Cutting Forces and Surface Quality in Precision Milling of Hardened Steel with Cubic Boron Nitride Cutting Tools

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Abstract

Understanding the effects of cutting parameters on cutting forces and surface quality is very important for the evaluation of the machined surface. This paper presents an experimental study of cutting forces and surface quality in precision milling of hardened steel (60 HRC) using cubic boron nitride (CBN) cutting tools. The observations are mainly concentrated on the effect of cutting speed and feed rate with constant depth of cut. The results show that the surface finish produced by CBN cutting tools were affected by cutting parameters and compatible with the results of grinding process. The changes of micro-hardness in the sub-surface of milled surface show gradual profiles which mean higher fatigue strength in the performance of the parts. In general, the results of measurement of residual stresses near the machined surface of hardened steel are compressive stress. Based on these results it can be concluded that precision milling of hardened steel is a suitable grinding process.

1. Introduction

Machining of hardened steel differs from conventional machining because of the hardness of the workpiece materials and the cutting tool materials that are required. Hard materials are characterized by high hardness (> 45 HRC) and abrasiveness. The machining process requires the cutting tool of much higher hardness and also higher resistance of the abrasive wear. Advanced cutting tool materials of ceramics such as cubic boron nitride (CBN) was considered to have the ability of cutting such steel. CBN tool materials show good performance during machining of hardened steel because of their hot hardness, low solubility in iron and good fracture toughness [1].

Precision milling of hardened steel as a potential alternative process compared with the grinding process (surface roughness R_a ~ 0.2 μm) offers many benefits over grinding, such as lower equipment costs, shorter set up time, reduced process steps, higher metal removal rates, improved surface integrity, and elimination of the hazard cutting fluids using dry cutting [2], [3], [4]. As a finishing process the machined surface of the final product needs to control the surface quality. The quality of machined surface can be determined by properties such as surface roughness, hardness variation, micro-structural changes, residual stress, etc. These properties are called the surface integrity of the workpiece material. The surface integrity affects significantly the mechanical properties of the parts such as fatigue limit, stress-corrosion resistance, dimensional stability, etc.

The study of surface characteristics of the machined surface in hard cutting has been the subject of research interest during the past few years [3]. Most research in machining of hardened steel has centered on hard turning especially in the areas of chip forming mechanisms and surface integrity issues of the hardened workpiece. El-Wardany, *et. al.* [5] have investigated the effects of cutting parameters and tool wear on the chip formation mechanisms and the surface integrity during turning of hardened D2 tool steel. Tool wear has shown to have the most significant effect on the subsurface distribution and variations of residual stress and micro-hardness. The residual stress of the machined surface strongly

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depends on various parameters including work hardness, phase transformation, tool wear, and cutting conditions [6]. When turning hardened AISI 52100 steel, Thiele, *et al*. [7] concluded that a larger cutting edge radius has a tendency to induce compressive residual stress in the axial and the hoop directions. The surface roughness of the machined product can be improved by suppressing the formation of the built-up edge chip if the hardness of the built-up edge chip is less than twice the hardness of the part [8]. The surface finish of medium hardened steel produced by CBN tools was affected by cutting speed, tool wear and plastic behavior of the workpiece material [9]. The mechanisms of chip removal and the thermo-mechanical effect on the tool and work surface were reviewed by Tonshoff, *et al*. [10]. The high hydrostatic pressure associated with the high rake angle of the cutting tool is considered to be the most important physical characteristic of plastic deformation in the machining process intended for generating the functional surface of hardened steel.

Advances in cutting tool materials and machine tool technologies have made possible the precision machining of hardened steel in the machining industries, especially for the mould and die manufacturers. Although not as extensively investigated as in turning, hard milling has received attention from the research community. Elbestawi, *et al*. [11] observed the effects of different process parameter on the tool performances and the surface finish and integrity of H13 tool steel. The resultant average forces were compared at different feed rates, depths of cut, and edge preparation. The milling forces, surface roughness, and tool wear vary with the cutting speed, type of tool inserts, and coating in the milling of H13 tool steel at 52 HRC. The solid carbide mill with a TiAlN coating was shown to out perform cutters with CBN and cermets inserts in reducing tool wear and prolonging tool life. The highest values of the three measured component milling forces were compared qualitatively to reflect the effects of tool wear and cutting speeds. The workpiece surface roughness obtained in the face milling tests with CBN tool inserts was in the range 0.1 – 0.2 μm R_a for hardened AISI D2 steel (58 HRC) [12].

