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Effect of cutting edge preparation on tool performance in hard-turning of DF-3 tool steel with ceramic tools †

A. Davoudinejad[1,2,*] and M. Y. Noordin[1]

[1]*Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Malaysia*
[2]*Dipartimento di Meccanica, Politecnico di Milano, Milan, Italy*

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Abstract

This study presents an experimental investigation on turning hardened DF-3 tool steel (~58HRC) with PVD-TiN coated mixed ceramic. We focused on the effect of chamfer and honed edge geometry on tool wear, tool life, cutting forces and surface finish of the machined workpiece. The effects of the process parameters on performance characteristics were investigated using ANOVA. It was found that longer tool life was recorded with chamfered edge geometry at various cutting conditions. The typical damage observed as flank and crater wear for ceramic tools and abrasive wear was found as the main mechanism.The optimal cutting speed was 155 m/min, with which a tolerable tool life and volume of material removal was obtained for both edges geometry. Finer machined surface was left by chamfered tool with feeds and speeds in the range of 0.125-0.05 mm/rev and 155-210 m/min, respectively; also, cutting forces decrease with increased cutting speed. The obtained consequence of cutting forces shows that tool wear has a considerable effect on cutting forces and greater forces values recorded with honed tools.

Keywords: Ceramic tools; Cutting force; Edge geometry; Hard turning; Tool life; Tool wear; Surface roughness

1. Introduction

The machining of parts with hardness in excess of 45 HRC is generally called hard machining. Hard turning has gained considerable interest in many industries for its superior advantages over grinding such as reduced processing cost, elimination of coolant, improved material properties, reduced power consumption and higher productivity. This has resulted in an increased demand for cutting tool materials with improved toughness, elevated temperature strength and chemical inertness. These characteristics are critical when selecting the proper tools for hard machining [1, 2]. Sintered carbides, ceramics, PCBN, and CBN are the most common tool materials used for hard machining. Ceramic tools are mainly based on alumina (Al_2O_3) or silicon nitride (Si_3N_4), which are considered as hard and refractory materials, with resistibility more than 1500°C without chemical decomposition. These excellent characteristics make ceramics the material of choice for the machining of various types of steels and hard metals at high cutting speeds mostly in dry conditions [3].

Advanced ceramics with an extremely fine grain have greater impact resistance and improved wear properties. Tool wear investigation on different ceramic tools has revealed that oxide and mixed ceramic (aluminum oxide plus TiC or TiCN) are highly tailored for machining hardened steel than other ceramics due to it withstanding greater flank wear [4].

Tool wear and tool life investigations with alumina-based ceramic cutting tools in turning hardened martensitic stainless steel showed that flank and crater wears occurred due to abrasion of hard particle on tool faces. The progression of tool wear not only affected tool life but also influenced tool fracture or excessive chipping and surface roughness [5]. Another study on the wear mechanism of mixed ceramic inserts with wiper and conventional edge geometry performed on alloy steel AISI 5140 illustrated flank wear patterns consisting of visible grooves caused via the abrasive mechanism and slightly due to adhesion of the workpiece material [6]. In another study [7], five values of chamfer angle on wear of PCBN cutting tool for bearing steel were studied, and it was found that tool life increased with chamfer angle with the highest value occurring at angle of 15°. However, increasing chamfer angle resulted in higher cutting force. Thiele and Melkote [8] focused on CBN tools with up sharp, honed and chamfer edge geometry for AISI 52100 steel. They observed that cutting edge geometry and feed rate significantly affected the surface finish as well as the axial and radial cutting forces. Another study which used the same tool and workpiece material investigated the effect of process parameters such as cut-

*Corresponding author. Tel.: +39 3277408693, Fax.: +39 0223998585
E-mail address: ali.davoudinejad@polimi.it
† Recommended by Associate Editor Jihong Hwang

Table 1. Chemical composition of ASSAB DF-3.

Elements	Percentage %
C	0.38
Si	0.9
Mn	0.5
Cr	13.6
V	0.3

ting speed, feed rate and depth of cut on the performance characteristics of tool life, surface roughness and cutting forces [9].

A study on the effect of tool nose radius using Al_2O_3/TiC cutting tools alternatively on the same workpiece material found that surface roughness decreases with increasing nose radius [10]. They also found that growing tool wear degrades surface finish. Other authors have developed the effect of CBN chamfered and honed edge geometry by utilizing practical finite element (FE) simulations [11]. The results of these simulation studies showed lower cutting force with honed insert and lower temperatures on chamfered rake face tools. Another study on conventional and wiper mixed ceramic cutting tools in turning AISI 5140 reported better surface finish with wiper edge, and showed that with increasing tool wear, the surface roughness noticeably rises in wiper tools [6].

It is clear from the literature that CBN and PCBN have been frequently used in the machining of hardened steel. Nevertheless, ceramics have almost the same cutting performance as CBN and PCBN, and cost less. Despite the large volume of research, there is still a significant gap in understanding the effects of the cutting edge geometry of ceramic tools. Consequently, this paper presents the results of a detailed investigation of the effects of cutting edge geometry of ceramic tools on the tool life, surface finish and cutting forces in the finish hard turning of ASSAB DF-3 tool steel in different machining conditions. The main contribution in this study is the proper selection of edge preparation of ceramic cutting tools under various cutting conditions.

2. Experimental approaches

Machining was performed on an ASSAB DF-3 tool steel bar of hardness 54-58 HRC with 92 mm diameter and 220 mm length, with compressive strength of 2200 Mpa, compressive yield strength of 1800 Mpa and 185 Mpa modulus of elasticity. Due to its good machinability and dimensional stability during hardening, DF-3 has been proposed as a suitable material for the manufacture of tools which provide reasonable tool life and economical production. Its chemical composition is presented in Table 1. Extremely fine grain ceramic cutting tools were used with the composition of PVD-TiN coated mixed ceramic and a matrix of Al_2O_3 (70%): TiC (30%) +TiN, with KY4400 grade and 2200Hv hardness.

