WEAR MECHANISMS AND MATERIAL FLOW ANALYSIS IN HIGH SPEED TURNING OF SOFT GREY CAST IRON

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Abstract. *High speed machining has received important interests in automotive industry because it leads to an increase of productivity and better workpiece surface quality. However, at high cutting speeds, the tool wear increases dramatically due to the high temperature at the cutting zone. Tool wear impairs the surface finish and hence the tool life is reduced. That is why an important objective of metal cutting research has been the assessment of tool wear patterns and mechanisms. In this paper, the wear performance of CBN tool in high speed turning is presented when cutting grey cast iron. The tool wear patterns were examined through a toolmaker's microscope. With aim to minimize tool wear also chip formation was analyzed. The research results show that the tool wear types differed in various tool geometries. The main wear mechanisms were mechanical friction, adhesion and chemical wear promoted by high mechanical and thermal influence. Hence, the important considerations of CBN cutting tool material is high heat resistance, wear resistance and chemical stability. The research results will be of great benefit in the preparation of cutting tool edge and in the control of tool wear in high speed machining processes.*

Keywords: *High speed turning, Grey cast iron, Tool wear, CBN*

1. INTRODUCTION

A primary objective of manufacturing operations is the efficient production of accurate parts. In machining processes, significant research has focused on ways to increase material removal rates without sacrificing workpiece accuracy. To raise material removal rates cutting speed or the chip cross section can be increased. Increasing the chip cross section is limited owing to deflection and stability constraints, so that high speed machining becomes the major process to be exploited (Zuperl et al. 2004).

The high speed machining processes can produce more accurate parts as well as reduce the costs with high production. There has been strong resurgence of interest in high speed machining. So, it has already been applied in many manufacturing industries such as the aerospace and the automotive industry, to cut steel or wide used cast iron, etc. The application fields of high speed machining are continuing to expand rapidly.

High speed machining, however, leads to increase of cutting temperature which result in tool material soften (Fig. 1). It thereby accelerates tool wear or even leads to the tool fracture (Kopac 2004).

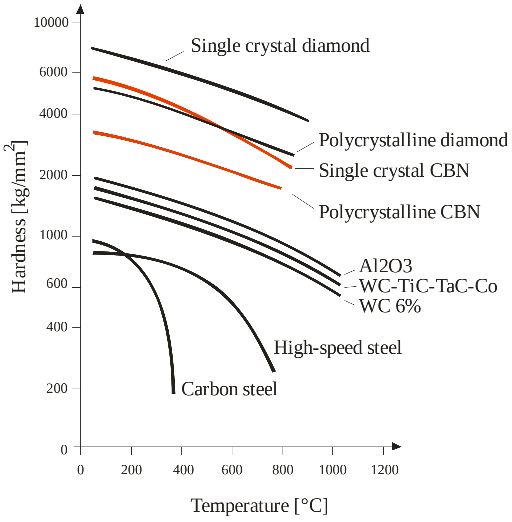


Figure 1- Typical hot hardness characteristics of some tool materials (Milfelner et al. 2001).

Hence, tool materials with high wear resistance take a crucial role in high speed machining. Recent developments in tool materials have given opportunity to the wide applications of high speed machining. Single and polycrystalline diamond, single and polycrystalline CBN, ceramics, cermets, coated and uncoated cemented carbides represent a range of tool materials applicable to high speed machining. But the use of those materials in cutting speeds above 1000 m/min are still lacking and different tool wear modes and characteristics may be observed at this cutting speed range.

In Automotive industry, high speed manufacturing of wide used grey cast machining still cause low machinability. This industry frequently uses high speed turning to remove the greatest possible quantity of material from the workpiece. Because of that in this paper, the wear performance of CBN cutting tool was investigated through wear mechanisms and chip formation analyses. Investigation is based on experiments, where turning wide used grey cast iron at a cutting speed 1100 m/min.

