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Insert geometry effects on surface roughness in turning process of AISI D2 steel*

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Abstract: Surface roughness is an important parameter for ensuring that the dimension of geometry is within the permitted tolerance. The ideal surface roughness is determined by the feed rate and the geometry of the tool. However, several uncontrollable factors including work material factors, tool angle, and machine tool vibration, may also influence surface roughness. The objective of this study was to compare the measured surface roughness (from experiment) to the theoretical surface roughness (from theoretical calculation) and to investigate the surface roughness resulting from two types of insert, ‘C’ type and ‘T’ type. The experiment was focused on the turning process, using a lathe machine Colchester 6000. The feed rate was varied within the recommended feed rate range. We found that there were large deviations between the measured and theoretical surface roughness at a low feed rate (0.05 mm/r) from the application of both inserts. A work material factor of AISI D2 steel that affects the chip character is presumably responsible for this phenomenon. Interestingly, at a high feed rate (0.4 mm/r), the ‘C’ type insert resulted in 40% lower roughness compared to the ‘T’ type due to the difference in insert geometry. This study shows that the geometry of an insert may result in a different surface quality at a particular level of feed rate.

Key words: Surface roughness, Turning, Insert geometry, Feed rate
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1 Introduction

Machining is a process to create a part or shape with specified dimensions and tolerances. Surface roughness is related to the quality of the product. It allows the proper function of the product in its usage (Mahardika, 2005). Surface quality significantly improves fatigue strength, corrosion resistance, or creep life (Lou *et al.*, 1999; Sharma *et al.*, 2008), and improved surface quality is increasingly needed in automotive, aerospace, die and mold manufacturing applications. Surface roughness is expressed as the surface roughness value. The higher is the value, the poorer is the surface finish and the shorter is the fatigue life. Therefore, the surface roughness required needs to be clearly stated in specific designs to ensure the machining process is adjusted to achieve it. The surface roughness can be theoretically calculated as

$$R_a = f^2 / (32r_e), \tag{1}$$

where R_a is the average surface roughness (mm), f is the feed rate (mm/r), and r_e is the tool nose radius (mm). Eq. (1) shows that to improve the surface roughness, the feed rate needs to be decreased, and the nose radius increased.

Due to its wide application, surface roughness is described in three main specifications (Lou *et al.*, 1999; Mahardika, 2005):

1. R_a is the average roughness. This parameter is

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known as the arithmetic mean roughness, arithmetic average (AA), or center line average (CLA) and is the most common parameter used to express surface roughness. This is the arithmetic mean of the difference in the roughness contour from the mean line.

2. R_q is the root-mean-square (RMS) roughness.

3. $R_{y\,(\max)}$ is the maximum peak-to-valley roughness height. This is the distance between the top profile peak line and the bottom profile on the contour within the roughness sampling rate.

The final surface roughness in a machining operation is determined by two independent factors (Lou *et al.*, 1999; Mahardika, 2005):

1. The ideal surface roughness. This is the result of the geometry of the tool and a machining parameter such as feed rate.

2. The natural surface roughness. This is the result of irregularities and uncontrollable factors in the cutting operations which are difficult to predict.

Groover (2007) described three groups of factors influencing surface roughness: (1) geometric factors; (2) work material factors; and (3) vibration and machine tools factors.

Geometric factors cover the type of machining operation, cutting tool geometry (nose radius) and feed rate. Machining process can achieve the ideal roughness if there are no disturbances caused by the work material, vibration, and machine tools factors.

For a single-point tool, the effect of the shape of the tool point is an important tool geometric factor. With the same feed rate, a larger nose radius causes smoother feed marks and creates a smoother finish. Vice versa, if the nose radius is kept the same, a larger feed will create a higher surface roughness value since the separation between feed marks is larger than that if a smaller feed rate is used. An end cutting edge angle (ECEA) factor becomes involved in surface roughness when the feed rate is quite large and the nose radius is small (Fig. 1). This is because when a smaller angle is used, it decreases the slope of feed marks and creates a smoother surface. In ideal conditions, a zero ECEA will result in a zero degree slope, and hence create a perfectly smooth surface. However, the imperfections of machining conditions and work materials result in a less than ideal finish (Groover, 2007).

An ideal surface finish is difficult to obtain in most machining operations because of work material factors and the way they interact with the tool (Carlsson and Stjernstoft, 2001; Groover, 2007). Work material factors that affect the surface finish include built-up-edge (BUE) effects, damage to the surface caused by the chip curling back into the work, tearing of the work surface during chip formation especially for ductile materials, cracks in the surface caused by discontinuous chip formation when machining brittle materials, and friction between the tool flank and the newly generated work surface.