The edge preparation provided on the insert contains cham-

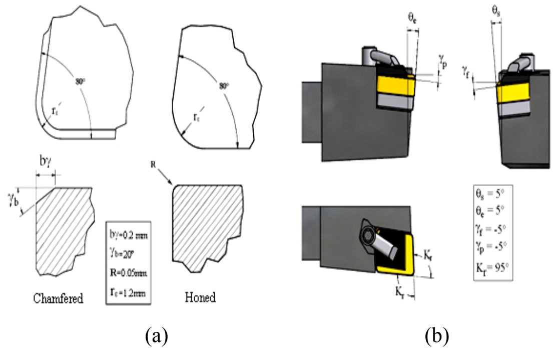


Fig. 1. (a) Tool geometry parameters; (b) schematic of the insert located on the holder used in tests.

fered edge geometry (T-land) 0.2 mm width and 20 degree chamfer angle and honed edges both with rhomboid shape, 1.2 mm nose radius applied in the experiments with ISO designation CNGA120412T01020 and CNGA120412E05 (Kennametal, Grade KY4400) respectively, as illustrated in Fig. 1(a). Inserts were mounted on a Kennametal tool holder codified as MCLNL1616H12 in order to obtain -5° back and side rake angles and 5° end and side relief angles as shown in Fig. 1(b). It is also noticeable that for hard machining, a negative rake angle with a reinforced cutting edge is highly recommended [6].

The experiments were performed on a Maho GR 200E, CNC lathe with maximum spindle speed of 6000 rpm and 8.3 kW motor drive power. Three directions of cutting forces tangential (Fc), radial (Fr), and feed (Ff) were measured using a dynamometer (Kistler, type 9265 B 3 axis), a multi-channel charge amplifier (Kistler, type 5019A) and a data acquisition system used at different stages of the tool lifetime. Fig. 2 is a schematic view of the experimental setup. Tool wear propagation was investigated after machining for a definite length. The machine was stopped and tool holder with insert was removed to reduce uncertainties on account of resumption of the experiments. An optical micrograph was obtained and the maximum width of flank wear was measured using a Zeiss optical microscope equipped with image analyzer software. Crater wear was also observed in the test but it was not measured. Moreover, at the end of the tool life, the SEM was used to analyze the pre-cleaned, worn inserts. Cutting with an insert was carried on until the maximum tool flank wear reached 0.2 mm (VBmax), which was a reference for stopping the experiment. Other researchers also reported similar wear patterns in finish turning various grades of hardened steels [2, 12].

The surface roughness was measured with a portable surface roughness tester profilometer (Taylor Hobson Surtronic) immediately after cutting. This was done without disassembling the workpiece from the chuck. A cut of length 0.8 mm was used to determine the surface roughness. After each cut, three different positions on the circumference of the machined surface were measured and the average was recorded as the surface roughness value (Ra). Experiments were carried out

Table 2. Variables in 3^2 central composite design.

	Levels used		
	Low (−1)	Middle (0)	High (1)
Independent variable, factor			
Feed rate (mm/rev)	0.05	0.125	0.2
Cutting speed (m/min)	100	150	210
Dependent variable, response			
Cutting tool length (m)			

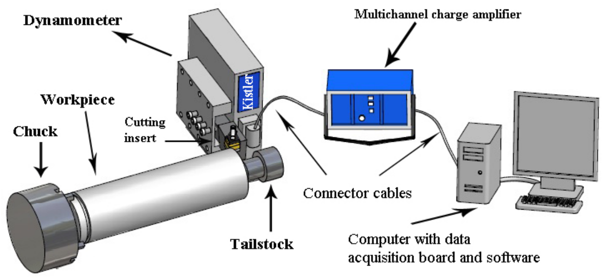


Fig. 2. Schematic view of experimental setup.

without using any lubrication with a constant depth of cut of 0.2 mm in all tests.

2.1 Experimental plan procedure

Two level factorial design (2^k) has commonly been used in the various experimental investigations on hard turning for studying the effect of cutting parameters on different responses. However, in the present study, two factors, three level (3^2 plus two center points) face centered, central composite design was used and response surface methodology was applied. The results for each insert were analyzed separately. The independent factors, their levels and the analyzed dependent responses are shown in Table 2.

3. Result and discussion

3.1 Tool life and wear mechanism

The geometry of the cutting edge and its preparation play a significant role on the insert performance, directly affecting tool life, surface finish and cutting forces. The chamfered and honed tools are recommended to prevent chipping of the cutting edge and to impart strength to the cutting edge [13]. The results of cutting tool length and failure modes are shown in Table 3. In all tests, tool life was reached at the stated wear criteria (VBmax 0.2 mm), except for one experiment which stopped due to chipping failure with chamfer edge geometry at highest cutting speed and feed rate. It is also evident that the tool life decreases with increases in any of the cutting parameters.

