INFLUENCE OF FLANK WEAR ON DECOMPOSITION OF CUTTING FORCES IN TURNING

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This paper deals with influence of flank wear on decomposition of cutting force in turning of roll bearing steel. The decomposition is carried out to evaluate the components of cutting force in the tool-chip as well as tool-workpiece interface. The decomposition enables evaluation of the shear and normal forces in the both interfaces. The results of experiments and the following calculations show that while conditions for chip separation in the tool-chip interface stays nearly untouched due to progressive development of flank wear, mechanical load of machined surface associated with components of cutting forces progressively increases with flank wear.

Keywords
cutting force, decomposition, flank wear, turning

1. Introduction

Searching for new information about cutting forces in machining has high practice as well as theoretical relevance. Energy needed for machining process can not be attributed to the pure energy needed for chip separation but certain energy consumption should be considered as the energy deposed in machined surface. Being so, cutting zone should be analyzed as a zone where tool-chip as well as tool-workpiece interfaces are considered.

Surface integrity can be expressed in a variety of parameters and features. Machined surface is a product of tool-workpiece interface. Due to a certain radius of cutting edge a certain volume of material undergoes the cutting edge. Thickness of the layer undergoing the cutting edge depends mainly on the cutting edge radius and this layer is well known as a minimum chip thickness. This layer can be reported as a minimum cutting depth needed for chip separation [Neslusan, 2007a]. Surface integrity in turning expressed in term of surface roughness depends mainly on the tool geometry and cutting conditions (mainly feed). On the other hand, surface integrity expressed in such term as residual stresses, structure and hardness alteration depends mainly on mechanical and thermal load of machined surface in tool-workpiece interface. Flank wear takes the significant role since remarkable affects tool-workpiece interface. Flank wear progressively increase within the cutting time and undergoing material is exposed to the high mechanical and thermal load, see Fig. 1. While mechanical alteration affects mainly the near-surface region, thermal load can penetrate deeply beneath the surface as the flank wear is progressively developed.

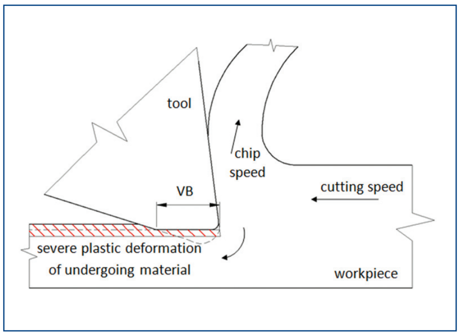


Figure 1. *Plastic deformation of undergoing material*

Many studies were reported about influence of flank wear on surface integrity expressed in such terms as stress state, microhardness profile and structure [Brandt 1999, Wang 1999, Dubec 2012]. As it was mentioned, these aspects of surface integrity are affected mainly by mechanical and thermal load. On the other hand, it should be also pointed that heat and temperature are only the different features associated with the energy consumption derived from forces needed for cutting process. Being so, information about components of cutting force attributed to the pure tool–workpiece interface is essential for analysis of surface integrity.

It is well known that decomposition of cutting force can be carried out in a variety of models. Conventional decomposition provided by Merchant can be found in Fig. 2. This decomposition ignores existence of cutting edge radius or flank wear. Decomposition of cutting force is associated with processes needed for chip separation in the tool-chip interface. Being so, measured components F_c and F_p (F_{cn}), tool geometry (mainly rake angle) and position of shear angle are needed. Normal and shear components can be evaluated afterwards to analyze shear and normal stresses in the tool-chip interface as the quantities depending on friction F_t and the normal force F_{tn}. Furthermore, a model of plastic deformation processes in the shear zone can be analyzed when shear F_s and normal F_{sn} forces are found. Calculations of components illustrated in Fig. 2 are based on equations (1-4).

$$F_t = F.\ \sin\beta\ (N) \tag{1}$$

$$F_{tn} = F.\ \cos\beta\ (N) \tag{2}$$

$$F_s = F.\ \cos\ (\beta - \gamma_n + \phi)\ (N) \tag{3}$$

$$F_{sn} = F.\ \sin\ (\beta - \gamma_n + \phi)\ (N) \tag{4}$$

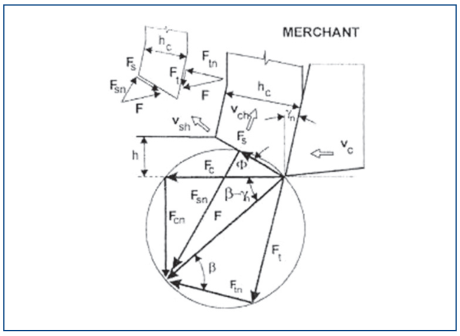


Figure 2. *Decomposition of cutting force in cutting zone [Merchant 1945, Beno 1999]*