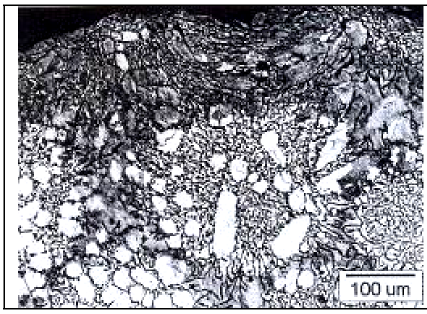
2. EXPERIMENTAL WEAR EVALUATION

All of the machining tests of tool wear were carried out using CBN tools during the finishing turning process of grey cast moulded semimanufacture. During tests two CBN tools worked consecutively. They were used with the same preferences, but had different tool geometries. All tests were carried out in the machining line of the manufacturing plant. The OKUMA LT 10–M CNC lathe machining centre was operated under specified machining conditions which will be described. The machining tests were carried out dry. Except for early breakage, the tool wear patterns were observed through a toolmaker’s microscope after 100 machined workpieces.

2.1 Workpiece material

In this study relatively soft grey cast iron was selected as the workpiece material. Most important preference of workpiece material is its hardness. For that reason hardness of used grey cast iron was measured (Dawson et al. 2003). Mostly the fast tool wear is a consequence of hard particles with high hardness. In grey cast iron that particles may be free cementite or phosphoric eutectic, but in this case the presence of hard inclusions is low. Used grey cast iron has a perlitic structure with lamellar graphite mostly of type A. In central part of cast, the grey cast structure is mostly perlitic, where density of ferrite is less then 5 %. On the surfaces the presence of ferrite is higher. Ferrite structures are located in pearlite like ice lands areas. So there is a concentration of ferrite more than 5 %, locally also more than 10 % to almost 100 %. Chemical structure of material that is added by foundry is presented above in Table 1.

Table 1. Chemical structure of used grey cast iron

	DIN 1691	CE [%]	C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cr [%]	Sn [%]
	GG20	4.06	3.5	2.2	0.55	0.025	0.05	0.08	0.007
		Cu [%]	Mo [%]	Ni [%]	V [%]	W [%]	Sc [%]	Rm [MPa]	HBN
		0.1	0.01	0.06	0.01	0.012	0.96	220	190

2.2 Cutting tool with machining conditions

It is known that the grey cast irons are relatively soft, but very abrasive. So using of CBN cutting tools, with their high abrasion resistance is the best choice for machining grey cast iron. Another reason for choosing CBN tools is permitting grey cast iron cutting at feeds and speeds much higher than with conventional cutting tool materials (Ekinovic et al. 2002). Because CBN tools maintain a sharp cutting edge, part surface finishes are excellent and close tolerances are easy to obtain (Thamizhmanii et al. 2006). Finally, from the view of ecology in mainly cases coolants are eliminated altogether.

For the comparison two cutting edge preparations were taken. Cutting tool geometries were negative and are compared in Fig. 2. Shapes of cutting tool insert had an ISO designation of TNMN 110304S.

Experiments are performed on dry finish turning. All the cutting conditions are given in Table 2.

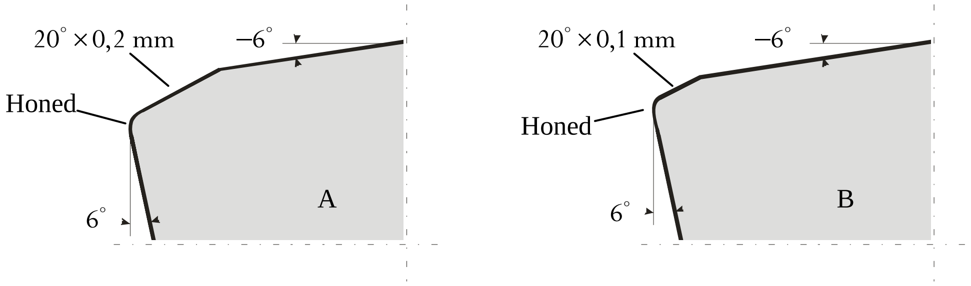


Figure- 2 Comparison of cutting tool geometries.

