Int J Adv Manuf Technol (2005) 25: 262–269
DOI 10.1007/s00170-003-1878-5

ORIGINAL ARTICLE

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Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened AISI H13 steel

Received: 22 April 2003 / Accepted: 17 July 2003 / Published online: 11 August 2004

Abstract In this study, the effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and resultant forces in the finish hard turning of AISI H13 steel were experimentally investigated. Cubic boron nitrite inserts with two distinct edge preparations and through-hardened AISI H13 steel bars were used. Four-factor (hardness, edge geometry, feed rate and cutting speed) two-level fractional experiments were conducted and statistical analysis of variance was performed. During hard turning experiments, three components of tool forces and roughness of the machined surface were measured. This study shows that the effects of workpiece hardness, cutting edge geometry, feed rate and cutting speed on surface roughness are statistically significant. The effects of two-factor interactions of the edge geometry and the workpiece hardness, the edge geometry and the feed rate, and the cutting speed and feed rate also appeared to be important. Especially honed edge geometry and lower workpiece surface hardness resulted in better surface roughness. Cutting-edge geometry, workpiece hardness and cutting speed are found to be affecting force components. The lower workpiece surface hardness and honed edge geometry resulted in lower tangential and radial forces.

Keywords Hard turning · CBN cutting tools · Surface roughness · Cutting forces

1 Introduction

Hard turning, machining ferrous metal parts that are hardened usually between 45–70 HRC, can be performed dry using polycrystalline cubic boron nitride (PCBN, commonly CBN) cutting tools as extensively reported in literature [1–8]. Some of the earlier research studied serrated chip formation mechanism and attempted to relate process characteristics and stability of cutting to the various chip shapes observed during hard turning [9, 10, 12–19]. Other researchers have investigated composition, temperatures and wear characteristics of CBN cutting tools [1, 8, 20–22, 28] and the effects of work material properties, tool geometry and cutting conditions on surface integrity of the finish-machined parts [23–28]. They reported challenges in identifying various process, equipment and tooling related factors affecting surface quality, tool life and productivity. In this study, factors affecting forces, tool wear/failure and roughness and integrity of the finished surfaces in hard turning and their influences on each other are illustrated with a chart shown in Fig. 1. In this chart, the parameters above the horizontal dashed lines are considered as factors or inputs to the hard turning process and they should be selected or adjusted properly prior to the execution of hard turning process. All other parameters, that are located below these dashed lines, considered as performance measures or outputs of the hard turning process. Review of the literature reveals that almost all of the factors given in this chart affect directly or indirectly performance of the hard turning process. Those factors can be classified as follows.

1.1 Cutting tool geometry and material properties

Hard turning with CBN cutting tools demands prudent design of tool geometry. CBN cutting tools have lower toughness than other common tool materials, thus chipping is more likely [2]. Therefore, a nose radius and proper edge preparation are essential to increase the strength of cutting edge and attain favorable surface characteristics on finished metal components [23]. CBN cutting tools designed for hard turning feature negative rake geometry and edge preparation (a chamfer or a hone, or even both). Specifications of the edge preparation design are often finalized after extensive experimentation. Figure 2 shows the types of edge preparations that are common for CBN cutting tools. According to recent studies, it is evident that effect of edge geometry on surface quality is significant [23–28].

Theile et al. [24, 25], presented research results of an experimental investigation of effects of cutting edge geometry and

