zadovoljivih rezultatov, kar bi lahko pripisali nezadostno bogati strukturi mreže in kar kaže na majhno zmožnost funkcije približevanja. Mreže s petimi ali več nevroni v skriti ravnini se zadovoljivo približajo odvisnosti razmerja med vstopnimi in izstopnimi veličinami, tako da je neka od teh topologij ustrezna za uporabo. Pri izbiri končne topologije je bila upoštevana splošna usmeritev, ki pravi, da naj bi bilo končno število nevronov v nevronski mreži čim manjše. S tem povečamo zmožnosti posploševanja mreže in se izognemo pojavu pretirane zahtevnosti. Ob upoštevanju omenjenih dejstev je bila izbrana kot dokončna struktura mreža s petimi nevroni v skriti ravnini.

Učenje nevronske mreže je bilo opravljeno s prožno spremembo osnovnega algoritma za učenje z vzvratnim razširjanjem napake, ki je bil oblikovan za nevronsko mrežo z drobljenjem prožilne funkcije, ki

The network used, as already said, had three layers: input, hidden and output, as shown in Figure 2; it presented a sufficient number of layers for the problem under observation, considering the fact that the multi-layer perception with one hidden layer could, with arbitrary accuracy 0, uniformly approximate any real continual function on the real final axis.

In the input as well as the output layer, the number of neurons was determined by the number of inputs, i.e., outputs, so that the input layer contained three neurons that corresponded to the input variables (FRtool, FRprom, Vm/min), and the output layer contained one neuron whose output gave the value of the estimated size of the flank wear VB.

The number of neurons in the hidden layer was determined by experiments comparing the network performances with a different number of neurons in the hidden layer. During the experiment, networks were tested with two to seven neurons in the hidden layer, and for every topology several trainings with the same training set were performed so that the performances of every topology could be estimated as objectively as possible. Networks with a small number of neurons (two and three neurons) in the hidden layer did not present satisfactory results, which can be attributed to an insufficiently rich network structure that implied a small capacity for the function approximation. Networks with five or more neurons in the hidden layer successfully approximated the input-output dependence, so any of those topologies was appropriate for implementation. In selecting the final topology, a general direction was used, saying that the total number of neurons in the neural network should be as small as possible, since in that way the generalization network abilities were increasing and the appearance of "over fitting" was avoided. Considering all the above mentioned, a network with five neurons in the hidden layer was selected for the final network structure.

Training of the ANN was performed with a "resilient" modification of the basic back-propagation algorithm that was designed for an ANN with skrči neskončno področje vstopne veličine v končni korak izstopne veličine (npr. sigmasta funkcija). Te funkcije bi lahko povzročale težave pri uporabi osnovnega algoritma za učenje z vzvratnim razširjanjem napake, ker ima gradient lahko zelo majhno vrednost in zaradi tega povzroča majhne spremembe pri utežnih koeficientih, ki vodijo k dolgem učenju. Zato je prožni algoritem uporabljen samo za označevanje delnih sklepov, da bi določili smer sprememb utežnih koeficientov, medtem ko je bila velikost spremembe določena s posebnim parametrom, čigar vrednost je bila med učenjem spreminjana po posebnem algoritmu ([14] in [15]).

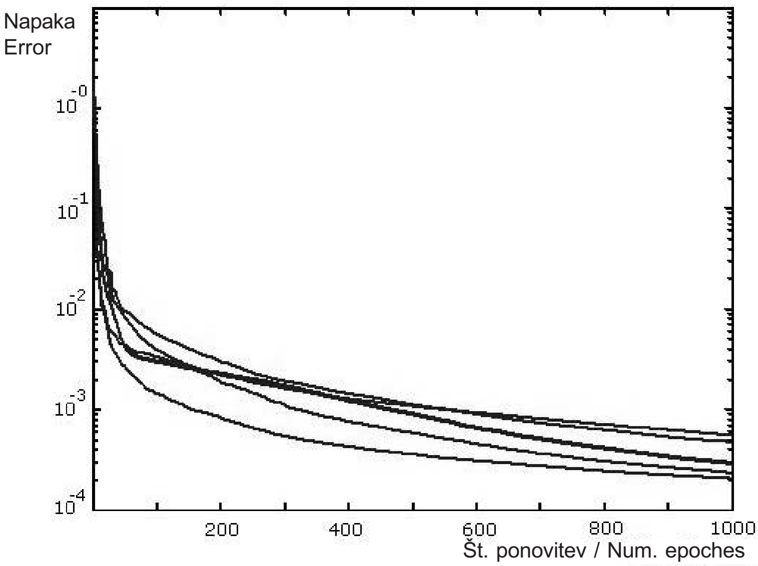
Končna topologija nevronske mreže je bila urjena večkrat z enako serijo za učenje, vsakokrat z novo, naključno ustvarjeno začetno vrednostjo utežnih koeficientov (sl. 3). Za največjo vrednost ponovitev je bilo vzeto število 1.000, ker je bilo ugotovljeno, da naslednje ponovitve niso znižale napake nevronske mreže pri neki značilni vrednosti. Vsako učenje nevronske mreže se konča z vmesno kvadratno napako (izračunano čez celotno serijo za učenje) v območju med 10^{-3} in 10^{-4}. Ta napaka je bila izračunana z normaliziranimi podatki; da bi torej dobili dejansko vrednost vmesne kvadratne napake je bilo treba pomnožiti dobljeno vrednost z vrednostjo standardnega odmika obrabe proste ploskve VB.