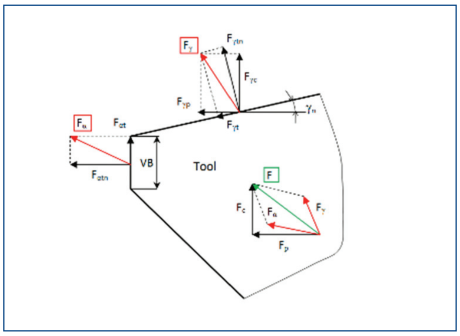


Figure 3. *Decomposition of cutting force in relation to too wear [Neslusan 2007]*

Decomposition of cutting force, as it is depicted by Fig. 2, represents only the simplified model. When the cutting edge radius is considered, decomposition of cutting force is considered as the decoupling of two basic components. First one is loading the tool rake and corresponds with chip separation while the second component is attributed to the tool-workpiece interface as Fig. 3 depicts. F_γ component is energy needed for chip separation in the tool-chip interface while F_α is component affecting mainly quality of machined surface. Cutting force can be then expressed as follows:

$$F = F_\gamma + F_\alpha (N) \tag{5}$$

Decomposition of cutting force, in relation to tool wear and cutting edge rounding, was discussed by many authors [Wang 1999, Endres 1995, Ee 2001]. It was found that flank wear (*VB*) affects produced surface integrity expressed in a variety of features such as stress state, surface roughness, microhardness and structure as well as topography of machined surface [Wang 1999, Dubec 2012, Dubec 2013].

For this reason this paper reports about experimental technique for decomposition of cutting force associated with equation (5). The paper is focused on turning bearing steel with cutting insert of variable flank wear to discuss why the cutting force is increasing with the progressive flank wear *VB* and how the components F_γ and F_α contribute to cutting force increase.

2. Experimental conditions

Experiments were conduced on annealed bearing steel 100Cr6 by the use of cutting insert SNMG 120408E-M (machine: CNC Lathe Hurco TM8). Used tool geometry: $\gamma_o = -6^\circ$, $\alpha_o = 6^\circ$, $\lambda_{se} = -6^\circ$ with TiN coating. Components of cutting force were measured by KISTLER dynamometer under the following cutting conditions:

f (mm)	v_c (m.min^{-1})	a_{p1} (mm)	a_{p2} (mm)	a_{p3} (mm)	a_{p4} (mm)	a_{p5} (mm)
0,09	100	0,25	0,5	1	1,5	2

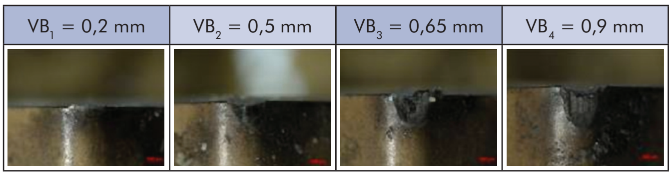


Figure 4. *Cutting insert of the different VB applied for cutting test*

To analyze the influence of flank wear *VB* on F_γ and F_α components inserts of variable *VB* were prepared during the preliminary turning, see Fig. 4. Workpieces illustrated in Fig. 5 were prepared to obtain the variable cutting depth and to analyze relation between the measured components and cutting depth. Separation (extraction) of F_α component is based on calculation of trend line as a relationship between measured cutting force components and the corresponding cutting depths. F_α can be found as a point on the trend line in position where cutting depth is equal to zero, see Fig. 6.

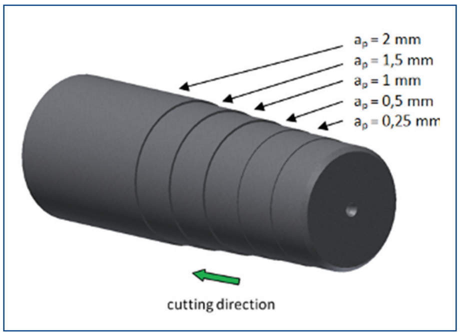


Figure 5. *Workpiece of variable cutting depth for measurement*

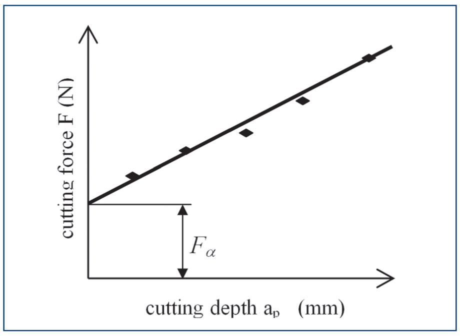


Figure 6. *Graphical illustration of Fα evaluation*

3. Results of experiments

Fig. 7 shows the typical record of components where their progressive increase is attributed to increasing removal rates. The similar records were obtained for all inserts of the different flank wear. Fig. 8 and Fig. 9 show plots where F_p and F_c for different cutting depths and flank wears.

