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ORIGINAL ARTICLE

Effect of cutting edge radius on surface roughness and tool wear in hard turning of AISI 52100 steel

T. Zhao [1,2] · J. M. Zhou [1] · V. Bushlya [1] · J. E. Ståhl [1]

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Abstract Performance of cutting tool in hard turning is significantly influenced by its microgeometry, such as edge radius. This study presents an experimental exploration to understand the effect of cutting edge radius on machining performance in terms of surface roughness and tool wear. The cutting tools (CBN) with three groups of nominal edge radius, 20, 30, and 40 μm, were used in the study. The cutting edge radii were characterized with an Alicona optical microscope, and variation of the edge radius was evaluated in this study. The machining tests were then conducted to experimentally assess the effect of cutting edge radius on surface quality and tool wear under different machining conditions. Three-level and two-factor experiments were designed in the test. The results in this study suggest that there is noticeable variation in the edge radius on a cutting tool with a certain nominal value of edge radius. The variations tend to be smaller with increase of the nominal value of edge radius. Besides, the results can be drawn that edge radii have a significant influence on surface roughness and tool wear. Considering all factors, the cutting tool with nominal edge radius of 30 μm demonstrate better machining performance among three groups of cutting tool in hard turning of AISI52100 steel.

Keywords Hard turning · Microgeometry · Surface roughness · Tool wear

✉ J. M. Zhou
jinming.zhou@iprod.lth.se

1 Division of Production and Materials Engineering, Lund University, 22100 Lund, Sweden

2 Northwestern Polytechnical University, Xi'an 710072, China

1 Introduction

As hard turning can offer attractive advantages in terms of higher material removal rate, shorter setup time, and reduced production cost, it has become a potential substitute for conventional grinding. In hard turning, workpiece hardness is usually higher than 45 hardness–Rockwell C (HRC) and a cutting tool is often subjected to extremely high local mechanical and thermal stresses, which can cause chipping and wear on the edge of the cutting tool and thereby influence the cutting force, tool wear, chip formation, surface integrity, and accuracy of machining. Hence, cutting tool geometry, especially microgeometry, such as edge radius and chamfer (length and angle) plays an important role in the performance of the cutting tool during the hard turning processes.

Over the years, many investigations have been conducted to explore the effect of cutting tool geometry on the surface integrity, cutting force, and tool life in hard turning. Özel et al. [1] studied experimentally the effect of cutting edge geometry and cutting speed, as well as workpiece hardness on surface roughness in finish hard turning of AISI H13 steel, and demonstrated the effect of two cutting parameters on the surface roughness. In the investigation conducted by Chou et al. [2], the surface roughness was found to be strongly influenced by tool nose radius and tool wear, and the results manifested that large tool nose radius can obtain finer surface finish, but it also increases tool wear. Fulemova et al. [3] studied the influence of cutting edge preparation and cutting edge radius on tool life and the roughness of machined surface. Zhou et al. [4] studied the effect of chamfer angle of the CBN tool on tool wear and tool life through FE simulation and experimental validation. A large difference was found in the tool life when the chamfer angle changes from 10° to

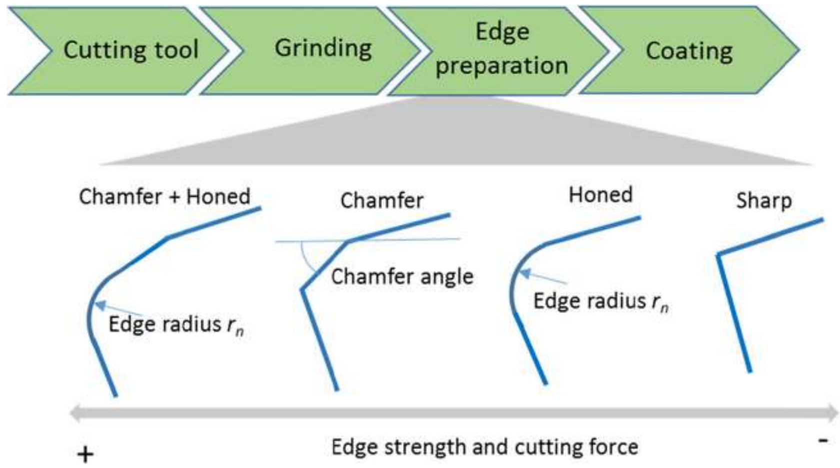

Fig. 1 Manufacturing process of microgeometry and three conditions of edge preparation [10, 11]