This paper investigated experimentally the influence of cutting speeds and feed rates and depth of cut on cutting forces and surface quality in milling of hardened steel (60 HRC) whereas the depth of cut was kept constant. The qualities of machined surface considered were surface roughness, micro-hardness changes and residual stress of the workpiece surface and subsurface.

2. Experimental Works

The objective of the present experiments were to identify the appropriate cutting condition when precision milling of hardened steel, primarily with ceramics and CBN tool materials under different cutting conditions. Cutting forces, surface roughness, micro-hardness and residual stresses of the prepared specimens were measured in the experimental works.

2.1. Workpiece material

The Czech standard of CSN 14 109.4 hardened steel, 60 HRC, (equivalent to AISI 52100) was selected as the workpiece material for all testing due to its wide spread use in the bearing industry. For these tests, the workpiece materials supplied in block sizes of 110 mm x 8 mm x 8 mm. This hardened steel has a nominal composition as shown in Table 1 [13].

Table 1 Composition of CSN 14 109.4 hardened steel.

Content	Composition (%wt.)
C	0.9 -1.1
Mn	0.3 – 0.5
Si	0.15 – 0.35
Cr	1.3 – 1.6
Ni	0.3
Cu	0.25
(Ni+Cr)	0.5
S	0.3
Fe	balance

2.2. Tool inserts

Tool inserts used in the experiments were square CBN – R290 12 T3 08 E CB50 (iC = 13.29 mm, thickness S = 3.97 mm, nose radius r_ε = 0.8 mm) from Sandvik Coromant. The tool insert geometry is shown in Fig.1.

The tool holder used for every single toothed cutter (fly mill) was Coromill 290, R290-063Q22-12M (D_c = 63 mm) for square CBN.

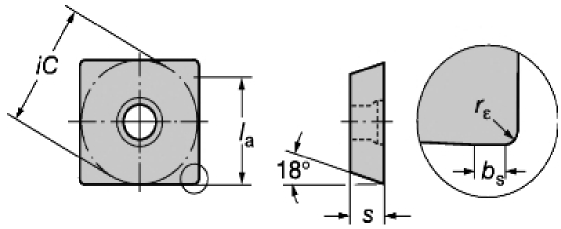


Fig.1 Tool insert geometry of square CBN – R290 12 T3 08 E CB50 from Sandvik Coromant

2.3. Experimental procedures

All cutting tests were performed on CNC milling machine FV25 with a programmable controller Heidenhaim TNC 310. This type of CNC machine was rigid, high precision machine that was suitable for milling hardened steel. All machining test were conducted as dry machining. The workpiece materials were machined with different cutting parameters as shown in Table 2.

Table 2 Cutting parameters

Cutting Parameters	
Cutting speeds, m/min	115 – 140 – 160
Feed rates, mm/tooth *)	0.07 – 0.10 – 0.12
Depth of cut, mm	0.2

*) For fly-mill (single cutter), feed rates are 0.07 mm, 0.10 mm, and 0.12 mm.

The block-shaped workpiece was mounted on a Kitsler model of 9272 dynamometer to measure the three direction of cutting forces. The force signals from the dynamometer were then fed into Kitsler model 5017/5019 multi channel charge amplifier. The analog force signals from the charge amplifier were passed through internal filter in the signal conditioner to prevent aliasing and then sampled with a DAS-1602 (or compatible A/D board) data acquisition card. A PC-based data acquisition program, Dynoware type 2825 A1-2 version 2.31, was used to acquire the sampled data and saved for analysis (Fig.2). Tool wear of every tool insert was observed using a CCD camera microscope system.

