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

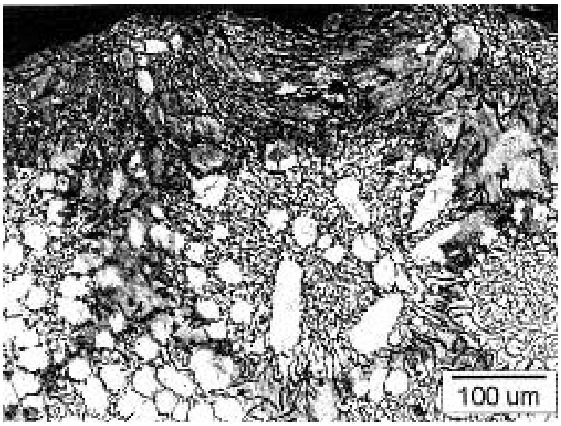
Cast iron that solidifies with the separation of graphite is called grey cast iron because the fracture surfaces appear grey because of the exposed free graphite. Cast iron is in fact an alloy with 2 to 3.5% carbon and 1 to 3% silicon content, and is one of the most widely used free machining ferrous 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

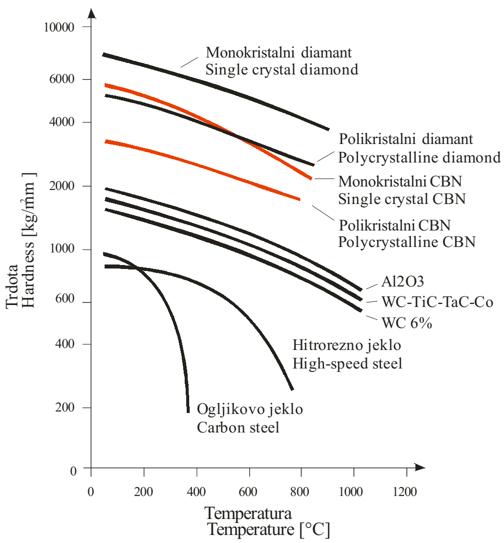
Slaba obdelovalnost mehke sive litine je vzrok izpostavljenosti materiala rezalnega orodja skrajnim toplotnim in mehanskim obremenitvam v okolici rezalnega robu. To povzroča plastifikacijo materiala in pospešeno obrabo orodja. Tipični mehanizmi obrabe pri odrezovanju mehke sive litine so: zareze na rezalnem 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).

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 Geometrijska oblika rezalnega orodja

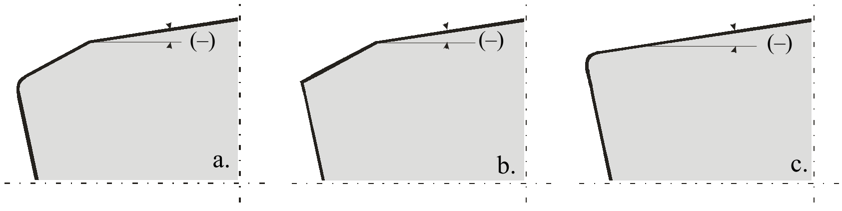
Kljub odličnim materialnim lastnostim mora imeti tudi material rezalnega orodja iz CBN primerno geometrijsko obliko. Na račun trdote je trdnost CBN manjša kakor pri drugih rezalnih orodjih, zato so orodja bolj občutljiva na krušenje. Zaradi tega je običajno potrebna uporaba negativne geometrijske oblike 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.

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

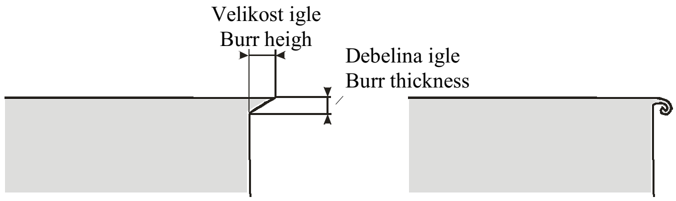
1.4 Probability of the appearance of burrs

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.

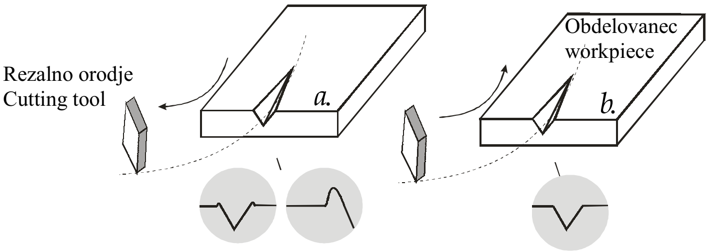
Burr avoidance in the manufacturing processes for the automotive industry has received a great deal of attention. As the demand for component tolerances and surface quality, which are in this industry more stringent in the relation with costs, the burr issues need to be addressed at the point of prevention 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.

