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Prehod iz običajne v zelo hitro obdelavo in analiza oblikovanja odrezkov

The Transition from the Conventional to the High-Speed Cutting Region and a Chip-Formation Analysis

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Zaradi najnovejših dosežkov razvoja na področju konstrukcije obdelovalnih strojev (glavnega vretena, podajalnih pogonov ipd.) je zelo hitra obdelava postala cenovno ugoden obdelovalni postopek za izdelavo izdelkov z veliko kakovostjo obdelane površine, zaradi manjših vplivov na obdelano površino in doseganja odličnih dimenzijskih natančnosti. S tem, ko poznamo tovrstne značilne prednosti zelo hitre obdelave pred običajno, je eno od ključnih vprašanj povezano z določitvijo ustreznih vrednosti rezalnih hitrosti, ki ustrezajo zelo hitremu območju. Vzrok za to leži v dejstvu, da se vpliv na obdelovalne značilnosti povečuje, ko prehajamo v območje velike hitrosti. Po drugi strani pa prevelike rezalne hitrosti niso priporočljive zaradi povečanja obrabe orodij in večje porabe energije na obdelovalnih strojih. Za podporo pri reševanju teh problemov je v članku predstavljen postopek, ki sloni na analizi mehanizma oblikovanja odrezkov in njihove oblike na podlagi uporabe metalografskih metod.

(Ključne besede: stroji obdelovalni, obdelave visokohitrostne, oblike odrezkov, hitrosti rezanja)

As a result of advances in machine-tool design (main spindle, feed drives, etc.), high-speed milling has become a cost-effective manufacturing process for making products with a high surface quality, low variations of the machined surface and excellent dimensional accuracy. Taking into account the evident advantages of high-speed machining over conventional machining, a key issue is to identify those cutting speeds that correspond to high-speed machining. The simple reason for this is that machining effects increase when entering the high-speed region but, on the other hand, an enormous increase in the cutting speed is not advisible due to the appearance of higher tool wear and machine-tool energy consumption. In order to solve the problem this paper describes a procedure based on a chip-formation mechanism and a chip-shape analysis, together with the use of metallographic methods.

(Keywords: machine tools, high speed cutting, chip formation, cutting speeds)

0 UVOD

Obdelava z veliko hitrostjo se šteje kot eno od novejših, perspektivnih izdelovalnih tehnologij zaradi višje produktivnosti, doseganja odličnih kakovosti obdelane površine, manjših vplivov na obdelano površino in ustreznih dimenzijskih obdelovalnih natančnosti. Od vseh zelo hitrih metod ima zelo hitro frezanje še najpomembnejši pomen ([1] do [3]). Zaradi prednosti, ki jih dajejo izboljšane karakteristike obdelovalnih strojev (glavno vreteno, podajalni pogoni ipd.), je zelo hitro frezanje postalo cenovno učinkovit izdelovalni postopek. Zaradi tega se zelo hitra obdelava veliko uporablja v letalski in avtomobilski industriji za obdelavo strojnih delov zapletenih oblik iz aluminija in njegovih zlitin. Zaradi napredka na področju rezalnih orodij in odrezovalnih tehnologij se v zadnjem času zelo hitro frezanje

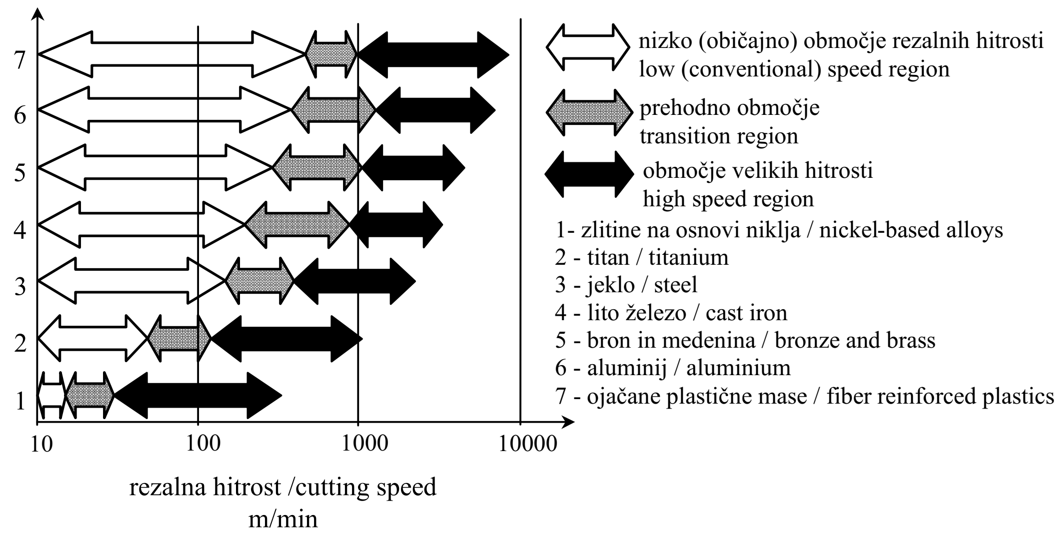
0 INTRODUCTION

High-speed machining is a relatively new production technology that allows a higher productivity, an excellent surface finish and a good dimensional accuracy in the manufacturing process. High-speed milling is one of the most important of all high-speed cutting methods ([1] to [3]). Thanks to the advances in machine-tool performance as a result of improvements to the main spindle, feed drives, etc., high-speed milling has become a cost-effective manufacturing process that produces products with a high surface quality, low variations in the machined surface and dimensional accuracy. High-speed milling was first used successfully in the aircraft and automotive industries for machining complex machine parts made of aluminum and its alloys. Recently, with the advances in cutting-tool materials and uporablja tudi za obdelavo legiranih jekel v kaljenem stanju (trdote od 30 HRc pa do 60 do 65 HRc) ([4] in [5]).