Table 2. Composition and properties of used CBN cutting tools (left), Cutting conditions (right)

Tool material parameters	Value
CBN content approx vol. [%]	90
Average starting grain size [μm]	22
Matrix/Binder	Al Cearmic
Format	Solid
Knoops hardness [Gpa]	30.4
Thermal conductivity [$Wm^{-1}K^{-1}$] (20°C)	130

Cutting condition parameters	Value
Cutting speed [m/min]	1100
Feed [mm/rev]	0.08
Depth of cut [mm]	2.2
Length of cut [mm]	30

3. WEAR RESULTS AND COMMENTS

Different modes of tool failure including rake face wear, flank wear, chipping, notch wear and breakage, were observed in this study. These tool wear patterns in high speed finish turning suggested that the tool wear mechanisms were diffusion, attrition, and wear by chemical interaction. It is common for several tool wear patterns, to be found to appear simultaneously with the same tool and to have an effect on each other.

3.1 Tool wear on rake face

Generally the end of tool life is determined by excessive wear of the tool flank face at conventional cutting speed. In high speed machining, however, tool wear on the rake face is also high. Typical tool wear on the rake face when in the high speed turning of grey cast iron using a CBN cutting tool is shown in Fig. 3(a) and (b), respectively for tool A and B.

From this figure, it can be seen that the tool wear on rake face in high speed machining is different from crater wear in conventional cutting speed machining. In the conventional cutting speed range, the tool wear on the rake face occurred in the form of a crater, which was formed at some distance from the cutting edge, while the tool wear on rake face during high speed machining was adjacent to the cutting edge. Actually, the maximum depth of tool wear on the rake face occurred on the main cutting edge. Experimental results showed that increasing the cutting speed also lead to the reduction of the wear area. However, the depth of wear area increased at the same time.

This mode of tool wear is mainly due to too high cutting temperature on tool edge. Extreme high cutting speed leads to very high temperature (800–1000 °C) occurring at the vicinity of the main cutting edge where the maximum depth of tool wear on rake face occurs. The hardness of the tool materials decreases at such high cutting temperatures, which aggravates the abrasive wear on tool rake face. High cutting temperature can also result in diffusion, adhesion, plastic deformation, etc. The tool–chip contact length is shorter in high speed machining than at conventional cutting speed, which causes the cutting force to be concentrated adjacent to the main cutting edge. The softer cutting edge due to high

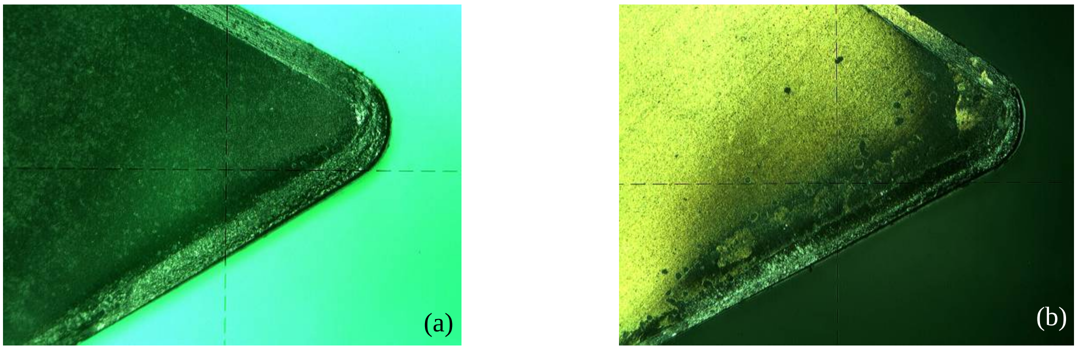


Figure- 3 Tool wear on rake face in high speed turning of grey cast iron (a – tool A, b – tool B).

temperature under the concentrated cutting force near the cutting edge, leads to deformation and deflection. Mechanical and thermal influences are non–negligible factors in forming this kind of tool wear morphology. Thus, the combined effect of cutting force and cutting temperature is the main factor that leads to this type of tool wear on the rake face at high cutting speed.

The matching of mechanical, physical and chemical properties between the tool and the workpiece materials at high temperature is a very important factor in the high speed machining process, but they are very hard to determine. However, it was clearly observed in this study that both the wear zone and the depth of wear area on the rake face for a CBN tool–A were greater than for a CBN tool–B. So it is obviously that tool geometry has great influence on tool performance in high speed cutting.