Fig. 3 compares tool life performance of chamfer and honed edge geometry in different cutting speeds and feed rates. The

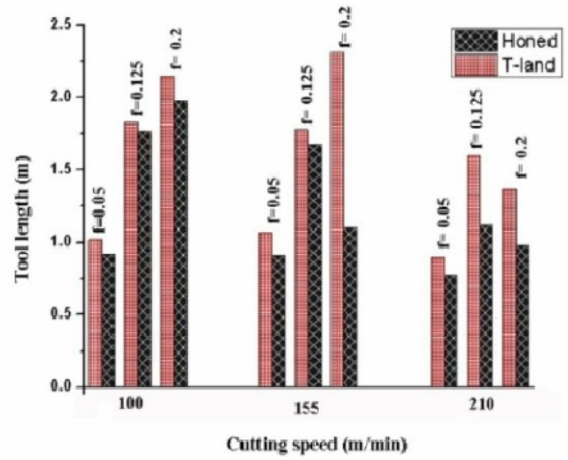


Fig. 3. Histogram of tool length versus cutting speeds for chamfered and honed edge geometry.

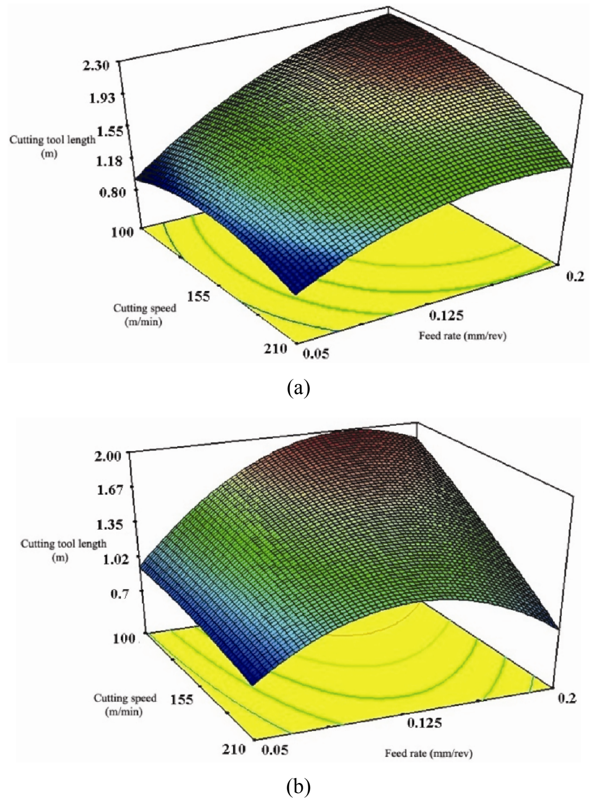


Fig. 4. Estimated response surface of tool length versus cutting speed and feed rate: (a) T-land tool; (b) Honed tool.

effect of tool edge geometry, T-land edge gives an improvement of machining tool length at various feed rates and cutting speeds. The percentage of each condition is shown in Table 3. Furthermore, the results were analyzed in design expert software. The results of the T-land tool experiment in the form of analyze of variance (ANOVA) are presented the same procedure was performed for Honed tool and the final result presented. Table 4 shows that the quadratic T-land tool model is

Table 3. Cutting conditions, failure mode and machining length.

Machining condition	Speed	Feed	Chamfered	Machining length (T-land)	Honed	Machining length (Honed)	Improvement of edge effect
	V (m/min)	F (mm/rev)	Mode of failure	(m)	Mode of Failure	(m)	(%)
1	100	0.05	VBmax exceeded	1.01	VBmax exceeded	0.92	8.9
2	100	0.125	VBmax exceeded	1.83	VBmax exceeded	1.77	3.2
3	100	0.2	VBmax exceeded	2.15	VBmax exceeded	1.98	7.9
4	155	0.05	VBmax exceeded	1.07	VBmax exceeded	0.91	14.9
5	155	0.125	VBmax exceeded	1.76	VBmax exceeded	1.68	4.5
6	155	0.125	VBmax exceeded	1.85	VBmax exceeded	1.73	6.4
7	155	0.125	VBmax exceeded	1.85	VBmax exceeded	1.71	7.5
8	155	0.2	VBmax exceeded	2.31	VBmax exceeded	1.1	52.3
9	210	0.05	VBmax exceeded	0.9	VBmax exceeded	0.77	14.4
10	210	0.125	Tool tip fracture	1.6	VBmax exceeded	1.12	30
11	210	0.2	Chipping	1.37	VBmax exceeded	0.98	28.4

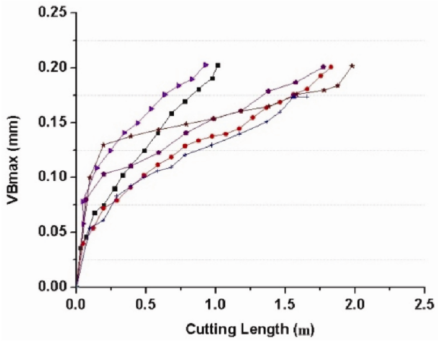
Table 4. ANOVA for tool length (T-land tool).

Source	Sum of squares	d.f.	Mean square	F-value	Prob > F	Remark
Model	0.93541	5	0.187082	17.60038	0.00343	Significant
A: Cutting speed	0.082042	1	0.082042	7.718423	0.0390	Significant
B: Feed rate	0.627369	1	0.627369	59.02195	0.000596	Significant
AB	0.028337	1	0.028337	2.665939	0.163	
A^2	0.038913	1	0.038913	3.66092	0.114	
B^2	0.109825	1	0.109825	10.33221	0.0236	
Residual	0.053147	5	0.010629			
Lack of fit	0.038885	3	0.012962	1.82		Not significant
Pure error	0.014262	2	0.007131			
Cor total	0.988557	10				
S.D	0.103		R^2	0.946		
Mean	0.424		R^2_{Adj}	0.892		
C.V (%)	24.3		R^2_{Pred}	0.635		

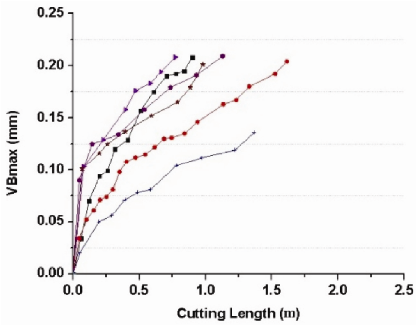
significant and cutting speed (A) and feed rate (B) are also significant factors in the model. But the effect of feed rate is the most significant factor associated with tool life. The same analyses were performed on the honed tools and the model is significant and cutting speed (A) and feed rates (B) are also significant factors in the model similar to T-land tool.