Kar nekaj kriterijev obstaja za definiranje območja zelo hitre obdelave oziroma kriterijev za določitev meje med običajno in zelo hitro obdelavo, takšni so npr. [6]: velikost rezalne hitrosti, število vrtljajev vretena ali vrtečega se orodja (hitrost vretena), DN število (DN je premer vretena v mm pomnožen s hitrostjo vretena v vrt/min), dinamično obnašanje in material obdelovanca. Najbolj ustrezna definicija zelo hitre obdelave je tista, ki sloni na vrsti materiala obdelovanca [6] (sl. 1). Na primer, vrednosti rezalne hitrosti med 500 do 700 m/min se nanašajo na zelo hitro območje za primere pri obdelavi legiranih jekel, po drugi strani se te vrednosti rezalne hitrosti šteje za počasnejše območje pri obdelavi aluminija.

technologies, high-speed milling has also been used in the machining of alloy steels in their hardened state (above 30 HRC up to 60 to 65 HRC) ([4] and [5]).

There are several criteria used for defining high-speed machining, i.e. the criteria for determining the boundary between conventional and high-speed machining. These include [6]: the magnitude of the cutting speed, the revolutions of the spindle or the rotating tool (the spindle speed), the DN number (DN is the spindle diameter in mm multiplied by the spindle speed in rev/min), the dynamic behaviour, and the workpiece material. The most appropriate definition of high-speed machining is based on the workpiece material grade (or type) being machined [6], Fig.1. For example, the cutting-speed values from 500 to 700 m/min is the high-speed region for machining alloy steels, however, these speeds are considered conventional or low for machining aluminum.



Sl. 1. *Področja rezalnih hitrosti za frezanje različnih obdelovanih materialov*
Fig.1. *Regions of cutting speed for milling a different workpiece material*

Nekatere od zadnjih raziskav zelo hitre obdelave so usmerjene v študij nekaterih značilnih področij: mehanizmov obrabe orodij ([2] in [7]), kakovosti obdelane površine in integritete površine ([8] in [9]), mehanizma oblikovanja odrezkov ([1] do [3]) in obdelave materialov v kaljenem stanju (obdelava v trdo) ([4], [5], [8], [10] in [11]). Skupen namen vseh teh raziskav je iskanje vseh možnosti za uporabo zelo hitre obdelave v industrijsko prakso.

Za doseganje nekaterih značilnih prednosti zelo hitre obdelave v primerjavi z običajno obdelavo je zelo pomembno, da določimo posamične vrednosti rezalnih hitrosti, ki pripadajo zelo hitri obdelavi. Seveda se pri tem postavlja vprašanje: zakaj? S tem ko vstopimo v območje zelo hitre obdelave postane vpliv odrezovalnih značilnosti boljši predvsem zaradi vzrokov, ki smo jih že omenili. Po drugi strani pa v področju zelo hitre obdelave ni priporočljivo preveč večati rezalne

More recent high-speed machining studies focus on several characteristic areas: tool-wearing mechanisms ([2] and [7]), surface quality and machined-surface integrity ([8] and [9]); chip-formation mechanisms ([1] to [3]); and machining of materials in their hardened state (known as hard machining) ([4], [5], [8], [10] and [11]). The common aim of all these investigations is to explore all the possibilities of high-speed machining applications in industrial practice.

Taking into account some of the obvious advantages of high-speed machining over conventional machining it is very important to find particular values of cutting speed that correspond to high-speed machining. The question is why? When entering the region of high-speed machining the effects of machining become better for the reasons mentioned above, however, it is not advisable to intensify the cutting speed while in the high-speed hitrosti, saj se močno poveča obraba orodja in poraba energije za odrezovanje.

Diagram na sliki 1 lahko uporabimo za približno določitev vrednosti rezalne hitrosti za območje vstopanja v velike rezalne hitrosti. Vendar pa je za vsak poseben, realen primer obdelave (na primer za določen obdelovani material) treba poiskati natančne vrednosti rezalne hitrosti za ta primer. Prispevek prikazuje eno od možnosti za realiziranje te naloge, ki sloni tako na analizi mehanizma oblikovanja kakor tudi oblike odrezka. Mehanizem oblikovanja odrezka je običajno učinkovito orodje za globlje razumevanje rezalnega postopka. Glede na objave A. Vyasa in M.C. Shawa [12] obstajata dve osnovni obliki odrezka: neprekinjen odrezek in ponavljajoč se odrezek. Prav tako obstajajo štirje tipi ponavljajočih se odrezkov: prekinjen odrezek, valovit odrezek, odrezek, ki nastaja ob pojavu nalepka in žagast odrezek.

1 EKSPERIMENTALNO DELO

Eksperimentalno delo je bilo opravljeno na Fakulteti za strojništvo, Univerze v Ljubljani. Za postopek odrezovanja smo uporabili frezalni stroj vrste Moriseiki-Frontier. Odrezovalni pogoji so bili: premer frezala D = 80 mm, globina rezanja a = 2mm, podajanje na rezalni rob f_z = 0,1 mm, vrsta frezalne glave SUM-UFO-400, oblika rezalne ploščice SFKN 12T3 A2TN-AC230, geometrična oblika γ =27°, λ =7°, χ=45°, rezalna hitrost v_c = 50 do 1500 m/min. Kemična sestava testnih jekel je prikazana v preglednici 1. Slika 2 prikazuje mikrostrukturo obdelovanih jekel in rezultate meritev mikrotrdote.

