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INVESTIGATION OF CONTACT PHENOMENA IN TURNING USING TOOLS MADE OF LOW-ALLOY HIGH-SPEED STEEL

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Original scientific paper

In this paper, the results of investigations of the temperature field distribution and tool wearing during C60 steel turning are presented. Abrasive wear resistance tests were carried out for cutters made of low-alloy high-speed steel. Steel samples were heat treated, and then were subjected to ion nitriding, TiN coating, or to complex treatment. The influence of cutting speed on the value of basic parameters characterising the phenomena in the tool-workpiece interface i.e., cutting ratio, friction coefficient, and length of contact zone, is analysed. An increase of the rake angle value causes an increase in the value of the friction coefficient. Furthermore, the value of the friction coefficient decreases as the thickness of the cut layer increases. Investigations of the durability of cutting edges confirm that to define the working conditions of the tool, resistance against hardness loss with increasing temperature at temperatures higher and lower than the tempering temperature is the most significant.

Keywords: *cut layer; cutting ratio; high-speed steels; turning; wear; wear resistance*

Ispitivanje fenomena dodira kod tokarenja primjenom alata od niskolegiranog brzoreznog čelika

Izvorni znanstveni članak

U ovom se radu daju rezultati ispitivanja raspodjele temperaturnog polja i trošenja alata tijekom tokarenja čelika C60. Provedena su ispitivanja otpornosti na abrazivno trošenje tokarskih noževa izrađenih od niskolegiranog brzoreznog čelika. Uzorci čelika su toplinski obrađeni i zatim podvrgnuti ionskom nitriranju, oblaganju TiN ili kompleksnoj obradi. Analiziran je utjecaj brzine rezanja na vrijednost osnovnih parametara karakterističnih za pojave u graničnoj površini alat-obradak, t.j. rezni omjer, faktor trenja i dužina zone dodira. Porast vrijednosti kuta nagiba dovodi do porasta vrijednosti faktora trenja. Nadalje, vrijednost faktora trenja se smanjuje kako raste debljina reznog sloja. Ispitivanja trajnosti rezne oštrice potvrđuju da je u definiranju radnih uvjeta alata, najvažnija otpornost na gubitak tvrdoće kod porasta temperature na temperaturama višim i nižim od temperature popuštanja.

Ključne riječi: *brzorezni čelici; otpornost na trošenje; rezni omjer; rezni sloj; tokarenje; trošenje*

1 Introduction

It is known that physical phenomena occurring in the area of contact between the tool point and the material subjected to machine cutting (i.e. plastic deformation of the material, heat release, friction of clean surfaces, etc.) are defined by the quality of the machined surface, tool durability, and the most effective conditions for machining [1, 2]. Therefore, the efficiency of a tool depends on the operating conditions of the cutter edge. To enable rational use of the tool it is necessary to identify phenomena in the contact area, most importantly such factors as normal and shear stress as well as thermal phenomena linked with the parameters of cutting, and blade material and geometry. Regardless of the differences in the values and trends of the normal and shear stresses at the contact interfaces, minimum tool wear occurs and apparent friction coefficient reaches its lowest value at the optimum cutting speed [3, 4]. The results reported by Wagner et al. [5] show that tool wear occurs in a few steps mainly due to the cutting process and chip formation. It is particularly important to examine the point of contact for tools made of high-speed steel characterized by the phenomenon of buildup accumulation. Friction and temperature at the point of contact between the tool blade and the machined material to a degree will have an impact upon the conditions of built-up accumulation and its dimensions, and as a consequence will affect wear and tear of the tool and the roughness of the machined surface.

The development of low-alloy high-speed steel is observed in manufacturing techniques, thermochemical treatment, and application of modern surface treatments. Improving properties of tools surfaces and development of ecological technologies of heat treatment can be done by using, for example, physical vapour deposition (PVD) methods.There is a variety of powder metallurgical manufacturing routes for high-speed steels resulting in metallurgical and economic advantages [5]. The properties of tools made of high-speed steels can be improved by application of thermochemical treatment, gas nitriding, ionised nitriding, vacuum nitriding and gas sulfonitriding [6, 7].

The tool durability depends primarily on wear resistance of tool material [1, 8]. This requires tool materials assuring a set of such important properties as: hardness, strength, temperability and thermal conductivity [9]. Low-alloy high-speed steels are a subgroup among the high-speed steels, generally having the content %W + 1,5 %Mo < 12 %. It is known that cobalt high-speed steels allow increasing tool edge durability on machining austenitic steels from 2 to 4 times. Their advantage is increased resistance to hardness decrease within the range of irreversible, as well as reversible, transformations, which is especially important when machining hardly machinable materials, where high temperatures and high local stresses arise in the cutting zone.