Figs. 4(a) and (b) present response surface plot, the influences of cutting speed and feed rate on the tool length for T-land and honed, respectively.

The longest tool life was recorded with the chamfer edge at 155 m/min cutting speed and 0.2 mm/rev feed rate. In all cutting conditions the chamfer edge tools performed better than honed tools and longer tool life was observed. The longest tool life for honed tools was recorded at 100 m/min and 0.2 mm/rev feed rate. The other aim of this investigation was to find the optimal cutting parameters in order to obtain the high-



(a)



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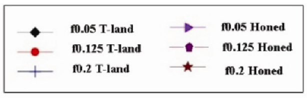
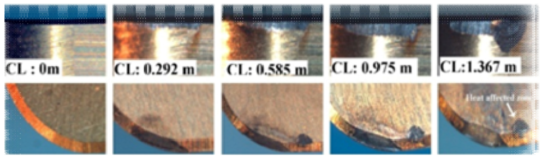


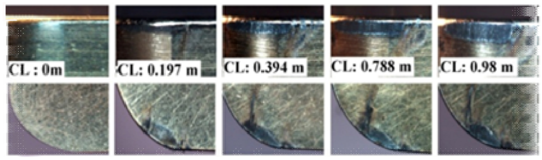
Fig. 5. Flank wear evaluation with chamfered and honed edge at (a) 100 m/min; (b) 210 m/min.

est tool life value during the hard turning process. The optimum cutting parameters in terms of tool life obtained from RSM optimization results of T-land tool were found to be a cutting speed of 112 m/min, feed rate of 0.2 mm/rev. For the honed tool, a cutting speed of 101 m/min and 0.163 mm/rev feed rate were optimal.

Figs. 5(a) and (b) illustrate the evaluation of flank wear on chamfered and honed ceramic tools as a function of the cutting length. At a low cutting speed of 100 m/min a gradual steady increase in VBmax was observed, whereas at a high cutting speed of 210 m/min flank wear increased remarkably and tool wear was reached rapidly. Also, flank wear growth accelerated in the honed edge and shorter tool life was recorded in comparison with the chamfered edge in the same conditions. The most widespread wear modes encountered during the experiments were flank and crater wear. Tool wear mainly occurred at the tool nose radius due to the small depth of cut used for the whole machining process. Crater wear significantly affected honed edges and a larger wear rate was observed on the rake face. In contrast, in T-land edges, crater wear was noticed at the chamfer area. Fig. 6(b) shows observable wear on flank and rake faces of the honed edge and it progressed up to the end of wear criteria at 210 m/min cutting speed and 0.2 mm/rev feed rate. Fig. 6(a) presents the chamfer

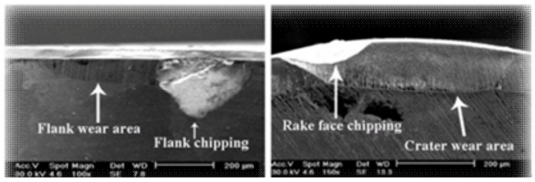


(a)



(b)

Fig. 6. Progression of the flank and crater wear with (a) chamfered; (b) honed cutting edges at 210 m/min and 0.2 mm/rev (CL: cutting length).



(a) (b)

Fig. 7. Chipping formation in (a) flank; (b) rake faces of tool at 210 m/min and 0.2 mm/rev.

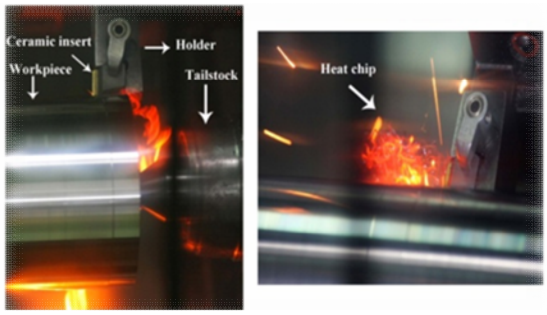
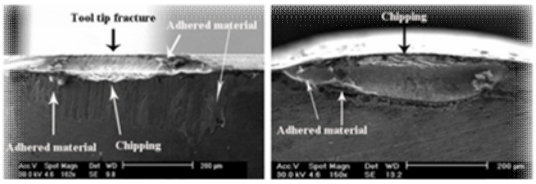


Fig. 8. Heat chips production through machining at 210 m/min.

tool for the same cutting condition where growth of wear was extended until visible chipping occurred only after 1.367 m of cutting. Chipping fracture deteriorated both rake and flank faces of the tool due to the highly brittle tool material. However, larger chipping was observed on flank face. Figs. 7(a) and (b) SEM pictures show both faces with higher magnification.

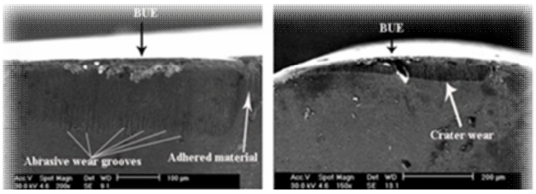
At a high cutting speed (210 m/min) melted red chips were produced due to the high temperature (Fig. 8) and this caused undesirable effects such as larger crater wear on honed tool and chipping on chamfer edge tool at 0.2 mm/rev. Also, some part of the tool tip was fractured and loss at 0.125 mm/rev feed rate which is shown in Fig. 9.