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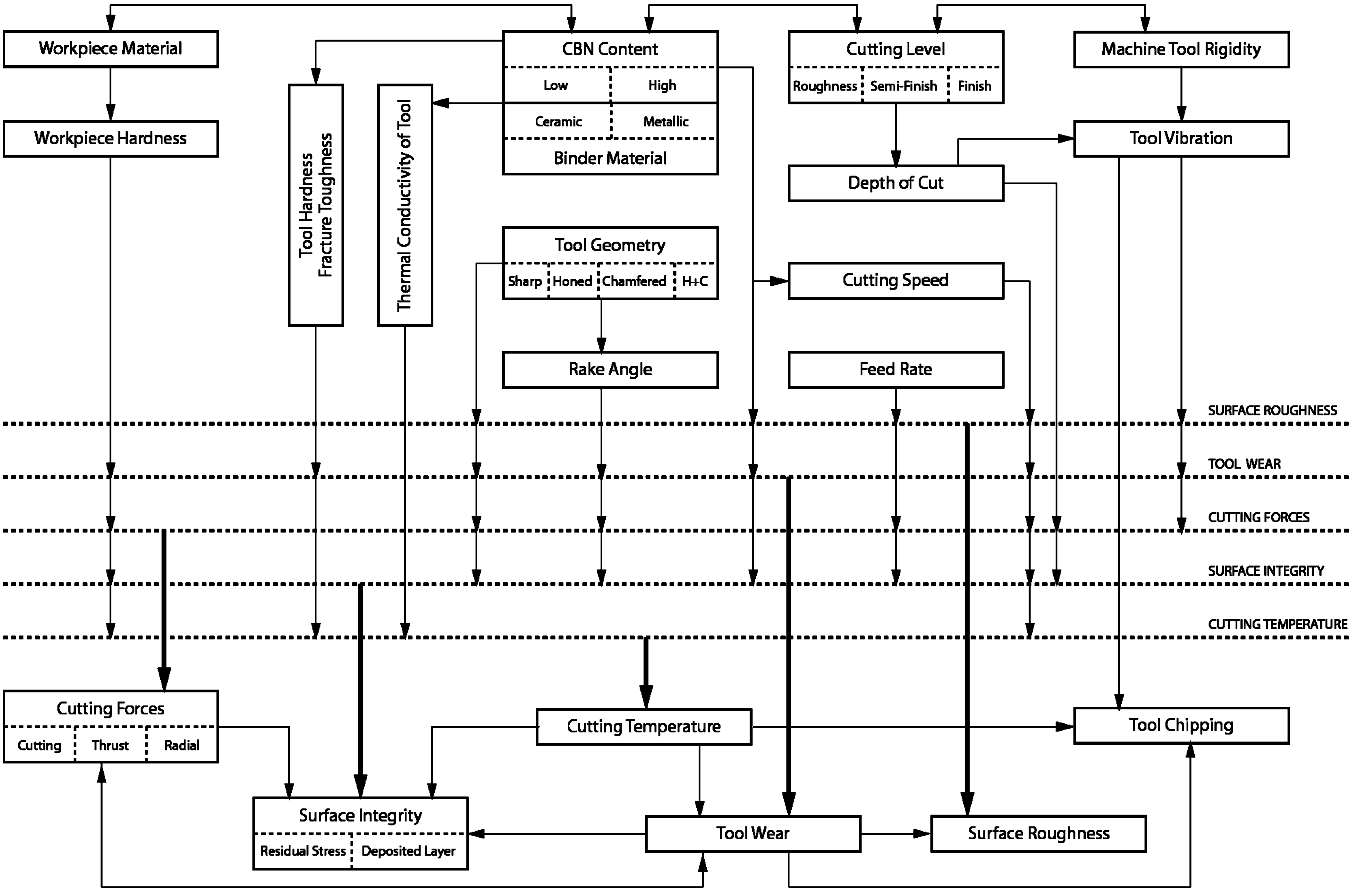

Fig. 1. A flow chart illustrating the relationships of factors in the hard turning process

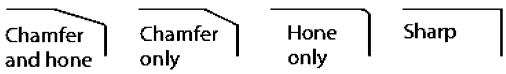

Fig. 2. Type of edge preparations used in CBN cutting tools

workpiece hardness on residual stresses in finish hard turning of AISI 52100 steel. They indicated that both factors are significant for the surface integrity of finish hard turned components. Specifically, they showed that large hone radius tools produce more compressive stresses, but also leave “white-layers”. Özel [26] investigated the influence of edge geometry in CBN tools with respect to stress and temperature development through finite element simulations in hard turning. Chou et al. [28] experimentally investigated the influence of CBN content on surface quality and tool wear in turning hardened AISI 52100 steel tool. This study concluded that low content CBN tools produce better surface roughness with respect to higher content CBN tools and depth of cut has minor effect on tool wear rate.

1.2 Workpiece hardness

Due to the changes in properties of hardened workpiece material, basic shearing process and formation of chips differ in hard turning [5]. Prior research showed that workpiece hardness has a profound effect on the performance of the CBN tools [1, 2, 8] and also on the integrity of the finish machined surfaces [23, 25]. Matsumoto et al. [23] and Thiele et al. [25] studied the effect of workpiece hardness on residual stresses. In a recent study, Guo and Liu [27] investigated material properties of hardened AISI 52100 bearing steel using temperature controlled tensile tests and orthogonal cutting tests and demonstrated that hardness greatly influences the material properties accounting for high variation in flow stress properties.