Pri seriji za učenje je imel standardni odmik obrabe proste ploskve vrednost 0,0013, dejanska vrednost vmesne kvadratne napake pa je bila med 10^{-6} in 10^{-7}.

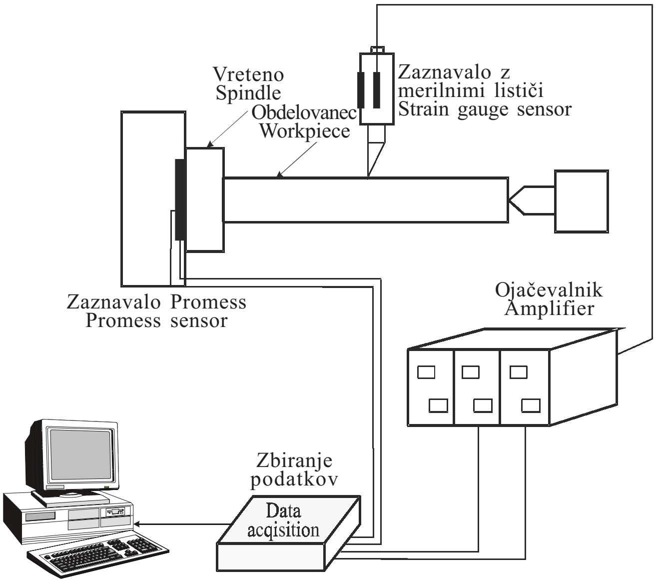
"squashing" activation functions, i.e., functions that compress the infinite input area into the final output interval (like a sigmoid function). These functions could cause a problem while using the basic back-propagation algorithm, since the gradient could have very small values and therefore cause small changes in the weight coefficients, which led to long-term training. Thus, the "resilient" algorithm utilized only the sign of partial inference in order to determine the direction of the weight-coefficient changes, while the change size was determined by a special parameter whose value was, during the training, changed, following the special algorithm ([14] and [15]).

The neural network's final topology was trained several times with the same training set, but each time with the new, randomly generated, initial values of the weight coefficients (Fig. 3). For the maximum value of iterations, the value 1,000 was adopted, since it was noticed that in the later iterations the neural-network error was not reduced by any significant value. Each neural-network training finished with an intermediate square error (calculated over the entire training set) in the interval between 10^{-3} and 10^{-4}. This error was calculated with the normalized data; so, to get a real value of the intermediate square error it was necessary to multiply the gained value by the value of the standard deviation of the flank wear VB.

On our training set, the standard deviation of flank wear had the value 0.0013, so the real value of the intermediate square error was between 10^{-6} and 10^{-7}.



Sl. 3. *Sprememba vmesne kvadratne napake med učenjem nevronske mreže*
Fig. 3. *The change of intermediate square error during neural-network training*



Sl. 4. *Osnovna zgradba eksperimentalnega merilnega sistema*
Fig. 4. *Basic configuration of the experimental measuring set-up*

3 IZVEDBA PREIZKUSOV

Parametri rezanja so bili izbrani tako, da so ustrezali industrijskim razmeram v realni proizvodnji. Parametri stroja za posamezni preizkus so podani v preglednici 1. Preizkusi so bili ponavljani v enakih razmerah kakor pri učenju,

3 EXPERIMENTAL SET-UP

The machine parameters were selected in order to respond to an industrial application in real manufacturing. The machine-tool conditions for every experiment are presented in Table 1. The experiments were repeated under the same conditions for the

Preglednica 1. *Eksperimentalni parametri*
Table 1. *Experimental parameters*

	Preiz. 1 Exp. 1	**Preiz. 2 Exp. 2**	**...**	**Preiz. 10 Exp. 10**
Obdelovalni stroj Machine tool	INDEX GU 600			
Držalo orodja Tool holder	PTGNL 25x25			
Ploščice Inserts	TNMG 220408			
Globina rezanja [mm] Cutting depth [mm]	1 mm			
Rezalna hitrost [m/min] Cutting speed [m/min]	200			
Material obdelovanca Workpiece material	Č.4730			
Število prehodov Number of passing	110	132	...	112
Skupni čas [min] Total time [min]	36	43	...	37
Premer [mm] Diameter [mm]	60	60	...	60
Dolžina prehoda [mm] Passing length [mm]	10	10	...	15

vrednotenju in urjenju modela nevronske mreže. V bistvu sta spreminjani rezalna hitrost in število učenj mreže. Bilo je skupno deset preizkusov, vsi so potekali z enako osnovno izoblikovanostjo. Vendar je bilo nekaj razmer pri preizkusih spreminjanih, da bi izločili motnje in ugotovili lastnosti ustreznega nadzorovanega signala. Posebna pozornost je bila na zagotavljanju, da so vse razmere pri preizkusih enake razen parametrov, ki so bili spreminjani nadzorovano. Osnovna izoblikovanost merilnega sistema pri preizkusih je prikazana na sliki 4 in sestoji iz RK stružniceopremljene z zaznavali za merjenje rezalne sile - zaznavalo Promess in posebej oblikovano zaznavalo z merilnimi lističi, pritrjenimi na držalo orodja.

possibilities of training, verifying and testing the neural-network model. Basically, the cutting speed and training number varied. There were ten experiments in total, all of them with the same basic configuration. However, some of the experimental conditions were changed to isolate disturbances and identify the properties of an appropriate monitoring signal. There was a special focus on ensuring that all the experimental conditions remained the same, except for the parameters that were changed under control. The basic configuration of the experimental measuring set-up is shown in Figure 4, and it contains a CNC lathe equipped with sensors for measuring the cutting force, those being: a promess sensor and a specially designed sensor with a measuring strain gauge placed on the tool holder.