Katuku et al. [14] also showed that at cutting speeds higher than 150 m/min the elevated temperatures to shear localization favored the partial melting of the chip with PCBN cutting



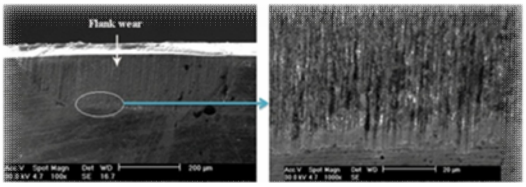
(a) (b)

Fig. 9. Tool tip fracture at 210 m/min and 0.125 mm/rev.



(a) (b)

Fig. 10. Built up edge formation at (a) flank; (b) rake faces of tool at 210 m/min and 0.2 mm/re.



(a) (b)

Fig. 11. Worn flank face indicating small grooves (a) and with higher magnification; (b) at 100m/min and 0.05 mm/rev.

tools. It was also remarkable that BUE formed on the honed cutting edge at the highest cutting condition of 210 m/min and 0.2 mm/rev. Some part of the workpiece material also adhered to the cutting tool at high temperature. Fig. 10 illustrates the flank and rake faces of tool. Aslantas et al. [15] also claimed BUE appearance on TiN coated ceramic tools mainly due to nitride (N) in TiN coating which is more unstable and reacts at high temperatures, whereas Al_2O_3 has a steady composition and enough durability and hardness to involve in a reaction with workpiece material. The dominant wear mechanism of abrasion was observed mainly on the flank face of the tool. As shown in Fig. 11, small grooves were observed on the ceramic cutting tool corner due to the abrasive action of the hardened tool steel.

Fig. 12 shows the total workpiece volume of material removed throughout the achieved tool life at various cutting conditions. The highest volume of material was removed at 100 m/min cutting speed and 0.2 mm/rev feed rate. When the feed rate is increased from 0.05 to 0.2 mm/rev, the volume of material removed can be seen to increase at the 100, 155 and 210 m/min speeds respectively by 135.3%, 133.1% and 61.9% for the chamfered edge, and 143.6%, 131.7% and 127% for the honed edge. On the other hand, as the cutting speed is increased, less material is removed at the same feed rate, mainly for the honed edge geometry.

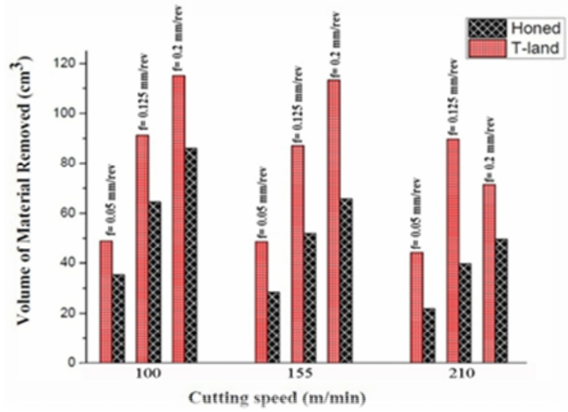


Fig. 12. Volume of material removed at various cutting conditions.

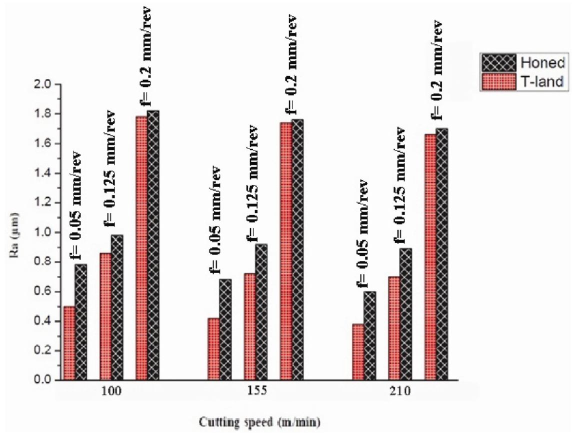


Fig. 13. variation of surface roughness with different edge preparation.

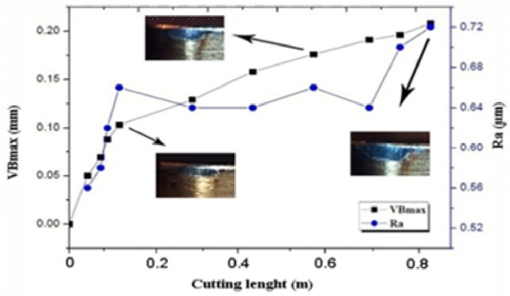
The following equation was used for calculating the volume of material removed:

$$\text{Volume of material removed} = V\, f\, d\, T. \qquad (1)$$

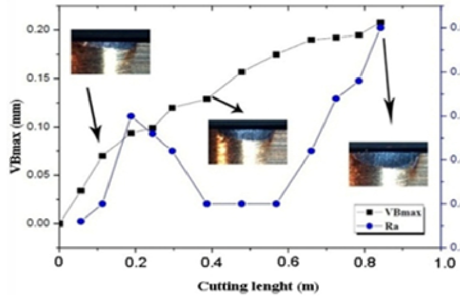
V is the cutting speed, and f represents the feed rate; subsequently d and T represent the depth of cut and machining time.