Mikrostruktura žarjenega konstrukcijskega jekla Ck 15 (sl. 2a) je feritno-perlitna. Mikrostruktura nerjavnega jekla X5CrNi189 (sl. 2b) je sestavljena iz avstenita z majhno količino delta ferita z znano obliko poligonalnih avstenitnih zrn. Mikrostruktura orodnega žarjenega jekla X63CrMoV51 (sl. 2c) je sestavljena iz ferita s krogelnimi karbidi in majhno količino perlita kot posledica nepopolnega žarjenja. Mikrostruktura enakega jekla v kaljenem stanju (sl. 2d) je sestavljena iz martenzita z evtektoidnimi karbidi in zaostalim avstenitom (jeklo je le kaljeno, ne popuščano).

Jeklo vrste Ck 15 je bilo obdelovano z rezalno hitrostjo 150 m/min in 1500 m/min (vsi drugi obdelovalni pogoji se niso spreminjali), prav tako jeklo

region because of increased tool wear and energy consumption.

The diagram in Fig.1 can be used for an approximate determination of the value of the cutting speed when entering the high-speed machining region. However, for any specific (real) case (e.g. a given workpiece material), it is necessary to find precisely the point at which a particular high-speed region begins. In this paper we describe a method which is based on analyses of the chip-formation mechanism and the chip shape. Usually, the chip-formation-mechanism analysis is an effective tool for a deeper understanding of the cutting process. According to A. Vyas and M.C. Shaw [12], there are two basic types of chips: steady-state continuous chips and cyclic chips. In addition, there are four types of cyclic chips: discontinuous chips, wavy chips, chips produced with a built-up edge and saw-tooth chips.

1 EXPERIMENTAL WORK

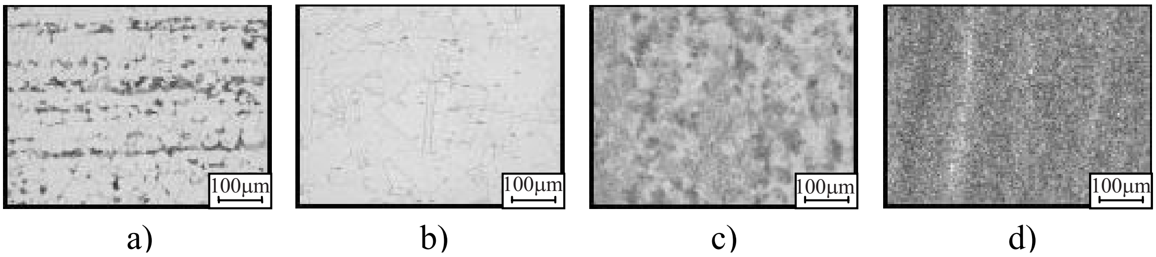
The experimental work was carried out in the the Faculty of Mechanical Engineering, University of Ljubljana. The machining was conducted on a Moriseiki-Frontier-type milling machine. The machining conditions were: cutter diameter D= 80 mm, depth of cut d=2mm, tooth feed f_z = 0,1 mm, cutter type SUM-UFO-4000, cutting insert SFKN 12T3 A2TN - AC230, cutting speed v_c = 50–1500 m/min, γ = 27°, λ = 7°, χ =45°. The chemical composition of the investigated steel grades is shown in Table 1. Fig. 2 shows the microstructures and results of Vickers microhardness measurements on the machined steel grades.

The microstructure of Ck15, Fig. 2a, is bonded; it consists of ferite-perlite, in the annealed state. The microstructure of X5CrNi189, Fig. 2b, consists of austenite with a small quantity of delta-ferite with the obvious polygonal austenite grains. The microstructure of X63CrMoV51, Fig. 2c, in the annealed state, consists of ferite with spheroidal carbides and a small quantity of perlite as a result of incomplete annealing. The microstructure of the same steel in the tempered state, Fig. 2d, is martensitic with eutectoide carbides and retained austenite (the sample was not quenched).

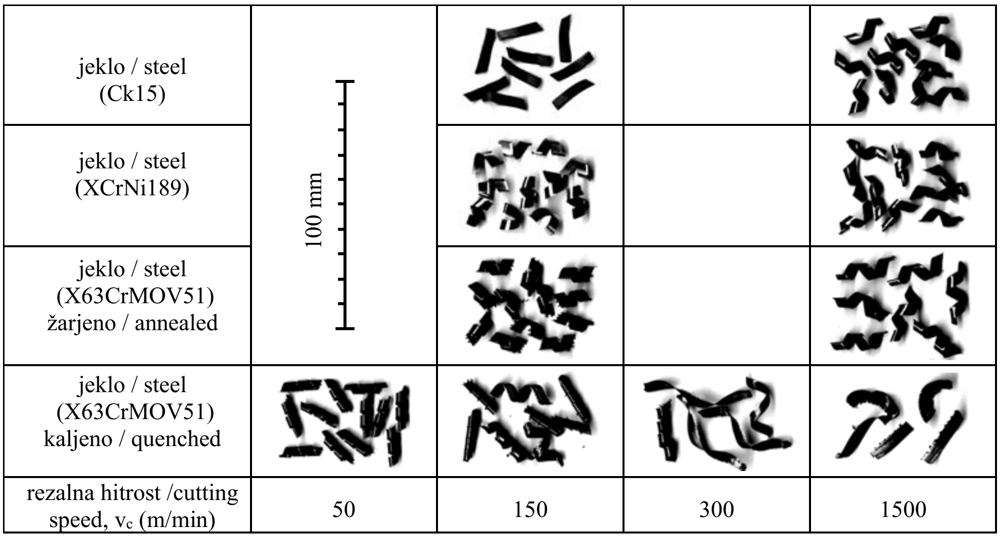
The Ck 15 grade steel was machined with cutting speeds of 150 m/min and 1500 m/min (the other conditions were the same), as was the XCrNi189 steel and the