1.3 Cutting speed, feed rate and depth of cut

Performance of CBN cutting tools is highly dependent on the cutting conditions i.e., cutting speed, feed, feed-rate, and depth of cut [7]. Especially cutting speed and depth of cut significantly influence tool life [22]. Increased cutting speed and depth of cut result in increased temperatures at the cutting zone. Since CBN is a ceramic material, at elevated temperatures chemical wear becomes a leading wear mechanism and often accelerates weakening of cutting edge, resulting in premature tool failure (chipping), namely edge breakage of the cutting tool. In addition, Thiele et al. [24] noticed that when feed rate is increased, residual stresses change from compressive to tensile.

1.4 Surface integrity, residual stresses and tool wear

In general, residual stresses become more compressive as workpiece hardness increases. The hardness and fracture toughness of CBN tools decrease with reduced CBN content [8]. Owing to ceramic binder phase, low content CBN (CBN-L) tools have a lower thermal conductivity, which causes increasing temperatures of cutting edge during hard turning. Chou and Barash [9] reported that CBN-L tools are more suitable for finish turning of hardened steel. At low cutting speeds, tool life of CBN-L tools is superior to high content CBN (CBN-H) tools, whereas at higher cutting speeds, the reverse is true, and also surface roughness is less favorable when using CBN-H tools [28]. Thiele et al. [24] reported that residual stresses generated by large edge hone tools are typically more compressive than stresses produced by small edge hone tools and they also leave white-layers. In addition, the effects of edge geometry play an important role in thermoplastic deformation of the workpiece. Koenig et al. [3] reported that an increase in feed rate raises the compressive residual stress and deepens the affected zone. It was also suggested that the chamfered edge preparation is unfavorable in terms of attainable surface finish when compared to honed or sharp edges.

1.5 Accuracy and rigidity of the machine tool

Another parameter that is often ignored is tool vibration. It is well known that vibration and chatter are important problems that degrade the part quality and the tool performance. In order to reduce tool vibration it is necessary to provide sufficiently rigid tooling and workpiece fixtures. Assuring that there is minimal tool vibration is an easy way to improve surface roughness. It is also necessary that the tooling system be extremely rigid to withstand the immense cutting forces. It is well known that the radial force is the largest among force components observed during hard turning. Many researchers indicated that extremely rigid, high power, and high precision machine tools are required for hard turning because CBN tools are brittle and prone to chipping [3, 7, 8, 14, 23]. It is also suggested that having higher rigidity in machine tool-clamping-tooling system achieves better surface quality on the part.

To improve the overall efficiency of finish hard turning, it is necessary to have a complete process understanding. To this end, a great deal of research has been performed in order to quantify the effect of various hard turning process parameters to surface quality. In order to gain a greater understanding of the hard turning process it is necessary to understand the impact of each of these variables, but also the interactions between them. It is impossible to find all of the variables that impact surface quality in finish hard turning. In addition, it is costly and time-consuming to discern the effect of every variable on the output.

2 Experimental procedure

2.1 Workpiece material

The workpiece material used in this study was AISI H13 hot work tool steel, which is used for high demand tooling. The cylindrical bar AISI H13 specimen that are utilized in this experiments had a diameter of 1.25 inches and length of 2 feet. The bar specimens were heat treated (through-hardened) at an in-house heat treatment facility in order to obtain the desired hardness values of 50 and 55 HRC. However, the subsequent hardness tests by using Future Tech Rockwell type hardness tester revealed that the actual hardness of each specimen was 51.3 ± 1.0 and 54.7 ± 0.5 HRC. Henceforth, the hardness values are defined by the mean values of the measured workpiece hardness.

2.2 Tooling and edge geometry

CBN inserts with two distinct representative types of edge preparations were investigated in this study. These edge preparations include: a) “chamfered” (T-land) edges and b) “honed” edges as illustrated in Fig. 2. Solid top CBN inserts (TNM-433 and GE Superabrasives BZN 8100 grade) inserts were used with a Kennametal DTGNR-124B right hand tool holder with 0° lead and −5° rake angles. Honed and chamfered insert edge geometry were measured in coordinated measurement machine with three replications using a high precision touch-trigger probe. For the honed inserts, an average radius of 10.5 ± 4.0 μm was found. Chamfered insert edge geometry was found to have 20° chamfer angle and 0.1 ± 0.03 mm chamfer width using same instruments with three replications and was approximated to an equivalent hone radius of 101.6 ± 5.1 μm.

2.3 Experimental design

A four-factor two-level factorial design was used to determine the effects of the cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and resultant forces in the finish hard turning of AISI H13 steel. The factors and factor levels are summarized in Table 1. These factor levels result in a total of 16 unique factor level combinations. Sixteen replications of each factor level combinations were conducted resulting in a total of 256 tests. Each replication represents 25.4 mm cutting length in axial direction. The response

Table 1. Factors and factor levels

Factor	Factor levels
Edge preparation	Honed, Chamfer
Workpiece hardness	51.3, 54.7
Feed rate	0.05, 0.1, 0.2 (mm/rev)
Cutting speed	100, 200 (m/min)

variables are the workpiece surface roughness and the cutting forces.