There has been a constant search for new methods to improve the durability of turning tools. Depending on the machining conditions, the wear process of cutting tools can affect one, two or all active faces of the tool [10, 11]. The wear of cutting tools can occur through abrasion, adhesion, erosion, and diffusion [12] (Fig. 1). The monitoring of the cutting process and determining the exact time when it is necessary to replace the cutting edge during the cut increases the productivity and reduces costs [13, 14].

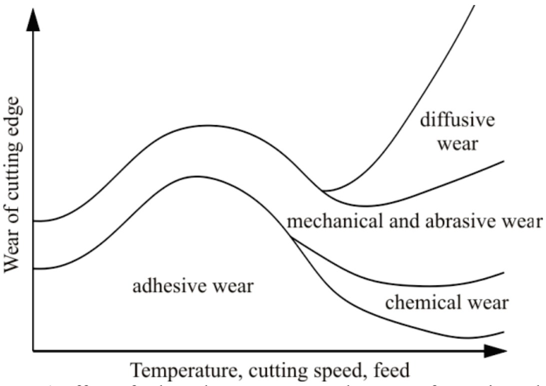

Figure 1 Effect of selected parameters on the wear of a cutting edge [15]

A detailed review of tool wear mechanisms in machining has been undertaken by e.g., Akhtar et al. [16] and Dolinšek et al. [17]. Knowledge of tool material properties is essential in development of new steel grades [18], especially economic high-speed steel [9].

It is necessary to carry out experimental investigations to identify the optimal conditions of machining in terms of cutting tool materials, turning conditions and coating. Here, the results of investigations of the temperature field distribution and abrasive wear resistance tests of tools made of low-alloy high-speed HS23-1-2 and HS6-5-2 steel are presented. Investigations of the temperature distribution in cutting edges and durability tests were made during constructional steel turning. The influence of cutting speed on the value of basic parameters characterising the phenomena in the tool-workpiece interface i.e., the cutting ratio, friction coefficient, and length of contact zone, are also analysed.

2 Abrasive wear resistance test

The durability of tools depends on the abrasive wear resistance of the tool materials. Abrasive wear is material removal caused by material micro-cutting, shearing or tearing off. Abrasive wear takes place under conditions of a small increase in tool temperature. The performance of tools from high-speed steels can be assessed by testing its abrasive wear resistance. Wear intensity increases with increase of hard particles in workpiece, such as iron carbide grains or carbides in steels [19].

The tribological test was conducted on the SKODA-SAVINE machine. A specimen in the form of a rectangular prism co-acted with a counter-specimen disk from sintered carbide of diameter 30 mm and width 2,5 mm. Specimens of sizes 18 × 18 × 8 mm were made from low-alloy high-speed steels HS3-1-2 and HS6-5-2 for which selected physical-mechanical properties are presented in Tab. 1. The normal force was 150 N, and the rotational speed of disk was 500 rev./min. Wear was determined by the volume of removed material from specimen after 5, 10, 20 and 30 min duration. The steel samples were heat treated, after which their hardness was 63 ÷ 64 HRC. Some specimens were then subjected to ion nitriding (IN) in order to obtain layer of 0,01 ÷ 0,05 depth and hardness of 1100 ÷ 1200 HV, or to TiN coating (TiN) (depth 0,005 mm, hardness of 2200 ÷ 2500 HV) or to complex treatment IN+TiN (initial ion nitriding and TiN coating).

Table 1 Selected physical-mechanical properties of HS3-1-2 and HS6-5-2 steels

Steel grade	Hardness HRC	Bending strength R_g / MPa	Impact resistance U / J/m^2	Hardening temperature T_h / ºC
HS3-1-2	63 ÷ 68	3000 ÷ 3600	4,6×10^5	1080 ÷ 1170
HS6-5-2	64	3200 ÷ 3600	4,8×10^5	1200 ÷ 1230

Fig. 2 presents the results of the abrasive wear resistance tests.