Surface roughness variation

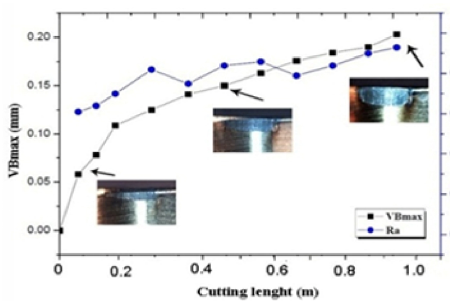
Fig. 13 characterizes the variation of surface roughness (Ra) of machined surfaces with different cutting conditions and edge preparation for chamfered and honed cutting edges. The highest improvement of cutting edge geometry observed at the lowest feed rate (0.05 mm/rev) for ceramic tools. The effect of tool edge geometry, T-land edge in comparison with honed gives a 2% improvement of surface quality at the high feed-rate considered, while giving an average improvement of 36% at low feeds. The best surface finish was achieved at 210 m/min cutting speed. In addition, the result for 155 m/min was just a bit inferior than the corresponding value at 210 m/min. The worst surface finish was obtained at 100 m/min cutting speed and 0.2 mm/rev feed for both cutting edges. Further-



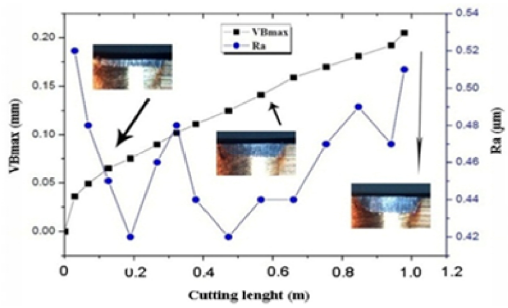
(a) V = 210 m/min, f = 0.05 mm/rev honed



(b) V = 210 m/min, f = 0.05 mm/rev chamfered



(c) V = 100 m/min, f = 0.05 mm/rev hone

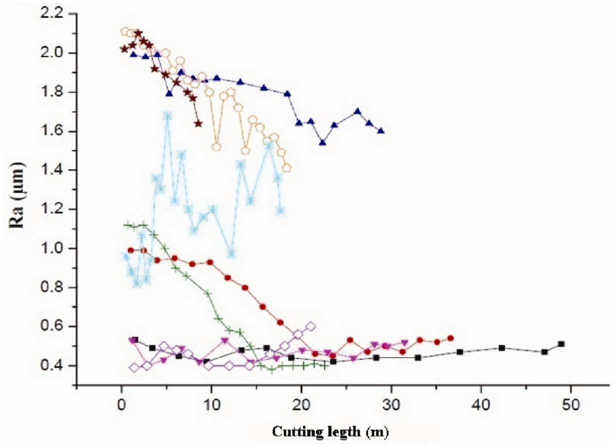


(d) V = 100 m/min, f = 0.05 mm/rev chamfered

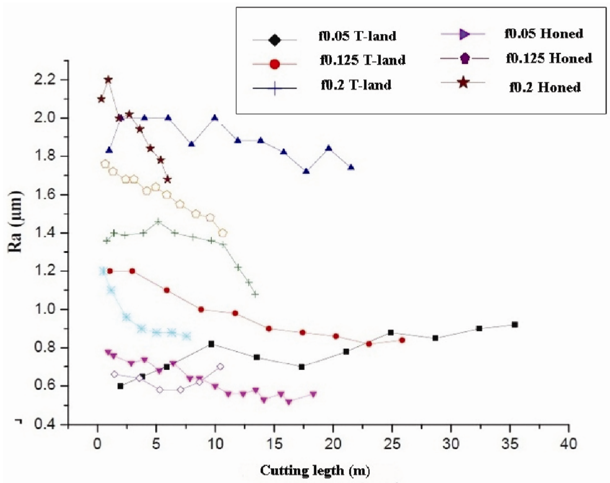
Fig. 14. Variation of flank wear and surface roughness at different cutting time with (a), (c) honed; (b), (d) chamfered tools.

more, at small feed rate the effect of cutting edge geometry is more significant in comparison with high feed rate, which indicated not too much variation in generated surface finish with both cutting edges.

Fig. 14 shows the surface roughness value corresponding to the wear test at 100 and 210 m/min cutting speeds and 0.05 mm/rev feed. It was illustrated with increase of tool wear increased surface roughness and erratic surface recorded for



(a) Chamfered edge geometry

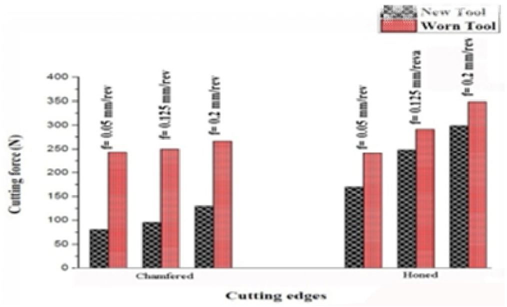


(b) Honed edge geometry

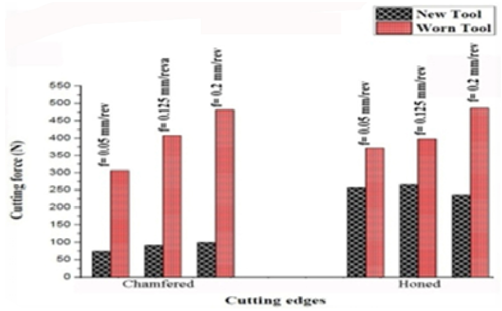
Fig. 15. Surface roughness as a function of cutting time for various cutting conditions.

chamfered edge Figs. 14(b) and (d). This variation is explained through the change in cutting edge sharpness, of T-land tool which affected in each cutting pass. For the honed edge, Figs. 14(a) and (c), the honed edge radius increased with growth of flank wear and this expanded the contact area between the cutting tools and the workpiece which resulted in higher surface roughness.