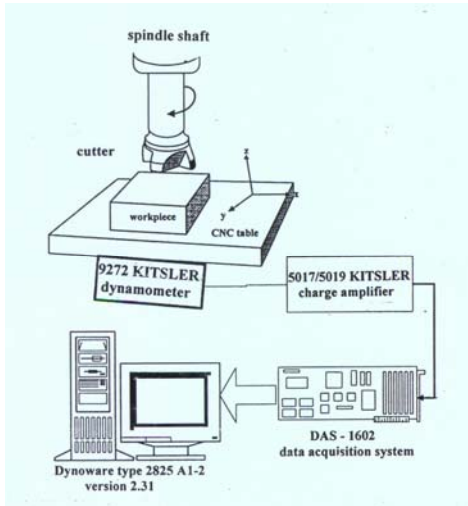


Fig.2 The experiment set-up for measuring cutting forces

A contact profile-meter Talysurf 6 from Rank Taylor Hobson, Ltd., was used to determine the surface roughness of every machined surface. This contact profile-meter utilized a diamond stylus with a radius of 2 μm (0.002 mm). Surface roughness measurements were repeated three times for every experimental point at five places along the milled surface.

The changes in the micro-hardness of the machined surface and subsurface were measured on the machined workpiece using a Vickers micro-hardness tester with a load of 9.807 N. The micro-hardness was measured at a line perpendicular to the surface in order to get an estimate of the depth of the machined-affected zone.

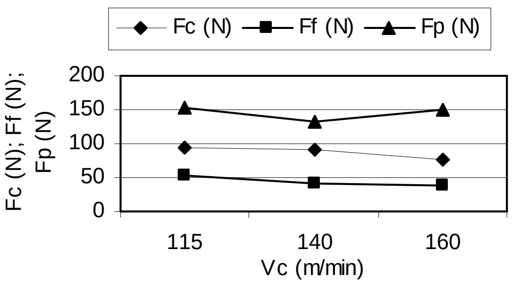
Residual stresses developed during the precision milling were determined using an electrolytic etching deflection technique. This measurement was done by the method of stress relieving which is based on the fact that removal of layers of material from the machined surface relieves a portion of the residual stresses and disturbs the existing conditions of equilibrium. This causes the remaining stresses to redistribute themselves and attain a new equilibrium by producing a change of the deflection of the workpiece. Measurements of the changes in deflection can then be used to compute the residual stresses.

3. Results and Discussion

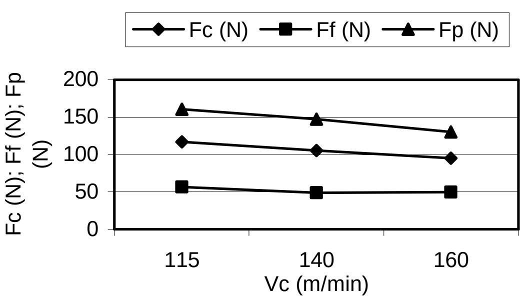
3.1. Cutting forces

The three components of cutting force were recorded during the life of each tool at regular intervals. The three force components are referred to as cutting force F_c, passive force F_p, and feed force F_f. Forces were measured with a piezoelectric force dynamometer and recorded with a PC based data acquisition system, as detailed in the section before.

(a)



(b)



(c)

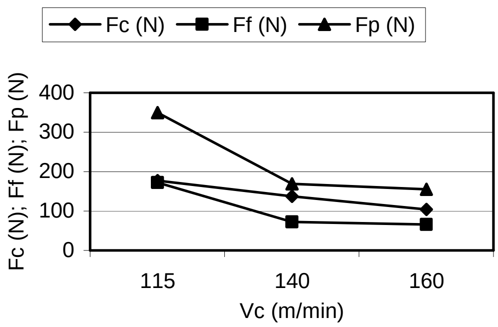


Fig.3 Effect of cutting speed on cutting force components for feed rates (a) f_z = 0.07 mm, (b) f_z = 0.10 mm, (c) f_z = 0.12 mm

Fig. 3 shows the effect of process conditions with square CBN cutting tool inserts on cutting forces. The passive force is typically the largest of the three components followed by the cutting force and finally the feed force [14]. For machining of hardened steel, there is a tendency that all cutting force components are higher for higher feed rate on different cutting speeds. Research in general has also shown that cutting forces increase with feed rate [15], [9] and depth of cut [9].