4 REZULTATI

Izbrani model se je pokazal kot zanesljiva metoda za nadzor obrabe orodja med struženjem v trdo. Med raziskavo je bilo uporabljeno in preštudirano nekaj različnih izoblikovanj mrež za njihovo uporabo pri nadzoru obrabe orodja.

Poznano je, da so statične rezalne sile dober kazalnik obrabe orodja, vendar ustrezna analiza dinamičnih rezalnih sil lahko tudi poda zadovoljive značilnosti za nadzor obrabe. Slika 5 prikazuje komponente rezalne sile, izmerjene med nadzorom obrabe orodja.

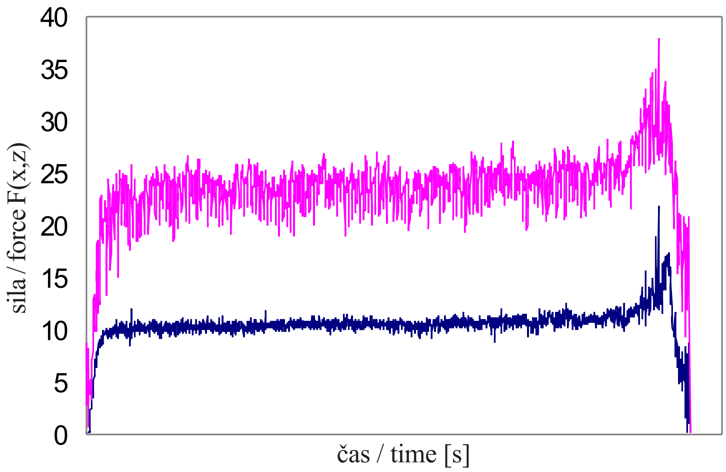
Obraba orodja (VB) je bila izmerjena po vsakem prehodu in vrednost vnesena v preglednico. Merjenje obrabe je bilo izvedeno z orodjarskim mikroskopom s 30-kratno povečavo. Rezalne ploščice, uporabljene pri preizkusih, so

4 RESULTS

The selected appropriate model was established to be a relatively reliable method for monitoring the tool wear during hard turning. During the research, several different network configurations were used and studied for their application in monitoring tool wear during hard turning.

It is known that static cutting forces are good tool-wear indicators; however, adequate dynamic analysis of the cutting forces can also give satisfactory properties for wear monitoring. Figure 5 presents the cutting-force components measured during tool-wear monitoring.

The tool wear (VB) was measured after each turning and the value suiting one passing was linearly put into the table. The wear measuring was performed using a Tool microscope with a 30 times magnification.



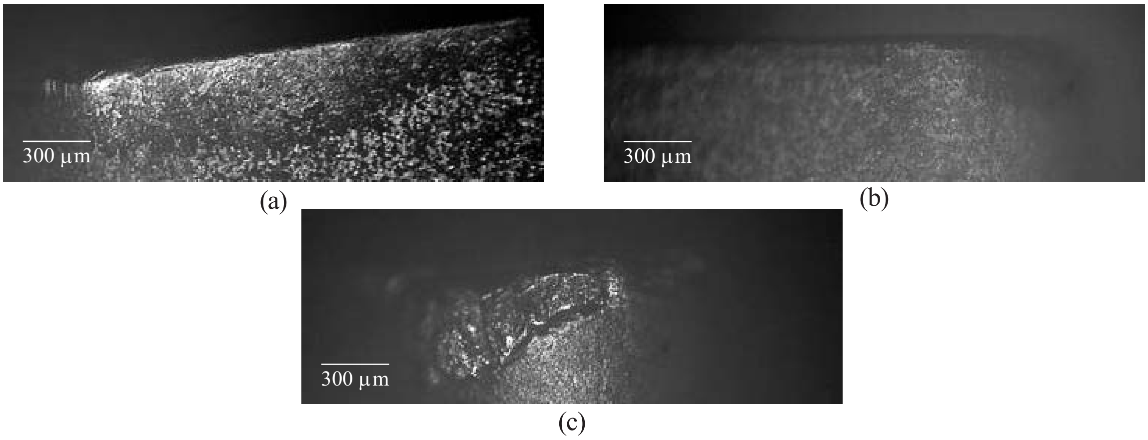
Sl. 5. *Rezalne sile, izmerjene med nadzorom*
Fig. 5. *Cutting forces measured during monitoring*

bile prekrite s prevleko iz TiN. Njihova pričakovana obstojnost se je nagibala k nenadnemu koncu, potem ko je prevleka izginila z rezalnega robu, kar naj bi bilo razvidno iz naglega in nenadnega skoka rezalne sile. Slika 6 kaže videz obrabljenih ploščic med izvajanjem preizkusov: a) ploščica iz preizkusa 1, b) ploščica iz preizkusa 3, c) ploščica iz preizkusa 5.