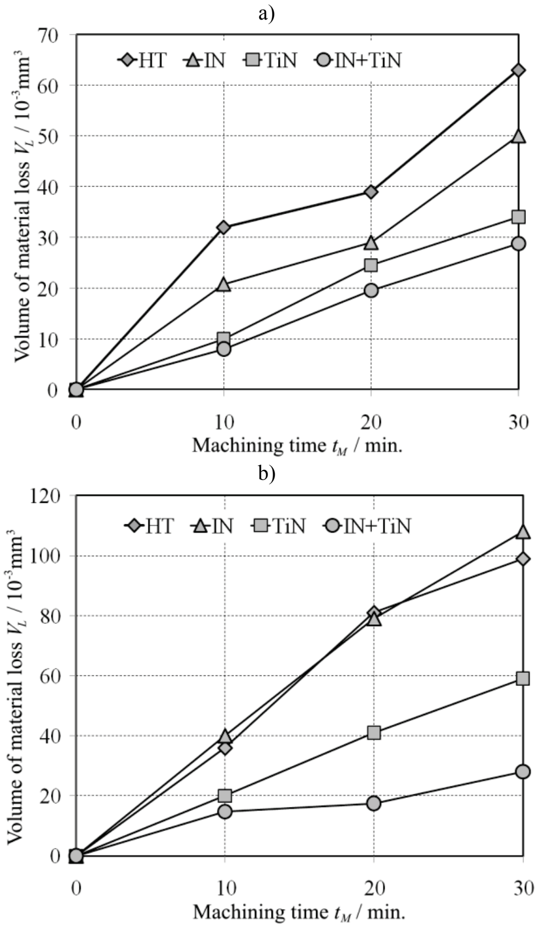

Figure 2 The results of the abrasive wear resistance test after only heat treatment (HT), after ion nitriding (IN), after TiN coating (TiN) and after complex treatment (IN+TiN) for HS6-5-2 (a) and HS3-1-2 (b) steels

We found that the abrasive wear resistance of economical high-speed steels for applied tribological conditions were not considerably different from results of steel HS6-5-2. Abrasive wear resistance of steel HS6-5-2 was about 2 times higher than of steel HS3-1-2. Abrasive wear resistance of used steel grades increased as a result of ion nitriding, TiN coating and complex treatment (ion nitriding and TiN coating). The application of ion nitriding resulted in increasing wear resistance not greater than 3 times, use of TiN coating up to 3 times; however complex treatment was found to be the most efficient surface treatment: abrasive wear resistance increased 4 times. These results indicated that ion nitriding should be applied before TiN coating. It is necessary to optimise the thickness of these layers.

Reducing the cost of the machined parts and improving the quality of the machined surface are generally addressed by improving cutting tool materials, improving the tool geometry, applying advanced coating, and optimizing operating parameters. Significant tool cost reductions can be achieved by development and the use of tool coatings, which result in higher turning speeds. Coatings have been observed to reduce cutting forces and wear resistance of cutting tools, and provide longer tool life resulting in greater productivity [20].

The properties and hardness of tools made of high-speed steel can be changed at relatively broad spectrum by the values of parameters of heat treatment. The effect of heat treatment conditions on the wear of tools made of high-speed steel is significant to withstand harsh machining conditions, such as a high cutting speed and a high feed rate. For assuring maximum tool life, it is necessary to assure high temperability and simultaneously high strength of high-speed steel. These properties are mainly determined by the hardening and tempering temperature values.

3 Investigation of parameters at the workpiece/tool interface

3.1 Materials and methods

Research into temperature distribution in a cutting edge made of HS3-1-2 and HS6-5-2 steels during C60 steel turning was carried out using a semi-natural constantan thermo-element (with cutting edge material). This method is very useful to indicate the effects of the cutting speed, feed rate, depth of cut and the tool parameters on the temperature [21]. For preparing the thermo-element, the ∅0,1 mm diameter constantan wire was flattened at the end to dimensions: 0,15 × 0,15 × 0,005 mm and it was isolated.

The value of friction coefficient μ was determined as ratio of the circumferential force F_z and thrust force F_y. The value of cutting ratio λ_L according to PN-92/M-01002/04 as a ratio of cross-sectional area of chip A_C and cross-sectional area of cutting layer A_D can be evaluated according to the formula:

$$\lambda_L = \frac{A_C}{A_D} \quad (1)$$

The value of the cutting ratio is usually greater than 1, and only in the case of certain machined materials (e.g. titanium alloys, hardened steel) and cutting conditions is the value lower than 1. The cutting ratio λ_L is a physical index of machinability identifying the material's susceptibility to plastic deformations in specific cutting conditions [1, 22].

The average coefficient of friction on the rake face is the primaryfactor influenced by the formation of a built-up edge. Here, the friction coefficient μ is calculated through the measurement of the machining forces as the ratio of feeding force F_f and cutting force F_c.

3.2 Temperature distribution

The distribution of temperature fields in the cutting edge of the cutters made of HS3-1-2 and HS6-5-2 steel during turning of C60 is presented in Fig. 3. The character of the temperature distribution decides the location of cutting edge wear.