30° in hard turning, and the best tool life was found at 15° of chamfer angle. However, effect of edge radius was not studied in the paper. Attanasio et al. [5] studied the effect on tool wear and cutting parameters on white layer and dark layer formation in hard turning. The results revealed that cutting parameters and tool wear affect noticeably white and dark layer formation. Yong et al. [6] proposed a prediction model by applying the modified Oxley's approach to explore the effect of tool thermal property on cutting force then employed the predicted results to compare with experiments. Huang et al. [7] presented a cutting force prediction algorithm which takes into account the effect of tool edge radius and verified the prediction algorithm by comparing the experiment results and the predicted value.

Although cutting tool geometry has an effect on surface quality, tool wear, and cutting force, few studies were made on the variation of edge radius on surface quality and tool performance in hard turning and variation of the edge radius on the cutting tool can sometimes be very significant. In this paper, an attempt has been made to characterize the edge radius of CBN cutting tools, analyze the variation of the edge radius from their nominal values created during the process of edge preparation, and experimentally assess the effect of the edge radius on surface quality, cutting forces, and tool wear in hard turning of AISI52100 steel under different process conditions.

2 Characterization of edge radius

The microgeometry of the cutting tool is often produced in the process called edge preparation, which includes different methods, such as brushing, drag finishing, microblasting wet edge honing, laser treatment, etc. [8, 9]. The tools with superior edge preparation often provide the strength that is required to withstand the large stresses induced during the machining. As a result, various types of edge preparation such as honed edge, chamfered edge, and chamfered edge with honed radius are applied to the insert as shown in Fig. 1. These various types of edge preparation can be applied for different hard turning processes with consideration of factors as machining efficiency, surface quality, and tool life; for example, the chamfered edge with honed edge radius can often be used for roughing due to its superior edge strength, while the edge with honed edge radius can obtain better surface quality and it is thus better for finishing. In addition, the CBN tools generally have lower toughness than other tool materials; thus, edge chipping tends to be more likely during hard turning. The proper edge preparation can improve the strength of the cutting edge and attain favorable surface finishing.

For the CBN tools used in hard turning, the preparation of the edge radius on the cutting tool is critical for both tool performance and quality of the machined component [12]. Variation of the edge radius may influence on chip formation, minimum chip thickness, cutting forces, tool wear, and tool life, as shown in Fig. 2, and it may also affect the process stability and process quality. Therefore,