3.2 Tool flank wear

This pattern of wear produces wear lands on the side and end flanks of the tool on account of the abrasive action of the machined surface. From Fig. 4(a) and (b), it is noted that the wear land is not of uniform width as in conventional cutting speed. The widest of the wear land in high speed machining, however, is in the vicinity of the tool nose. This is different from the convenient cutting where tool flank wear occurs far from cutting tool nose. This is due the same fact describe above for tool wear on the rake face. In this study, flank wear was observed throughout all of the experiments.

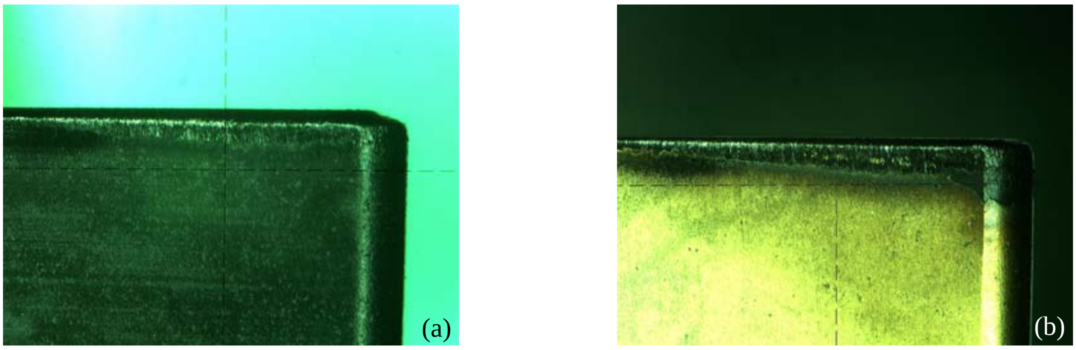


Figure- 4 Tool flank wear in high speed turning of grey cast iron (a – tool A, b – tool B).

3.3 Tool edge chipping

If the cutting edge appears jagged or there are cavities or depressions in the wear land, it means that chipping has occurred. Small chips break off from the tool cutting edge in result of mechanical impact, transient thermal stresses due to cycled heating and cooling caused by intermitting machining process, chatter and excessive cratering and flank wear. In high speed turning, the cutting tool is exposed not only to rapid and high thermal as well as mechanical shocks every time it enters the workpiece, but also to high cutting temperature. Traction–pressure arise alternating stress and leads to longitudinal and transversal cracks. When that cracks spread, tool chipping occurred along the boundary of the rake and flank faces. Chipping in that case is shown in Fig. 5(a), where that kind of chipping is caused by the mechanical fatigue cracks on the flank face.

3.4 Tool edge breakage

Tool materials with low transverse rupture strength and fracture toughness, like pCBN are prone to fracture. The transverse tensile strength for lower CBN content pCBN tool is only round 500 MPa, while for higher CBN content pCBN, this value is greater. Generally, the lower CBN content pCBN tool materials do not have effective crystal to crystal bonding, which weakens the mechanical strength and impact resistance. Thus, a lower CBN content pCBN tool is not suitable for the high speed machining of hard materials and is especially unstable in an intermittent machining process. It can be seen from Fig. 5(b) that the cutting edge of low content CBN pCBN tool was broken during machining of deal with grey cast iron. Hence, it is necessary to select a higher CBN content pCBN tool material.