Preglednica 1. *Kemična sestava testnih jekel*
Table 1. *Chemical composition of the investigated steel grades*

Vrsta jekla / Steel grade	Kemična sestava / Chemical composition, %										
	C	Si	Mn	P	S	Cu	Cr	Ni	Mo	V	Al
Ck15 - žarjeno / annealed	0,17	0,27	0,41	0,019	0,013	0,31	0,12	0,08	0,01	-	0,053
X5CrNi189 - avstenit / austenite	0,04	0,45	1,55	0,028	0,035	0,53	18,26	8,80	0,63	0,08	0,017
X63CrMoV51 - žarjeno /annealed X63CrMoV51- kaljeno / tempered	0,62	1,0	0,59	0,017	0,004	0,26	5,46	0,23	1,21	0,46	0,028



Sl. 2. *Mikrostruktura obdelovanih jekel: a) Ck15 (156 HV), b) X5CrNi189 (221HV), c) X63CrMoV51 (žarjeno 282 HV), d) X63CrMoV51(kaljeno 629 HV).*
Fig. 2. *Microstructures of the machined steel grades: a) Ck15 (156 HV), b) X5CrNi189 (221HV), c) X63CrMoV51 (annealed, 282 HV), d) X63CrMoV51(quenched, 629 HV).*



Sl. 3. *Oblika odrezkov pri obdelavi različnih jekel*
Fig. 3. *Chip shapes produced during machining*

X5CrNi189 in žarjeno jeklo X63CrMoV51, medtem ko smo za kaljeno jeklo X63CrMoV51 uporabili hitrosti 50, 150, 300 in 1500 m/min. Oblika odrezkov pri odrezovanju je prikazana na sliki 3.

2 REZULTATI IN RAZPRAVA

Fotografije mikrostrukture odrezkov pri obdelavi jekla Ck 15 so prikazane na sliki 4. Pri rezalni hitrosti v_c = 150 m/min (sl. 4a) je povprečna debelina odrezka 0,34 mm, tako da znaša koeficient nakrčevanja odrezka k = 0,34/0,1 = 3,4. Struktura materiala ustreza običajni obliki deformacije z vzdolžno deformiranimi zrni. Na zunanji strani odrezka je mogoče opaziti drugotno deformacijsko plast. Glede na znano klasifikacijo oblike odrezkov [12] je to značilen primer zveznega odrezka. Ta oblika je značilna pri obdelavi deformljivih jekel pri uporabi majhnih rezalnih hitrosti.

Pri rezalni hitrosti v_c = 1500 m/min (sl. 4b) je povprečna debelina odrezka 0,13 mm in koeficient nakrčevanja k = 0,13/0,1 = 1,3. Struktura je prav tako deformirana (stlačena), pojavlja pa se več izrazitih vrhov na zunanji strani odrezka (zob – označeno s

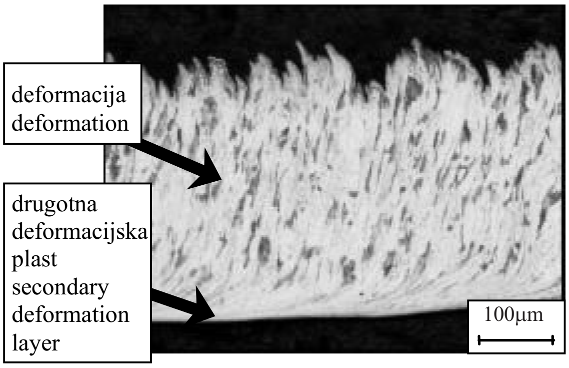
X63CrMoV51 (annealed) steel. The X63CrMoV51 (quenched) steel was machined with cutting speeds of 50, 150, 300 and 1500 m/min. The chip shapes produced during machining are presented in Fig. 3.

2 RESULTS AND DISCUSSION

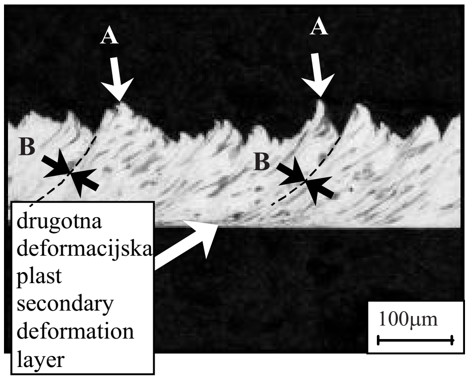
The microphotos of the chips produced during the Ck15 machining are shown in Fig .4. When the cutting speed (v_c) was 150 m/min, Fig. 4a, the average chip thickness was 0.34 mm, so the chip compression coefficient (λ) was 0.34/0.1 = 3.4. The structure of the material suggests a classical type of deformation with elongated grains. A secondary deformation layer appears on the inner side of the chip. According to the classification of chip types given in [12] this is an example of a steady-state continuous chip. This type of chip is characteristic of ductile steel grades that are machined with low cutting speeds.