Fig.3 also shows that cutting force components using square CBN cutting tools decrease with increasing cutting speeds. The main reason is due to the increase of cutting temperature in the shear zone caused by higher cutting speed result in the reduction of the yield strength of the workpiece material, chip thickness and tool chip contact length [15], [16], [17].

After machining process the result of the cutting tool insert was shown Figure 4. The square CBN cutting tool showed no chipping or wear in cutting this bearing hardened steel, as in Figure 4. It means that the CBN tool inserts is a proper tool for interrupted machining like face milling of hardened steel.

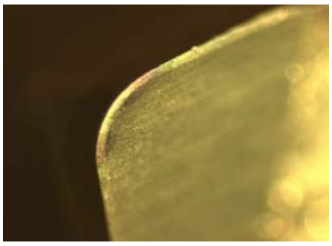


Fig.4 Cutting tool inserts: square CBN with no chipping, after milling process

3.2. Surface roughness

The most universally used roughness parameter for the quality control of machined surface is the arithmetic average height parameter R_a or the center line average (CLA).The parameter R_a is defined as the average absolute deviations of the roughness irregularities from the mean line over one sampling length. Fig.5 shows the R_a values determined for several combinations of cutting speeds and feed rates with a fixed depth of cut 0.2 mm using the square CBN cutting tool insert. The machined surface roughness shown are related to the cutting speeds and feed rates.

Fig.3 shows the surface roughness after machining with different cutting speeds and feed rates. In this set of data, the results of surface generation have a tendency to increase with increasing cutting speeds. The R_a values tend to increase for the higher feed rates for different cutting speeds. The small difference in surface roughness to increase is contrary to the general expectation that roughness improves with increasing cutting speed due to the suppression of built-up edge formation.

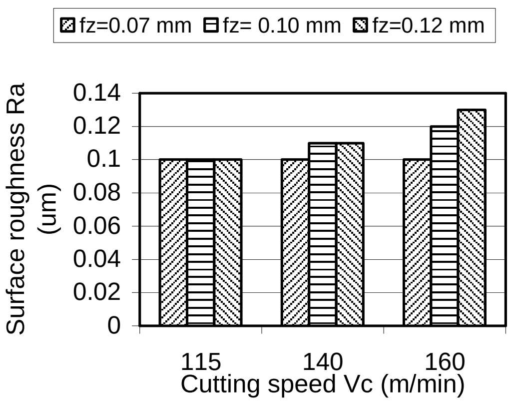


Fig.5 Effect of cutting speed on surface roughness for feed rates f_z: 0.07 mm, 0.10 mm, and 0.12 mm

Based on the surface roughness results of the face milling process, a performance of the square CBN cutting tools can be obtained. Several small values of surface roughness are obtained when the machining process used this square shape of CBN cutting tool, as shown in Fig.5. The surface roughness results (R_a) are in the range of 0.1 – 0.13 μm. The machined surface roughness values are related to the cutting speeds and feed rates. This suggests that milling process using CBN inserts is likely to be viable alternative to grinding for generating plane surfaces of CSN 14 109.4 hardened steel (60 HRC).

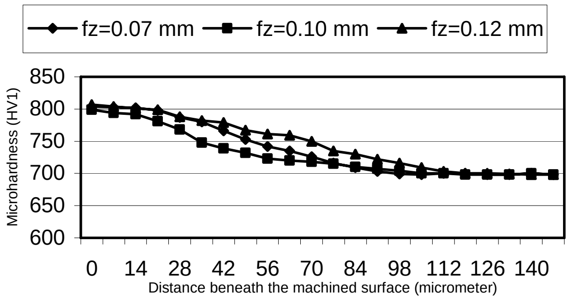
As reported in the scientific papers of [9], [18], [12], the surface finish produced in metal machining was affected by machining parameters and tool wear. The workpiece surface roughness tends to increase related to the tool wear in the machining process. The CBN tool insert after machining shows no chipping or wear as in Fig.4 that means the condition of cutting tool did not influence the result on milled surfaces.