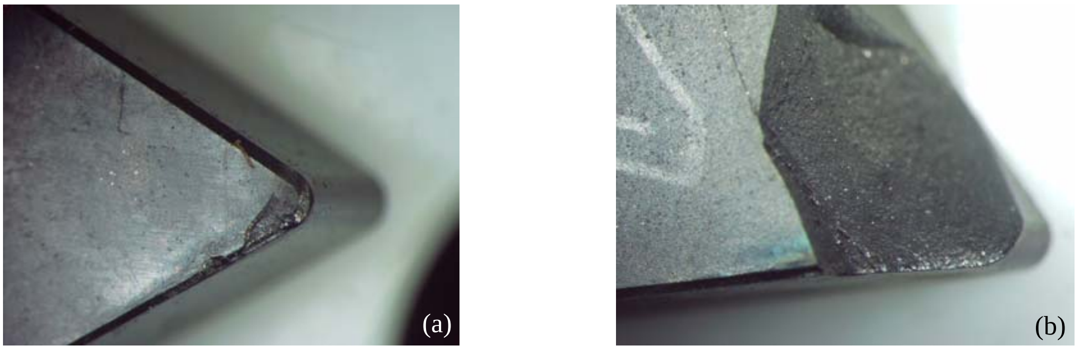


Figure- 5 Chipping and breakage of CBN cutting tool during high speed turning of grey cast iron (a – chipping, b – breakage).

So, from tool wear mechanisms it is possible to conclude, that the main tool wear factors in high speed turning of grey cast iron are high thermal and mechanical impacts on cutting tool edge. But it is not enough just to find wear mechanisms to increase productivity. So, beside main causes, also the way of decreasing wear rate has to be found. Intention for that is the fact, that in cutting process it comes to deformation of workpiece material. Those deformations lead to high mechanical and thermal influence of cutting edge and are directly related with cutting tool wear. To get those informations, more detailed tool wear evolution or better chip formation must be analysed. That is presented in the next paragraph.

4. CHIP FORMATION ANALYSIS

Characteristic of the metal cutting process is that, the workpiece material is being deformed at extremely intense conditions in a small volume. The extreme deformation conditions make metal cutting a remarkable process if compared to other production processes and reflect high mechanical and thermal influences on cutting tool through tool wear. Because of that it is necessary to analyse chip growth, with aim to describe the determination of the conditions under which deformation takes place. For that cutting process has to be intermitted, in the real cutting conditions.

4.1 Cutting process interruption procedure

To study the deformation zone in the chip root experimentally, a so called “quick stop” device has been constructed. The fundamental idea of this method is that the tool is retracted rapidly from the workpiece thereby “freezing” the process. The explosive quick stop device that was constructed is shown in Fig. 6. This device is constructed such that the tool holder can rotate around a pivot placed at its rear end. The rotation point of the tool holder is placed deliberately above the cutting edge, so the tool is retracted not only from the chip but from the workpiece also. At the front, the tool holder is supported by a notched pin made out of brittle cast iron. The shear pin has to be strong enough to withstand the cutting force, and weak enough to enable rapid fracture. To break the shear pin a cylindrical pin is fired at the top of the tool holder using a powder actuated tool. At the end of the movement the tool holder has to be stopped by a damper, to prevent repulsion. So, the definition of the QSD needs to respect these three specifications:

- to remove tool edge from cutting zone faster than the cutting speed is
- to preserve the free way of cutting edge from cutting zone
- to conserve the chip contact during the decrease in velocity and after stopping