At great thicknesses of the cut layer (f = 0,3 mm/rev.), the basic character of temperature distribution for both cutter materials are similar (Fig. 3). Our observations correspond to the results of Abhang and Mameedullah [23]. The thickness of a cut layer depends on the mechanism of chip formation. The maximum temperature occurs in the proximity of the rake face, yet the difference is that in a knife blade made of HS3-1-2 steel the maximum is moved towards the main cutting edge and is located approximately at the distance of 1/3 rather than in the middle of the length of contact line of the chip with the rake face, and the contact line for an HS3-1-2 steel knife is shorter.

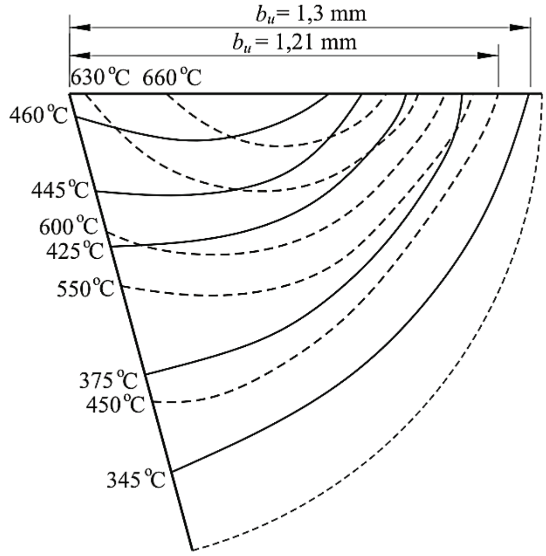

Figure 3 Distribution of temperature field in the cutting edge of the cutter made of HS6-5-2 (dotted lines) and HS3-1-2 (black lines) steels at large cut layer thickness: v_c = 25 m/min, f = 0,3 mm/rev., h_D = 2 mm

While turning at f = 0,3 mm/rev and v_c = 25 m/min durability of the cutter edge made of HS3-1-2 steel amounts to T_c = 15 min and durability of the cutter edge made of HS6-5-2 steel, to T_c = 300 min [24].

The flank wear and crater wear are important, especially at high cutting speeds (i.e. greater than 150 m/min). They often result in the breakdown of the tool nose and then they result in the inaccuracy of the tolerances of the workpiece [10]. For both steel grades, the maximum temperature occurs near the main cutting edge on the clearance surface side and is a little lower at the cutting edge of the cutter made of HS3-1-2 steel by reason of lower cutting speed.

3.3 Effect of cutting speed

The parameters that characterize the phenomena at tool/workpiece interface are length of contact zone b_u, friction coefficient μ, cutting ratio λ_L cutting forces F_y and F_z. The values of these parameters were determined for cutters made of HS3-1-2 nd HS6-5-2 steel during straight turning of C45 steel at v_c = 10 ÷ 60 m/min, at cutting depth h_D = 0,215 mm without cooling.

An increase in the thickness of the layer subjected to cutting coincides with an increase of the height of buildup [1]. The cutting fluids reduce to form the built up edge on the cutting tool, decrease the friction and protect the workpiece and cutting tool surfaces from corrosion. The values of cutting forces $F_y$and F_z (Fig. 4), length of contact zone b_u and cutting ratio λ_L (Fig. 5) for cutters made of HS3-1-2 are smaller than in case of cutters made of HS6-5-2. A decrease in the values of these paramaters is much greater at higher cutting speeds (i.e. v_c > 60 m/min) and occurs outside of the built-up creation zone for both cutter materials. With the changing values of cutting forces and length of contact zone b_u changes the value of the average normal σ and tangential τ stresses also change.

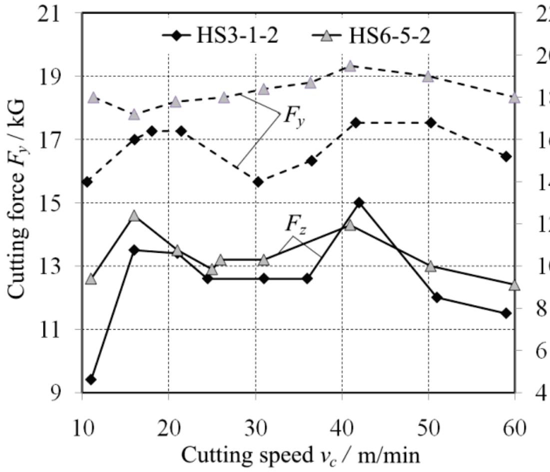

Figure 4 Influence of cutting speed v_c on the value of the cutting forces F_y and F_z during turning at v_c = 30 m/min, h_D = 0,215 mm, stock is C45 steel, without cooling