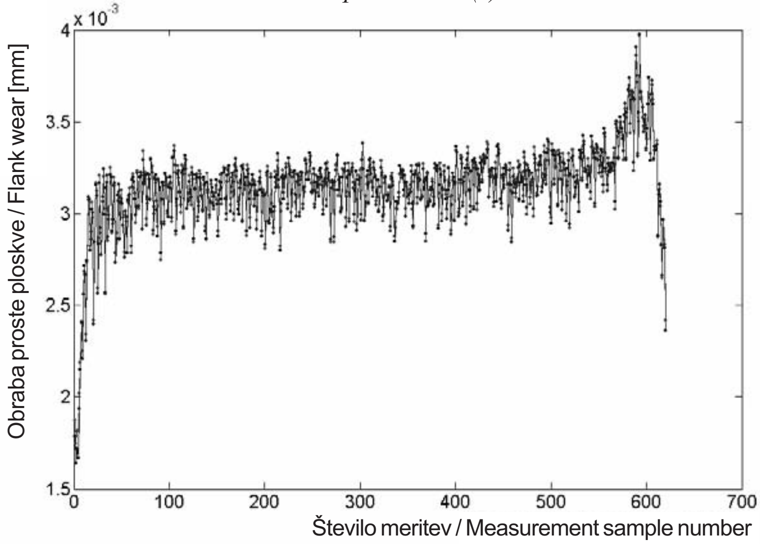
Slika 7 prikazuje razmerje med modelom ocenjenih vrednosti naučene nevronske mreže in natančnih vrednosti, dobljenih z merjenjem. Za boljši pregled slika 8 prikazuje normalizirane vmesne vrednosti ocenjenih vrednosti in izmerjenih rezultatov. Rezultati merjenja obrabe,

The cutting inserts used in the experiments were coated with TiN. Their tool-life expectancy had a tendency to decrease suddenly after the coating disappeared from the cutting part, which could be seen in a swift and sudden jump of the cutting force. Figure 6 shows the appearance of worn inserts during the experiments: a) tool insert from experiment 1, b) tool insert from experiment 3, c) tool insert from experiment 5.

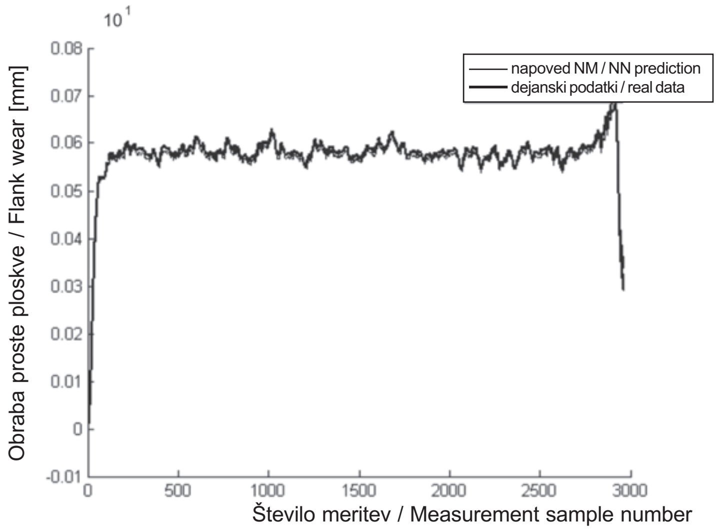
Figure 7 presents the agreement between the model of the estimated value of the trained neural network and the exact value gained from measurements. For a better survey, Figure 8 presents the normalized intermediate value of the estimated value gained from the model results and the measured results. The wear measuring results used



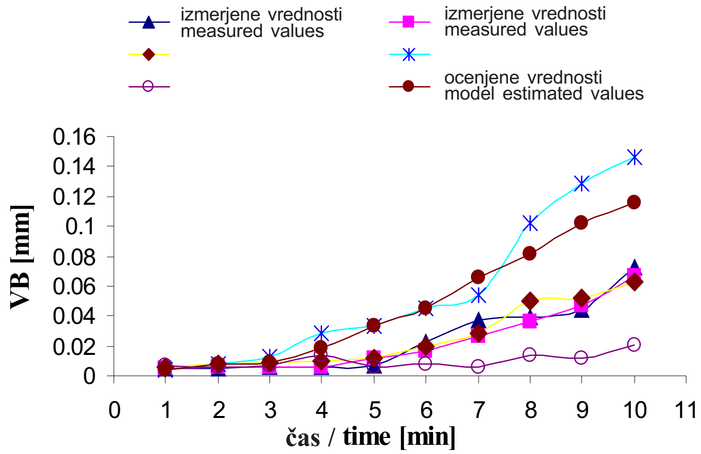
Sl. 6. *Obrabljena ploščica za preizkusne meritve: po preizkusu 1 (a), preizkus 3 (b) in preizkus 5 (c)*
Fig. 6. *Worn tool insert for experimental measurements: after experiment 1 (a), experiment 3 (b) and experiment 5 (c)*



Sl. 7. *Nevronska mreža za natančne in za ocenjene vrednosti*
Fig. 7. *Neural network exact value and estimated value*



Sl. 8. *Normalizirane vmesne vrednosti dejanskih izmerjenih in ocenjenih vrednosti*
Fig. 8. *Normalized intermediate values of real measurements and estimated values*



Sl. 9. *Deajnski izmerjeni rezultati*
Fig. 9. *Real measurement results*

uporabljeni za urjenje, so podani na sliki 9 za preizkuse 1 do 5. V vsakem primeru je bil model preverjen na podatkih, ki niso bili uporabljeni za učenje mreže.

Preglednica 2 prikazuje vmesne vrednosti parametrov izstopnih veličin in standardni odmik.

for training were given in Figure 9 for Experiments 1 to 5. In each case, the model was tested on previously unseen data since these parameters remained constant during every individual test of the tool-life expectancy.

Table 2 presents intermediate value parameters of the input sizes and with the standard deviation.