Longitudinal turning was conducted on a rigid, high-precision CNC lathe (Romi Centur 35E) at a constant depth of cut at 0.254 mm. The bar workpieces were held in the machine with a collet to minimize run-out and maximize rigidity. The length of cut for each test was 25.4 mm in the axial direction. Due to availability constraints, each insert was used for one factor level combination, which consisted of 16 replications. (A total of three honed and three chamfer inserts were available). In this manner each edge preparation was subject to the same number of tests and the same axial length of cut. Finally, surface roughness and cutting force measurements were conducted when the cutting length reached 203.2 mm (8 inches) and 406.4 mm (16 inches) during each factor level combination. The surface roughness was measured with a Taylor-Habson Surtronic 3+ profilometer and Mitutoyo SJ-digital surface analyzer, using a trace length of 4.8 mm, a cut-off length of 0.8 mm. The surface roughness values were recorded at eight equally spaced locations around the circumference every 25.4 mm distance from the edge of the specimen to obtain statistically meaningful data for each factor level combination. CBN inserts were also examined using a toolmaker microscope to measure flank wear depth and to detect undesirable features on the edge of the cutting tool by interrupting finish hard turning process.

2.4 Cutting force measurements

The cutting forces were measured with a three-component force dynamometer (Kistler Type 9121) mount on the turret disk of the CNC lathe via a custom designed turret adapter (for Kistler type 9121) for the toolholder creating a very rigid tooling fixture. The charge signal generated at the dynamometer was amplified using charge amplifiers (Kistler Type 5814B1). The amplified signal is acquired and sampled by using a data acquisition PCMCIA card and Kistler DynoWare software on a laptop computer at a sampling frequency of 2000 Hz per channel. Time-series profiles of the acquired force data reveal that the forces are relatively constant over the length of cut and factors such as vibration and spindle run-out were negligible. Three components of the resultant force are shown schematically in Fig. 3.

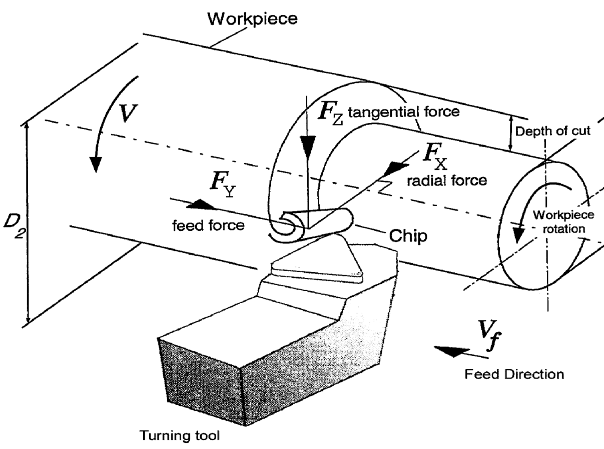

Fig. 3. Measured cutting-force components

3 Results and discussion

An analysis of variance (ANOVA) was conducted to identify statistically significant trends in the measured surface roughness and cutting force data. Separate ANOVA analyses were conducted for Ra surface roughness values and for each component of the cutting force i.e., axial (feed), radial (thrust), and tangential (cutting) forces. Additionally, plots of significant factors corresponding to each ANOVA analysis were constructed. These plots provide a more in-depth analysis of the significant factors related to the surface roughness and cutting forces in finish hard turning of AISI H13 steel using chamfered and honed CBN inserts.

3.1 ANOVA results

ANOVA tables for Ra surface roughness parameters are given in Table 2. In addition to degree of freedom (DF), mean square (MS) and F values (F) the table shows the P-values (P) associate with each factor level and interaction. A low P-value indicates statistical significance for the source on the corresponding response. Table 2 shows that the main effects of edge geometry, cutting speed and feed rate except hardness, interactions between edge geometry and hardness, feed rate, and cutting speed, the interactions between cutting speed and feed rate are significant to surface roughness. Feed rate is the dominant parameter associated with the surface roughness. This is expected because it is well known that the theoretical surface roughness is primarily a function of the feed for a given nose radius and changes with the square of the feed rate value [8].

