CODEN STJSAO ISSN 0562-1887
ZX470/1356 UDK 621.941.621.785.616.539.374

Chip Formation Analysis During Hard Turning

***Robert ČEP*[1)]**
***Miroslav NESLUŠAN*[2)]**
***Branimir BARIŠIĆ*[3)]**

1) Faculty of Mechanical Engineering, VSB - TU Ostrava, 17. listopadu 15, Ostrava, **Czech Republic**
2) Faculty of Mechanical Engineering, Zilina University, Univerzitna 1, Zilina, **Slovakia**
3) Faculty of Engineering, University of Rijeka, Vukovarska 58, HR - 51000 Rijeka, **Republic of Croatia**

barisic@riteh.hr

Original scientific paper

The paper deals with analysis of chip formation and related aspects of chip formation, like chip thickness, chip ratio, shear angle and chip segmentation during turning of hardened steel 100Cr6. The paper makes a comparison of some aspects of chip formation between turning annealed and hardened roll bearing steel 100Cr6. The results of the analysis show that there is formation of a segmented chip in the case of hard turning. This process of the chip formation significantly affects all parameters related to the plastic deformation in the cutting zone. Moreover, the formation of the segmented chip causes instability of a cutting process, the high intensity of tool wear and generation of significant heat in the cutting zone. The heat causes high temperature in the cutting zone (thermal load of a cutting tool).

Keywords
Chip Formation
Hardened Steel
Plastic Deformation
Turning

Ključne riječi
Formiranje odvojenih čestica
Otvrdnuti čelik
Plastična deformacija
Tokarenje

Received (primljeno): 2008-06-30
Accepted (prihvaćeno): 2008-10-25

Analiza formiranja odvojenih čestica kod tvrdog tokarenja

Izvornoznanstveni članak

Rad analizira formiranje odvojenih čestica i popratne aspekte njihovog formiranja, poput debljine, omjera, kuta smicanja i segmentiranja odvojenih čestica kod tokarenja otvrdnutog (kaljenog) čelika 100Cr6. Rad uspoređuje različite spekte prilikom formiranja odvojenih čestica između žarenog i otvrdutog (kaljenog) čelika za kotrljajne ležaje 100Cr6. Rezultati analize prikazuju postojanje segmentiranih odvojenih čestica u slučaju tvrdog tokarenja. Ovakav process formiranja odvojenih čestica značajno utječe na sve parametre povezane s plastičnom deformacijom u području rezanja. Čim više, formiranje segmentiranih odvojenih čestica uzrokuje nestabilnost procesa rezanja, visok intenzitet trošenja alata i značajno stvaranje topline u zoni rezanja što uzrokuje visoke temperature (toplinsko opterećenje reznog alata).

1. Introduction

Cutting hardened steel is an interesting topic of today's industrial production and scientific research. Machine parts consisting of hardened steel are high performance components, which are often loaded near their physical limits. The functional behavior of machined parts is decisively influenced by the fine finishing process, which represents the last step in the process chain, and can easily be done by cutting, as by grinding or turning. For this reason, fine finishing is defined as an important process, and its results have to satisfy high quality requirements. The product specific issues and demands also require effectiveness, time to market and process agility.

Developments in machine tools, as well as in process technology, focus on cutting hardened steel and rapidly lead to increased industrial relevance of hard cutting. In fact, hard cutting can be seriously regarded as an alternative for grinding operations under certain circumstances. High flexibility and ability to manufacture complex work piece geometry in one-go represent the main advantages of hard cutting in comparison to grinding [1]. Furthermore, the substitution of a grinding process by the cutting process enables us to avoid coolants, and therefore can actually be regarded as an interesting alternative even from the ecological point of view [1].

Applying hard cutting as a finishing process requires generation of machined surface by pure plastic

Symbols/Oznake

v	- cutting speed, $m \cdot min^{-1}$ - brzina rezanja	$\bar{\varepsilon}$	- equivalent strain - ekvivalentna deformacija
f	- feed, mm - posmak	β	- force angle inclination, ° - nagib sile
a_p	- cutting depth, mm - dubina rezanja	F	- resultant force, N - rezultantna sila
h_c	- chip thickness, mm - debljina odvojenih čestica	F_{tn}	- normal forces on the rake plane, N - normalna sila na nagnutoj ravnini
h	- undeformed thickness, mm - debljina nedeformiranih odvojenih čestica	F_{cn}	- cutting force in normal plane, N - sila rezanja u normalnoj ravnini
Φ_1	- deformation angle, ° - kut deformacija	F_s	- force in shear direction, N - sila u smjeru smicanja
v_{ch}	- chip speed, $m \cdot min^{-1}$ - brzina odvojenih čestica	F_p	- radial compnent of cutting force - radijalna komponenta sile rezanja
v_{sh}	- shear speed, $m \cdot min^{-1}$ - brzina smicanja	F_t	- tangential forces on the rake plane, N - tangencijalna sila na ravnini rezanja
γ_{sh}	- ship deformation - deformacija odvojenih čestica	Q	- heat in the shear zone, kJ/min - toplina u zoni smicanja
γ_n	- rake angle, ° - kut rezanja	Q_f	- heat caused by friction, kJ/min - toplijna uzrokovana trenjem
K	- chip ration - omjer odvojenih čestica	μ_s	- friction energy in the shear plane, kJ/mm^3 - energija trenja u ravnini smicanja
G	- degree of segmentation - stupanj segmentiranja	μ_F	- friction energy of the tool rake and chip - energija trenja nagiba alata i odvojenih čestica
Θ	- cutting temperature, °C - temperature rezanja		

deformation. The proper understanding of the material removal mechanisms that take place during hard cutting is essential for process evaluation. The analysis of the work area is necessary to describe chip generation in hardened materials. Depending on cutting parameters and work piece material properties, cutting may either lead to continuous or discontinuous chip formation [2, 3].