5 PRIHODNJE DELO

Pomanjkanje nevronskih mrež (podobno kakor pri številnih drugih preizkusnih modelih) zahteva dolgotrajno urjenje z normaliziranjem podatkov in vrednostmi, ki jih pričakujemo v dejanskih razmerah. Mreža ne more delovati brez predhodnega učenja. Da bi razrešili določen problem, je treba uporabiti tako numerične kot preizkusne metode. Glede na dejstvo,

5 FUTURE WORK

The lack of neural networks (as with many other experimental models) requires long-term training with data normalization of the values expected to be working in the real conditions. The network cannot work without previous training. To expand one's work, it is necessary to utilize both numerical and experimental methods. Considering the fact that the

Preglednic 2. *Parametri vstopnih veličin in standardni odklon*
Table 2. *Parameters of input sizes and standard deviation*

Vmesne vrednosti vstopnih veličin Intermediate value of input sizes	**Vmesne vrednosti izstopnih veličin Intermediate value of output size**
481,2658	0,0034
964,7022	
264,3197	
Standardni odklon vstopnih veličin Standard deviation of input sizes	**Standardni odklon izstopnih veličin Standard deviation of output size**
346,0206	0,0013
453,1569	
39,2540	

da je mrežo treba pri spremembi delovnih razmer ponovno učiti, štejemo lahko to za največjo pomanjkljivost pri uporabi nevronskih mrež v dejanski proizvodnji. Torej bi raziskave v prihodnje lahko vključile vgradnjo sedanjega sistema v obdelovalni RK stroj, namesto ločenih naprav kakor je to sedaj; s tem naj bi zagotovili, da bi sistem nadzora in obdelovalni stroj reagirala usklajeno - obdelovalni stroj bi se lahko ustavil, brž ko bi sistem ugotovil, da je orodje preveč obrabljeno. Ali drugače povedano, dinamične nevronske mreže zagotavljajo dodatne poprave naučene statične mreže pri praktičnem delovanju in lahko tudi razširijo sedanji model.

6 SKLEP

Prispevek je pokazal, da nevronske mreže lahko uporabljamo za učinkovito nadziranje obrabe med struženjem v trdo, z omenjenimi omejitvami. Po upoštevanju številnih mogočih ureditev modelov za nadzor obrabe, ki uporabljajo različne tipe razporeditev nevronskih mrež in temeljijo na vstopnih in izstopnih parametrih, je bila izbrana opisana z najboljšimi rezultati za izbrano število ravni mreže in nevronov. Model je bil postavljen tako, da se ga lahko precej preprosto dogradi z dinamično nevronsko mrežo, kar je ena izmed razmeroma novih raziskovalnih smeri na tem področju.

network should be re-trained from time to time, the training period can be considered as a major drawback in the application of neural networks in real manufacturing. However, future research could include the integration of the existing system into a CNC machine tool, instead of the currently separated device; this would ensure that the monitoring system and the machine tool could react synchronically, i.e., the machine tool could react by stopping once the over-worn tool is detected. More precisely, dynamic neural networks to ensure additional correction of the trained static network in an online work regime could also expand the existing model.

6 CONCLUSION

The paper presents neural networks (NNs) that can be used for efficient wear monitoring during hard turning, with the listed limitations. After considering many possible set ups for the wear-monitoring model using different configuration types of neural networks, and based on input and output parameters, the one selected performed with optimal results for the selected number of network layers and neurons. The model was set so it could be upgraded relatively easily with a dynamic neural network, which is one of the relatively new research directions in this field.

7 LITERATURA
7 REFERENCES

[1] C. Scheffer, H. Kratz, P.S. Heyns, F. Klocke (2003) Development of a tool wear-monitoring system for hard turning, *International Journal of Machine Tools & Manufacture* 43, (2003), pp. 973-985.

[2] M. Balazinski, E. Czogala, K. Jemielniak, J. Leski (2002) Tool condition monitoring using artificial intelligence methods, *Engineering Applications of Artificial Intelligence* 15, (2002), pp. 73-80.

[3] B. Siek (2002) On-line indirect tool wear monitoring in turning with artificial neural networks, a review of more than a decade of research, *Mechanical Systems and Signal Processing* 16(4), (2002), pp. 487-546.

[4] Shang-Liang Chen, Y.W. Jen (2000) Data fusion neural network for tool condition monitoring in CNC milling machining, *International Journal of Machine Tools & Manufacture* 40, (2000), pp. 381-400.

[5] D.E. Dimla Sr., P.M. Lister (2000) On-line metal cutting tool condition monitoring. II: tool-state classification using multi-layer perception neural networks, *International Journal of Machine Tools & Manufacture* 40, (2000), pp. 769-781.

[6] T. Ozel, A. Nadgir (2002) Prediction of flank wear by using back propagation neural network modelling when cutting hardened H-13 steel with chamfered and honed CBN tools, *International Journal of Machine Tools & Manufacture* 42, (2002), pp. 287-297.

[7] R. Kothamasu, S.H. Huang (2002) Intelligent tool wear estimation for hard turning: Neural-fuzzy modelling and model evaluation, *Proceedings of the Third International Conference on Intelligent Computation in Manufacturing Engineering*, Ischia, Italy, pp. 343-346.

[8] C. Scheffer, P.S. Heyns (2004) An industrial tool wear monitoring system for interrupted turning, *Mechanical Systems and Signal Processing* 18 (2004), pp. 1219-1242.

[9] A. Antic, J. Hodolic, R. Gatalo, M. Stevic (2001) Contribution to the development of the multi-sensor system for tool monitoring, *Annals of DAAAM & Proceedings of the 12th international DAAAM Symposium*, Vienna, Austria, pp. 009-010.