Table 2. Analysis of variance for Ra

Source	DF	MS	F	*P*
HRC	1	0.044	0.87	0.354
Edge	1	3.226	63.77	0
V	1	0.173	3.41	0.067
Feed	2	7.138	141.11	0
Length	15	0.019	0.3812	0.982
HRC∗Edge	1	0.768	15.19	0
HRC∗V	1	2.076	41.03	0
HRC∗Feed	1	0.009	0.18	0.679
HRC∗Length	15	0.028	0.54	0.910
Edge∗V	1	0.991	19.59	0
Edge∗Feed	1	0.490	9.68	0.002
Edge∗Length	15	0.028	0.55	0.907
V∗Feed	1	0.589	11.64	0.001
V∗Length	15	0.022	0.44	0.965
Feed∗Length	30	0.031	0.62	0.935
Error	116	0.051		
Total	217			

The radial force is usually the largest, tangential force is the middle and the axial (feed) force is the smallest in finish hard turning. In general, cutting speed, edge geometry and feed rate influence cutting force components. Tables 3–5 are ANOVA tables corresponding to the radial, axial (feed force) and tangential components of the cutting force, respectively. These tables show that the main effects of workpiece hardness, edge geometry, cutting speed and feed rate (except for axial force) are all significant with respect to the forces in radial, axial and tangential directions.

Table 3 shows that the main effects of the edge geometry, cutting speed, hardness and the interactions between edge geometry and hardness, cutting speed, feed rate are significant with respect to the forces in the axial (feed) direction. Axial (feed) force is not much influenced by the change in feed rate.

Table 4 shows that the main effects of the edge geometry, cutting speed, hardness and only the interactions between edge geometry and cutting speed, feed rate are significant with respect to the forces in the radial direction.

Table 5 shows that the main effects of the edge geometry, cutting speed, hardness, feed and only the interactions between edge geometry and hardness, cutting speed, feed rate are significant with respect to the forces in the tangential direction.

Table 3. Analysis of variance for axial (feed) force

Source	DF	MS	F	*P*
HRC	1	6518	8.6	0.004
Edge	1	21923	28.8	0
V	1	10982	14.5	0.002
Feed	2	329	0.43	0.650
Length	15	1168	1.54	0.103
HRC∗Edge	1	2687	3.53	0.063
HRC∗V	1	195	0.26	0.613
HRC∗Feed	1	188	0.25	0.620
HRC∗Length	15	567	0.75	0.734
Edge∗V	1	3329	4.38	0.039
Edge∗Feed	1	2682	3.53	0.063
Edge∗Length	15	1220	1.6	0.083
V∗Feed	1	197	0.26	0.612
V∗Length	15	846	1.11	0.353
Feed∗Length	30	223	0.29	0.999
Error	116	760		
Total	217			

Table 4. Analysis of variance for radial force

Source	DF	MS	F	*P*
HRC	1	9738	9.04	0.003
Edge	1	74612	69.29	0
V	1	152861	141.97	0
Feed	2	7806	7.25	0.001
Length	15	5462	5.07	0
HRC∗Edge	1	57	0.05	0.818
HRC∗V	1	97	0.09	0.765
HRC∗Feed	1	509	0.47	0.493
HRC∗Length	15	282	0.26	0.997
Edge∗V	1	3476	3.23	0.075
Edge∗Feed	1	2203	2.05	0.155
Edge∗Length	15	420	0.39	0.979
V∗Feed	1	71	0.07	0.798
V∗Length	15	1100	1.02	0.438
Feed∗Length	30	498	0.46	0.992
Error	116	1077		
Total	217			

Table 5. Analysis of variance for tangential force

Source		MS	F	*P*
HRC	1	9522.3	7.34	0.008
Edge	1	57341.9	44.23	0
V	1	118751.9	91.59	0
Feed	2	47575.3	36.69	0
Length	15	1772.0	1.37	0.175
HRC∗Edge	1	5537.8	4.27	0.041
HRC∗V	1	2048.8	1.58	0.211
HRC∗Feed	1	25.9	0.02	0.888
HRC∗Length	15	321.3	0.25	0.998
Edge∗V	1	2601.1	2.01	0.159
Edge∗Feed	1	10073.9	7.77	0.006
Edge∗Length	15	633.2	0.49	0.942
V∗Feed	1	29202.2	22.52	0
V∗Length	15	1369.7	1.06	0.405
Feed∗Length	30	520.8	0.40	0.997
Error	116	1296.5		
Total	217			

3.2 Effect of feed rate and edge preparation on surface roughness

Graphs of Ra surface roughness parameters are shown in Figs. 4 and 5. These figures have been constructed to illustrate the main effects of edge geometry and feed rate parameters on the surface roughness. Based on the previous analysis, the main effects of the interaction between edge geometry and feed rate are found