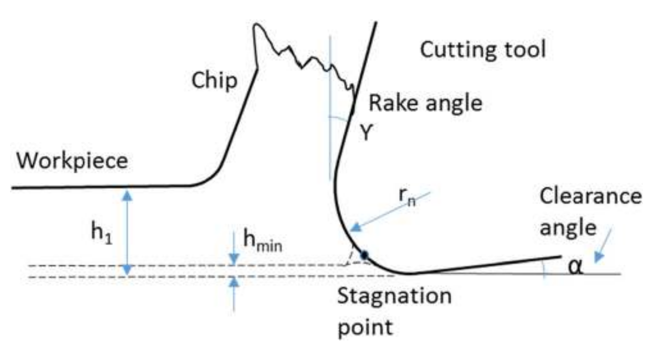

Fig. 2 Characterization of cutting tool microgeometry

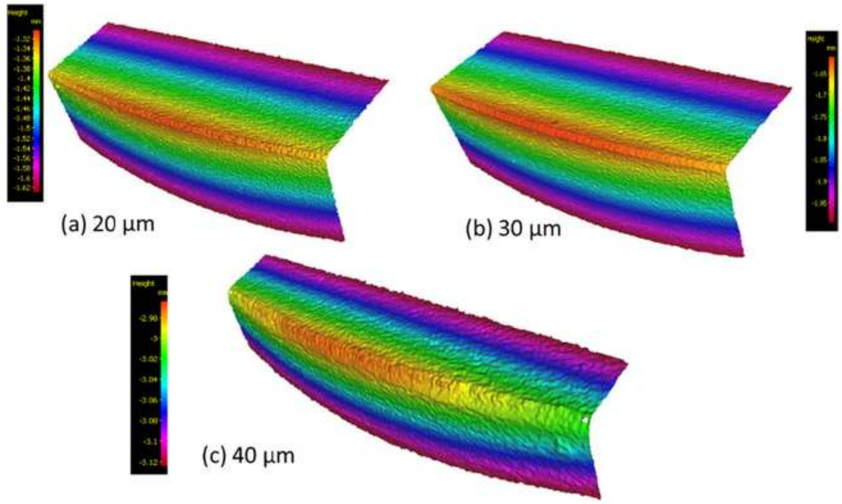

Fig. 3 Profile of cutting edge in three inserts with different edge radii

the edge radius needs to be evaluated before conducting the experiment so as to ensure the consistence of the edge radius and process stability. The required edge radius is often created by the combination of speed and the duration of abrasive movement element effect. The machining error exists in the process; thus, the real edge radius may differ from the nominal value. The present experimental study will focus on the finishing hard turning process; the CBN tools employed in the present study were tools with honed edge with a radius of 20~40 μm.

A Gaussian fitted circle method was applied in this study to characterize the edge radius of the CBN tools [13]. The method includes the following steps: (1) Draw an appropriate least squares straight line on the fit flank face and the clearance face. (2) Make a fitted straight line on the flank face and clearance face intersecting and crossing the point of intersection. The angle with the fitted straight insert is β. (3) Draw a circle which intersects the tangent of the fitted straight and the point P_{int}. (4) Repeat the above steps to make sure the point P_{int} and the fitted straight reach the optimal fit. (5) The radius of the fitted circle represents the cutting edge radius.

The inserts used in this study included three groups with different nominal values of 20, 30, and 40 μm, respectively.