The continuous chip is formed during turning of conventional annealed steels (Fig. 2). On the other hand, there is formation of the segmented chips during the hard turning [2- 4]. Fig. 1 and 3 illustrate the segmented chip during turning hardened steel 100Cr6. Recht [3] introduced the adiabatic shear theory to characterize the chip segmentation process during the hard turning. The thermoplastic instability occurs where a decrease in flow stress due to thermal softening associated with increase in strain more than offsets associated strain hardening [4]. The process of plastic deformation in the cutting zone affects many aspects of the cutting process. Therefore, this paper deals with analysis of the chip formation during hard turning of the roll bearing steel 100Cr6.

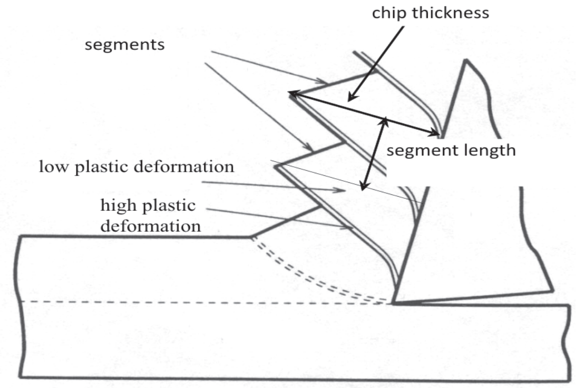


Figure 1. Illustration of chip formation during hard turning

Slika 1. Prikaz formiranja odvojenih čestica kod tvrdog tokarenja

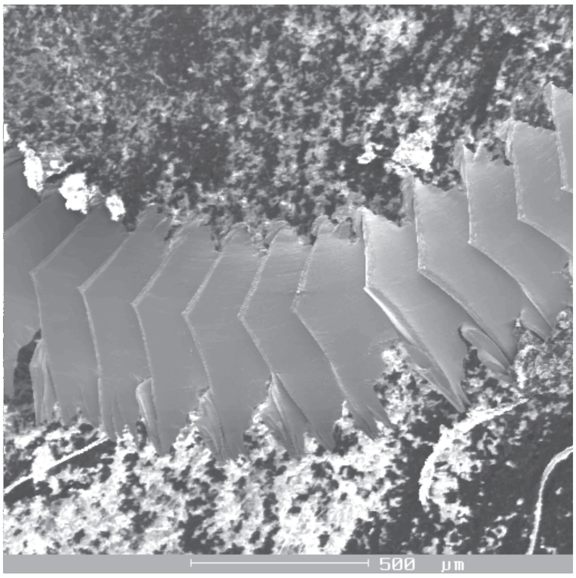


Figure 2. Chip after turning of 100Cr6 (hardened 62 HRC), REM, v_c = 100 m·min^{-1}, f = 0.271 mm

Slika 2. Odvojene čestice nakon tokarenja 100Cr6 (otvrdnuto stanje 62 HRC), REM, v_c = 100 m·min^{-1}, f = 0.271 mm

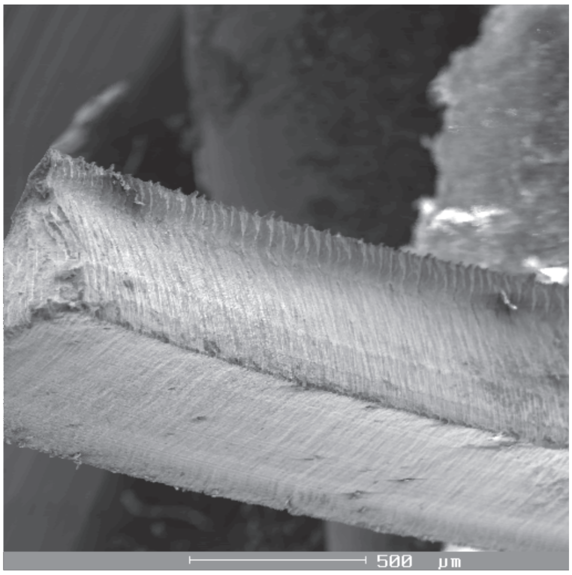


Figure 3. Chip after turning of 100Cr6 (annealed), REM, v_c = 100 m·min^{-1}, f = 0.271 mm

Slika 3. Odvojene čestice nakon tokarenja 100Cr6 (žareno stanje), REM, v_c = 100 m·min^{-1}, f = 0.271 mm

2. Description of work methodology, materials and experiments

The roll bearing material 100Cr6 of the diameter 56 mm and the length of 125 mm was used in the experiments. It was used both in annealed, and hardened (62HRC) specimens. The measurements were carried out by application of the ceramic inserts DNGA150408 (TiN coating), using the lathe SUI 40. The chip thickness was measured by an optical microscope. Cutting conditions: cutting speed v_c = 25 to 250 m·min^{-1}, feed f = 0,09 mm, cutting depth a_p = 0,25 mm. The forces were measured by the piezoelectric dynamometer KISTLER, type 9257A. The temperatures were measured by a natural thermocouple.

3 Results of experiments

Measurement of the chip thickness (h_c) enables calculation of the chip ratio K (equation (1), h is equal to feed) and other related parameters, like deformation angle Φ_1, chip speed (v_{ch}), shear speed (v_{sh}) and chip deformation (γ_{sh}) [5, 6].

$$K = \frac{h_c}{h}, \tag{1}$$

where:

h – undeformed chip thickness,

h_c – chip thickness.

The deformation angle can be calculated through the equation (2):

$$tg\Phi_1 = \frac{\cos\gamma_n}{K - \sin\gamma_n}, \tag{2}$$

where:

Φ_1 – deformation angle,

γ_n – rake angle.

The chip speed can be calculated by the equation (3).

$$v_{ch} = v_c \frac{\sin\Phi_1}{\cos(\Phi_1 - \gamma_n)}, \tag{3}$$

where:

v_{ch} – chip speed,

v_c – cutting speed.