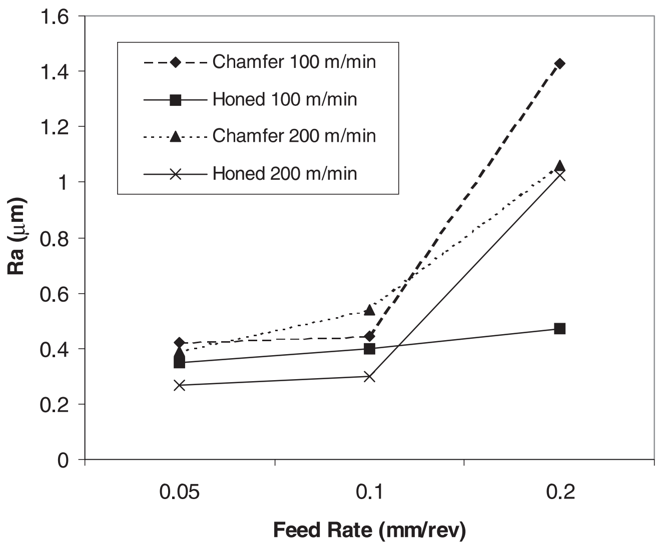

Fig. 4. Effect of cutting edge geometry and feed rate on surface roughness (54.7 HRC, length = 101.6 mm)

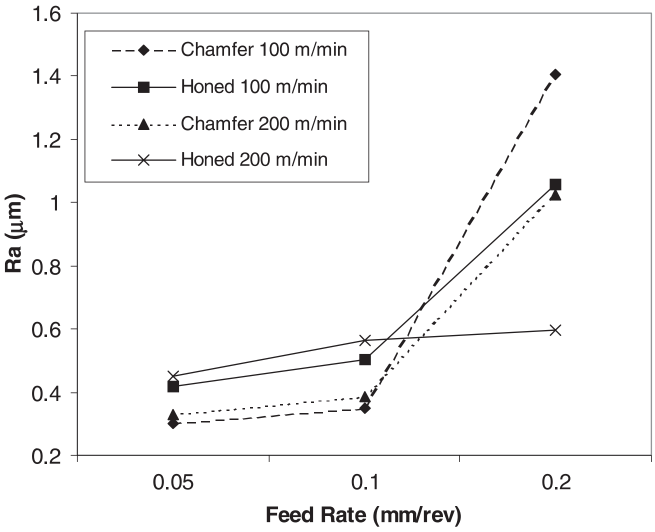

Fig. 5. Effect of cutting edge geometry and feed rate on surface roughness (51.3 HRC, length = 101.6 mm)

to be statistically significant on surface roughness Ra. Figure 4 shows the effect of edge geometry and feed rate on the Ra surface roughness parameter for 54.7 HRC, cutting speed 200 m/min and cutting length of 406.4 mm. Figure 5 shows the effect of edge geometry and feed rate on the Ra surface roughness parameter for 51.3 HRC with cutting speed of 100 m/min and cutting length of 25.4 mm.

These two figures show that all edge preparations are confounded at the lowest feed rate (0.05 mm/rev). However, chamfered edge geometry resulted in better surface roughness when higher hardness and cutting speed selected, whereas it is the opposite when lower hardness and cutting speed selected. Finally, it should be noted that the main effect due to feed is readily apparent for each edge preparation. Specifically, the surface roughness increases as the feed rate increases as the surface roughness being proportional to the square of the feed rate.

3.3 Effect of surface hardness and edge preparation on surface roughness

Figure 6 is constructed to illustrate the main effects of edge geometry and surface hardness parameters on the surface roughness with cutting speed 200 m/min, feed rate 0.2 mm/rev and cutting length 406.4 mm. Based on the previous analysis, the main effects of the interaction between edge geometry and workpiece surface hardness are statistically significant to surface roughness Ra parameters. The figure shows that honed edge geometry and lower workpiece surface hardness resulted in better surface roughness.