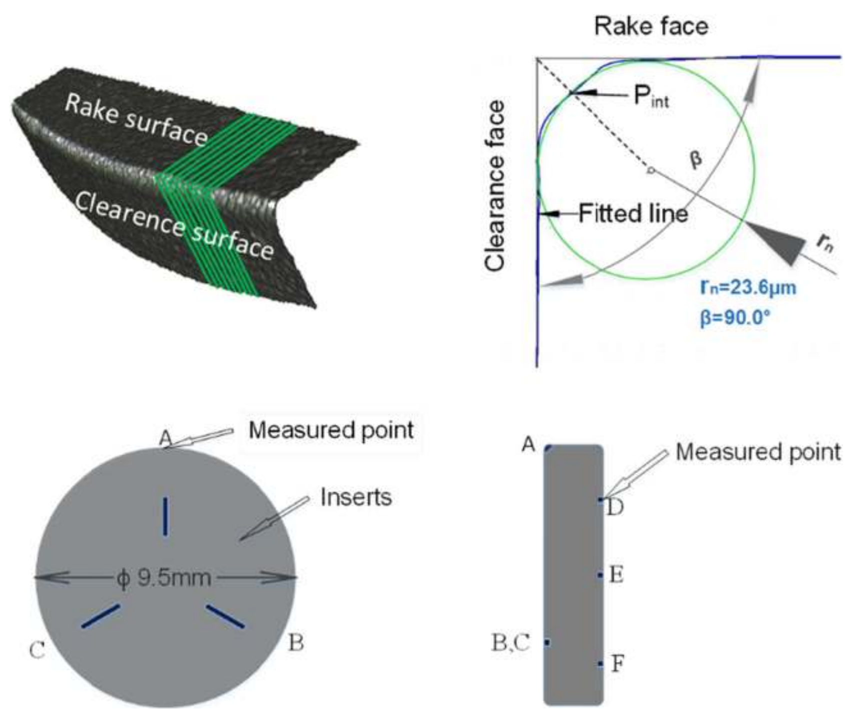

Fig. 4 Measurement of edge radius

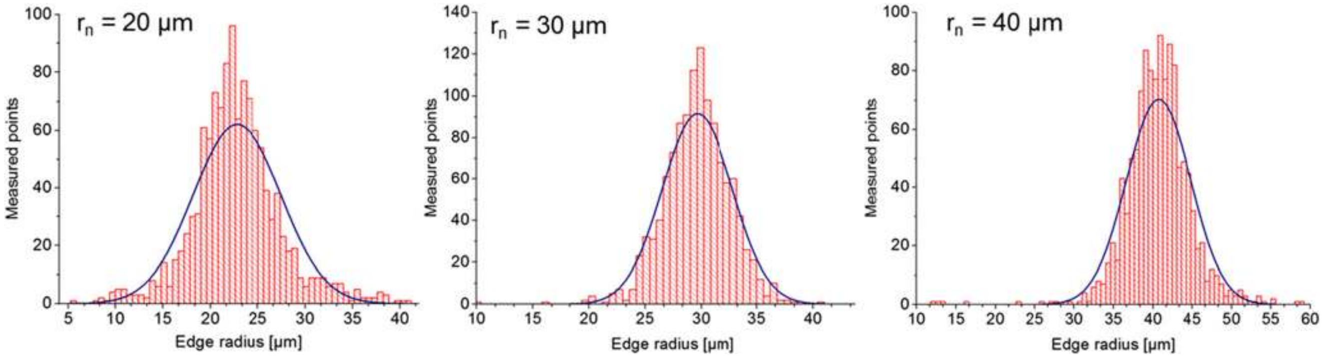

Fig. 5 *Histogram* of the edge radius in three groups of insert

Table 1 The means and variance of edge radius and wedge angle

Group	Nominal edge radius (μm)	Edge radius			Wedge angle		
		Mean (μm)	Variance (μm)	Deviation ratio (%)	Mean (μm)	Variance (μm)	Deviation ratio (%)
1	20	22.801	4.625	23.124	89.9	0.838	0.931
2	30	29.661	3.134	10.447	89.9	0.658	0.731
3	40	40.718	2.418	6.045	89.4	2.361	2.623

Figure 3 represents a typical profile of the cutting edge with different edge radii. Each group has four inserts. For each insert, three measurement points were placed on each side of the inserts and a total of six measurement points were measured in order to study the variation of the edge radius on each insert. Meanwhile, 50 measurements were conducted from each measurement point to obtain statistically reliable values, as shown in Fig. 4. In total, 1200 measurement data were obtained in each group of the edge radius. The distribution of the three groups' edge radius and wedge angle is drawn, as shown in Fig. 5, which clearly demonstrates the variation of the edge radius from its nominal values. Additionally, the means and variance of each group edge radius and wedge angle is also calculated, as summarized in Table 1.

Figure 5 shows that most of the measurement points are in the range of nominal value ±5 μm, although with different levels of variation in each group of inserts. The variation tends to be higher for the insert with smaller edge radius (20 μm) than the insert with larger edge radius. Figure 6 demonstrates a clear trend of change in the variation. With increase in nominal value, the tool with larger edge radius is closer to the nominal value and is more stable. The variation of the wedge angle, however, shows a different trend. For the group with an edge radius of 40 μm, the variation of the wedge angle is higher than the group with an edge radius of 20 μm. Nevertheless, the majority of measurements from the wedge angle are within the range of ±1°, which is

Fig. 6 Variance of edge radius and wedge angles in three groups of inserts with different nominal values