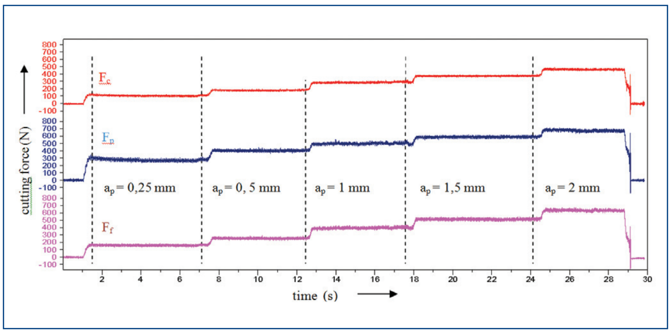


Figure 7. *Record of cutting force component for different cutting depths*

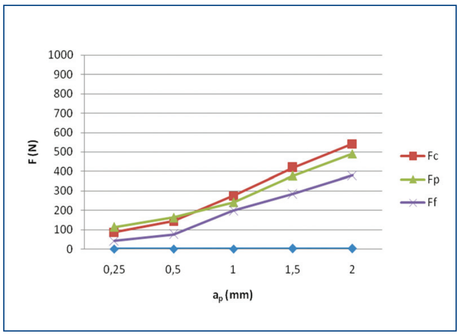


Figure 8. *Influence of ap on components of cutting force, VB = 0,05 mm – sharp insert*

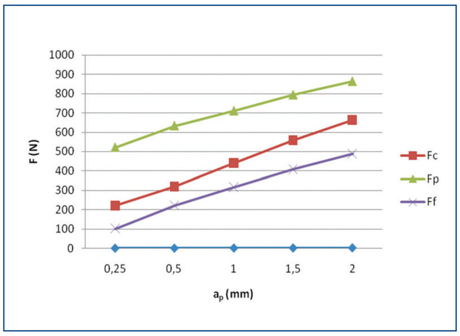


Figure 9. *Influence of ap on cutting force components, VB = 0,9 mm*

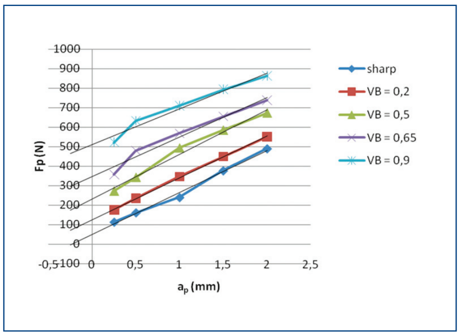


Figure 10. *nfluence of cutting depth and flank wear on thrust force F_p*

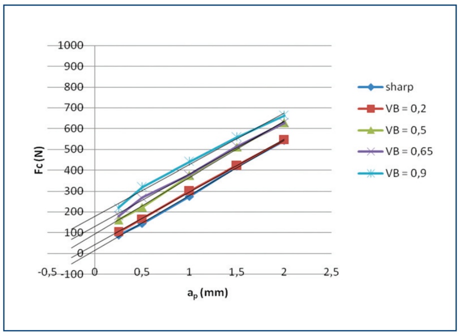
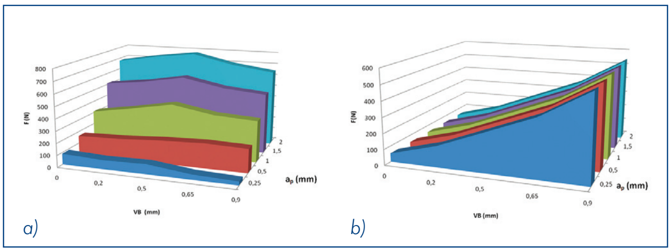


Figure 11. *Influence of cutting depth and flank wear on thrust force F_c*

Fig. 10 also shows that flank wear affects mainly thrust force component F_p since the trust force component is mostly attributed to the processes in tool-workpiece interface while only the moderate increase of F_c component is mostly associated with chip separation in the tool-chip interface, see Fig. 11. Being so, increasing area of flank wear contributes mainly to the more pronounced increase of thrust force. It should be also mentioned that except flank wear, which is progressively increasing within the cutting time, tool wear in form of a crater is also developed on the rake face of the insert. However, the crater alters mainly the rake angle of the insert when initial negative geometry (negative rake angle for sharp insert) becomes more positive along with increasing flank wear *VB*. Results of force measurements indicate that the effect of flank wear dominates over the effect of crater developed on the rake of the insert since cutting force components progressively increase.