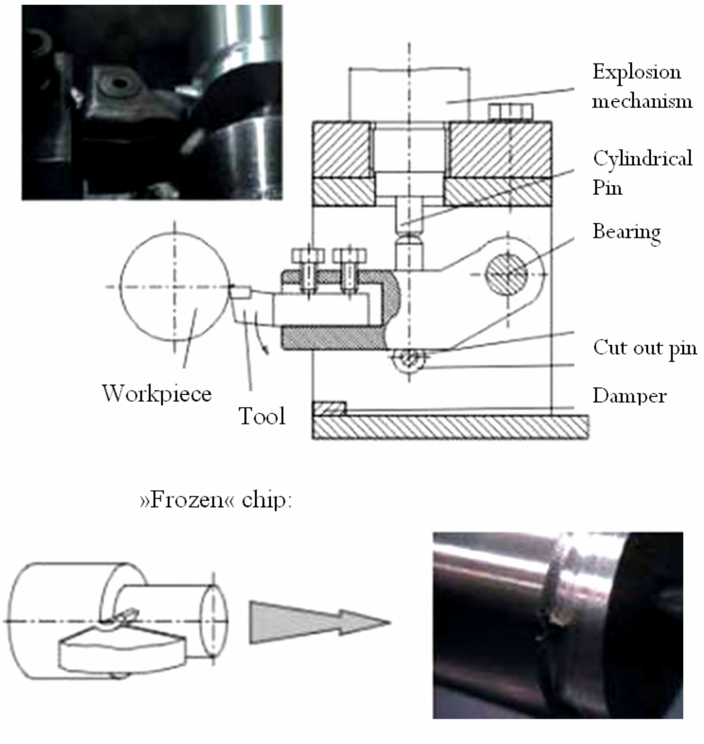


Figure- 6 Structure of Quick Stop Device.

4.2 Chip root results

Using the QSD device described above, experiments were made to obtain the characteristics of the deformation zone. After freezing of chip formation, chip was embedding in bakelite. The chip root is ground such that it can be examined along the centre, so side spread effect is neglected. Next the specimen was polished and etched to show the microstructure.

Thus result of chip rood is found as shown by the microscopic photo in Fig. 7(a). An enlarge photo is given in Fig. 7(b), showing in more detail the deformation of material in the primary shear zone. Though, it is difficult to determine the exact boundaries of the primary shear zone, from this picture it is obviously their very narrow shape. And Fig. 7(a) shows the secondary shear zone, which is caused by friction at the tool rake face.

The deformed area of the chip's back resulting from the secondary shear zone is referred to as the build-up layer (BUL). In contrast with build-up edge, the formation of the BUL in the secondary shear zone is a stable and continuous process, leading to an uniform thickness of the BUL along the chip's back. Interesting with respect to the BUL is the influence of the cutting edge chamfer. It is known that from the view of BUL, there is no considerable influence of the cutting edge chamfer on the thickness of the BUL. Basically, the tribological behaviour between the tool and chip is of much greater importance to the BUL formation than the shape of cutting edge (Kopac 1991). But on the other hand, the tool edge chamfer affects location of stagnation point. Flow with material above the stagnation point result in flowing into the chip, and material below the stagnation point flowing into the workpiece material. The rubbing of the workpiece material underneath the cutting edge is undesired, since it affects the surface finish of machined workpiece. With this respect sharp cutting tool edges should be prevailed, because it results in less deformation of the workpiece surface.

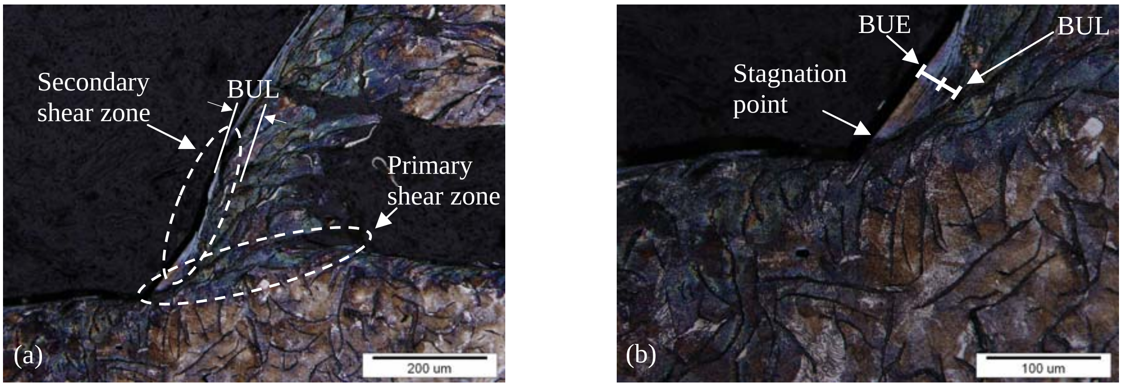


Figure- 7 (a) Chip root obtained with the QSD (v_c=1100 m/min, f=0.08 mm), (b) magnification of picture with indication of stagnation point.