[10] A. Antić (2002) A contribution to the development of tool monitoring system in flexible manufacturing systems, Master's thesis, *Faculty of Technical Sciences*, Novi Sad.

[11] A. Antić, J. Hodolić, M. Soković (2006) Development of an intelligent system for tool wear monitoring applying neural networks, *Journal of Achievements in Materials and Manufacturing Engineering* 14 (2006) 1-2, pp. 146-151.

[12] P. D. Lippman (1989) Neural computing - theory and practice, *Van Nostrand Reinhold*, N.Y.

[13] M. Riedmiller, H. Braun (1993) A direct adaptive method for faster back-propagation learning: The RPROP algorithm, *Proceedings of the IEEE International Conference on Neural Networks*.

[14] J. Kopač, S. Dolinšek, F. Čuš (1993) Control of the dynamical behaviour of a machine tool with neural networks for precision cutting. *International Progress in Precision Engineering : Proceedings of the 7th International Precision Engineering Seminar*, Kobe, Japan, May 1993, pp. 884-893.

[15] S. Dolinšek, J. Kopač, F. Čuš (1994) Possibility to control a drilling with indexable tipped drills by use a neural network. *Manufacturing in Southern Africa*, Sea Point, Cape Town, 22-26 August 1994 : Proceedings, pp. 69-73.

Naslova avtorjev: mag. Aco Antić
prof. dr. Janko Hodolič
Univerza v Novem Sadu
Tehnična fakulteta
Trg Dositelja Obradovića 6
21000 Novi Sad, Srbija

prof. dr. Mirko Soković
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
mirko.sokovic@fs.uni-lj.si

Authors' Addresses: Mag. Aco Antić
Prof. Dr. Janko Hodolič
University of Novi Sad
Faculty of Technical Sciences
Trg Dositelja Obradovića 6
21000 Novi Sad, Serbia

Prof. Dr. Mirko Soković
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
1000 Ljubljana, Slovenia
mirko.sokovic@fs.uni-lj.si

Prejeto:
Received: 20.7.2006

Sprejeto:
Accepted: 25.10.2006

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

Osebne vesti - Personal Events

Akademik profesor dr. Janez Peklenik 80-letnik, zaslužni profesor Univerze v Ljubljani - 80th Anniversary of Professor Dr. Janez Peklenik, Academician and Professor Emeritus of the University of Ljubljana

Vodilni znanstvenik na področju strojništva v Sloveniji akademik profesor Janez Peklenik se je rodil devetega junija pred osemdesetimi leti v Tržiču. Zanimanje za strojništvo, ki ga je vodilo skozi vse življenje, mu je vzbudilo že v rani mladosti ustvarjalno obrtniško okolje doma. V šoli je zelo dobro napredoval, vendar mu je nemški okupator ob začetku vojne leta 1941 onemogočil nadaljnje šolanje v gimnaziji. Zato se je izučil za orodjarja v tovarni LGW - Luftfahrtgerätewerk v Kranju, iz katerega se je kasneje razvila Iskra. To je bila prva strokovna stopnica, ki jo je uspešno prestopil. Leta 1944 se je kot borec Prešernove brigade in kasneje Jeseniško-Bohinjskega odreda pridružil NOV. Še danes je ponosen, da se je v teh hudih časih boril za osvoboditev domovine.

V povojnih letih je najprej dopolnil zamujeno gimnazijsko izobrazbo in opravil veliko maturo. Po študiju strojništva na Univerzi v Ljubljani in občasnem konstrukterskem delu v industriji je odšel v Laboratorij za obdelovalne stroje Tehniške visoke šole v Aachnu, ki je vodilna raziskovalna ustanova na področju proizvodnih tehnologij in sistemov. Po dveh letih uspešnega raziskovalnega dela je leta 1957 z odličnim uspehom doktoriral na področju fizikalnih osnov brušenja. Razvil je novo metodo merjenja temperature na konici zelo hitro gibajočih se brusilnih zrn in pri analizi eksperimentalnih rezultatov prvi upošteval naključni značaj brusilnega postopka. Pri tem je tudi prvi uvedel statistično vrednotenje merilnih rezultatov. S tem je postavil raziskavam in razlagam zahtevnih tehnoloških postopkov nove temelje.

Raziskovalno delo je nadaljeval na področju avtomatizacije obdelovalnih sistemov. Na podlagi dela Problemi natančnosti pri avtomatizaciji proizvodnje je bil leta 1961 habilitiran ter postal docent na Tehniški visoki šoli v Aachnu. Naslednje leto je bil povabljen kot gostujoči izredni profesor na Carnegie-Melon Univerzo v Pittsburghu, ZDA. Temu je leta 1964 sledila izvolitev za rednega profesorja na Univerzi v Birminghamu v Angliji. Tedaj je začela računalniška tehnologija prodirati v proizvodne sisteme in postopke ter učinkovito spreminjati Taylorjevo zasnovo načina proizvodnje. S Peklenikovo ustanovitvijo prve katedre za računalniško krmiljene obdelovalne sisteme na svetu in dopolnitvijo tehnoloških raziskav z upošte-vanjem naključnega značaja obdelovalnega postopka ter statistično obdelavo eksperimen-talnih podatkov, so bila postavljena nova izhodišča za raziskovalno delo na področjih modernih proizvodnih tehnologij. Najvidnejše uspehe je akademik Peklenik dosegel na področjih sprotne razpoznave ter prilagodljivega krmiljenja obdelovalnih postopkov in sistemov, opisa in določitve naključnih lastnosti tehničnih površin ter površinskih vmesnikov. V številnih objavah je svoja dognanja predstavil mednarodni strokovni javnosti. Leta 1959 je bil za svoje znanstvene dosežke odlikovan s Taylorjevo medaljo, ki jo mednarodna akademija College International pour l'Étude Scientifique des Techniques de Production Mécanique - CIRP podeljuje najuspešnejšim mladim znanstvenikom starosti do 35 let. Leta 1966 je bil izvoljen za rednega člana te akademije, ki ji je tudi predsedoval v letih 1979-80, sedaj pa je njen častni član. Leta 1970 je postal dopisni in leta 1979 redni član SAZU.

