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Tool Wear and Surface Roughness in Machining AISI D2 Tool Steel

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Abstract

Background: Along with the recent developments in hard milling technology, tool wear and surface integrity has become a very important consideration in order to achieve optimum cutting conditions. The purpose of this research paper is to study the tool wear and surface roughness while machining American Iron Steel Institute (AISI) D2 tool steel using coated carbide tool. **Method:** A series of cutting tests have been carried out to verify the change in surface roughness of the workpiece due to increasing tool wear. The tests have been done under various combinations of speed and feed in the dry condition. The machined surface was evaluated in terms of surface roughness. **Findings:** Mechanical wear or abrasion is typically dominant during the initial cutting. Thermal wear is dominant at higher cutting speeds due to high cutting temperature. Majority of the tool wear modes were due to flank face wear and excessive chipping on the tool edge. The results also reveal that the variation in cutting speed and feed would not significantly change the surface roughness of the machined surface. Generally, surface produced are very smooth with Ra values in the range of 0.1 μm to 0.37 μm. **Conclusions:** Roughness values (Ra and Rmax) were found to be almost constantly with the progression of the flank wear under all cutting conditions. It indicates that surface roughness did not play a significant role in limiting tool life.

Keywords: Chipping, Cutting Speed, Flank Wear, Feed Rate, Temperature

1. Introduction

Recent advances in machine and cutting tool capabilities enable hardened steel alloy can be cut quickly and accurately.Fundamentally, hard milling means performing rough and/or finish milling after heat treatment instead of milling only when the steel is still in its softer state. The main advantages of hard milling are the ability to produce complex shapes, good surface roughness, higher material removal rate, reducing of finishing time, cost reduction and offsetting the environmental concerns by dry machining[1]. However, hard milling caused severe tool wear and changes in quality and performance of product due to higher mechanical stress and heat generation. Thus, proper criteria should be adopted to keep longer tool life and maintaining the quality of surface integrity. Therefore, further study should be conducted to determinehow cutting parameters affect both tool wear and surface integrity.

Normally, tool wear is used as the main criteria in assessing the effectiveness of the machining process. The productivity in terms of machining operation and machining cost, as well as quality assurance and the quality of the workpiece machined surface and its integrity are strongly depend on tool wear. Consequently, it depends on the tool life of the tool[2].

The quality of machined surface is determined by surface integrity, i.e. surface texture and surface metallurgy[3]. Generally, the surface roughness can be the parameter to evaluate the machined surface texture. According to Abrao and Aspinwall[4], surface roughness is also known as one of the crucial factors towards fatigue life performance. Niemi[5] also support the statement by saying that surface roughness may influence the high cycle fatigue. Bonifacio and Diniz[6] believe that surface roughness is one of the main parameters used to determine the changing cutting tool. The surface roughness also influence on surface friction, wear, light

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reflection, heat transfer and hold lubricant and coating. Therefore, surface finishes need to determine on the suitability of the process that need to be chosen in order to reach out the target quality.

Machining research on hardened steel have been carried out by researchers[7-10] which involving the turning and milling operation. Becze et al.[11] have reviewed the performance of carbide and Polycrystalline Cubic Boron Nitride (PCBN) tool in five axis high speed milling towards D2 tool steel. Braghini Jr and Coelho[12] also have comparing the two cutting tools in end milling of hardened steel. They also found that carbide tool gives small value to the surface roughness like PCBN tool, where the value is in the normal range achieved in grinding process which is R_a from 0.15 µm to 0.45 µm. The value of surface roughness is comparable to what they got through grinding which have been reported by Chen[8] who turning the hardened steel using PCBN tool. Hadi and Atefi[13] have studied the effects of cutting parameters on surface roughness when milling American Iron Steel Institute (AISI) D3 steel using HSS end mill tools. For the finishing of milling, parameters involve are the cutting speed and feed rate meanwhile the depth of cut can affect less to the surfaces[14]. The aims of this work were to investigate tool wear and surface roughness effects when machining hardened AISI D2 tool steel.