The surface roughness is not the only property to estimate the quality of machined surface. In finishing operation some properties such as micro-hardness and residual stresses should also be considered for the surface finish.

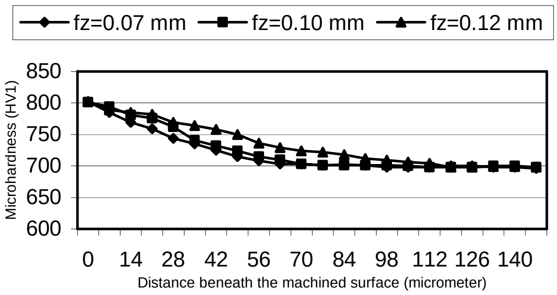
3.3. Micro-hardness

The change of the subsurface micro-hardness was measured to identify the alterations in the machined product. The micro-hardness measurements were repeated at least five times for each specimen to reduce some biased readings caused by the presence of the carbide particles beneath the surface. Fig.6 shows the variations of the

(a) v_c = 115 m/min



(b) v_c = 140 m/min



(c) v_c = 160 m/min

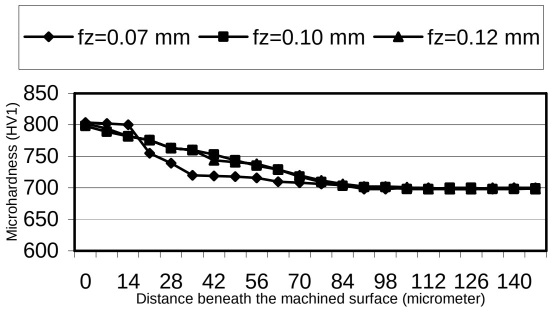


Fig.6 Micro-hardness variations beneath the machined surface produced at different cutting conditions

micro-hardness (HV) with the depth beneath the milled surface by different cutting parameters .

The average micro-hardness in the generated surface increased to approximately 800 HV (64 HRC) for CBN cutting tool. The hardness profiles on the surface gradually decrease to the hardness of the bulk material 698 HV (60 HRC) as shown in Fig.6. These surface hardened by milling has advantageous for higher fatigue strength and corrosion resistance [19]. Hardened depth of the average hardness beneath the machined surface is in the range of 80 – 100 μm.

The changes in the values of the micro-hardness caused by machining process can be related to the dependence of the heat generation and subsurface deformation on the feed rate where the depth of cut was constant. The small changes in the micro-hardness beneath the machined surface were observed for all cutting process. The highest increase of the micro-hardness is 810 HV (64.5 HRC) compared with 698 HV (60 HRC) as the hardness of the parent material. This result indicates that thermal damage was minimal during the machining process.

Tool wear on cutting tool also has an effect on micro-hardness alteration of the machined surface. This relationship between tool wear and micro-hardness alteration is related with the higher temperature generated during the machining process [20].

3.4. Residual Stresses

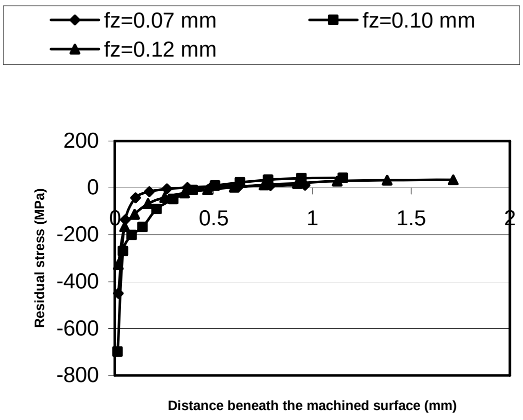
Residual stresses resulting from machining operations has important aspects in assessing surface integrity. Even though such residual stresses are limited to a thin surface layer they have a direct influence on performance of the machined component. In general, compressive residual stresses are to be preferred since they improve the fatigue life of parts and increase stress-corrosion cracking resistance, where as tensile residual stresses are usually detrimental to these properties.