The shear speed can be calculated through the equation (4), and the chip deformation through the equation (5) as:

$$v_{sh} = v_c \frac{\cos\gamma_n}{\cos(\Phi_1 - \gamma_n)}, \tag{4}$$

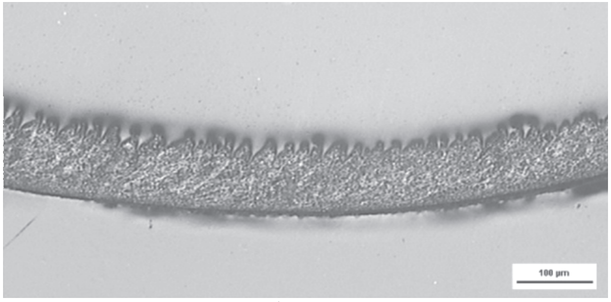
where:

v_{sh} – shear speed.

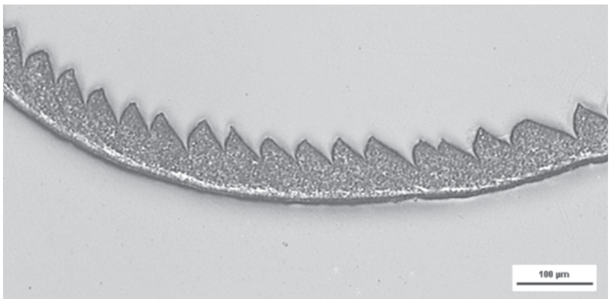
Chip deformation (γ_{sh}) can be presented as:

$$\gamma_{sh} = \frac{\cos\gamma_n}{\cos(\Phi_1 - \gamma_n).\sin\Phi_1}. \tag{5}$$

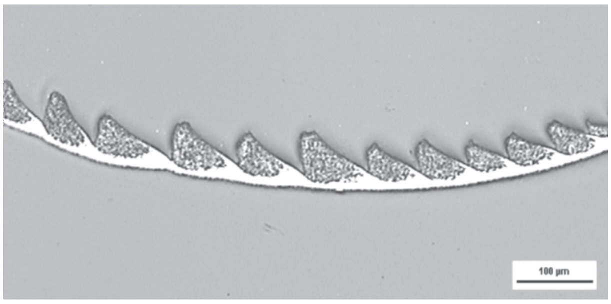
Measurements of the chip thickness were carried out by the optical microscope BK5 and measured chips are presented in Figure 4.



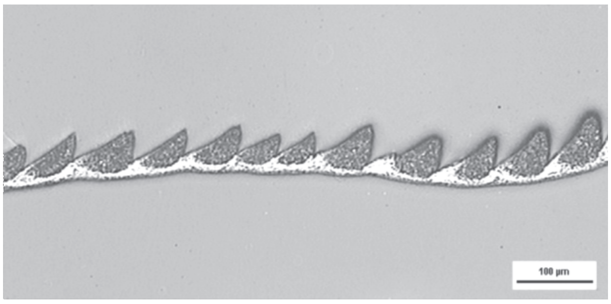
a)



b)



c)



d)

Figure 4. Chips after hard turning a) v_c = 25 m·min^{-1}, f = 0.09 mm, b) v_c = 50 m·min^{-1}, f = 0.09 mm, c) v_c = 100 m·min^{-1}, f = 0.09 mm, d) v_c = 200 m·min^{-1}, f = 0.09 mm

Slika 4. Odvojene čestice nakon tvrdog tokarenja a) v_c = 25 m·min^{-1}, f = 0.09 mm, b) v_c = 50 m·min-1, f = 0.09 mm, c) v_c = 100 m·min-1, f = 0.09 mm, d) v_c = 200 m·min-1, f = 0.09 mm

Figure 5 illustrates that the chip thickness during turning of hardened steel is much lower than for turning of annealed one. Formation of the segments during the turning of the hardened steel causes their elongation and decreasing of chip thickness. The result is formation of thin and long chips, the chip ratio is smaller than 1, in comparison with the turning of annealed steel (thick and short continuous chip, with the chip ratio higher than 1, Figure 6).

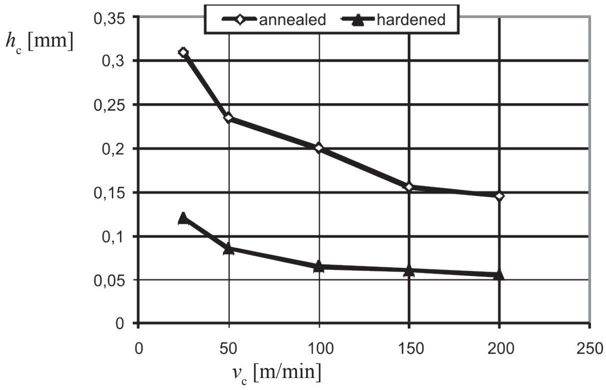


Figure 5. Influence of cutting speed on chip thickness

Slika 5. Utjecaj brzine rezanja na debljinu odvojenih čestica

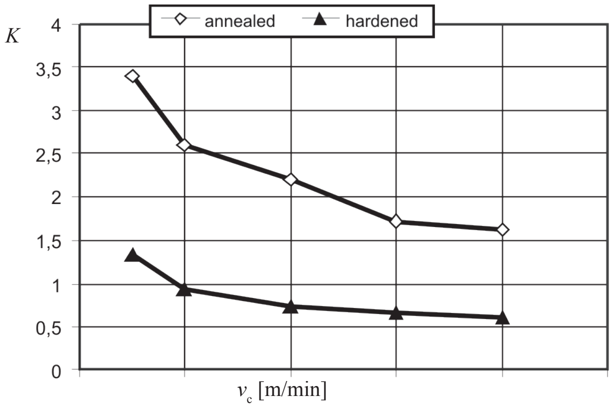


Figure 6. Influence of cutting speed on chip ratio

Slika 6. Utjecaj brzine rezanja na omjer odvojenih čestica

Intensity of plastic deformation is much lower during hard turning, in comparison with turning of the annealed steel. Intensity of plastic deformation in the cutting zone can be expressed by various parameters. With the exception of the chip ratio K, there are the other parameters, like the degree of segmentation (G), chip deformation (γ_{sh}), or equivalent strain ($\bar{\varepsilon}$).

The degree of segmentation can be calculated through the equation (6) and presented in Figure 7.

$$G = \frac{h_c - h_o}{h_c}, \qquad (6)$$

where

h_c – higher part of chip (Figure 7),

h_o – lower part of chip (Figure 7).