When v_c = 1500 m/min, Fig. 4b, the average chip thickness was 0.13 mm, with λ = 0.13/0.1 = 1.3. The structure is also deformed (elongated) but with more intense chip peaks (teeth): see arrows A in Fig. 4b. By analyzing the elongation of the grains in puščico A na sliki 4b). Na podlagi analize deformacije strukture zrn lahko opazimo posamezne deformacijske proge, ki nakazujejo možnost segmentacije odrezka, če bi se rezalna hitrost zvečala prek 1500 m/min (puščica B, sl. 4b). Po obliki odrezka in njegove strukture lahko kljub vsemu sklepamo, da razmer pri obdelavi žarjenega jekla Ck 15 (mikrotrdote 156 HV) z rezalno hitrostjo v_c = 1500 m/min še ne moremo šteto za zelo hitro obdelavo. Tudi drugotna deformacijska cona je tanjša kakor pri prejšnjem primeru.

the structure we can see some lines that point to the possibility of chip segmentation if the cutting speed increases over 1500 m/min: see arrows B, Fig. 4b. Nevertheless, the chip shape and its structure definitely show that milling with a cutting speed of 1500 m/min cannot still be considered as high-speed machining in the case of annealed Ck 15 with a microhardness of 156 HV. The secondary deformation layer is not as thick as in the previous case.



a) rezalna hitrost 150m/min
cutting speed 150 m/min



b) rezalna hitrost 1500m/min
cutting speed 1500 m/min

Sl. 4. *Prečni prerez odrezkov, nastalih pri obdelavi jekla Ck 15*
Fig. 4. *Cross-section of chips produced during machining of Ck 15*

Slike mikrostrukture odrezkov, nastalih pri obdelavi nerjavnega jekla X5CrNi189, so prikazane na sliki 5. Pri rezalni hitrosti v_c = 150 m/min so odrezki podobni žagasti obliki, toda z močno povezanimi segmenti. Vendar tovrstna oblika odrezkov ni rezultat segmentacije, ampak močne plastične deformacije materiala. To je tudi prikazano v povečanem izrezu na sliki 5a. V tem primeru se notranji lomi pojavijo zaradi intenzivne deformacije. V strukturi tega jekla so poligonalna avstenitna zrna očitno plastično deformirana.

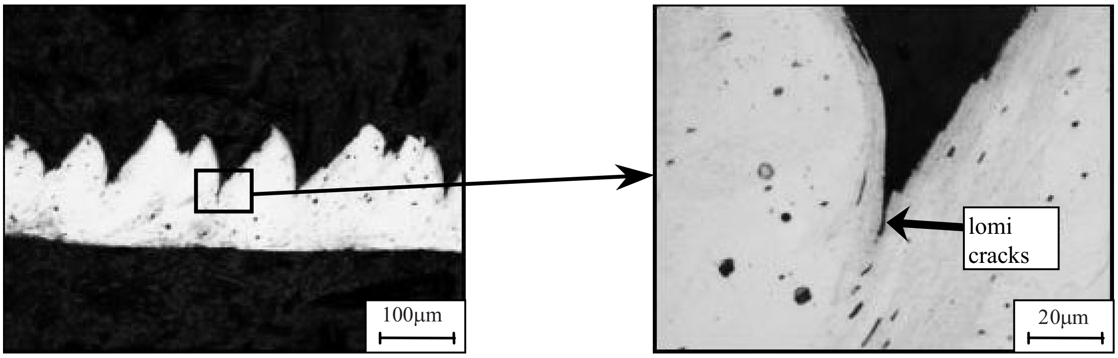
Slika 5b pa kaže neobičajno obliko odrezka pri obdelavi tega jekla s hitrostjo v_c = 1500 m/min. Kljub veliki rezalni hitrosti s slike ni mogoče opaziti segmentacije odrezka kot posledice plastične deformacije. Na zunanji strani odrezka se pojavi neka vrsta nabiranja materiala. Očitno je, da je to neenakomerna zvezna oblika odrezka. Nabiranje materiala in spremenljivost deformacijskega postopka je mogoče tudi jasno opaziti na posnetku SEM (detajl na sliki 5b). Glede na dobljeno obliko odrezka za ta material ne moremo postaviti sklepov o tem, ali je hitrost odrezovanja v_c = 1500 m/min že v območju zelo hitre obdelave ali ne.

Slike mikrostrukture odrezkov, dobljenih pri obdelavi žarjenega jekla X63CrMoV51, so prikazane na sliki 6. Pri rezalni hitrosti v_c = 150 m/min (sl. 6a) je odrezek podoben tistim, dobljenih pri obdelavi jekla Ck15 (sl. 4a), le da je koeficient nakrčevanja manjši (k = 0,17/0,1 = 1,7). Opaziti je tudi večji kot nagnjenosti

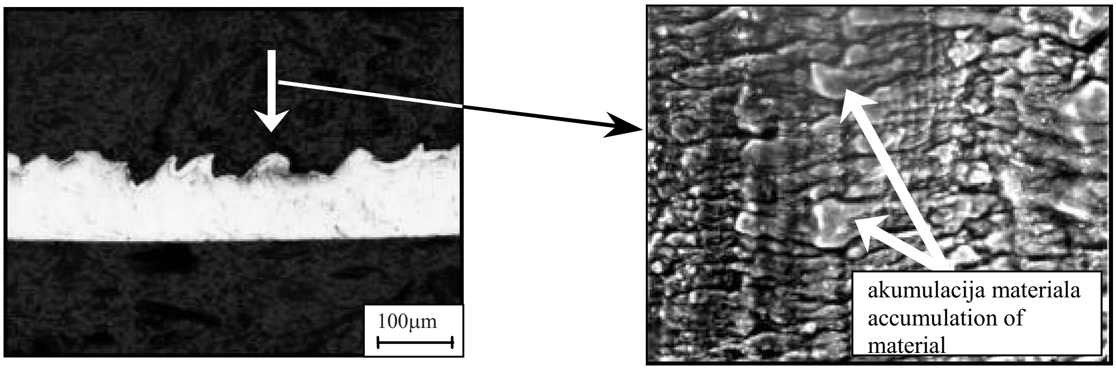
The microphotos of chips produced during the machining of XcrNi189 are shown in Fig. 5. When v_c was 150 m/min the chip had a saw-tooth shape with strongly bonded segments. However, this type of chip is not the result of chip segmentation, rather, it occurs because of severe plastic deformation of material, which is shown in detail in Fig. 5a. In this case the initial crack appears due to intense deformation. The polygonal austenite grains are evidently elongated in the structure of this particular steel grade.