2. Methodology

2.1 Workpiece Material

In the present study, the workpiece materials used was AISI D2 tool steel that has completely hardened to 62 Rockwell C Hardness (HRC). With the shape of rectangular blocks, its dimension is 305 x 70 x 53 mm^3. The chemical composition and physical properties of working material are shown in Tables 1 and 2.

Table 1. Workpiece chemical elements (% weight)

C	Si	Mn	Cr	Mo	V
1.42	0.3	0.4	11.2	0.8	0.2

Table 2. Physical properties of workpiece material

Density (kg/m^3)	**7700**
Modulus of elasticity (N/mm^2)	193000
Thermal Conductivity (W/m°C)	20.2
Hardness (HRC)	60-62
Specific Heat (J/kg°C)	460

2.2 Cutting Tool

Cutting tool used in experiments is coated tungsten carbide type grade T25M with ISO designation XOX 120408TR-D14. Cutting tool rigidly installed on the end milling tool holder (ISO R217. 69-2020.3- 12-2A standard) 20 mm diameters and has two cutting edges. The substrate of the insert consists of WC-10% Co alloy. The carbide insert is coated by technique of Chemical Vapour Deposition (CVD) process which has the advantages of the milling process. It has a total of 13 layers of multiple coating visible by light optical microscope which consist of TiN, TiCN and Al_2O_3 with the thickness of 0.2 µm, 2.5 µm and 0.2 µm each. The mechanical properties of the insert are shown in Table 3.

Table 3. Mechanical properties of the insert at room temperature

Transverse rupture strength (N/mm^2)	3300
Density (g/cm^3)	14.5
Thermal conductivity (W/mk)	120
Young's modulus (GPa)	600
Hardness (HV)	1450

2.3 Machining Tests

The milling experiment is done using vertical milling machine Computer Control (CNC) Cincinnati Sabre 750 without cutting fluid. The cutting speed employed during the machining tests was 50 m/min, 65 m/min, 72 m/min, 80 m/min and 95 m/min while the feed rates was 0.02 mm/rev and 0.04 mm/rev. Fixed parameters included a radial depth of cut of 20.0 mm and axial depth of cut of 1.0 mm.

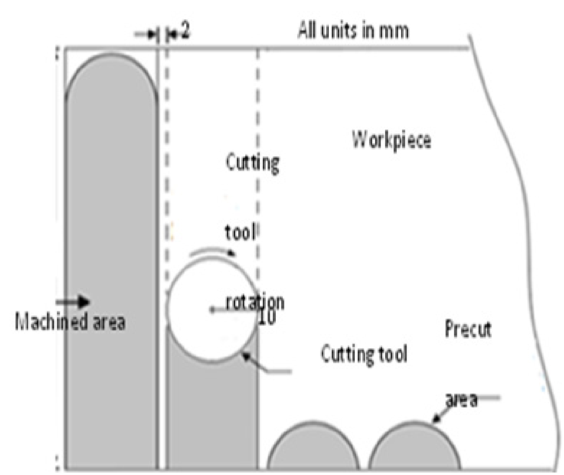

Figure 1. Cutter position and condition of workpiece.

The highest cutting speed is limited to 95 m/min since further increment resulted extremely short tool life or even premature tool breakage occurred soon after the beginning of the tests. In order to maintain a constant entry and exit angles during cutting, the end of the bar where the cutter starts cutting was premachined according to its diameter and the corners of the other end were left uncut as illustrated in Figure 1.

2.4 Wear Measurements

Tool wear was observed and measured by using digital vernier caliper microscope with the magnification power ranging from five to ten times. ISO 8688[15] was used as a guideline in establishing wear criterion; VB_{max} was taken as 0.7 mm on any insert while the width of flank wear (VB) average was 0.3 mm since all the experiments were tested on two inserts (fully mounted). To ensure a more accurate result is obtained, all the tests were repeated three times and the result with shorter tool life was taken because of safety reason. Flank wear was observed and measured at various cutting intervals throughout the milling test until the tools failed and the smooth increment of it was the major concern.