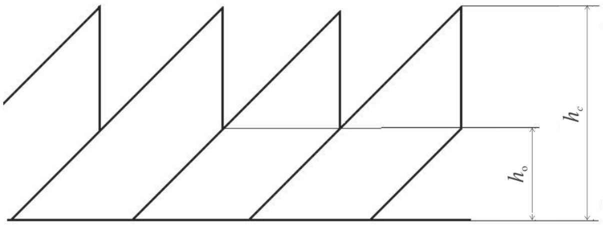


Figure 7. Illustration for calculation of segmentation degree

Slika 7. Prikaz za izračun stupnja segmentiranja

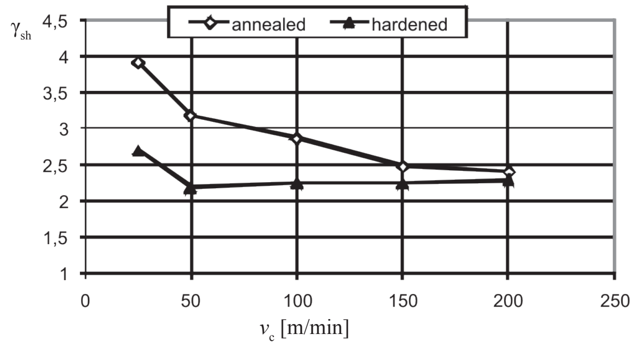


Figure 8. Influence of cutting speed on chip deformation

Slika 8. Utjecaj brzine rezanja na deformaciju odvojenih čestica

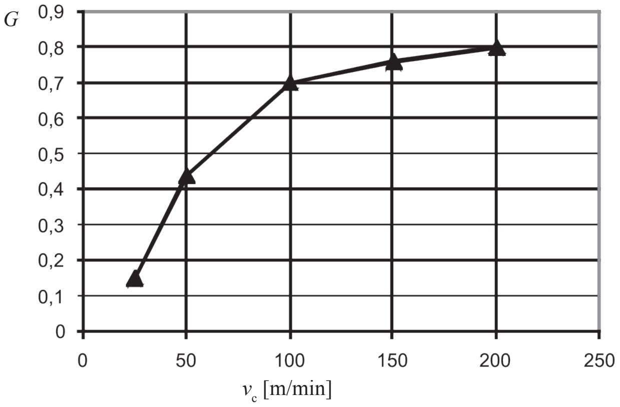


Figure 9. Influence of cutting speed on degree of segmentation

Slika 9. Utjecaj brzine rezanja na stupanj segmentiranje

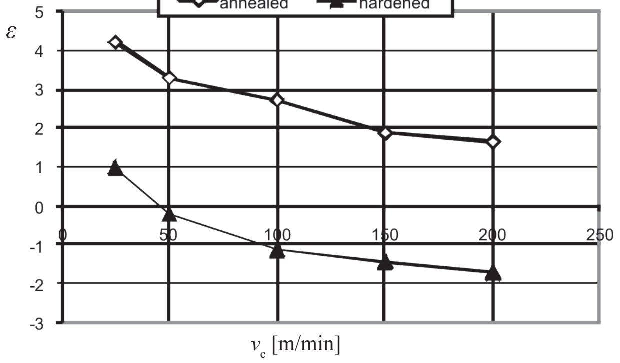


Figure 10. Influence of cutting speed on equivalent strain

Slika 10. Utjecaj brzine rezanja na ekvivalentnu deformaciju

Equivalent strain is determined based on analogy between plastic deformation of the work material in the chip forming zone and upsetting:

$$\bar{\varepsilon} = \frac{2\varepsilon_1}{\sqrt{3}}, \tag{7}$$

where (for orthogonal cutting):

$\varepsilon_1 = ln\,(h_c / h)$, $\varepsilon_1 = \varepsilon_2 \cdot \varepsilon_3 = 0$.

The low intensity of plastic deformation is attributed to the material inside of a segment. The plastic deformation inside the segment is low, and material in this area stays untouched. Although, the plastic deformation in the localized areas of the segmented chip is extremely high (white areas), the total deformation of segmented chip is much lower than that of the continuous chip (during turning annealed steel), Figure 8. On the other hand, intensity of plastic deformation significantly changes with cutting speed in the case of hard turning. The segmented chip is becoming more continuous with a decreasing cutting speed. This aspect is verified by the degree of segmentation (Figure 9). The continuous chip can be expressed as a segmented chip with the zero degree of segmentation. Figure 9 illustrates that the degree of segmentation strongly decreases with a decreasing cutting speed. Chip thickness, chip ratio, chip deformation or equivalent strain increases with a decreasing cutting speed, because of the intensity of plastic deformation increases, and the chip is becoming more and more continuous. Because of formation of the thin and long chips during hard turning, the equivalent strain is smaller than 0 (chip elongation), as opposed to the turning of annealed steel (thick and short continuous chip, chip shortening, therefore the equivalent strain is higher than 1, Figure 10).

As a result of the formation of the thin and long chips (when turning hardened steel), the shear speed and the chip speed are much higher than while turning the annealed steel (Figures 11 and 12). Formation of the segments is a very rapid process, and despite the low intensity of the plastic deformation inside the segments, the cutting temperature is very high (in comparison to the turning of annealed steel, Figure 13).

The energy entering the cutting zone is dissipated to the localized areas with very high intensity of plastic deformation (the narrow bands between segments rake – chip contact and back – machined surface contact). The heat is concentrated in those thin layers (the white layers in Figure 4) and is much higher than the heat, while turning annealed steel (Figure 13). The specific character of the chip formation is related to the very high shear angle; much higher than the shear angle for turning of annealed steel (Figure 14). The deformation speed is increasing with the cutting speed, and therefore the shear angle is increasing also.