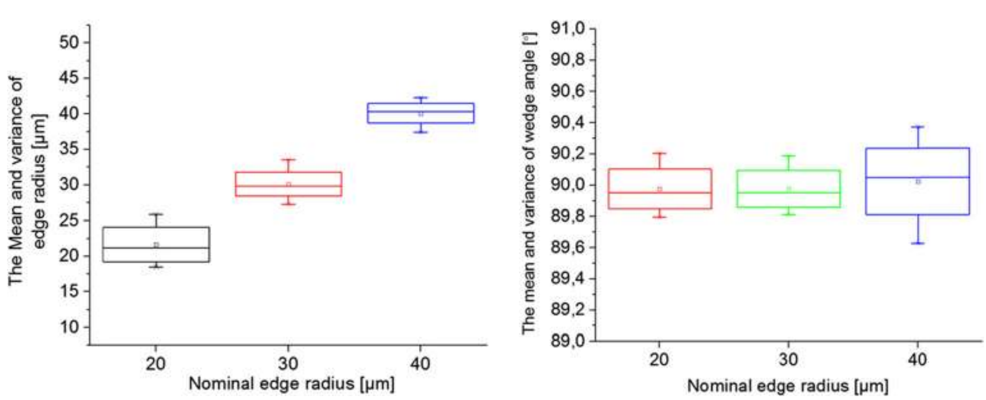

Table 2 Chemical composition of workpiece material

AISI52100	C	Si	Mn	P	S	Cr	Mo	Al	Cu	Fe
	0.95~1.05	0.15~0.35	0.25~0.45	0.025	0.015	1.40~1.65	0.10	0.05	0.30	96.9

close to their nominal value. Table 1 summarizes the mean values and the variation of the edge radius and wedge angle from three groups of insert. It apparently can be seen that the variance decreases when the edge radius increases, and the variance of the edge radius of 40 μm is significantly less than the edge radius of 20 μm. Additionally, the edge radius of 30 μm is the closet nominal value. Therefore, to reduce the processing errors and ensure the consistency of experiments, the edge radius with the nearest nominal value was chosen according to the measured results.

3 Experimental setup

3.1 Workpiece material

The workpiece material used in this study was AISI52100 steel, which is widely employed for bearing and roller in an internal combustion engine, drive shaft, etc. The workpiece was in the bar shape with diameter of 50 mm and length of 150 mm. The hardness of the workpiece is in the range of 53~58 HRC. The composition of the workpiece material is shown in Table 2 [14, 15].

3.2 Cutting tools

CBN cutting tools were used in the test. The tool material contains 50% CBN contents with an average grain size of 2 μm. The binder material is the mixture of cobalt, tungsten, and aluminum ceramic. The cutting tool uses a round insert with a diameter of 9.5 mm, and the tool holder is CRSNL3225 which gives a tool geometry of −6° in rake angle −7° in clearance angle.

Table 3 Experimental conditions

Factors	Description
Edge radius	20, 30, 40 μm
Cutting speed	120, 160, 200 m/min
Feed rate	0.08 mm/rev.
Depth of cut	0.1 mm
Coolant	Dry

Before machining experiment, a pre-cut was conducted for each workpiece to remove the rough outer layer remaining from the previous process and ensure the consistency of the surface. Additionally, the workpiece was grooved with a width of 10 mm to avoid the interaction of different processing parameters. The experiment was performed on the three axial turning lathes, as shown in Fig. 7. During machining, cutting forces were measured with a force dynamometer, Kistler 9121. The process parameters are listed in Table 3.

3.3 Measurement tools

An Alicona InfiniteFocus optical microscope as a key measurement tool in this paper was used to measure the edge radius and tool wear. In addition, the Th-1100 hardness tester from Innova Test Company was used in the measurement of the hardness of the workpiece.

4 Results and discussion

4.1 Surface roughness

The surface roughness measurement and analysis were performed by means of an InfiniteFocus Microscope, Alicona, which is an optical 3D measurement device. The microscope allows for the capture of images with a lateral resolution down to 400 nm and a vertical resolution down to 10 nm.

The surface produced by a hard turning process has the characters of anisotropic and periodical in the geometrical