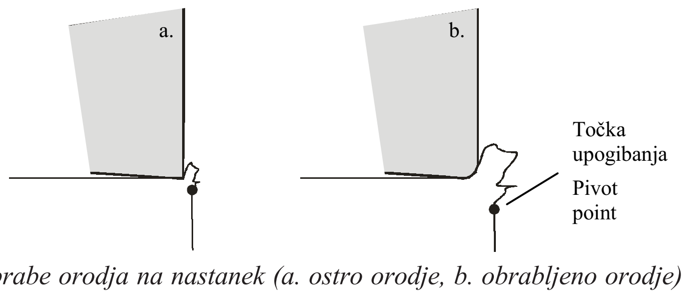
Dodatna dejavnika, ki vplivata na nastanek igle, sta geometrijska oblika in ostrina rezalnega robu. Ko je orodje ostro, je točka upogibanja blizu roba obdelovanca (sl. 6). Z obrabljanjem orodja se ta točka upogibanja materiala pomika v nasprotni smeri od roba obdelovanca. To oddaljevanje točke upogibanja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

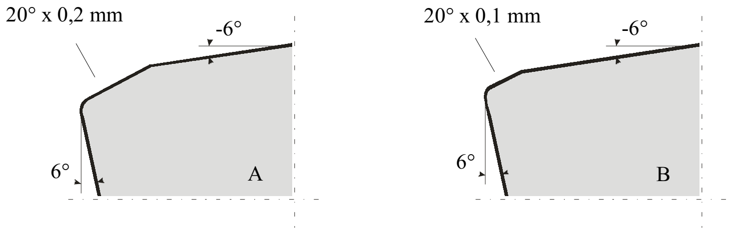
2.2 Cutting-tool geometries

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).

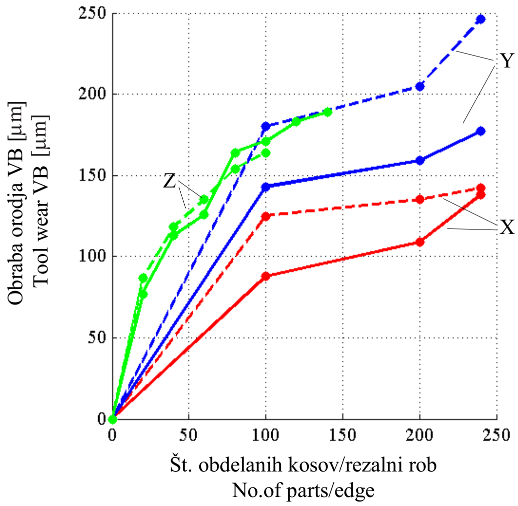
From these results one can see a rapid increase in the wear at the beginning, followed by an area of steady linearly increasing wear. A large thermal influence can also be recognized. After 100 machined workpieces (for tool A) and 140 (for tool B), the burr appeared and the tool edge had to be changed. 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.

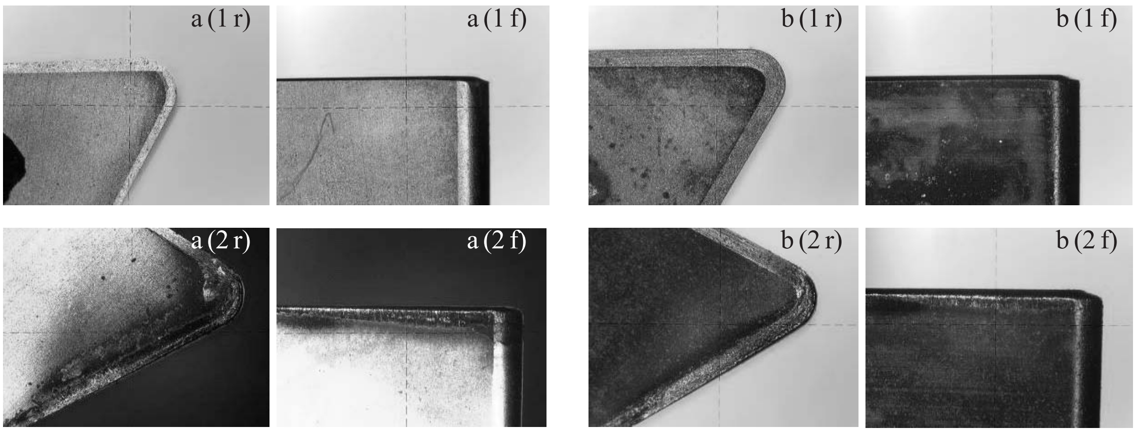
Prosta in cepilna ploskev orodja z rezalnim robom sta podvrženi veliko obrabnim mehanizmom, ki jih je moč določiti z orodjarskim mikroskopom. V začetnem stanju odrezovanja, sta bila prisotna mehanizma hitre začetne zaokrožitve in obraba proste ploskve, ki se je hitro povečevala. Nato obraba proste ploskve 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