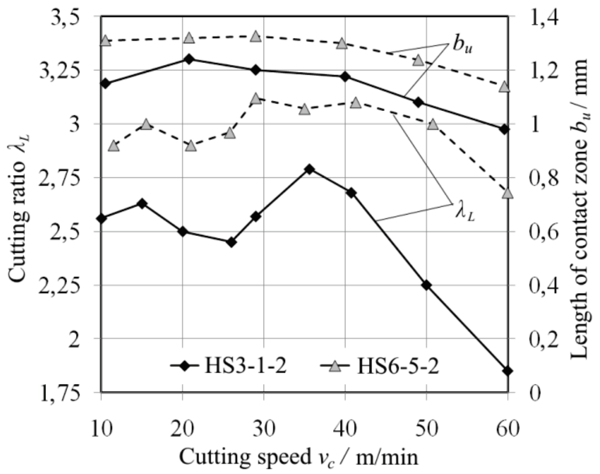

Figure 5 Effect of cutting speed v_c on the value of the cutting ratio λ_L and length of the contact zone b_u during turning at v_c = 30 m/min, h_D = 0,215 mm, stock is C45 steel, without cooling

As the value of cutting speed increases, the values of cutting ratio, length of contact zone of chip and rake surface, and the friction coefficient, decrease. A decrease in the friction coefficient value after exceeding the cutting speed value of v_c= 60 m/min is found by Sebhi et al. [10].

3.4 Effect of rake angle and cut layer thickness

Because the value of the tangential stress τ mainly depends on the shear strength of the workpiece material [4], their values while turning with the cutters made of HS3-1-2 and HS6-5-2 steel are similar. Smaller length of the contact zone b_u for the cutter made of HS3-1-2 leads to an increase in the value of the normal stress σ and a corresponding decrease in the friction coefficient value (Fig. 6).

As the value of rake angle γ increases, the value of friction coefficient μ also increases (Fig. 7). Furthermore, the value of friction coefficient μ decreases as the thickness of cut layer h_D increases.

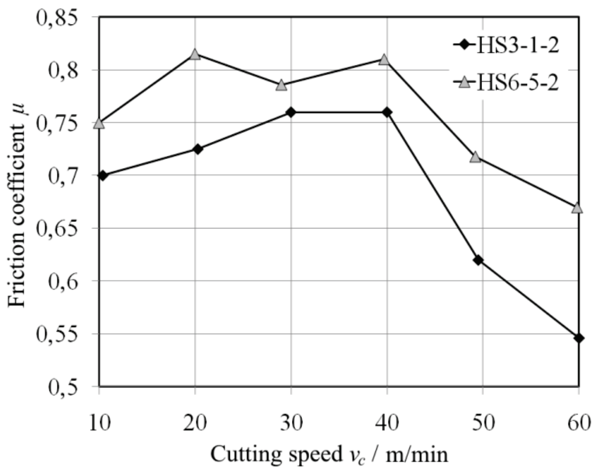

Figure 6 Effect of cutting speed v_c on value of friction coefficient μ during turning at v_c = 30 m/min, h_D = 0,215 mm, stock is C45 steel, without cooling

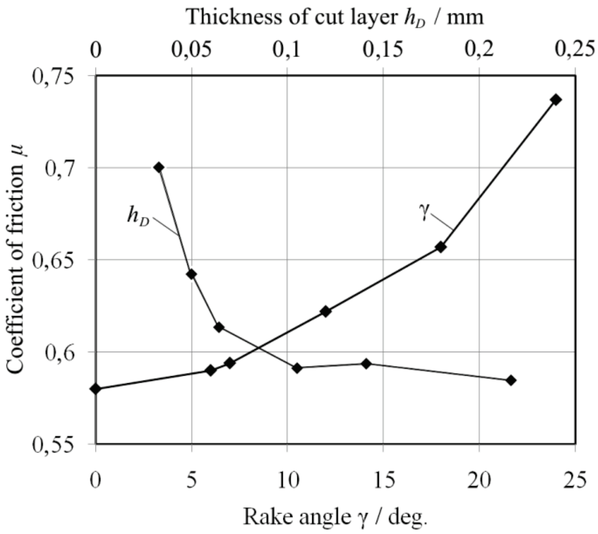

Figure 7 Effect of rake angle γ and thickness of cut layer h_D on the friction coefficient value μ on the rake surface

3.5 Built-up formation

The average coefficient of friction on the rake face is the primary factor influenced by the formation of a built-up edge [24, 25]. Built-up edges on tools made of different materials may differ significantly from each other (Fig. 8). On the cutting edge of a cutter made of HS6-5-2 steel, a massive built-up edge is formed (Fig. 8a), which increases the tool rake angle to the value of γ = 40 ÷ 50°.