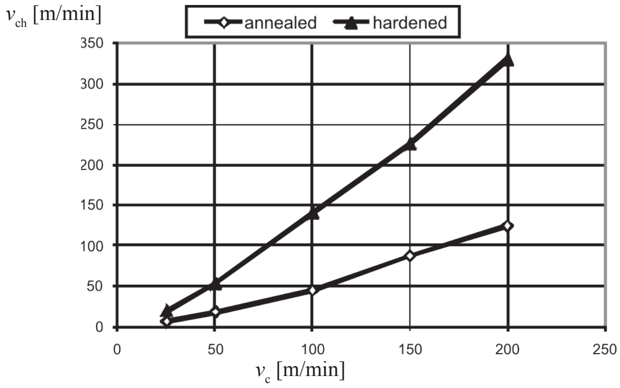


Figure 11. Influence of cutting speed on chip speed

Slika 11. Utjecaj brzine rezanja na brzinu odvojenih čestica

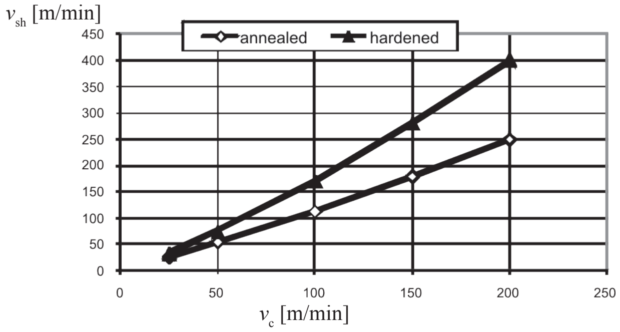


Figure 12. Influence of cutting speed on shear speed

Slika 12. Utjecaj brzine rezanja na smičnu brzinu

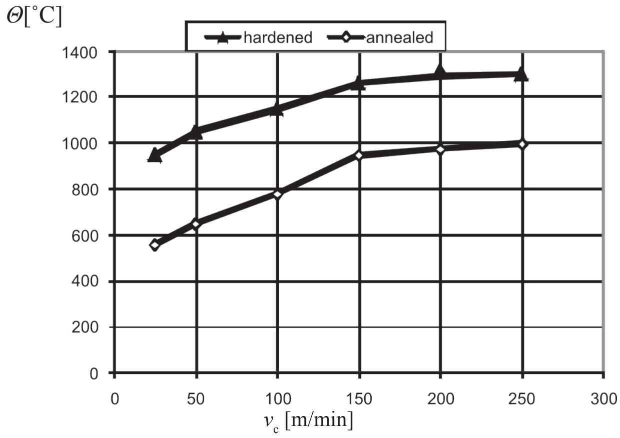


Figure 13. Influence of cutting speed on cutting temperature

Slika 13. Utjecaj brzine rezanja na temperaturu rezanja

Based on the measured cutting forces F_c and the radial component of cutting force F_p, it is possible to decompose the cutting forces [5, 6] (Figure 15) in relation to the rake of the tool, and in relation to the shear plane (Figures 16, 17). The components of cutting force related to the rake of the tool enable analysis of its mechanical loading.

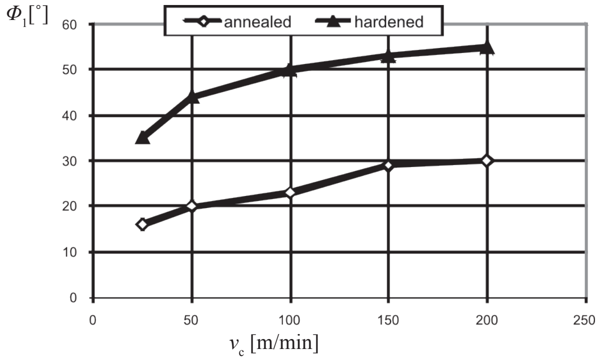


Figure 14. Influence of cutting speed on deformation angle

Slika 14. Utjecaj brzine rezanja na deformacijski kut

The components of cutting forces related to the shear plane must be attributed to the character and the intensity of the plastic deformation defined by the deformation angle Φ_1. It means:

$$F_t = F \cdot \sin\beta, \tag{8}$$

where:

F – resultant force,

β – force angle inclination.

Also, F_{tn} is calculated as:

$$F_t = F \cdot \cos\beta. \tag{9}$$

Size of the angle β can be calculated through the equation (10):

$$\sin(\beta - \gamma_n) = \frac{F_{cn}}{F}, \tag{10}$$

where:

F_{cn} – cutting force in normal plane.

Force in shear direction F_s can be calculated through the equation (11):

$$F_s = F \cdot \cos(\beta - \gamma_n + \Phi_1). \tag{11}$$

The high hardness of the machined material and the specific character of chip formation cause an increase in the radial component of cutting force F_p (Figure 15). This component is much higher than F_c in the case of hard turning. On the other hand, there is no significant difference in the cutting force components during turning of annealed steel (Figure 15). Based on the measured forces and equations (8), (9) and (10), it is possible to calculate the tangential F_t and normal F_{tn} forces on the rake plane of the cutting tool (Figure 15). Figure 15 illustrates that F_{tn} and especially F_t is much higher during hard turning than the forces while turning of annealed steel. Moreover, components of the cutting force related to the shear plane are much higher during hard turning than the forces while turning of annealed steel (Figure 17).