2.5 Surface Roughness Measurements

The value of surface roughness, R_a and R_{max}[16] measured using surface profilometers (Mitutoyo Surftest 420). The measurement took about three times at three different places with straight movement of the stylus tip in a parallel direction to feed at various cutting intervals for all cutting situations.

3. Results and Discussion

3.1 Tool Wear Mechanism

From the flank wear curves obtained in Figures 2(a) and 2(b), it can be seen that those flank wear curves are similar in nature with an initial stage, followed by the gradual stage and finally the abrupt stage of wear. This behavior was also discussed in detailed reported elsewhere[17-18]. The initial wear pattern on the flank face and the nose of the coated carbide tool under feed of 0.02 mm/rev was similar to the result when under the feed of 0.04 mm/rev. Its width increased rapidly with further cutting accompanied by the formation of severe abrasive marks. When certain values were reached, the flank wear values were relatively constant and it was followed by the abrupt wear until the wear criterion was reached.

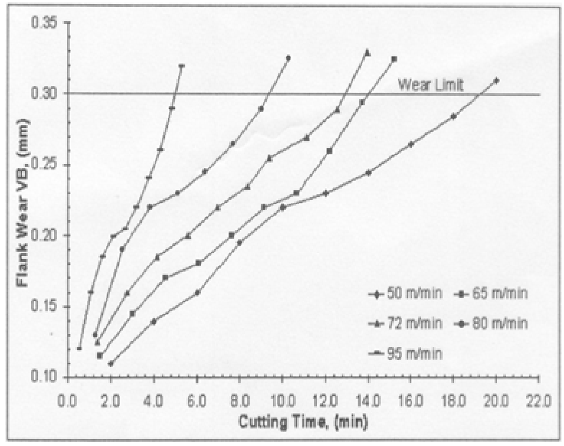

Figure 2a. Average flank wear curves at the feed of 0.02 mm/rev.workpiece.

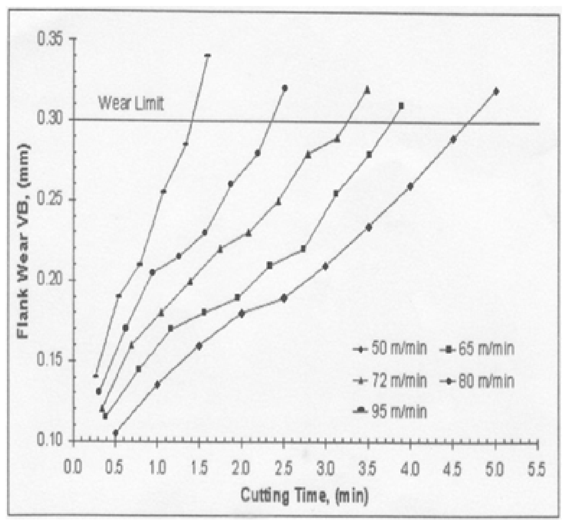

Figure 2b. Average flank wear curves at feed of 0.04 mm/rev.

The clear picture of those stages can be seen from the curves of flank wear in Figure 2(a) at cutting speed of 95 m/min, and Figure 2(b) at cutting speed of 80 m/min. At the feed of 0.04 mm/rev and cutting speed of 50 m/min, it took 2.75 minutes of machining time to reach the wear of 0.20 mm (Figure 2(b)). However, at the feed of 0.02 mm/rev and with the same cutting speed, the 0.20 mm of wear only achieved after 8.40 minutes of machining time (Figure 2(a)). From the curves when machining at the feedof 0.04 mm/rev, extremely short tool life was recorded due to flank wear and fracture of cutting edge (Figure 3(a)).

The chipping or fracture of cutting edge was caused by high hardness of the workpiece material which is 62 HRC, and normally occurred in the area closer to the nose (Figure 3(a) and 3(b)). Figure 3(b) is an enlarged view of the nose area. It shows that attrition wear took place on the flank face and there are some workpiece material adhered on the chipping area.