Po dvajsetih letih znanstvenega in pedagoškega dela v tujini se je 1973 vrnil na Fakulteto za strojništvo Univerze v Ljubljani in ustanovil Katedro ter Laboratorij za tehnično kibernetiko, obdelovalne sisteme in računalniško tehnologijo. Na Fakulteti za strojništvo je kot dekan začel posodabljati študij ter intenzivno širiti zanstveno-raziskovalno in razvojno delo. V študij strojništva je uvedel modularni koncept in projektni način dela s študenti v zadnjem letniku. Ta oblika študija je pospeševala ustvarjalnost in skupinsko delo študentov ter sistemsko reševanje inženirskih problemov na podlagi teoretičnih metod.

Akademik Peklenik je bil leta 1987 izvoljen za rektorja Univerze v Ljubljani. Kot rektor je izdelal predlog za Univerzitetno podiplomsko šolo, ki bi bila zasnovana na sodobnih zasnovah in omogočala magistrski ter doktorski študij s poudarkom na interdisciplinarnosti in visoki kakovosti. K sodelovanju je povabil tudi vodilne inštitute, kakor sta Institut "Jožef Stefan" in Kemijski inštitut. Žal se ta zamisel iz nerazumljivih razlogov na univerzi ni uveljavila.

Akademik Peklenik je objavil več kot 300 znanstvenih del s področja proizvodnih tehnologij, tehničnih površin, strukturiranja in krmiljenja proizvodnih sistemov. Poleg tega je avtor 15 patentov v Sloveniji, ZDA, Veliki Britaniji in Nemčiji. Ob svojem delu je vzgojil več ko 200 diplomiranih inženirjev, magistrov in doktorjev strojništva. V mednarodni strokovni družbi je postal član mnogih uredniških odborov znanstvenih revij ter ustanovil CIRP - Journal of Manufacturing Systems, katerega glavni urednik je.

Za znanstvene dosežke je akademik Peklenik prejel številna mednarodna in domača priznanja. Poleg medalje CIRP je leta 1982 prejel še ameriško medaljo F. W. Taylorja, ki se podeljuje znastvenikom s področja proizvodnega inženirstva, in (1988) berlinsko nagrado Georga Schlesingerja. Doma je prejel državno Kidričevo nagrado (1975), državno nagrado Republike Slovenije za življenjsko delo (1996) in bil imenovan za Ambasadorja znanosti Republike Slovenije (1992) ter zaslužnega profesorja Univerze v Ljubljani. Akademik Peklenik je častni profesor Univerze v Birminghamu v Angliji ter Univerze za aeronavtiko in astronavtiko v Nanjingu na Kitajskem. Poleg tega je redni član SAZU, ustanovitelj in častni predsednik Inženirske akademije Slovenije, častni član mednarodne akademije CIRP, Evropske akademije in Ruske inženirske akademije.

Sodelavci Fakultete za strojništvo Univerze v Ljubljani smo ponosni, da lahko uspešno nadaljujemo njegovo znanstveno-raziskovalno in strokovno delo ter mu ob njegovem visokem življenjskem jubileju prisrčno čestitamo.

Akademik prof. dr. Igor Grabec

Magisterij, specializacije in diplome - Master’s, Specialisation’s and Diploma Degrees

MAGISTERIJ

Na Fakulteti za strojništvo Univerze v Ljubljani je z uspehom zagovarjal svoje magistrsko delo:

dne *10. oktobra 2006*: **Andrej Kotar**, z naslovom: "Analiza in optimiranje induktivnega segrevanja kovinskih materialov na osnovi računalniške simulacije".

S tem je navedeni kandidat dosegel akademsko stopnjo magistra znanosti.

SPECIALIZACIJE

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

dne *10. oktobra 2006*: **Peter Humar**, z naslovom: "Vpliv različnih vrst goriva na emisijo škodljivih snovi v izpušnih plinih dizelskega motorja";

dne *13. oktobra 2006*: **Miran Fujs**, z naslovom: "Tehnološka posodobitev proizvodnje bivalnih enot v Arcont d.d." in **Gregor Govekar**, z naslovom: “Racionalizacija procesa izdelave in montaže krmilnega ventila”.

S tem so navedeni kandidati dosegli akademsko stopnjo specialista.

DIPLOMIRALI SO

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv univerzitetni diplomirani inženir strojništva:

dne *4. oktobra*: Suvad BAJRIĆ, Aleksander KLANČIŠAR, Primož ZUPAN;

dne *27. oktobra*: Peter DOLENEC, Jure FIDERŠEK.

Na Fakulteti za strojništvo Univerze v Mariboru je pridobil naziv univerzitetni diplomirani inženir strojništva:

dne *26. oktobra 2006*: Vladimir ZALOŽNIK.