The workpiece material always shows the tendency to stick to the tool in the first part of the secondary shear zone, and thereby forming a BUL. However, for some cutting conditions the amount of material adhering to the tool can gradually rise. Thus forming of BUE, which is also present in that case. The difference between the BUE and the BUL is also visible from Fig. 7(b), which reveals that the BUL has shifted from the tool face to the front of the BUE. As the BUE becomes larger, it eventually becomes unstable and breaks up and affects quality of machined workpiece surface. After a part of the BUE has been removed, it will start to grow again until it becomes unstable again. This procedure of BUE formation and destruction is repeated continuously.

Because of negative cutting tool geometry and tough grey cast material combination, cutting tool "push away material", which lead to increase of cutting forces. These deformations are especially good seen from graphite flakes orientation. They are source of high thermal and mechanical pressure influence on cutting tool. At extreme point, where this material deformation cause very high mechanical and thermal influence on cutting tool edge, premature edge breakdown can occur, or even catastrophic insert fracture (Fig. 5(b)).

4.3 Shear zone analysis

The material immediately in front of the tool is bent upward and is compressed in a narrow zone of shear which is shown in Fig. 8. For most analyses, this shear area can be simplified to a plane. As the tool moves forward, the material ahead of the tool passes through this shear plane. If the material is ductile, fracture will not occur and the chip will be in the form of a continuous ribbon. If the material is brittle, the chip will periodically fracture and separate chips will be formed. In this case the material is grey cast iron but it is not so brittle.

It is within the shear zone that gross deformation of the material takes place which allows the chips to be removed. The material ultimately must yield in shear. As the material flows from the workpiece to the shear area, it is violently sheared, and then continues into the chip section. From Fig. 8 the main part of plastification is recognized in front of cutting tool chamfer, because of too small feed rate or too big cutting tool chamfer. Because that the real rake angle is not -6°, it is even more negative, -26°. That plastification can be characterized with shrinking coefficient, which represent ratio between uncut and cut chip thickness λ. Value of shrinkage coefficient in this case is λ=2, while the share plane angle is Φ=20°. Share plane angle increase if the shrinkage angle is decreased. With increasing of cutting speed and feed rate, the share plane angle is decreasing. But the share plane angle is also increasing with increasing of rake angle. So important is to decrease share plane because that leads to reducing of cutting forces and temperatures in cutting zone (Kopac 2002, Poulachon et al. 2004).

From increasing of feed rate it can be also expected different chip shape. Most striking, from all chip figures, is the serration of the chip found for the feed rate 0.08 mm/rev. The serrated chips are caused by flow localization during the chip deformation. Flow localization results in deformation bands of intense chip shear dividing into the segments. The layers with extremely concentrated shear can be broken easily, so this kind of chip is considered to be ideal to dispose during machining process automation. But it should be noted that the fluctuations of the cutting forces due to the serrated chip, can lead to chatter of the tool depending on the stiffness of the machine, and can additional effect tool wear rate (Kopac et al. 2006).