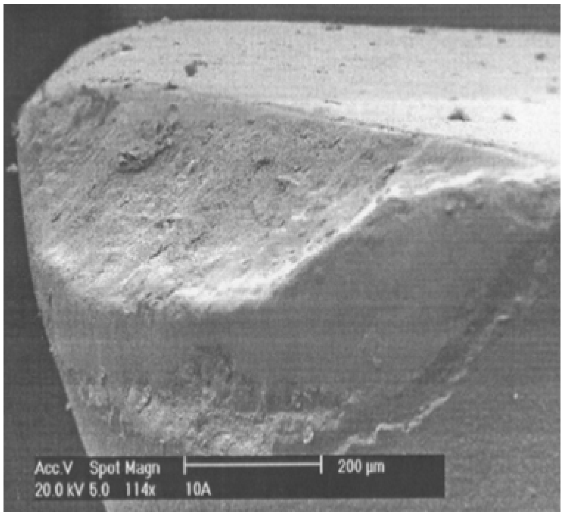

Figure 3a. Fracture of cutting edge at the cutting speed of 95 m/min and feedof 0.04 mm/rev.

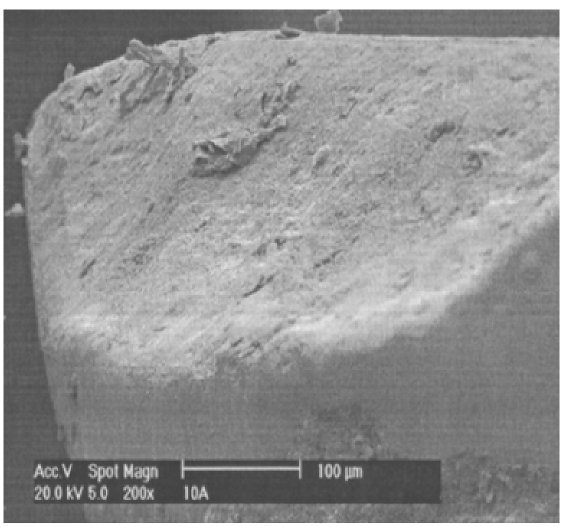

Figure 3b. Close-up view of the nose for the insert at Vc = 95 m/min and f = 0.04 mm/rev.

Figure 4(a) shows a smoothly worn area on the flank face, which is caused by the diffusion and dissolution processes. The intimate contact between the tool and workpiece at high cutting temperature provides an ideal environment for interdiffusion of the tool and workpiece material across the tool-chip interface. The processes of diffusion and dissolution are increased by the high temperature of machining when feed rate and cutting speed is high. However, melting of the workpiece material to the rake face is a phenomenon leading to the diffusion. At the speed of 95 m/min and feed of 0.04 mm/rev, carbide insert failed at the nose (Figure 4(b)). The failure at this speed could be attributed to the temperature effect due to the high speed as well as abrasion[19]. The excessive wear observed in Figure 5(a) and 5(b) can be due to the chemical reaction and adhesion between the tool and workpiece material.

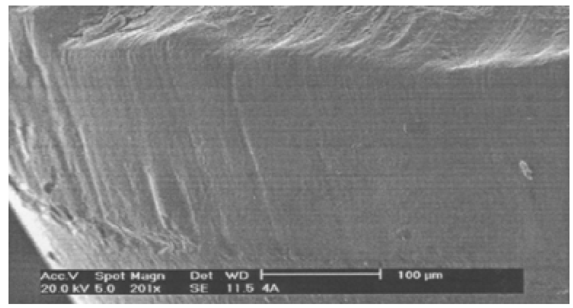

Figure 4a. Smoothly worn of the flank face when machining at Vc = 95 m/min and f = 0.02 mm/rev.