Figs. 15(a) and (b) show the variation of surface roughness with chamfered and honed edge tools, respectively, at different cutting conditions. Different surface roughness was noted in various cutting conditions. Mostly, a short increase of Ra records at the beginning of the cut, then it starts to decrease below the initial value recorded with fresh tool. This increase of surface value is defined through the tool wear, which change the shape of the cutting edge in short time at first of machining mainly at high feed rate 0.125 and 0.2 mm/rev. Senthil et al. [5] reported that in some conditions cutting nose stabilized by toughening mechanism before flank wear effect cutting edge; subsequently flank wear had slightly impact on

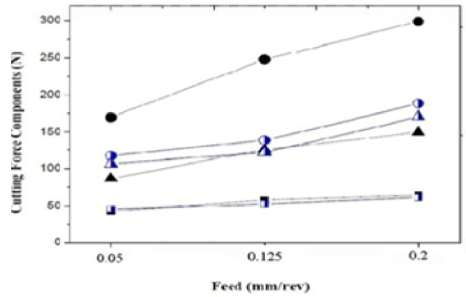


(a)

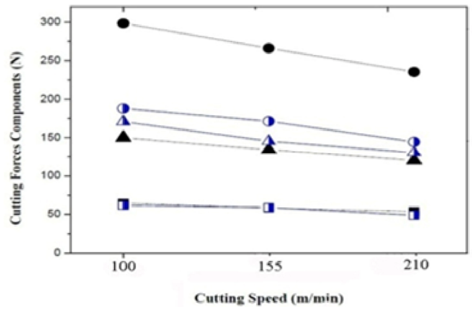


(b)

Fig. 16. Tangential cutting forces for new and worn tools with both edge geometry at different feed rates: (a) 100 m/min; (b) 210 m/min cutting speeds.



(a)



(b)

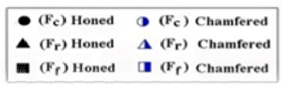


Fig. 17. (a) Feed rates effect on cutting forces at V = 100 m/min; (b) cutting speeds effect on forces at f = 0.2 mm/rev.

surface roughness until wear affected tool nose area. Unstable or zigzag surface roughness at condition eight chamfered edge Fig. 15(a) can be explained by the tool fracture at the tip of insert which clearly shown in Fig. 9.

Cutting force

A significant aspect in design of cutting tools is cutting forces and should be considered in machining furthermore minimizing cutting forces affect machine component and workpiece distortion [16]. The cutting forces for ceramic chamfered and honed cutting tools were measured at first of cutting with fresh insert and after exceeded to wear criteria (VBmax0.2mm). Figs. 16(a) and (b) show changes in tangential cutting force (Fc) with different cutting edges for both new and worn tools which was the main and the largest of three forces components and act on the rake face of the insert. It is clearly observed that cutting forces increased in worn tools in comparison with new tools for both cutting edges. However, it was noticeable that chamfered edge reacts more responsive to tool wear than honed edge, and there was larger variation in forces, about two or three times higher forces obtained at worn tools.

Other previous research findings also confirm this result where increase in flank wear, increase cutting forces due to the deformation of the cutting edge larger contact area of cutting tools rubbing on workpiece material [17, 18]. The effect of edge preparation on cutting forces, the average cutting forces achieved with a honed edge were higher than forces obtained with a chamfer edge at all cutting conditions.

Insignificant variation of forces between chamfered and honed worn tools as illustrated in Fig. 15(b) can be explained by tool failure at 0.2 and 0.125 mm/rev feed with chamfered edge.

Figs. 17(a) and (b) depict changes in tangential (Fc), feed (Ff) and radial forces (Fr) for new chamfered and honed tools with various feed rates and cutting speeds. It shows that increasing the feed rate from 0.05 to 0.2 mm/rev caused larger forces in the cutting edge and raised Ff, Fr and Fc by 50.9%, 71.9% and 75.9%, respectively, for honed edge also for chamfered edge 34.1%, 60.59% and 61.2%. However, lower forces recorded with increase in cutting speeds from 100 to 210 m/min for three component of cutting forces with fresh tools. The decrease in the Ff, Fr, Fc observed to be reduced 16.7%, 19.8 % and 21.1%, respectively, for honed and 20.6%, 27.3% and 29.9% drop for chamfered edges Fig. 17(b). Other studies also reported similar decrease trend in cutting forces at high cutting speeds due to the more heat generated on cutting tools, resulted in plastic softening of machined material and less friction forces [19, 20]. Tangential force (Fc) was recorded as the largest among other forces and most sensitive to cutting condition variation, which can be clearly described by negative rake angle in the hard turning process. While feed force (Ff) was the smallest at any particular experimental tests for both cutting edge preparations when turning DF-3 tool steel. It is also illustrated that feed forces had less altering trend than cutting force and radial forces.

4. Conclusions

The following conclusion was drawn according to the experimental results and ANOVA analysis, on the effect of cutting edge preparation on tool life, tool wear, machined surface, and variations of cutting forces in hard turning of ASSAB DF-3 tool steel with mixed ceramic tools. Maximum cutting length was recorded with chamfered edge geometry at low cutting speed and high feed rate. In general, chamfered edge geometry demonstrated stronger and longer machining length at each individual cutting condition. Additionally, the effect of cutting parameters on tool life was found significant, at 155 m/min which was the most appropriate cutting speed with respect to tool life and volume of material removal achieved. Dominant wear mechanism was observed as abrasion on rake and flak faces of the tools. Furthermore, in some of the machining conditions, fracture, chipping and material adhesion from workpiece on cutting tool edges occurred. In terms of surface roughness behavior, the chamfered edge produced lower roughness value, mainly at 0.05 mm/rev feed rate, whereas more stable trend was observed in the honed edge with propagation of tool wear. Finally, honed tools generated higher forces and chamfered tools were more sensitive to tool wear, of which cutting forces drastically increased by increasing machining length. Additionally, the tangential force was obtained as largest among other force components.