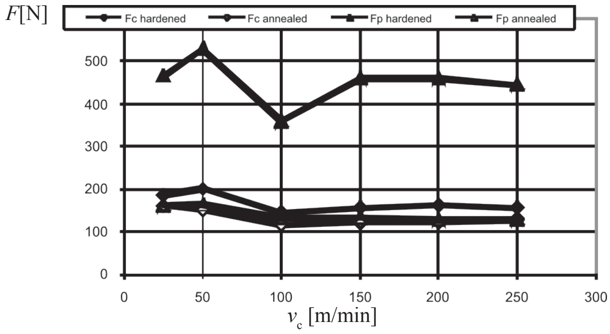


Figure 15. Influence of cutting speed on F_c and F_p

Slika 15. Utjecaj brzine rezanja na F_c i F_p

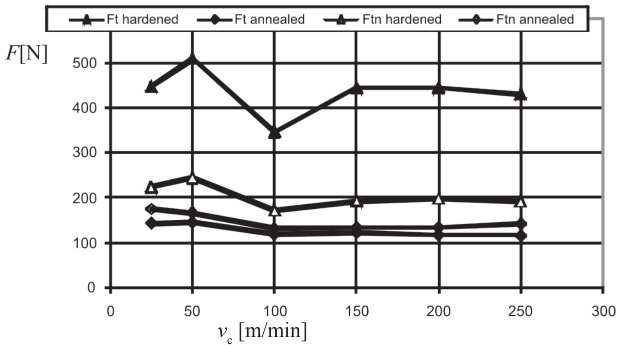


Figure 16. Influence of cutting speed on F_t and F_{tn}

Slika 16. Utjecaj brzine rezanja na F_t and F_{tn}

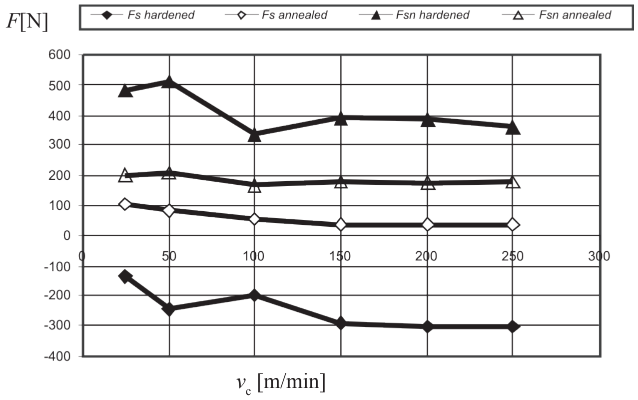


Figure 17. Influence of cutting speed on F_s and F_{sn}

Slika 17. Utjecaj brzine rezanja na F_s i F_{sn}

As a result of the high shear angle for hard turning and the high F_p, F_s component is oriented in the negative direction in comparison to turning of annealed steel (Figures 18, 19).

High mechanical load of a tool is connected with thermal loading. Based on F_t and v_{ch}, it is possible to calculate the heat created by friction between tool rake and chip ($Q_f = F_t \cdot v_{ch}$), and based on F_s and v_{sh}, it is possible to calculate the heat generated by the plastic deformation in the shear zone ($Q = F_s \cdot v_{sh}$), Figure 20.

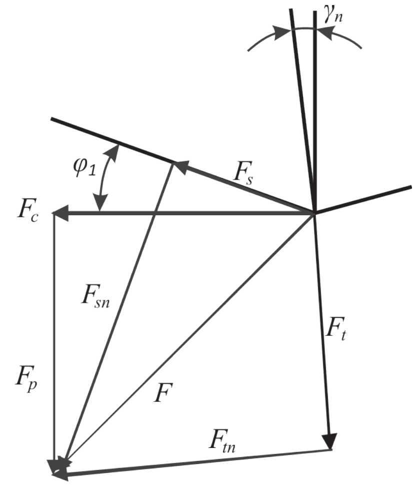


Figure 18. Decomposition of cutting force in the cutting zone, annealed steel

Slika 18. Rastavljanje sile rezanja u zoni rezanja, žareni čelik

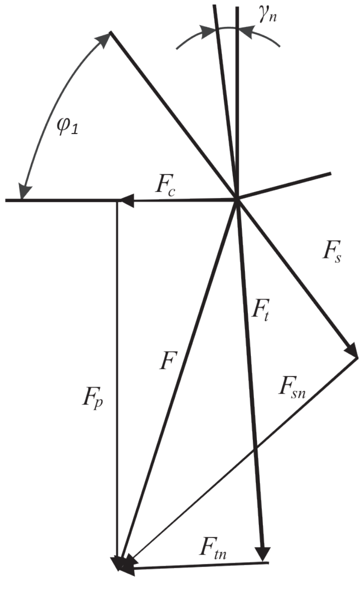


Figure 19. Decomposition of cutting force in the cutting zone, hardened steel

Slika 19. Rastavljanje sile rezanja u zoni rezanja, otvrdnuti čelik

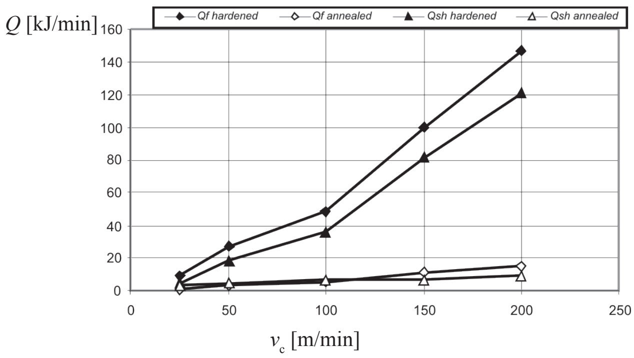


Figure 20. Influence of cutting speed on heat generated in the cutting zone

Slika 20. Utjecaj brzine rezanja na stvaranje topline u zoni rezanja

The heat generated at the contact of the tool rake and chip and the heat generated in the shear plane are related to friction energy. The friction energy in the shear plane μ_s may be obtained as:

$$\mu_{\mathrm{s}} = \frac{F_{\mathrm{s}} \cdot v_{\mathrm{sh}}}{v_{\mathrm{c}} \cdot b \cdot h}, \tag{12}$$

where:

b– cutting width,

h– cutting depth.

The friction energy at the contact of the tool rake and chip μ_F may be obtained as follows:

$$\mu_{\mathrm{F}} = \frac{F_{\mathrm{t}} \cdot v_{\mathrm{ch}}}{v_{\mathrm{c}} \cdot b \cdot h}. \tag{13}$$

The higher friction energy during hard turning is related to the high v_{ch} and v_{sh}, respectively F_t and F_s in comparison with turning of annealed steel (Figurew 21 and 22). Figures 23 and 24 illustrate that the friction energies μ_F and μ_s are much higher during hard turning than during turning of annealed steel, despite the lower coefficient of friction in these areas during hard turning, The coefficient of friction in the shear plane is related to the relationship between F_s and F_{sn} , and is calculated as the ratio F_{sn} / F_s (Figure 22). The coefficient of friction in contact of the tool and chip is related to the relationship between F_t and F_{tn}, and is calculated as the ratio F_{tn} / F_t (Figure 21).