The massive built-up edge protects the tool flank from direct contact with the machined surface and facilitates the chip formation process. The built-up edge on the cutter made of HS3-1-2 steel has a lower height (Fig. 8b) and the angle γ = 15 ÷ 20°; it can be assumed that it has less impact on the reduction of friction on the tool flank and, to a lesser extent, protects the cutter from the influence of the heat generated in the chip formation zone and secondary deformations.

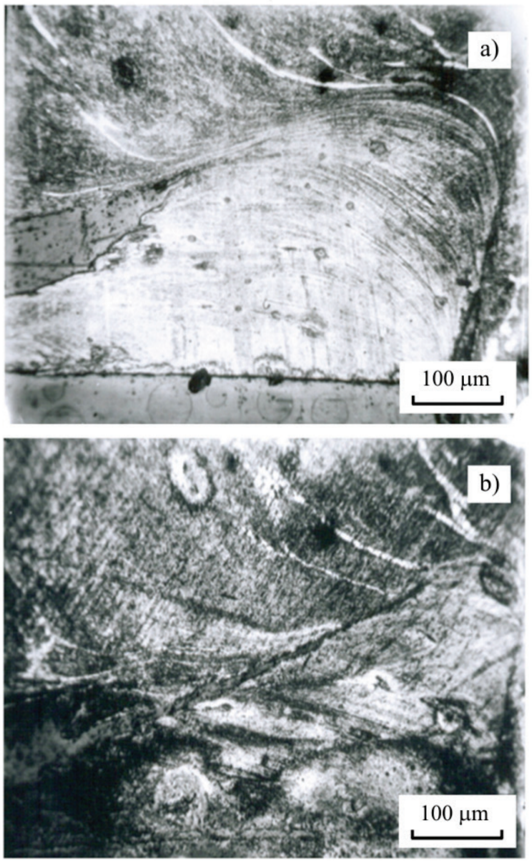

Figure 8 Built-up edge on the turning tools made of HS6-5-2 (a) and HS3-1-2 (b) steels: v_c = 30 m/min, h_D = 0,215 mm, stock is C45 steel, without cooling.

It was determined experimentally that at the large cut layer thickness, the built-up edge mainly determines the location on the cutting blade that has the highest temperature. Cassier et al. [25] demonstrated that since the built-up edge increases the wear of the tool and affects the surface roughness of the work-piece, the study of this phenomenon is very important in predicting and minimizing the wear of a cutting tool. Different types of wear in high-speed cutting tools have been analysed by Dolinšek et al. [17]. In general, increasing the cutting speed increases the temperature at the contact zone, leading to a drastic reduction of the tool life [26, 27].

It was found experimentally that, at the large cutting layer thickness the built-up edge mainly determines the location in the cutting blade that has the highest temperature.

4 Durability of cutting edge
4.1 Materials and methods

The durability of the cutting edge of cutters made of HS3-1-2 and HS6-5-2 steel was analysed on straight turning the C45 steel with hardness of 195 ÷ 220 HB at f = 0,34 and 0,08 mm/rev. Durability tests were conducted at thickness of cut layer h_D = 1 mm and at cutting speed ranged from 30 to 120 m/min. Investigations of cutters with replaceable inserts were conducted on a lathe with a stepless change of speed. All inserts were made according to the same technology and heat-treated at optimum temperatures. The design of replaceable inserts was tetragonal with the dimensions of 18 × 18 × 8 mm. The inserts were clamped in a special cutter holder. The cutting edge geometry was as follows: $\alpha = 10°$, $\gamma = 8°$, $\chi = 45°$, $\chi_1 = 15°$, $\varepsilon = 120°$, $\beta = 72°$, r_ε = 1,5 mm.

4.2 Results of cutting edge durability

Analysing the research results (Fig. 9), we found that, at both feed values, the effectiveness of cutters made of selected high-speed steel grades does not change. The cutters made of HS3-1-2 steel have the lowest durability, and the best results are ensured by cutters made of HS6-5-2 steels. At feed value of f = 0,32 mm/rev. the cutters made of HS3-1-2 have the same cutting edge durability as the cutters made of HS6-5-2 steel at 30 % lower cutting speed. Together with the feed value decrease to the value of f = 0,08 mm/rev., the durability of the cutters made of HS3-1-2 steel corresponds to the durability of the cutters made of HS6-5-2 at a cutting speed 25 % lower. At higher cutting speeds, the durability differences will be larger still.