Results of decomposition, based on evaluation of intersection points (in position when cutting depth is equal to zero), enable evaluation of components associated with the tool-chip as well as tool-workpiece interface (and the corresponding shear and normal components). Fig. 12a depicts that F_γ depends mainly on cutting depth and the corresponding removal rates. On the other hand, this component stays nearly untouched when flank wear is progressively developed. In other words, flank wear does not contributes to the processes of chip separation in the tool–chip interface and affects mainly mechanical load of surface produced in the tool-workpiece interface. Fig. 12b illustrates that F_α stays nearly untouched at the different cutting depths but abruptly increases with flank wear *VB*.



a) *b)*

Figure 12. *Influence of tool wear and cutting depth on a.) F_γ – face , b.) F_α – flank*

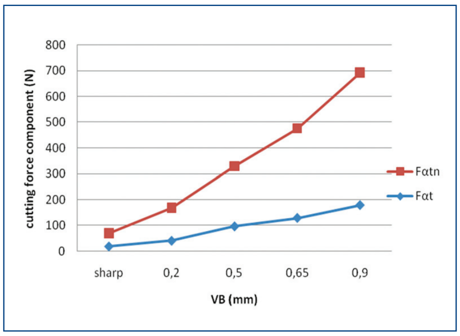


Figure 13. *Influence of flank wear on Fαt and Fαtn*

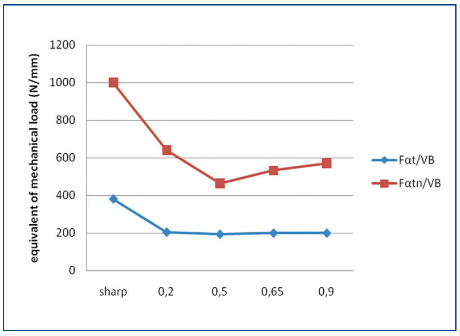


Figure 14. *Equivalent of mechanical load in the tool-workpiece interface*

Fig. 13 shows that normal force component in the tool-workpiece interface dominate over the shear component in correspondence with more pronounced increase of thrust force along with increasing flank wear *VB*. Additional calculation indicates that average friction coefficient in the tool-workpiece interface varies in the range of 0,3 to 0,4. Fig. 14 shows that the equivalent of mechanical load, which expresses the average shear and normal force per 1 mm of flank wear *VB*, is higher in the initial phases of tool wear due to restricted flank wear area (for sharp tool *VB* = 0,05 mm is considered). The equivalent of mechanical load stabilizes afterwards in the normal phase of tool wear.

4. Conclusions and final comments

As it was reported, F_α and its corresponding components, illustrated in Fig. 13, increase along with the gradual increase of flank wear within the cutting time. In correspondence with higher F_α at higher flank wear mechanical and thermal load of machined surface increases since heat generation in the tool-workpiece interface can be calculated when cutting speed and shear force $F_{\alpha t}$ component are known [Neslusan 2007b]. Flank wear *VB* also corresponds with the distance during which the undergoing surface is exposed to the severe plastic deformation and higher temperatures. Time factor takes a significant role especially from the thermal point of view and the time during which the heat generated in the tool-workpiece interface dissipate beneath the surface. The previous studies focused on the analysis of surface integrity (under the same cutting conditions) reported that machined surface obtained at the different flank wear is altered substantially. Residual stresses are shifted to the tensile zone and the zone of tensile stresses extends deeper beneath the surface at higher *VB*. Further, significant increases of microhardness near the surface, remarkable texture and structure transformations can be found when flank wear reaches 0,65 mm.

Roll bearings are usually heat treated to obtain high hardness of the surface and the corresponding wear and fatigue resistance. Despite the surface produced before heat treatment is removed after heat treatment by the following grinding of hard turning, surface integrity expressed in many terms (mainly stress state, microhardness and structure) strongly affects deformation of parts (especially of parts made of thin wall or expressed in other words the parts of high wall thickness to diameter ratios). Additional investigations show that deformations after heat treatment depend on surface integrity and the corresponding flank wear *VB*. Being so, detailed understanding of these aspects can help us to suppress these deformations and reduce the corresponding stocks, time and cost savings.

Acknowledgement

This article was also edited under the financial support of VEGA (project No. 1/0223/11 and 1/0097/12) and KEGA (project No. 031ŽU-4/2011 and 023TUKE-4/2012) agencies.

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