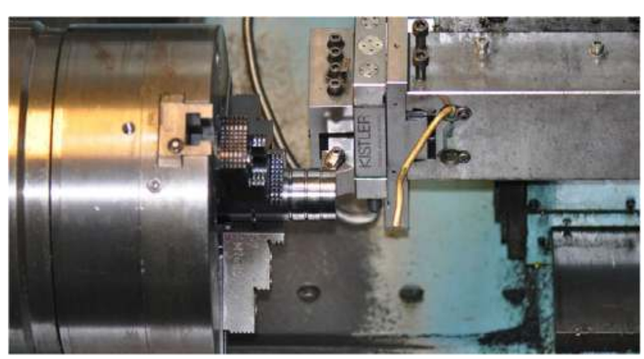

Fig. 7 Setup of machining test

$$S_a = \iint_a |Z(x,y)| dxdy \qquad (1)$$

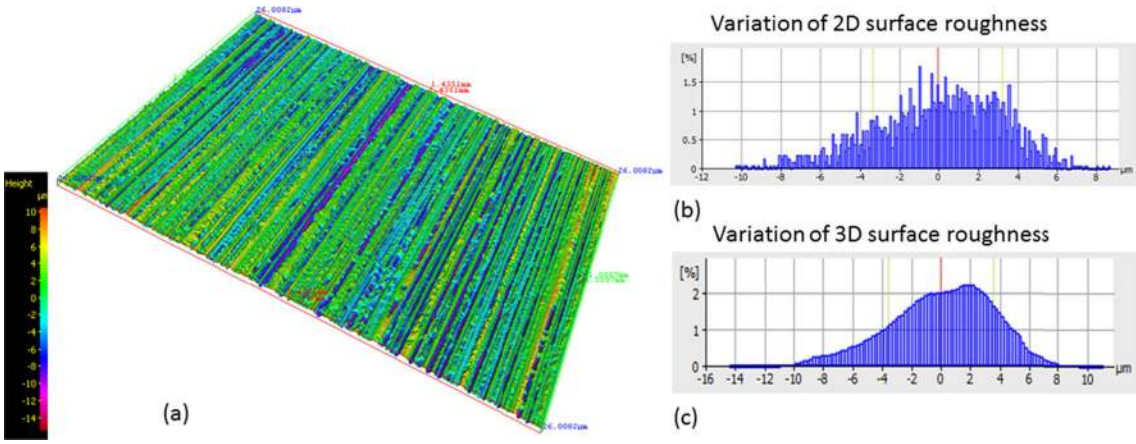

Fig. 8 **a** Typical surface topography. **b**, **c** Variation of 2D and 3D surface roughness

structure, as shown in Fig. 8a. The anisotropic features include lays and grooves induced by edge chipping and built-up edge, and periodic features include feed marks created by the nose of the cutting tools. This means that conventional 2D surface roughness R_a is not enough to represent the surface character and 3D surface roughness S_a can provide better criteria for surface roughness, as shown in Fig.8b, c. 3D surface roughness S_a can be calculated by an average of the measurement points over a certain area, as follows:

$$S_a = \iint_a |Z(x,y)| \mathrm{dxdy} \qquad (1)$$

Influence of the edge radius on the roughness of the machined surface in 2D (R_a) and 3D (S_a) can be seen in the Fig. 9a, b, respectively. The 3D surface roughness values are generally higher than 2D surface roughness values, which clearly indicate that some surface features are missed by the 2D measurement. The lowest roughness of the machined surface is arrived with an edge radius of 30 µm in both 2D and 3D surface roughness. The stability of the cutting process could be the major reason for this. The roughness on the machined surface produced by edge radii of 20 and 40 µm are high in all the tests. A microscope study observed the micro-grooves and chip flows on the machined surface, which could attribute to the high roughness value of the surfaces. Cutting speed, however, shows little influence on the surface roughness except for the edge radius of 40 µm at the speed of 200 m/min, in which a small vibration was observed during the test.

4.2 Cutting forces

Figure 10 shows the effect of edge radius and cutting speed on cutting force F_t, feed force F_f, and radial force F_r. As can be seen from the figure, all three force components increase when increasing the cutting edge radius. Among