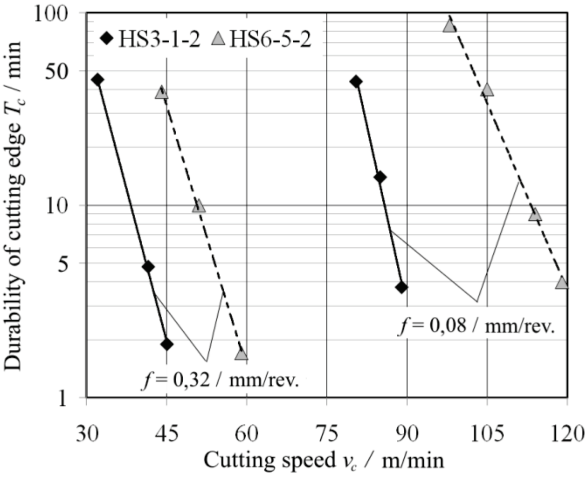

Figure 9 Durability of cutting edge of cutters made of selected low-alloy high-speed steels with hardness of 195 ÷ 220 HB at h_D = 1 mm

5 Conclusions

The intensity of the wear increases with increasing content of hard particles such as grains of cementite and complex carbides in the workpiece material [26].The mechanism of adhesive wear occurs mainly at low cutting speeds and high unit pressures.

The results of investigations of cutters durability conducted at the same cutting parameters show that at large cut layer thickness durability of the cutter edge made of HS3-1-2 steel amounts to T_c = 15 min and durability of the cutter edge made of HS6-5-2 steel, to T_c = 300 min. It can be assumed that for the tools made of HS3-1-2 steel at high cutting speeds the tool wearing process is caused by progressive hardness loss and also connected with it plastic deformation of the cutting edge.

We can assume that in the case of tools made of HS3-1-2 steel, the hardness loss and then the plastic deformation of a blade are the phenomena that limited their use for high-speed machining. Therefore, it follows that the catastrophic wear of cutting edge of tools made of HS3-1-2 will occur at lower cutting speeds than for HS6-5-2 steel.

It was found experimentally that at the large cut layer thickness, the built-up edge mainly determines the location of the cutting blade that has the highest temperature. The point in the HS3-1-2 steel knife blade is moved towards the main cutting edge, hence the tip of the blade is found in more extreme temperature conditions.

6 References

[1] Shaw, M. Metal Cutting Principles. Oxford University Press, New York, 2005.

[2] Youssef, H. A.; El-Hofy, H. Machining Technology: Machine Tools and Operations. CRC Press, Boca Raton, 2008.

[3] Astakhov, V. P. The assessment of cutting tool wear. // International Journal of Machine Tools and Manufacture. 44, 6(2004), pp. 637-647. DOI: 10.1016/j.ijmachtools.2003.11.006

[4] Jaworski, J. The study of thermal processes as a basis for quality production of tools of low-alloy high-speed steels. // International Journal of Applied Mechanics and Engineering. 9, 3(2003), pp. 493-503.

[5] Wagner, V.; Baili, M.; Dessein, G. The Relationship Between the Cutting Speed, Tool Wear, and Chip Formation During Ti-5553 Dry Cutting. // International Journal of Advanced Manufacturing Technology. 76, 5-8(2015), pp. 893-912.DOI: 10.1007/s00170-014-6326-1

[6] Nogueira, R. M. U.; da Costa, C. E. Sinterability of High-speed Steels M2, M3/2 and T15. // Materials Science Forum. 498-499, (2005), pp. 238-243. DOI: 10.4028/www.scientific.net/MSF.498-499.238

[7] Wentzcovitch A.; Filho F. A.; da Silva L. C. E.; das Neves M. D. M. Sintering of AISI M2 High Speed Steel with addition of NbC. // Materials Science Forum. 727-728, (2012), pp. 90-95. DOI: 10.4028/www.scientific.net/MSF.727-728.90

[8] Kula, P.; Jachowicz, D.TiN Arc Coatings on the Former Vacuum Nitrided Substrates of HSS Steels. // InżynieriaMateriałowa.19, 4(1998), pp. 1002-1006.

[9] Farhat, Z. N. Wear Mechanism of CBN Cutting Tool During High-speed Machining of Mold Steel. // Materials Science and Engineering A. 361, 1-2(2003), pp. 100-110. DOI: 10.1016/S0921-5093(03)00503-3

[10] Sebhi, A.; Osmani, H.; Rech, J.Tribological Behaviour of Coated Carbide Tools During Turning of Steels with Improved Machinability. // StrojniskiVestnik - Journal of Mechanical Engineering. 58, 12(2012), pp. 744-749. DOI: 10.5545/sv-jme.2012.561

[11] Galoppia, G. D. S.; Stipkovic, F. M.; Batalhaa, G. F. Hard Turning of Tempered DIN 100Cr6 Steel with Coated and No Coated CBN Inserts. // Journal of Materials Processing Technology. 179, 1-3(2006), pp. 146-153. DOI: 10.1016/j.jmatprotec.2006.03.067

[12] Bouchelaghem, H.; Yallesse, M. A.; Amirat, A.; Belhadi, S. Wear behaviour of CBN tool when turning hardened AISI D3 steel. // Mechanika. 65, 3(2007), pp. 57-65.