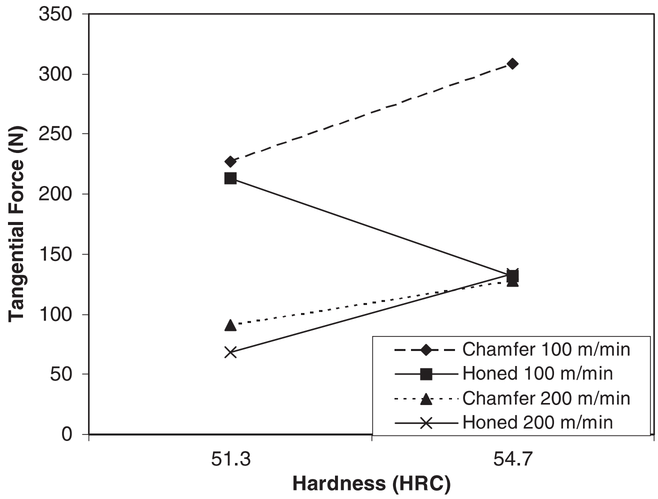

Fig. 7. Effect of cutting edge geometry and surface hardness on tangential force (feed rate = 0.2 mm/rev, length = 203.2 mm)

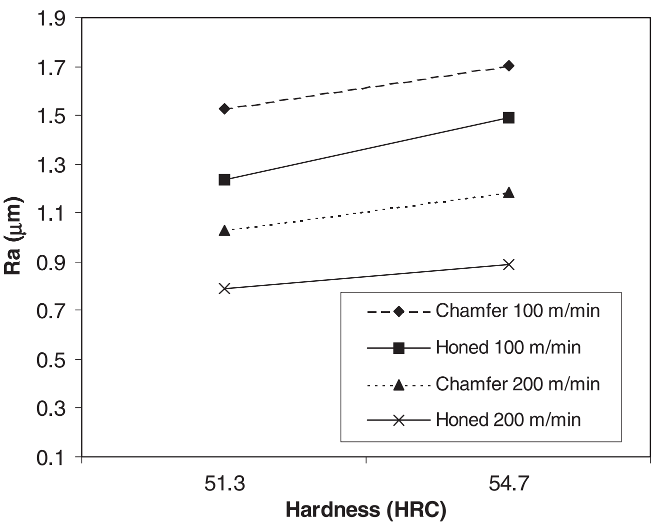

Fig. 6. Effect of cutting edge geometry and surface hardness on surface roughness (feed rate = 0.2 mm/rev, length = 203.2 mm)

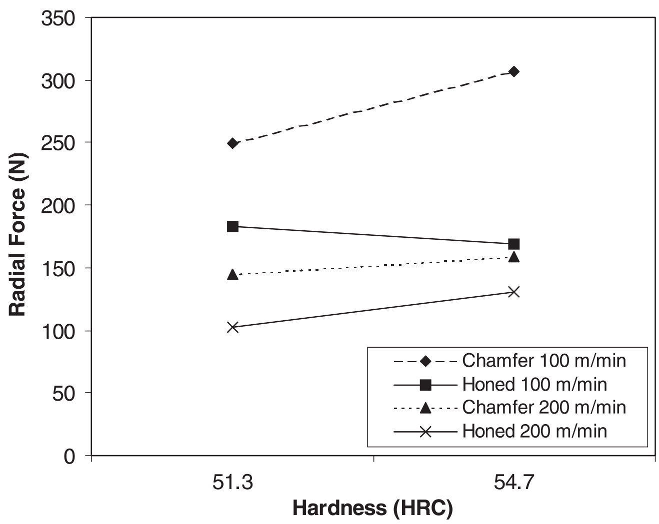

Fig. 8. Effect of cutting edge geometry and surface hardness on radial force (feed rate = 0.2 mm/rev, length = 203.2 mm)

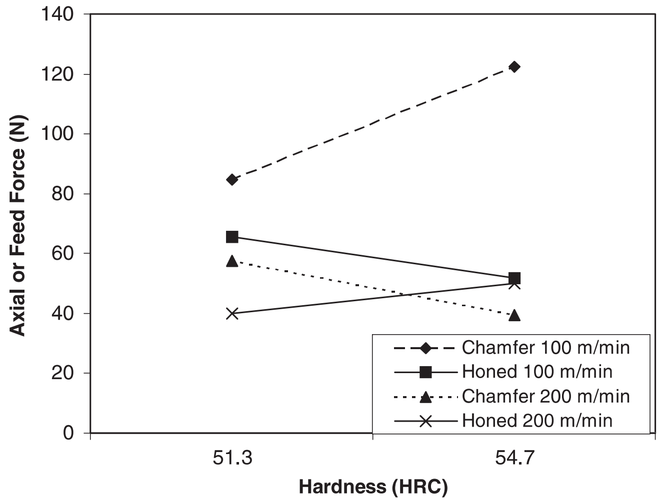

Fig. 9. Effect of cutting edge geometry and surface hardness on axial force (feed rate = 0.2 mm/rev, length = 203.2 mm)