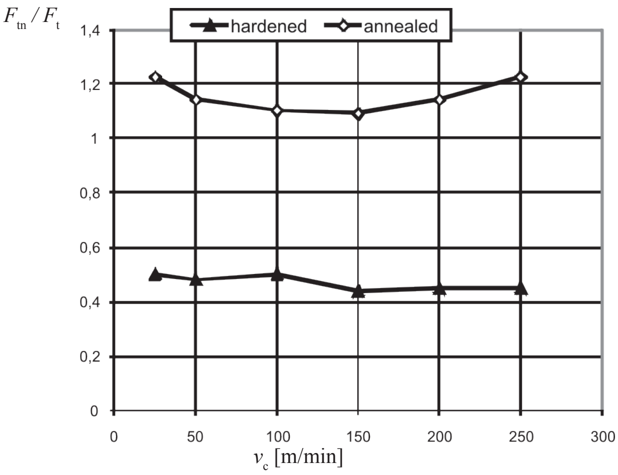


Figure 21. Coefficient of friction at the contact of the tool rake and chip

Slika 21. Koeficijent trenja pri kontaktu nagiba alata i odvojenih čestica

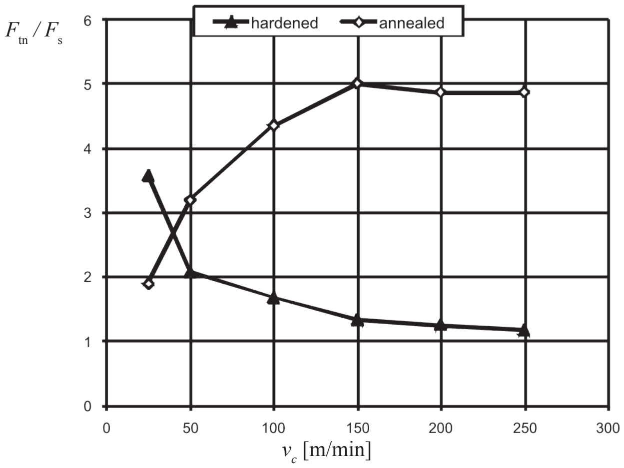


Figure 22. Coefficient of friction in the shear plane

Slika 22. Koeficijent trenja u ravnini smicanja

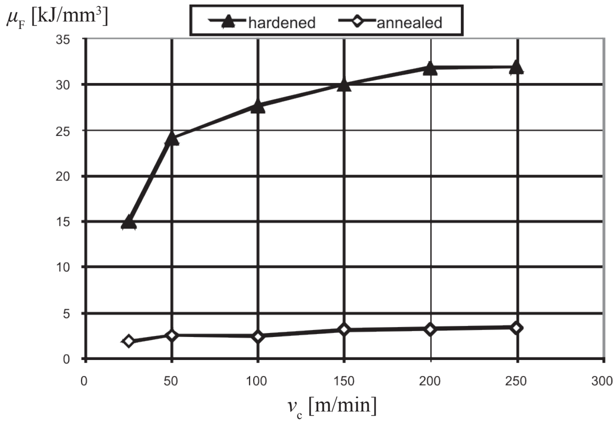


Figure 23. Friction energy at the contact of the tool rake and chip

Slika 23. Energija trenja pri kontaktu nagiba alata i odvojenih čestica

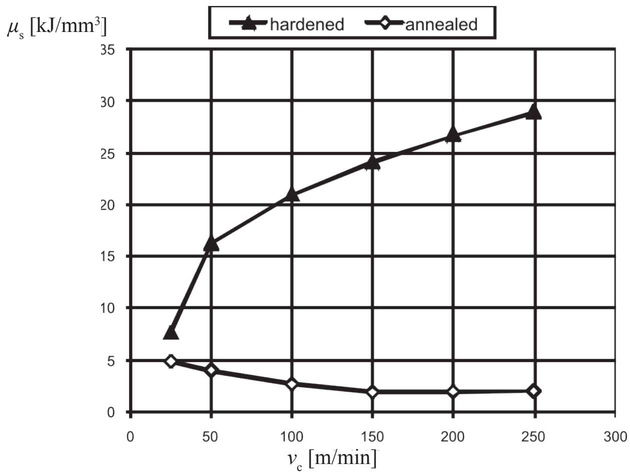


Figure 24. Friction energy in the shear plane

Slika 24. Energija trenja u ravnini smicanja

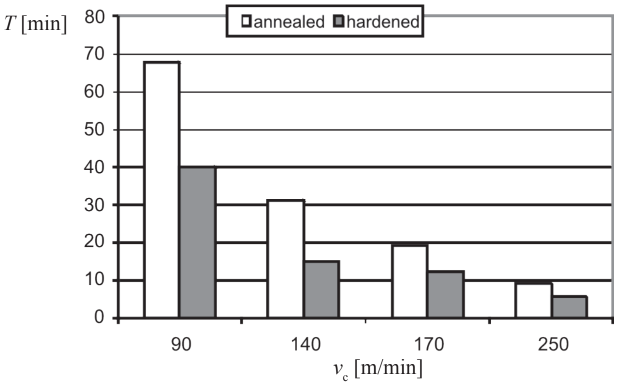


Figure 25. Influence of cutting speed on tool life

Slika 25. Utjecaj brzine rezanja na postojanost alata

The high temperatures in the cutting zone during hard turning are attributed to the friction processes, and therefore they are related to the heat generated in the cutting zone. Heat generated in the cutting zone during hard turning is much higher than the heat during turning of annealed steel (Figure 20). This heat increases very steeply with cutting speed and causes structural changes and the high temperatures (Figure 13) in the cutting zone. Because of the high temperatures at the cutting zone the most often applied tool materials for hard turning are Al_2O_3/TiC ceramics and CBN tools. Their high hardness combined with the high temperature stability enables these materials to resist the thermal and mechanical loads during the hard cutting process. The application of cemented carbide tools is also limited by their comparatively low temperature stability [2, 3, 7]. Moreover, the previous research of chip segmentation showed that the length of segments and the segmentation frequency increases with cutting speed. Application of high speeds leads to rapid decreasing of tool life due to increase of the thermal loading of the tool and decreasing process stability (high frequency of segmentation and high segment length). Tool life decreases very steeply with cutting speed (Figure 25).