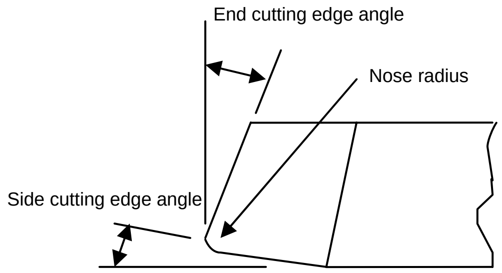

Fig. 1 End cutting edge angle (ECEA)

Several studies of surface roughness have been conducted. Lou *et al.* (1999) built a surface roughness prediction technique in CNC end-milling. The machining parameters used were spindle speed (r/min), feed rate (ipm), and depth of cut (in) (1 in=25.4 mm). Multiple regressions were used to build a surface roughness (R_a) prediction model from the machining parameter as input. It was proven that surface roughness can be predicted from spindle speed, feed rate, depth of cut, and their interactions. Feed rate was the most significant parameter affecting surface roughness. However, this study did not consider different cutting tools. Different cutting tools and materials may produce different results.

Bhattacharya *et al.* (2009) investigated the effect of cutting conditions on power consumption and surface finish using the Taguchi method on AISI 1045 steel. Parameters used were cutting speed, feed rate, and depth of cut, and the outputs were three values of surface roughness and power consumption. The experiment was analyzed using analysis of variance (ANOVA) to investigate the contribution of each factor. A trade-off was observed: when a higher cutting speed was applied, it led to a better surface roughness, but also higher power consumption. A compromise needs to be made between the surface quality and economic requirements (Bhattacharya *et al.*, 2009).

In this study we investigated the surface roughness resulting from inserts of different geometry. To analyze the results, differences between experimental and theoretical surface roughness values were compared.

2 Experimental

The turning process of AISI D2 steel was conducted using the manual lathe machine Colchester 6000. AISI D2 was chosen to represent hard material. It is a hot work chromium type that is commonly used in punching and blanking applications. Two insert geometry types were used: CNMG 120408, which represents ‘C’ type, a rhombus shape with an 80° angle (Fig. 2a), and TPMR 160308, which represents ‘T’ type, a triangle shape with a 60° angle (Fig. 2b). Both inserts have the same nose radius, 0.8 mm.

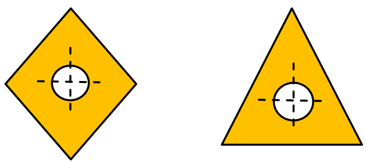

Fig. 2 Insert shapes of (a) ‘C’ type and (b) ‘T’ type

The feed rate was the machining parameter considered in this study because theoretically, this is the parameter that affects surface roughness (Eq. (1)).

The three feed rate values used in our experiment were 0.05, 0.2, and 0.4 mm/r, which were the machining parameter recommended by the material manufacturer (ASSAB Steel XW-42, 2009). The surface roughness of the work piece after the turning process was measured using a portable and wireless perthometer (MarSurf PS1, Mahr Ltd., Germany). This portable device allows measurement of an object clamped on the chuck of a machine. The traversing length used was 17.5 mm. Measurements were made on two areas along the *x* axis (turning direction).

3 Results and discussion

Several studies indicated that a higher feed rate, higher depth of cut, and lower cutting speed would increase the surface roughness value (Lou *et al.*, 1999; Puertas Arbizu and Perez Luis, 2003; Bhattacharya *et al.*, 2009). However, our experiment did not produce the same results. A feed rate of 0.05 mm/r resulted in a roughness value very similar to that of a feed rate of 0.2 mm/r for both types of inserts. There was a large difference in roughness resulting from feed rates of 0.20 and 0.40 mm/r (Fig. 3). This result was compared to the theoretical surface roughness.

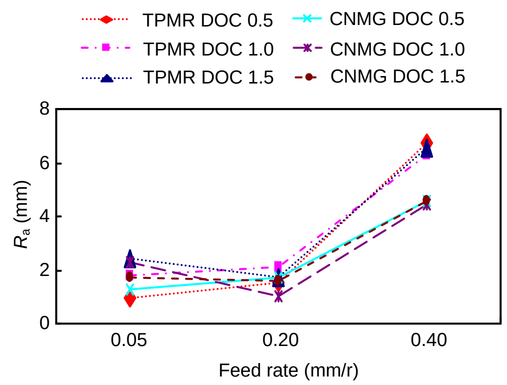

Fig. 3 R_a plot of TPMR versus CNMG at a cutting speed of 150 m/min (DOC 0.5: depth of cut 0.5 mm)

The deviation (D) between theoretical R_a (R_{at}) and actual R_a from experiment (R_{ae}) was calculated. The deviation between the theoretical and measured values was used to compare the difference between the two values. The percentage deviation (PD) was calculated to determine the extent to which the actual value deviated from the theoretical value.

$$\mathrm{PD}=\frac{R_{ae}-R_{at}}{R_{at}}\times 100\%. \tag{2}$$

The deviations between the measured and theoretical values of surface roughness were calculated for TPMR and CNMG inserts (Table 1).