[13] Sadílek, M.; Kratochvíl, J.; Petrů, J.; Čep, R.; Zlámal, T.; Stančeková, D. Cutting tool wear monitoring with the use of impedance layers. // Tehnicki vjesnik – Technical Gazette. 21, 3(2014), pp. 639-644.

[14] Duspara, M.; Sabo, K.; Stoić, A. Acoustic emission as tool wear monitoring. // Tehnickivjesnik – Technical Gazette. 21, 5(2014), pp. 1097-1101.

[15] Wysiecki, M. Modern Tool Materials. WNT, Warszawa, 1997.

[16] Akhtar, W.; Sun, J.; Sun, P.; Chen, W.; Saleem, Z. Tool Wear Mechanisms in the Machining of Nickel Based Super-alloys: A Review. // Frontiers of Mechanical Engineering. 9, 2(2014), pp. 106-119. DOI: 10.1007/s11465-014-0301-2

[17] Dolinšek, B.; Šuštaršič, J.; Kopač, J. Wear mechanisms of cutting tools in high-speed cutting processes. // Wear. 250, 1-12(2001), pp. 349-356. DOI: 10.1016/S0043-1648(01)00620-2

[18] Qi, H. S.; Mills, B. On the Formation Mechanism of Adherent Layers on a Cutting Tool. // Wear. 198, 1-2(1996), pp. 192-196. DOI: 10.1016/0043-1648(96)80023-8

[19] Sharma, V.S.; Sharma, S.K.; Sharma, A.K. Cutting Tool Wear Estimation for Turning. // Journal of Intelligent Manufacturing. 19, 1(2008), pp. 99-108. DOI: 10.1007/s10845-007-0048-2

[20] Kakaš, D.; Terek, P.; Miletić, A.; Kovačević, L.; Vilotić, M.; Škorić, B.; Krumes, D. Friction and wear of low temperature deposited TiN coating sliding in dry conditions at various speeds. // Tehnicki vjesnik – Technical Gazette20, 1(2013), pp. 27-33.

[21] Kamisine, A. K.;Guimarães, G.; da Silva, M. B. Development of a Tool–work Thermocouple Calibration System with Physical Compensation to Study the Influence of Tool-holder Material on Cutting Temperature in Machining. // International Journal of Advanced Manufacturing Technology. 73, 5-8(2014), pp. 735-747. DOI: 10.1007/s00170-014-5898-0

[22] Olartegui-Yume, J. A.; Kwon, P. Y. Tool Wear Mechanisms in Machining. // International Journal of Machinability of Materials. 2, 3-4(2004), pp. 316-334. DOI: 10.1504/IJMMM.2007.015469

[23] Abhang, L. B.; Mameedullah, M. The measurement of chip-tool interface temperature in the turning of steel. // International Journal of Computer Communication and Information Systems. 2, 1(2010), pp. 1-5.

[24] Thamizhmanii, S.; Hassan, S. Effect of Tool Wear and Forces by Turning Process on Hard AISI 440 C and SCM 440 Materials. // International Journal of Material Forming. 2, 1(2009), pp. 531-534. DOI: 10.1007/s12289-009-0429-5

[25] Cassier, Z.; Prato, Y.; Muñoz-Escalona, P. Build-Up Edge Effect on Tool Wear When Turning Steels at Low Cutting Speed. // Journal of Materials Engineering and Performance. 13, 5(2004), pp. 542-547. DOI: 10.1361/10599490420629

[26] Čep, R.; Janásek, A.; Čepová, L.; Petrů, J.; Hlavatý, I.; Car, Z.; Hatala, M. Experimental Testing of Exchangeable Cutting Inserts Cutting Ability. // Tehnicki vjesnik – Technical Gazette. 20, 1(2013), pp. 21-26.

[27] Jaworski, J.; Kluz, R.; Trzepieciński, T. Operational Tests of Wear Dynamics of Drills Made of Low-alloy High-speed HS2-5-1 Steel. // EksploatacjaiNiezawodnosc- Maintenance and Reliability. 18, 2(2016), pp. 271-277. DOI: 10.17531/ein.2016.2.15

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