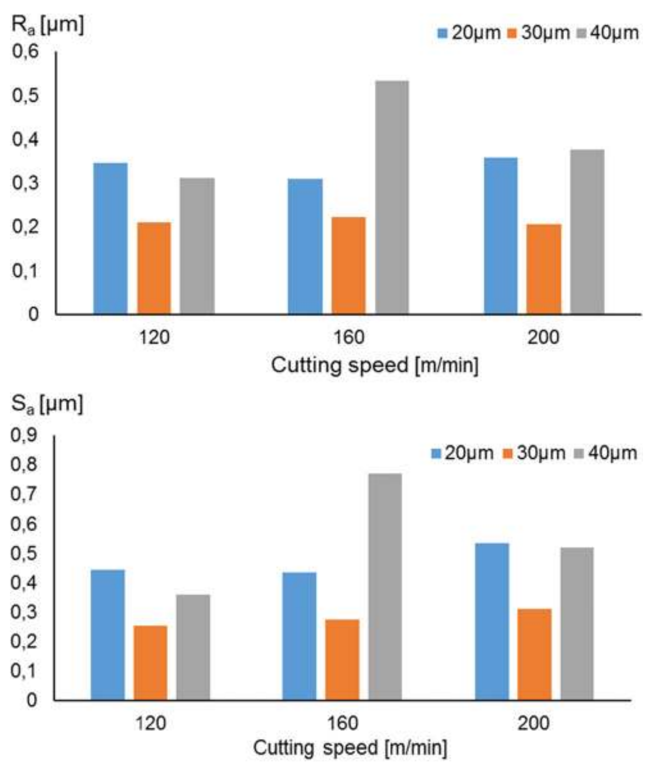

Fig. 9 Effect of edge radius on 2D and 3D surface roughness

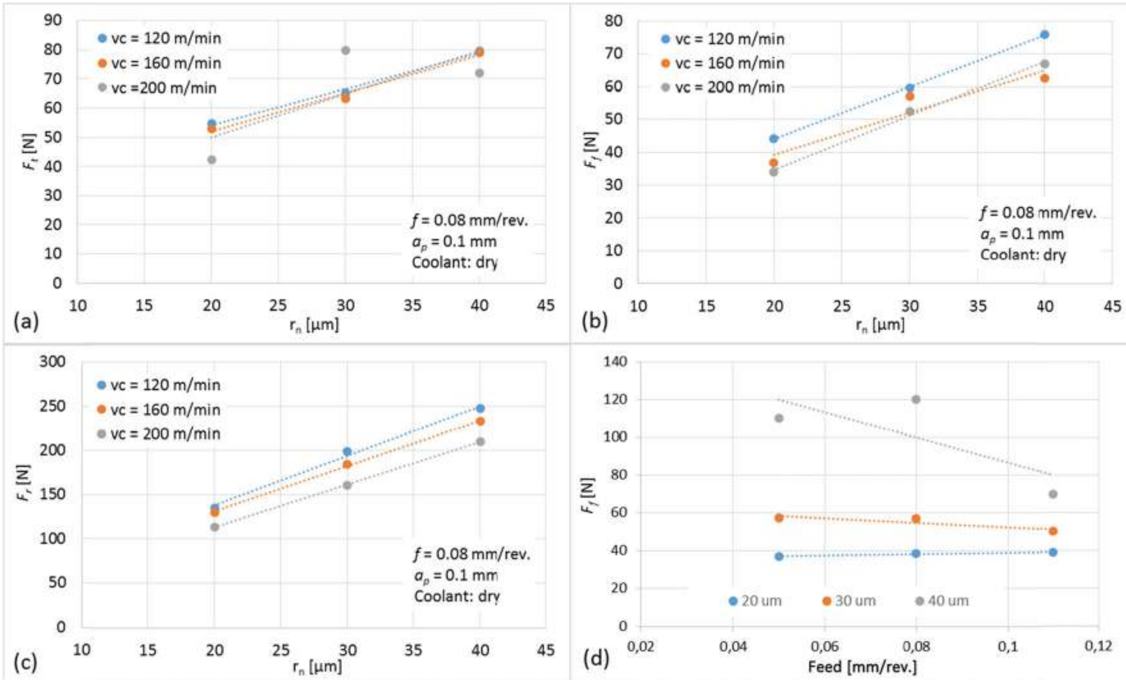

Fig. 10 Effect of cutting speed and edge radius on cutting force

the three force components, radius force is the most sensitive to the change of the edge radius; as a result, the ploughing effect is significantly affected by the size of the edge radius. Cutting speed has negatively affected the level of three force components. With increase in the cutting speed, the force magnitude is decreased primarily due to increase in the cutting temperature which may soften the work material in the cutting area. Figure 10d reveals the influence of the feed rate and edge radius on the feed force component, which further demonstrates the increase of the ploughing force with the increase in the edge radius as the feed rate approaches zero value. A higher ploughing force component means higher friction force between cutting edge and work material, which could significantly affect the formation of machining surface quality and chip formation. This could be the explanation of higher roughness values when the cutting tool with an edge radius of 40 µm was used in the test.