Table 1 Deviations between R_{at} and R_{ae}

Feed rate (mm/r)	R_{at} (mm)	TPMR 160308			CNMG 120408		
		R_{ae} (mm)	D (mm)	PD (%)	R_{ae} (mm)	D (mm)	PD (%)
0.05	0.10	1.81	1.71	94.59	1.60	1.50	93.91
0.20	1.56	1.74	0.18	10.18	1.42	0.14	10.13
0.40	6.25	6.45	0.20	3.13	3.84	2.41	62.91

A feed rate of 0.05 mm/r resulted in large deviations of 94.59% and 93.91% between the measured and theoretical values for TPMR and CNMG inserts, respectively (Figs. 4a and 4b). These deviations may be caused by the work material factor. This was highlighted by Carlsson and Stjenstoft (2001) and Groover (2007), who suggested that the deviation from ideal surface roughness (in theory) can be caused by work material factors such as built-up layers, BUE formation, chip interface, chip squeezing, tool vibration, tool wear, workpiece vibration, and temperature and cutting speed variations. Cyclically BUE formations have huge occurrence probabilities at low feed rates. Chip interface and chip squeezing were the most significant factors in our experiment. When a low feed rate was applied, the chips were small, curly, and large (Fig. 5a). Moreover, the movement of feed was very slow. Therefore, chips curling back to the workpiece became trapped in between the tool and the workpiece, pressing against the workpiece surface (Fig. 5a). This caused scratching on the new surface as the chips passed. Finally, when a low feed rate was employed, it resulted in a high surface roughness (Fig. 5b).

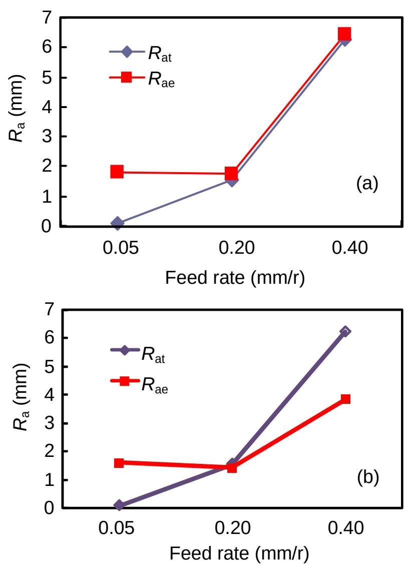

Fig. 4 Surface roughness deviation using (a) insert TPMR 160308 (insert 60°) and (b) insert CNMG 120408 (insert 80°)

A feed rate of 0.2 mm/r seems to be suitable for this material. At this rate, both inserts resulted in a similar PD (10%) from the theoretical surface roughness value. Chips were broken easily and smaller chips were formed (Fig. 5c). Also, the gaps between feed marks created by the tool tip were very narrow, even smaller than the nose radius. Hence, this feed rate resulted in a good quality surface (Fig. 5d).

When a feed rate of 0.4 mm/r was applied, the chips formed appeared to be similar to those formed at 0.2 mm/r (Fig. 5e). However, the gaps between feed marks were bigger, resulting in a rough surface. Fig. 5f shows the appearance of uniform texture. Hence, this feed rate resulted in a low quality surface.