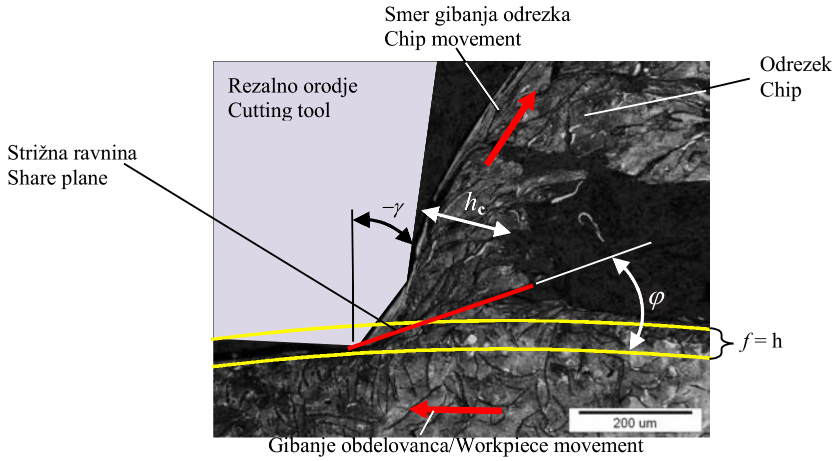
The QSD test was performed only for the most critical cutting technology, *Z*, because of its complexity. The result is presented in Fig. 11. It is possible to recognize that in front of the cutting-tool chamfer, there is a zone of high deformation of the cutting material. This large workpiece-material 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.

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

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.

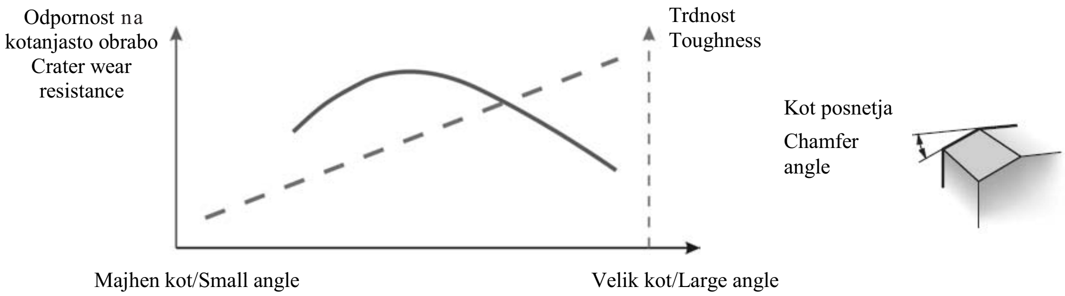
5 IMPROVEMENT OF THE CUTTING CONDITIONS

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

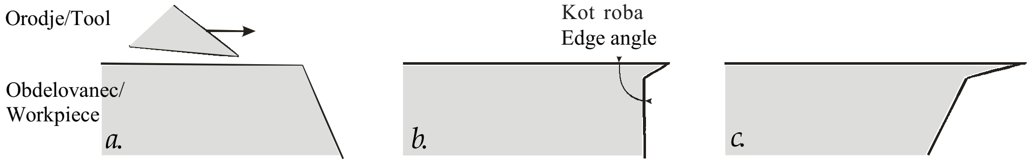
nology Z refers to a low feed rate (f = 0.08 mm/rev). Increasing the rate will not just increase the tool life, but it will also diminish the probability of a burr-formation possibility on the workpiece edge, because it is known that the higher the feed rate, the smaller the possibility for plastic deformation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