*

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv diplomirani inženir strojništva:

dne *12. oktobra 2006*: Simon GANZA, Ivan MIKLAVC, Matjaž POŽAR, Miha VENCELJ, Uroš ZGONEC;

dne 13. oktobra 2006: Aleš GLOGOVŠEK, Janoš KAVNIK, Gregor KLANČAR, Mitja KOLBEZEN.

Na Fakulteti za strojništvo Univerze v Mariboru so pridobili naziv diplomirani inženir strojništva:

dne *26. oktobra 2006*: Tomaž ANŽIN, Štefan GABER, Bojan HABJANIČ, Andrej KRAJNC.

Navodila avtorjem - Instructions for Authors

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

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

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

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

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

For papers from abroad (in case that none of authors is Slovene) authors should provide Slovenian translation. Translation could be organised by editorial, but the authors have to pay for it. If the paper is reviewed as scientific, it can be published only in English language with Slovenian abstract, that is prepared by the editorial board.

VSEBINA ČLANKA

Članek naj bo napisan v naslednji obliki:
- Naslov, ki primerno opisuje vsebino članka.
- Povzetek, ki naj bo skrajšana oblika članka in naj ne presega 250 besed. Povzetek mora vsebovati osnove, jedro in cilje raziskave, uporabljeno metodologijo dela,povzetek rezulatov in osnovne sklepe.
- Uvod, v katerem naj bo pregled novejšega stanja in zadostne informacije za razumevanje ter pregled rezultatov dela, predstavljenih v članku.
- Teorija.
- Eksperimentalni del, ki naj vsebuje podatke o postavitvi preskusa in metode, uporabljene pri pridobitvi rezultatov.
- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
- Sklepi, v katerih naj bo prikazan en ali več sklepov, ki izhajajo iz rezultatov in razprave.
- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

THE FORMAT OF THE PAPER

The paper should be written in the following format:
- A Title, which adequately describes the content of the paper.
- An Abstract, which should be viewed as a mini version of the paper and should not exceed 250 words. The Abstract should state the principal objectives and the scope of the investigation, the methodology employed, summarize the results and state the principal conclusions.
- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

OBLIKA ČLANKA

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

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

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

THE LAYOUT OF THE TEXT

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

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

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

Enote in okrajšave

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

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

Slike

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

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

Vse označbe na slikah morajo biti dvojezične.

Preglednice

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

Vsi podnaslovi preglednic morajo biti dvojezični.

Seznam literature

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

[1] A. Wagner, I. Bajsić, M. Fajdiga (2004) Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors, *Stroj. vestn.* 2(2004), pp. 72-79.
[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.
[3] Muhs, D. et al. (2003) Roloff/Matek Maschinenelemente – Tabellen, 16. Auflage. *Vieweg Verlag*, Wiesbaden.

Podatki o avtorjih

Članku priložite tudi podatke o avtorjih: imena, nazive, popolne poštne naslove in naslove elektronske pošte.

SPREJEM ČLANKOV IN AVTORSKE PRAVICE

Uredništvo Strojniškega vestnika si pridržuje pravico do odločanja o sprejemu članka za objavo, strokovno oceno recenzentov in morebitnem predlogu za krajšanje ali izpopolnitev ter terminološke in jezikovne korekture.

Avtor mora predložiti pisno izjavo, da je besedilo njegovo izvirno delo in ni bilo v dani obliki še nikjer objavljeno. Z objavo preidejo avtorske pravice na Strojniški vestnik. Pri morebitnih kasnejših objavah mora biti SV naveden kot vir.

Units and abbreviations

Only standard SI symbols and abbreviations should be used in the text, tables and figures. Symbols for physical quantities in the text should be written in italics (e.g. *v, T, n,* etc.). Symbols for units that consist of letters should be in plain text (e.g. ms^{-1}, K, min, mm, etc.).

All abbreviations should be spelt out in full on first appearance, e.g., variable time geometry (VTG).

Figures

Figures must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Fig. 1, Fig. 2, etc. Pictures may be saved in resolution good enough for printing in any common format, e.g. BMP, GIF, JPG. However, graphs and line drawings sholud be prepared as vector images.

When labelling axes, physical quantities, e.g. *t, v, m,* etc. should be used whenever possible to minimise the need to label the axes in two languages. Multi-curve graphs should have individual curves marked with a symbol, the meaning of the symbol should be explained in the figure caption.

All figure captions must be bilingual.

Tables

Tables must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Table 1, Table 2, etc. The use of names for quantities in tables should be avoided if possible: corresponding symbols are preferred to minimise the need to use both Slovenian and English names. In addition to the physical quantity, e.g. *t* (in italics), units (normal text), should be added in new line without brackets.

All table captions must be bilingual.

The list of references

References should be collected at the end of the paper in the following styles for journals, proceedings and books, respectively:

[1] A. Wagner, I. Bajsić, M. Fajdiga (2004) Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors, *Stroj. vestn.* 2(2004), pp. 72-79.
[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.
[3] Muhs, D. et al. (2003) Roloff/Matek Maschinenelemente – Tabellen, 16. Auflage. *Vieweg Verlag*, Wiesbaden.

Author information

The information about the authors should be enclosed with the paper: names, complete postal and e-mail addresses.

ACCEPTANCE OF PAPERS AND COPYRIGHT

The Editorial Committee of the Journal of Mechanical Engineering reserves the right to decide whether a paper is acceptable for publication, obtain professional reviews for submitted papers, and if necessary, require changes to the content, length or language.

Authors must also enclose a written statement that the paper is original unpublished work, and not under consideration for publication elsewhere. On publication, copyright for the paper shall pass to the Journal of Mechanical Engineering. The JME must be stated as a source in all later publications.