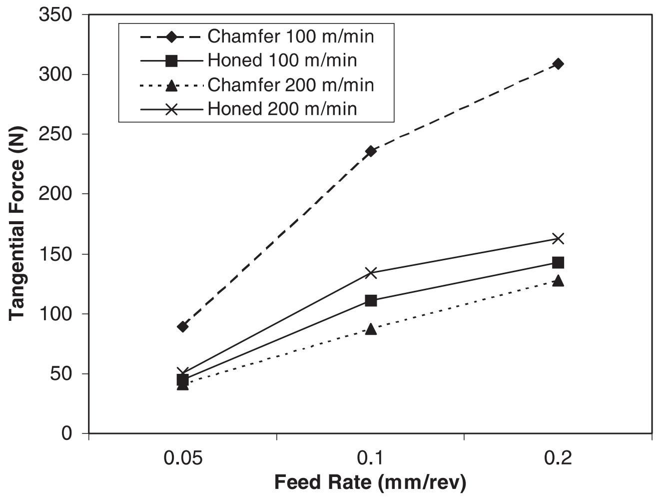

Fig. 11. Effect of cutting speed and feed rate on tangential force (54.7 HRC, length = 203.2 mm)

3.4 Effect of surface hardness and edge preparation on tangential, radial and axial (feed) forces

Graphs of the force components as functions of edge geometry and workpiece surface hardness are shown in Figs. 7–9. These figures show that chamfered edge geometry and higher workpiece surface hardness result in higher tangential and radial forces but not in axial (feed) force. Additionally, honed edge geometry results in higher forces in the axial (feed) directions.

3.5 Effect of cutting speed and cutting edge geometry on tangential force

Figure 10 is obtained to illustrate the main effects of edge geometry and cutting speed parameters on tangential force. Based on the previous analysis, the main effect of the edge geometry and cutting speed are statistically significant to tangential force. Figure 10 shows that higher cutting speed and honed edge geometry resulted in lower tangential force.

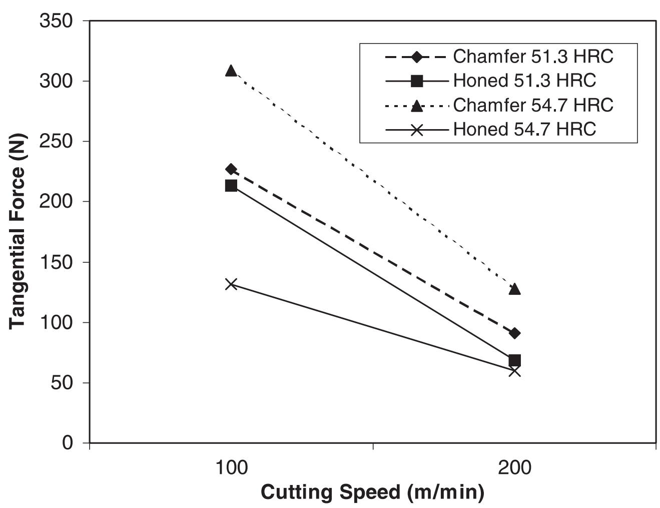

Fig. 10. Effect of cutting speed and cutting edge geometry on tangential force (feed rate = 0.2 mm/rev, length = 203.2 mm)

3.6 Effect of cutting speed and feed rate on tangential force

Figure 11 is obtained to illustrate the main effects of cutting speed and feed rate parameters on tangential force. Based on the previous analysis, the interaction of cutting speed and feed rate are statistically significant to tangential force. Figure 11 shows that lower cutting speed and lower feed rate resulted in lower tangential force.

4 Conclusions

In this study, a detailed experimental investigation is presented for the effects of cutting edge preparation geometry, workpiece surface hardness and cutting conditions on the surface roughness and cutting forces in the finish hard turning of AISI H13 steel. The results have indicated that the effect of cutting edge geometry on the surface roughness is remarkably significant. The cutting forces are influenced not only by cutting conditions but also the cutting edge geometry and workpiece surface hardness.

This study shows that the effects of workpiece hardness, cutting edge geometry, feed rate and cutting speed on surface roughness are statistically significant. The effects of two-factor interactions of the edge geometry and the workpiece hardness, the edge geometry and the feed rate, and the cutting speed and feed rate are also appeared to be important. Especially, honed edge geometry and lower workpiece surface hardness resulted in better surface roughness. Cutting edge geometry, workpiece hardness and cutting speed are found to be affecting force components. The lower workpiece surface hardness and small edge radius resulted in lower tangential and radial forces.

Acknowledgement The authors would like to acknowledge Mr. Joseph Lippencott and Talat Khaireddin for their assistance in conducting the experiments.

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