4.3 Tool wear

The effect of the edge radius combined with cutting speed on tool flank wear was also evaluated during the study. The flank wear was measured by an Alicona infinite optical microscope with resolution of ×10, as shown in Fig 11. The measurement was conducted after every 300 mm of machining length. Five tool wear measurements were made with a total 6000 mm of cutting length or 85 cm^3 of material removal volume (MRV). The progression of tool wear (VB) for the cutting tool with different cutting edge radii under 6000 mm of cutting length is demonstrated in Fig. 12.

From Fig. 12, it can be seen that the cutting edge radius and cutting speed have a significant effect on flank wear. Flank wear decreases as the cutting edge radius is increased. Especially when the tool with a cutting edge radius 20 µm was used to process the workpiece, the flank wear rate is higher than the tool with a larger edge radius. This is because the tool with a smaller edge radius is sharper; flank wear is thus higher. With the increase in the cutting speed, flank wear is increased significantly, and the increase in flank wear is almost linear with increasing material removing volume primarily, contributing to the increase in cutting speed which increases the

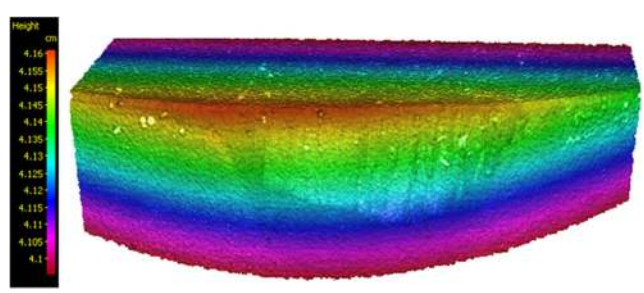

Fig. 11 Topography of typical tool wear

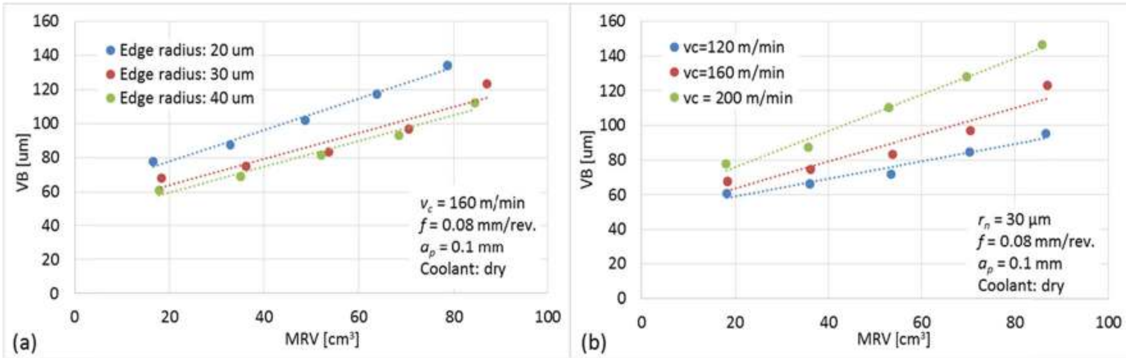

Fig. 12 **a** Influence of edge radius on tool wear. **b** Influence of cutting speed on tool wear

temperature of the contact zone. Therefore, flank wear when using the tool with edge radius of 20 μm at 200 mm/min reaches the maximum value of 159 μm.

5 Conclusions

Variation of edge radius in CBN tools was characterized in this study, and their effects on surface quality and tool wear was also experimentally evaluated in hard turning of AISI52100 steel. The results show that there is a noticeable difference between the actual values of edge radius and the correspondent nominal edge radius. The variation of the edge radius and wedge angle is significant both for the cutting edge on the same insert and the cutting edge from a group of inserts. The deviation of most of measurement points is within the range of ±5 μm, while the majority of measurement points are within the range of ±1° and close to the nominal. With the increase of the edge radius, the variation of the edge radius tends to be smaller and the distribution of the edge radius is closer to their nominal values. Among the three groups of tool, the means of the second edge radius group with a nominal value of 30 μm show the closest to its nominal value. The variation edge radius can significantly influence the cutting force, tool life, and surface quality. The edge radius with 20 μm nominal value demonstrates highest tool wear during the test. Among the three groups of tool, the edge radius with 30 μm exhibits better performance in terms of surface quality and tool wear.

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