Fig. 5b shows an unusual shape of chip, which was produced with a cutting speed of 1500 m/min. No chip segmentation appears as this steel passes through the plastic deformation region, even at high cutting speeds. There is some kind of material “accumulation” on the outer side of the chip; this is obviously an unsteady-state continuous chip. The accumulation of material and the unsteadiness of the process are clearly visible on the SEM photograph (detail in Fig. 5b). By looking at the chip shape it is not possible to conclude whether the cutting speed of 1500 m/min belongs to the high-speed machining region for this type of steel grade.

The microphotos of the chip produced during the machining of X63CrMoV51 (annealed) are shown in Fig. 6. When v_c was 150 m/min (Fig. 6a) the chip looks like the one produced by machining Ck15 (Fig. 4a), only with a lower chip compression coefficient (λ = 0.17/0.1 =1.7) and a higher grain texture angle (i.e.



a) rezalna hitrost 150 m/min
cutting speed 150 m/min



b) rezalna hitrost 1500 m/min
cutting speed 1500 m/min

Sl. 5. *Prečni prerez odrezka, nastalega pri obdelavi nerjavnega jekla X5CrNi189*
Fig. 5. *Cross-sections of chips produced during X5CrNi189 machining*

strukture (kot med drugotno deformacijo zrn in strižno ravnino). Ta oblika odrezka je tudi značilen primer enakomernega, zveznega odrezka.

Pri obdelavi tega jekla z rezalno hitrostjo v_c = 1500 m/min (sl. 6b) pa je odrezek segmentiran in nazobčan. Nastaja na podlagi intenzivnega striga vzdolž mej med posameznimi segmenti, zato je to tudi tipičen primer segmentnega odrezka, nastalega na podlagi lokaliziranega striga. Segmenti so skoraj enake širine (povprečje 0,06 mm) in oblike, kar kaže na stabilnost postopka deformacije odrezka. Natančno je to prikazano na fotografiji SEM na sliki 6b. Preostali detajli na fotografiji pa prikazujejo deformiran in nedeformiran del odrezka. Iz oblik odrezkov na sliki 6 lahko sklepamo, da rezalna hitrost v_c = 150 m/min ustreza običajnem območju, hitrost v_c = 1500 m/min pa zelo hitrem območju obdelave.

Slika 7 prikazuje mikrostrukture odrezka, nastalega pri obdelavi kaljenega jekla X63CrMoV51. Pri rezalni hitrosti v_c = 50 m/min (sl. 7a) je mehanizem oblikovanja odrezkov enak kakor v primeru obdelave konstrukcijskega jekla Ck15 (sl. 4a) in žarjenega orodnega jekla X63CrMoV51 (sl. 6a). Ugotovimo lahko, da so hitrosti obdelave v območju običajnih rezalnih hitrosti.

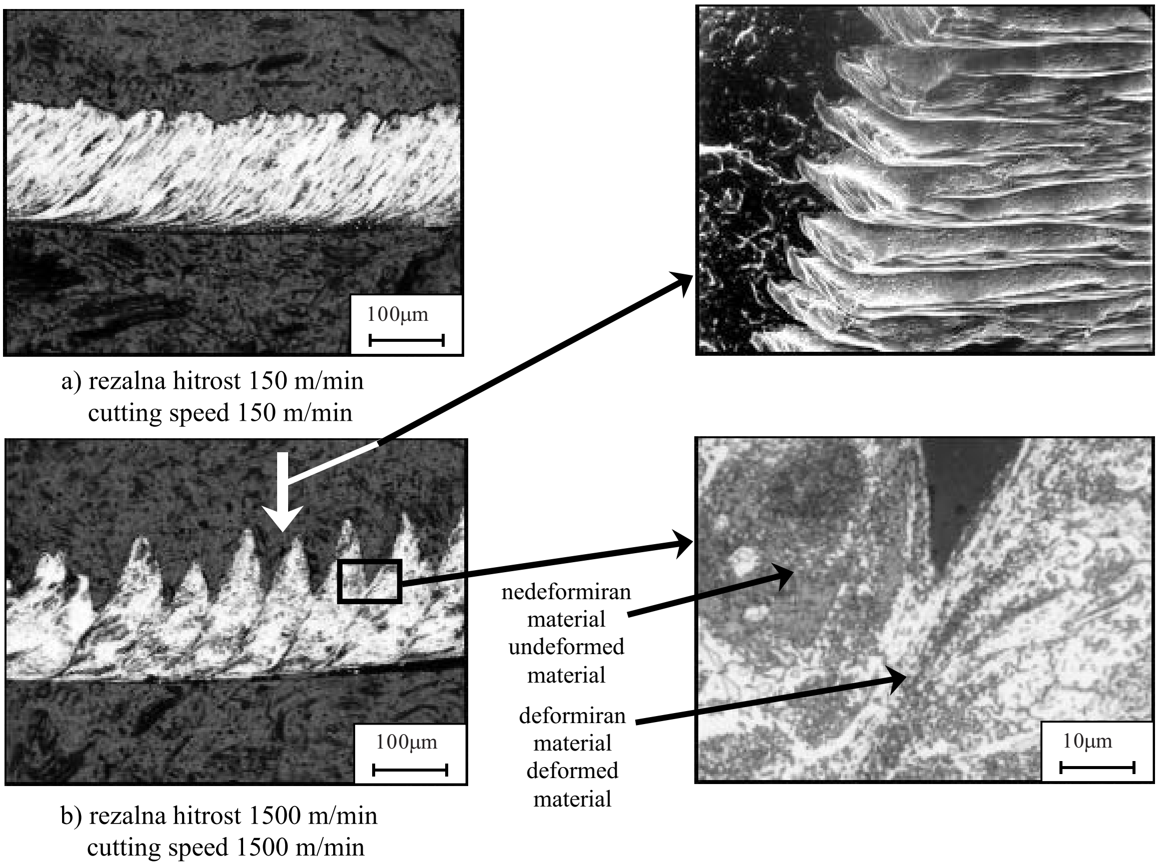
Pri obdelavi z rezalno hitrostjo v_c = 150 m/min (sl. 7b) nastaja tipično nazobčana, segmentirana oblika

the angle between the secondary grain elongation direction and the shear plane). This kind of chip is also a typical example of a steady-state continuous chip.