There are other aspects of high temperatures and low coefficients of friction in the cutting zone. There is formation of the built-up-edge (BUE) during turning of annealed steels, because of the high friction and temperatures in the cutting zone, especially when the cutting speed is lower than 100 $m \cdot min^{-1}$. The plasticity of machined material and the intensive friction during turning of soft steels cause adherence of machined material to the tool rake [8]. Formation of BUE negatively affects the surface roughness, because BUE can be re-deposited on the machined surface. There is a BUE free machined surface during hard turning, because of too high temperatures (strength of machined material is too low under the elevated temperatures for formation of adhesion), the low coefficient of friction and very high speeds of deformation processes in the cutting zone. Increasing of cutting speed (increasing of temperature in the cutting zone), or application of cutting fluid can significantly alleviate the BUE generation. The differences in the surface roughness decrease with increasing cutting speed.

4. Conclusion

The chip thickness during turning of hardened steel 100Cr6 is much lower than for turning of annealed one. Formation of the segments during the turning of the hardened steel causes their elongation and decreasing of the chip thickness. The result is formation of thin and long chips, the chip ratio is smaller than 1, in comparison with the turning of annealed steel (thick and short continuous chip, with the chip ratio higher than 1). Also, intensity of plastic deformation is much lower during hard turning, in comparison with turning of the annealed steel but intensity of plastic deformation significantly changes with cutting speed in the case of hard turning. The segmented chip becomes more continuous with decreasing cutting speed (aspect is verified by the degree of segmentation). Because of formation of the thin and long chips during hard turning, the equivalent strain is smaller (chip elongation), as opposed to the turning of annealed steel (thick and short continuous chip, chip shortening, therefore the equivalent strain is higher). As a result of the formation of the thin and long chips (when turning hardened steel), the shear speed and the chip speed are much higher than while turning the annealed steel. Formation of the segments is a very rapid process, and despite the low intensity of the plastic deformation inside the segments, the cutting temperature is very high (in comparison to the turning of annealed steel). The energy entering the cutting zone is dissipated to the localized areas with very high intensity of plastic deformation (the narrow bands between segments rake – chip contact and back – machined surface contact). The heat is concentrated in thin layers and is much higher than the heat while turning annealed steel. The specific character of the chip formation is related to the very high shear angle; much higher than the shear angle for turning of annealed steel. The high hardness of the machined material and the specific character of chip formation cause an increase in the radial component of cutting force F_p. This component is much higher than cutting force F_c in the case of hard turning. On the other hand, there is no significant difference in the cutting force components during turning of annealed steel. F_t is much higher during hard turning than the forces while turning of annealed steel. Moreover, components of the cutting force related to the shear plane are much higher during hard turning than the forces while turning of annealed steel. The higher friction energy during hard turning is related to the high v_{ch} and v_{sh}, respectively F_t and F_s in comparison with turning of annealed steel. Also, the friction energies μ_F and μ_s are much higher during hard turning than during turning of annealed steel, despite the lower coefficient of friction in these areas during hard turning. The high temperatures in the cutting zone during hard turning are attributed to the friction processes, and therefore they are related to the heat generated in the cutting zone. Heat generated in the cutting zone during hard turning is much higher than the heat during turning of annealed steel. The length of segments and the segmentation frequency increase with cutting speed. Application of high speeds leads to rapid decreasing of tool life due to increase of the thermal loading of the tool and decreasing process stability (high frequency of segmentation and high segment length). Tool life decreases very steeply with cutting speed. Also, there is formation of the built-up-edge (BUE) during turning of annealed steels, because of the high friction and temperatures in the cutting zone, especially when the cutting speed is lower than 100 $m \cdot min^{-1}$. Formation of BUE negatively affects the surface roughness, because BUE can be re-deposited on the machined surface. On the other hand, there is a BUE free machined surface during hard turning, because of too high temperatures.

The availability of hard and super hard cutting tool materials provided machine hardened steel. Investigation in the cutting tool area, accompanied by development and design of the machines, supports the success story of this relatively new development. The comparison between hard turning and grinding shows that the first offers several important advantages. Therefore, hard turning turns out to have high potential to replace some grinding operations.

Acknowledgements:

The authors would like to acknowledge the support provided by the National CEEPUS Office Czech Republic (head: Jitka Nováková), National CEEPUS Office Croatia (head: Davor Šovagović) and National CEEPUS Office Slovakia (head: Monika Breckova) which helped in the research over our of mobility and scholarships in the scope of the CEEPUS II CZ 0201 (head: Rober Cep, PhD) and CEEPUS II HR 0108 projects (head: Branimir Barisic, PhD).

REFERENCES

[1] TONSHOFF, H. K.; ARENDT, C.; BEN MOR, R.: *Cutting of Hardened Steel*, CIRP Annals 49/2/200, 547 – 564.

[2] SHAWN, M. C.: The *Mechanism of Chip Formation with Hard Turning Steel*, CIRP Annals 47/1/1998, 77-82.

[3] RECHT, R. F.: *Catastrophic Thermoplastic Shear*, Trans ASME, 86 (1964), 189-193.

[4] NAKAYAMA, K.; ARAI, M.; KANDA, T.: *Machining Characteristics of Hardened Steels*, CIRP Annals 37/1/1988, 89-92.

[5] BEŇO, J.: *Teória rezania kovov*, Vienala Košice, 1999, ISBN 80-7099-429-0.

[6] NESLUŠAN, M.; TUREK, S.; BRYCHTA, J.; ČEP, R.; TABAČEK, M.: *Experimentálne metódy v trieskovom obrábaní*, Edis Žilina, 2007.

[7] HUMÁR, A.: *Slinuté karbidy a řezná keramika pro obrábění*, CCB spol. s r. o. Brno ISBN 80-85825-10-4.

[8] HATALA, M.: *Simulácia technologických procesov*. FVT TU Košice, 2007. ISBN 978-80-8073-756-6.