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Nomenclature

b_γ : Chamfer width (mm)
γ_b : Chamfer angle (°)
R : Hone radius (mm)
r_ε : Tool nose radius (mm)
θe : End relief angle (°)
θs : Side relief angle (°)
γ_p : Back rake angle (°)
γ_f : Side rake angle (°)
Kr : Cutting edge angle of the insert (°)
(Fc) : Tangential force (N)
(Fr) : Radial force (N)
(Ff) : Feed force (N)
V : Cutting speed (m/min)
F : Feed (mm/rev)
d : Depth of cut (mm)
T : Tool life (min)
VB_{max} : Maximum widths of flank wear land (mm)
BUE : Built up edge
PVD : Physical vapor deposition

References

[1] D. I. Lalwani, N. K. Mehta and P. K. Jain, Experimental investigations of cutting parameters influence on cutting forces and surface roughness in finish hard turning of MDN250 steel, *J. of Materials Processing Technology*, 206 (2008) 167-179.

[2] M. Y. Noordin, V. C. Venkatesh and S. Sharif. Dry turning of tempered martensitic stainless tool steel using coated cermet and coated carbide tools, *J. of Materials Processing Technology,* 185 (2007) 83-90.

[3] J. Paulo Davim, Machining of hard materials, *Springer,* 978-1-84996-450-0 (2011).

[4] A. Senthil Kumar, A. Raja Durai and T. Sornakumar, Machinability of hardened steel using alumina based ceramic cutting tools, *International Journal of Refractory Metals & Hard Materials,* 21 (2003) 109-117.

[5] A. Senthil Kumar, A. Raja Durai and T. Sornakumar, The effect of tool wear on tool life of alumina-based ceramic cutting tools while machining hardened martensitic stainless steel, *Journal of Materials Processing Technology,* 173 (2006) 151-156.

[6] W. Grzesik, Influence of tool wear on surface roughness in hard turning using differently shaped ceramic tools, *Wear,* 265 (2008) 327-335.

[7] J. M. Zhou, H. Walter, M. Andersson and J. E. Stahl, Effect of chamfer angle on wear of PCBN cutting tool, *International Journal of Machine Tools & Manufacture,* 43 (2003) 301-305.

[8] J. D. Thiele and S. N. Melkote, Effect of cutting edge geometry and workpiece hardness on surface generation in the finish hard turning of AISI 52100 steel, *J. of Materials Processing Technology,* 94 (1999) 216-226.

[9] S. Khamel, N. Ouelaa and K. Bouacha, Analysis and prediction of tool wear, surface roughness and cutting forces in hard turning with CBN tool, *J. of Mechanical Science and Technology,* 26 (11) (2012) 3605-3616.

[10] Y. Kevin Chou and Hui Song, Tool nose radius effects on finish hard turning, *J. of Materials Processing Technology,* 148 (2004) 259-268.

[11] Tugrul O¨ zel, Modeling of hard part machining: effect of insert edge preparation in CBN cutting tools, *J. of Materials Processing Technology,* 141 (2003) 284-293.

[12] A. S. More, W. Jiang, W. D. Brown and A. P. Malshe, Tool wear and machining performance of cBN-TiN coated carbide inserts and PCBN compact inserts in turning AISI 4340 hardened steel, *J. of Materials Processing Technology,* 180 (2006) 253-262.

[13] Y. Karpat and T. Ozel. Mechanics of high speed cutting with curvilinear edge tools, *International Journal of Machine Tools & Manufacture,* 48 (2008) 195-208.

[14] K. Katuku, A. Koursaris and I. Sigalas Wear, cutting forces

and chip characteristics when dry turning ASTM Grade 2 austempered ductile iron with PcBN cutting tools under finishing conditions, *J. of Materials Processing Technology,* 209 (2009) 2412-2420.

[15] K. Aslantas, İ. Ucun and A. Cicek, Tool life and wear mechanism of coated and uncoated Al_2O_3/TiCN mixed ceramic tools in turning hardened alloy steel, *Wear* (2011) 442-451.

[16] L. Qian and M. R. Hossan. Effect on cutting force in turning hardened tool steels with cubic boron nitride inserts, *J. of Materials Processing Technology,* 191 (2007) 274-278.

[17] R. Yigit, Er. Celik, F. Findik and S. Koksal, Effect of cutting speed on the performance of coated and uncoated cutting tools in turning nodular cast iron, *J. of Materials Processing Technology,* 204 (2008) 80-88.

[18] M. Remadna and J. F. Rigal. Evolution during time of tool wear and cutting forces in the case of hard turning with CBN inserts, *J. of Materials Processing Technology*, 178 (2006) 67-75.

[19] M. Athmane Yallese, K. Chaoui, N. Zeghib, L. Boulanouar and J.-F. Rigal, Hard machining of hardened bearing steel using cubic boron nitride tool, *J. of Materials Processing Technology,* 209 (2009) 1092-1104.

[20] K. Bouacha, M. A. Yallese, T. Mabrouki and J.-François Rigal, Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool, *Int. Journal of Refractory Metals & Hard Materials,* 28 (2010) 349-361.

Ali Davoudinejad is a Ph.D. candidate in Mechanical engineering, (Manufacturing and production system) at the University of Politecnico Di Milano. His M.S. degree is from Universiti Teknologi Malaysia. His research interest includes macro and micro scale machining and FEM modeling.