However, when machining with v_c = 1500 m/min (Fig. 6b) the chip is segmented and saw-tooth shaped. In this case the chip is formed by an intense shear along the boundaries between adjacent segments, and this is a typical example of a shear-localized segmental chip. These segments are almost of equal width (average 0.06 mm) and shape, which points to the stability of the chip-formation process. The SEM photograph shown in the detail of Fig. 6b also demonstrates this. The other detail of the same figure clearly shows the undeformed and deformed parts of the chip.

On the basis of chip shapes shown in Fig. 6 we can conclude that a cutting speed of 150 m/min is in the conventional speed range, and a cutting speed of 1500 m/min is in the high-speed range. Fig. 7 shows the microphotos of a chip produced during X63CrMoV51 (tempered) machining. When v_c = 50 m/min (Fig.7a), the chip-formation mechanism is the same as in the case of Ck15 (Fig. 4a) and X63CrMoV51 (annealed, Fig. 6a) machining. Obviously, this is the conventional cutting-speed region.

During machining with a cutting speed of 150 m/min (Fig. 7b) the chip is segmented and possesses



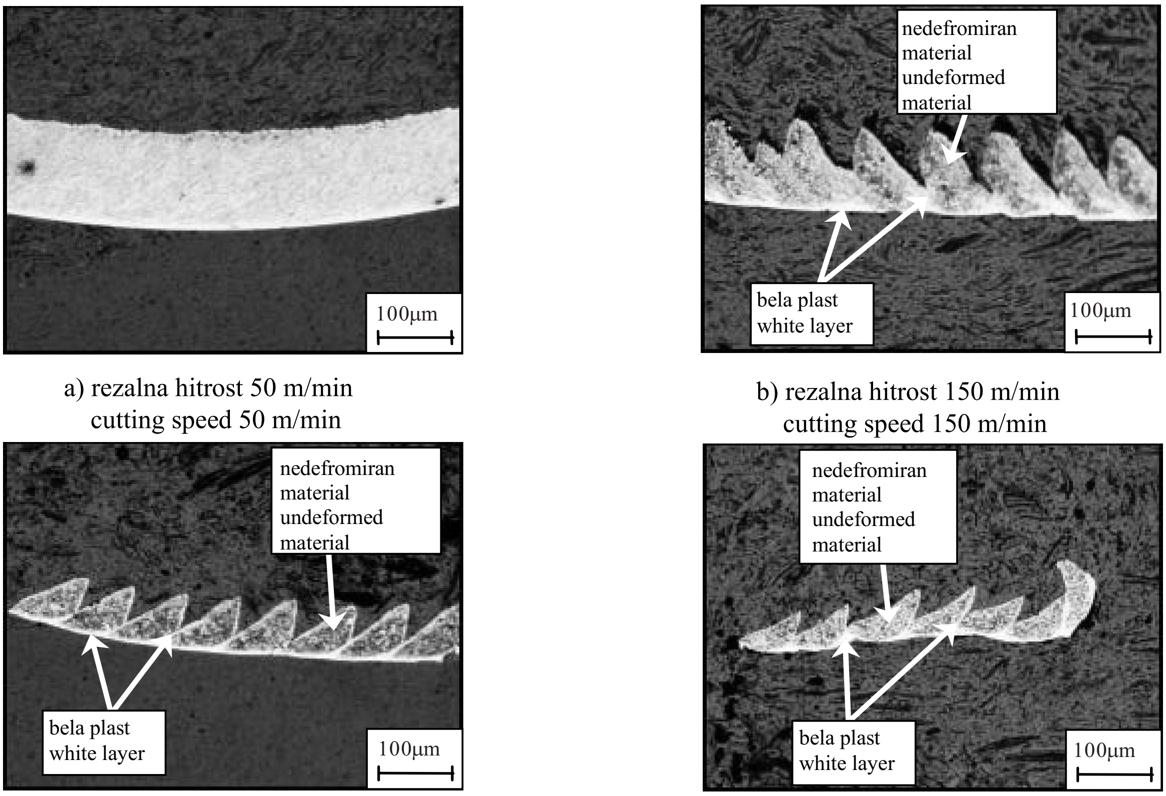
Sl. 6. *Prečni prerez odrezka pri obdelavi žarjenega jekla X63CrMoV51*
Fig. 6. *Cross-sections of chips produced during (annealed) X63CrMoV51 machining*

odrezka. V nasprotju z obdelavo tega jekla v žarjenem stanju s hitrostjo v_c = 1500 m/min (sl. 6b) se v tem primeru pojavi tako imenovana bela plast, ki kaže, da se v postopku oblikovanja odrezka pojavlja postopek termičnega mehčanja. V splošnem je žagasto oblikovanje odrezkov povezano z oblikovanjem odrezkov pri obdelavi trdih materialov. To lahko povezujemo s krhkostjo materiala in nastajanjem velikih tlačnih napetosti na obdelovancu. Med odrezovanjem namesto plastičnega tečenja materiala nastajajo lomi na površini obdelovanca. Ti lomi sproščajo notranjo energijo, s tem delujejo na dele materiala kot drsne ravnine in omogočajo posameznemu delu odrezka da odteka med stičnimi površinami. Zaradi visokih vrednosti lokalnih temperatur nastanejo bele plasti martenzita.