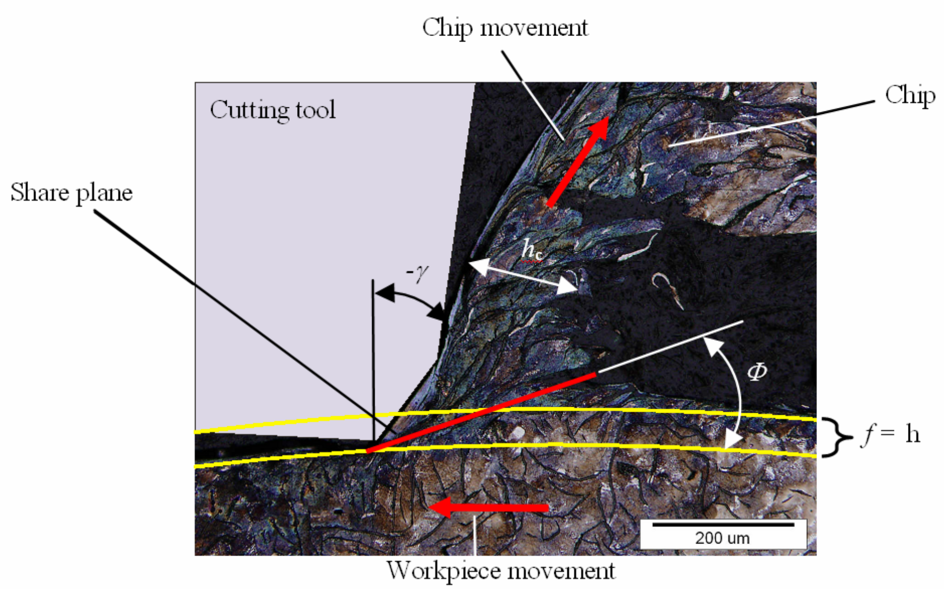


Figure- 8 Chip formation mechanism properties with shear plane representation (h_c – chip thickness, h – uncut chip thickness, Φ – share plane angle, γ – rake angle).

5. CONCLUSIONS

High speed turning of relatively soft grey cast was performed using CBN cutting tools, with two different cutting edge geometries. The tool wear patterns at a cutting speed 1100 m/min were observed through a toolmaker's microscope. The tool wear mechanisms in high speed machining were analyzed. The main tool wear types are practically the same in both cutting tool edge geometries, but the tool wear rate is slower in case of smaller cutting edge chamfer, as a consequence of too negative tool geometry. The dominant wear patterns observed in this study were rake face wear, flank wear, chipping and even breakage. The tool factors in high speed turning affecting tool life were cutting temperature and mechanical pressure impact, because it is recognizable that tool wear on the rake and flank faces were located adjacent to the cutting edge.

Since all tool materials lose their hardness at higher cutting conditions, it is not possible to avoid tool wear. But it is possible to extenuate the wear influence. So it is not enough just to find wear mechanisms affecting cutting tool. There is a genuine need to harness technologies and tool edge geometry specifically tailored, to minimise the temperature generated at the tool–workpiece and tool–chip interfaces. To increase productability through decreasing of wear rate, also some improvements have to be given. For that also interruption of cutting process was performed with Quick Stop Device (QSD), to analyse chip formation. With this, confirmation of presence of high workpiece material deformation was given. And, it has been found that wear rate can be decreased with changed cutting feed rate and cutting tool edge geometry. Where feed rate have to be increased and/or chamfering can be decreased.

REFERENCES

Dawson, G., Kurfess, T. R., 2003. *Wear Trends of PCBN Cutting Tools in Hard Turning*. Seminar, Georgia institute of Technology.

Ekinovic, S., Dolinsek, S., Kopac, J., Godec, M., 2002. The transition from the conventional to the high–speed cutting region and a chip–formation analysis. *Journal of Mechanical Engineering*, vol. 48, n. 3, pp. 133–142.

Kopac, J., 2002. Cutting forces and their influence on the economics of machining. *Journal of Mechanical Engineering*, vol. 48, n. 3, pp. 121–132.

Kopac, J., 1991. *Cutting processes*. Book, Faculty of Mechanical Engineering. (in Slovene).

Kopac, J., 2004. Cutting tool wear during high–speed cutting. *Journal of Mechanical Engineering*, vol. 50, n. 4, pp. 195–205.

Kopac, J., Stoic, A., Lucic, M., 2006. Dynamics instability of the hard turning process. *Journal of Achievements in Materials and Manufacturing Engineering*, vol. 17, n. 1–2, pp. 373–376.

Milfelner, M., Cus, F., 2001. An analysis of temperatures and thermal energy during cutting, *Journal of Mechanical Engineering*, vol. 47, n. 1, pp. 45–52.

Poulachon, G., Bandyopadhyay, B. P., Jawahir, I. S., Pheulpin, S., Seguin, E., 2004. Wear behaviour of CBN tools while turning various hardened steels, *Elsevier Science–Wear*, vol. 256, pp. 302–310.

Thamizhmanii, S., Hasan, S., 2006. Analyses of roughness, forces and wear in turning grey cast iron. *Journal of Achievements in Materials and Manufacturing Engineering*, vol. 17, n. 1–2, pp. 401–404.

Zuperl, U., Cus, F., 2004. A determination of the characteristic technological and economic parameters during metal cutting. *Journal of Mechanical Engineering*, vol. 50, n. 5, pp. 252–266.