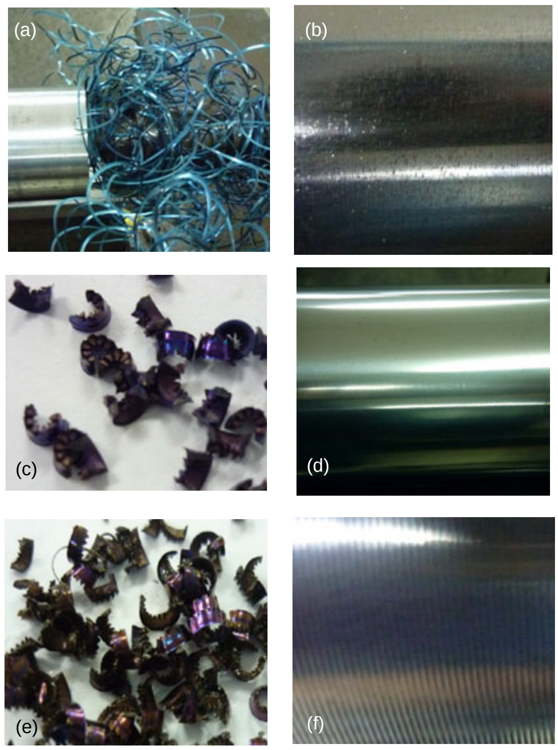

Fig. 5 Chips formed and surface roughness resulting from each feed rate
(a) Chips and (b) surface at the feed rate of 0.05 mm/r; (c) chips and (d) surface at the feed rate of 0.2 mm/r; (e) chips and (f) surface at the feed rate 0.4 mm/r

However, at a feed rate of 0.4 mm/r, the two inserts resulted in different surface roughness. The CNMG insert resulted in a surface roughness 40% lower than that of the TPMR insert. Thus, the CNMG insert formed a better surface than the TPMR insert at this feed rate.

The possible reason for this difference in surface roughness is the ECEA factor that becomes involved in surface roughness when the feed rate is quite large and the nose radius is small enough.

Figs. 6a and 6b show the effect of the ECEA of different insert types on surface roughness. The rhombus shape with 80° point angles had an ECEA of 10°, lower than that of the TPMR which had an ECEA of 30°. The CNMG insert created a shallower slope of feed marks than the TPMR insert. Hence, the CNMG resulted in a finer surface than the TPMR. This explains the significant difference in surface roughness resulting from the geometry of the two inserts.

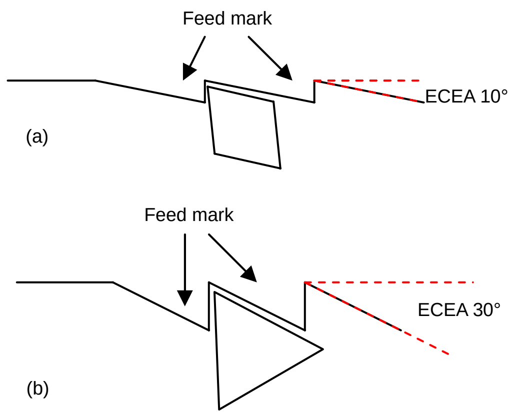

Fig. 6 Feed mark formations of (a) CNMG 120408 (rhombus) and (b) TPMR 160308 (triangle)

It is known that higher feed rates may consume more power (Kadirgama and Abou-El-Hossein, 2005; Campatelli, 2009). However, based on the Sandvik Metal Cutting Technological Guide (2009) (Fig. 7), the power requirement (P) is lower to the right of scale 2. Hence, the 'C' type insert requires more power than the 'T' type.

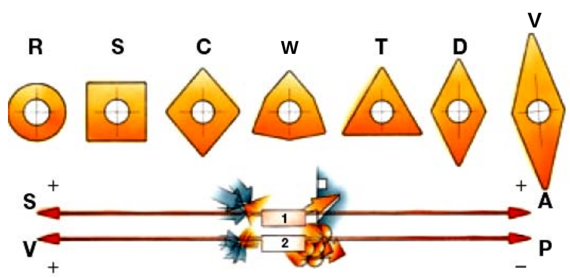

Fig. 7 Typical insert shapes available (Sandvik Metal Cutting Technological Guide, 2009)
R: round; S: square; C: rhombic 80°; W: trigon 80°; T: triangle; D: rhombic 55°; V: rhombic 35°

Therefore, even if the surface roughness formed by a CNMG insert is better than that of a TPMR insert, the application of a CNMG insert cannot be considered as beneficial if its power consumption is significantly higher. Further study on the trade-off between power consumption and surface roughness resulting from the different geometry of inserts and its optimization is required.

4 Conclusions

Surface roughness resulting from two types of insert used in the turning of AISI D2 steel was studied. There was a large deviation between the measured surface roughness (from experiment) and the calculated surface roughness (from theory) at a feed rate of 0.05 mm/r for both inserts. This was because of a work material factor of AISI D2 steel that creates curly chips that scratch the work piece surface when a feed rate of 0.05 mm/r is applied.

The surface quality resulting from two types of insert geometry, TPMR and CNMG, was similar at feed rates of 0.05 and 0.2 mm/r, but significantly different at high feed rates. Using the CNMG insert, the surface quality at a high feed rate of 0.4 mm/r was 40% better than that obtained using the TPMR insert.

However, this experimental result is limited to the material AISI D2 steel, the lathe machine Colchester 6000, and the cutting conditions applied. Different material characteristics and cutting tools may have different effects on surface roughness.

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