Termalno mehčanje materiala zatorej postaja vse pomembnejši vpliv na plastične lastnosti materiala v primerjavi z učinki deformacijskega utrjevanja. Deformacijsko utrjevanje je prevladujoč postopek med obdelavo teh vrst jekel z majhnimi rezalnimi hitrostmi (v_c = 50 m/min), ko pa rezalna hitrost doseže vrednosti 150 m/min, prevladujoč proces postane oblikovanje notranjih razpok in termičnega mehčanja. To se posebej izrazito kaže na slikah strukture odrezka pri rezalni hitrosti v_c = 300 m/min in 1500 m/min (sl. 7c in 7d). Ko se rezalna hitrost povečuje, se pojavlja hkrati več izrazitih plasti in

a typical saw-tooth shape. In contrast to the machining of this annealed steel grade with a cutting speed of 1500 m/min, Fig. 6b, the so-called white layer appears, indicating a thermal softening process during chip formation. Generally, saw-toothed chip formation is an inherent feature when machining steels in their hardened state. It can be related to the brittleness of the material and to the generation of high compressive stresses on the workpiece during cutting. Instead of the material flowing plastically during cutting, a crack will begin on the workpiece surface. This crack releases the stored energy and acts as a sliding plane for the material segments, allowing the chip segment to be forced out from between the parting surfaces. Because of the high local temperature the white layers of martensite are formed.

Therefore, the thermal softening of material becomes increasingly important and more and more influential on the plastic behaviour of the material in comparison to the effect of the strain hardening. Strain hardening is the dominant process during machining of this type of steel with a cutting speed of 50 m/min, but when the cutting speed reaches 150 m/min the formation of an initial crack and the thermal softening process are dominant. This is especially visible on photographs of the chip produced at cutting speeds of 300 m/min and 1500 m/min (Fig. 7c and 7d).



a) rezalna hitrost 50 m/min
cutting speed 50 m/min

b) rezalna hitrost 150 m/min
cutting speed 150 m/min

c) rezalna hitrost 300 m/min
cutting speed 300 m/min

d) rezalna hitrost 1500 m/min
cutting speed 1500 m/min

Sl. 7. *Prerez odrezka pri obdelavi kaljenega jekla X63CrMoV51*
Fig. 7. *Cross-sections of chip produced during X63CrMoV51 (tempered) machining*

tanjših odrezkov z manjšimi segmenti. Med obdelavo kaljenega jekla X63CrMoV51 (trdote 629 HV ali 52 HRc) torej preidemo v območje zelo hitre obdelave v primerih, ko znaša rezalna hitrost 150 m/min. To je mogoče skleniti na podlagi analize fotografij strukture in oblike odrezkov, dobljenih pri obdelavi z različnimi vrednostmi rezalnih hitrosti.

When the cutting speed increases more obvious layers and a thinner chip with smaller segments appear simultaneously. It is clear that during machining of X63CrMoV51 (tempered, 629 HV, 52 HRC) the high-speed region is entered when the cutting speed is 150 m/min, which can be concluded on the basis of the chip shape.

3 SKLEP

Med običajno in zelo hitro obdelavo naslednjih jekel: ogljikovega jekla Ck15, nerjavnega jekla X5CrMoV51 in legiranega jekla X63CrMoV51 z rezalnimi hitrostmi v območju od 50 do 1500 m/min se pojavljajo različni mehanizmi nastajanja in oblikovanja odrezkov. Pri manjših rezalnih hitrostih pri vseh vrstah jekel nastajajo enakomerne zvezne oblike odrezkov, značilna je tudi manjša ali večja plastična deformacija. Ko obdelujemo bolj deformljiva jekla z manjšimi hitrostmi, so le ta izpostavljena večji plastični deformaciji. Glavna značilnost teh primerov obdelave je enakomerno deformacijsko utrjevanje.

Pri obdelavi omenjenih vrst jekel z večjimi hitrostmi, posebno hitrostmi, ki ustrezajo območju velikih hitrosti, se pojavlja mehanizem oblikovanja odrezkov v obliki nastajanja razpok z večjim ali manjšim

3 CONCLUSIONS

During conventional and high-speed milling of the following steels: carbon steel (Ck15), stainless steel (XcrNi189) and alloy tool steel (X63CrMoV51), with a cutting-speed range from 50 to 1500 m/min, different mechanisms of chip-formation appear. When the cutting speed is low, the steady-state continuous chip is characteristic for all the investigated steel grades, and more or less plastic deformation occurs. When more ductile steel grades are machined with lower cutting speeds they undergo more plastic deformation. The main characteristic in this case is uniform strain hardening.

When machining the steels with higher cutting speeds, especially those speeds that belong to the high-speed region, the chip-formation mechanism is crack initiation along with more or less influence from the shear-localized mechanism. The consequence of vplivom lokaliziranega striga. Posledica tega je nastanek žagaste oblike odrezkov z medsebojno ločenimi lamelami, oziroma pojav nedeformiranega in deformiranega območja (bela plast). Pojav bele plasti je tesno povezan z obdelavo trdih materialov. To dejstvo je mogoče razložiti s povečanjem temperature v rezalni coni, zaradi česar se povečuje vpliv termičnega mehčanja in plastičnih lastnosti materiala v primerjavi z učinkom deformacijskega utrjevanja.

this is the formation of a saw-toothed chip with apparent chip parts, i.e. an undeformed part and an extremely deformed part (white layer). The appearance of the white layer is closely associated with machining of hard materials. This can be explained by an increase of the temperature in the cutting zone, which makes the thermal softening more influential on the plastic behaviour of material in comparison to the effect of the strain hardening.

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