Residual stresses may be produced by in-homogenous plastic deformation induced by mechanical and thermal load associated with the machining process. The thermal stress on the surface layer is capable to produce only tensile residual stress, but the applied mechanical load may produce both tensile and compressive residual stresses. However, a detailed explanation for the effects of cutting parameters on the characteristics of residual stress distribution in the surface region has not been advanced.

Results of residual stresses measured on and below the machined surface are presented in Fig.7 for all testing points. It may be expected that residual stresses will be high at the surface (~ - 700 MPa, maximum) and decrease with an increase in depth below the surface. The residual stresses are generally negative (compressive) for the square CBN tool. The compressive residual stress produced in the milled surface of hardened steel was likely caused by a predominantly mechanical, rather than thermal influence.

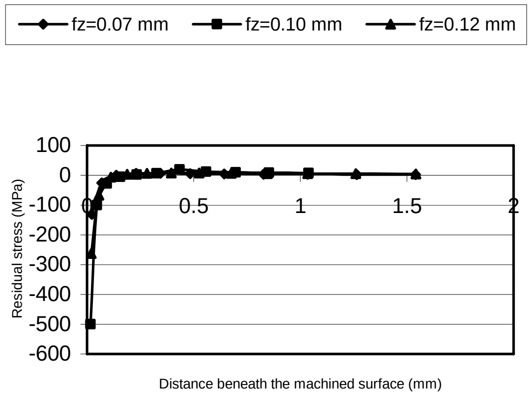
Experimental data (Fig.7) showed that increasing cutting speed caused the residual stresses to become smaller, but no significant tendency for feed rates. The effect of cutting speed is usually related to the amount of heat generated during machining process. The higher the cutting speed, the higher the cutting temperature generated. As the cutting speed increase, the residual stress will be tensile or compressive will depend to the extent on the depth of the permanent plastic deformation zone during machining. This zone depends on the stress generated by the mechanical and thermal loads in the process. If the stress does not reach the yield point of the material, a compressive residual stresses will exist on the workpiece surface [5].

(a) v_c = 115 m/min



(b) v_c = 140 m/min

4. Precision milling of hardened steel with CBN tools, where the milling conditions



(c) v_c = 160 m/min

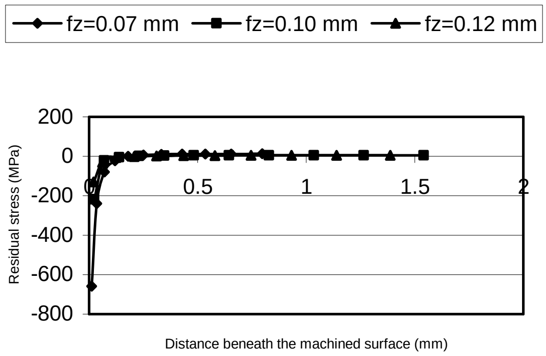


Fig.7 Residual stress variations beneath the surface produced at different cutting conditions.

4. Conclusions

Precision milling of the CSN 14 109.04 hardened steel (60 HRC) was conducted using the square CBN cutting tool. The effects of cutting speeds and feed rates on cutting forces and surface quality of the workpiece were discussed. The following conclusions can be made.

1. CBN cutting tools tend to decrease the cutting force components with increasing cutting speeds, without chipping.
2. Feed rates affect the cutting force components. Higher feed rates will increase the values of cutting force components.
3. Cutting speeds and feed rates have significant effect on the surface roughness of the machined surface.

applied produce the surface roughness (R_a) between 0.1 to 0.15 μm that was compatible with the results of grinding (R_a = 0.2 μm).

5. CBN tool insert is proper for intermittent cutting like face milling of hardened steel.
6. The micro-hardness changes below the machined surface are small and gradually decrease to the hardness of the bulk material.
7. Compressive residual stresses are the most appearing on the machined surface. These stresses are high at the surface and decrease with the increase in depth beneath the surface.
8. Increasing cutting speed caused the compressive residual stress to decrease, but no significant tendency for feed rates.

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