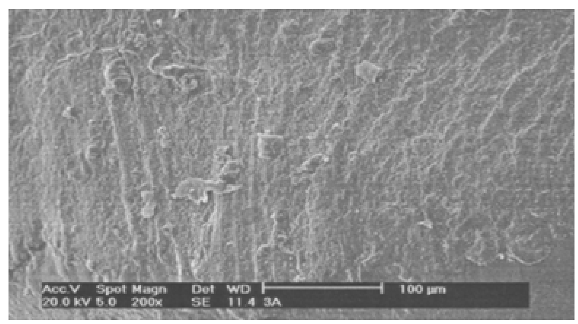

Figure 4b. Abrasive wear on the flank face when machining at Vc = 80 m/min and f = 0.02 mm/rev.

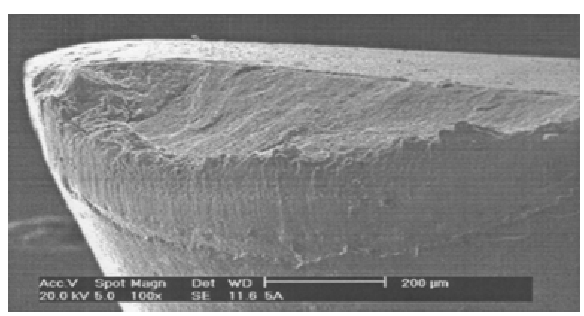

Figure 5a. Excessive wear when machining at Vc = 50 m/min and f = 0.04 mm/rev.

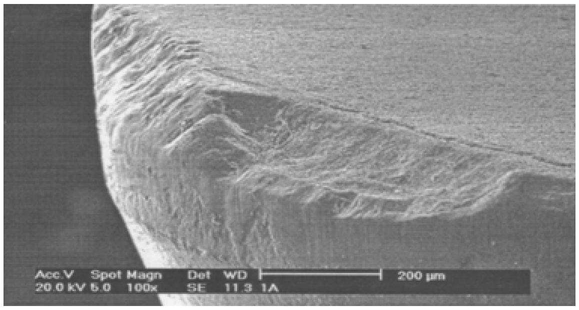

Figure 5b. Excessive wear when machining at Vc = 50 m/min and f = 0.02 mm/rev.

3.2 Surface Roughness

To obtain an overview related to surface roughness values and the development of flank wear in relation to cutting time, the graphs as shown in Figures 6 to 7 are plotted.

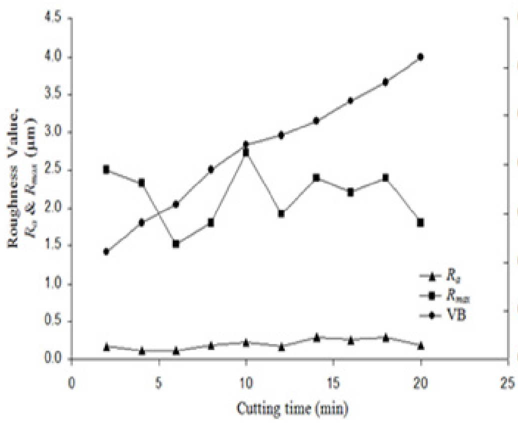

Figure 6a. Ra, Rmax and VB against cutting time at Vc = 50 m/min and f = 0.02 mm/rev.

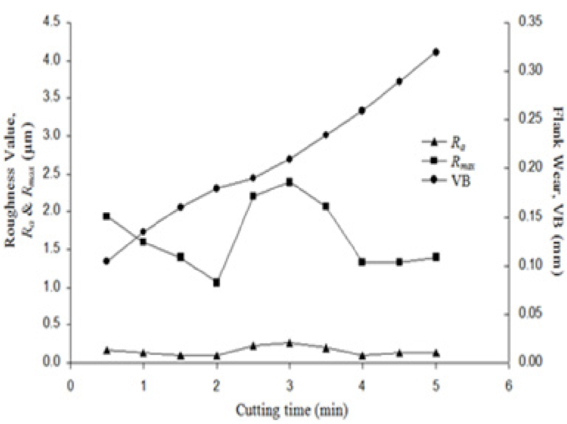

Figure 6b. Ra, Rmax and VB against cutting time at Vc = 50 m/min and f = 0.04 mm/rev.

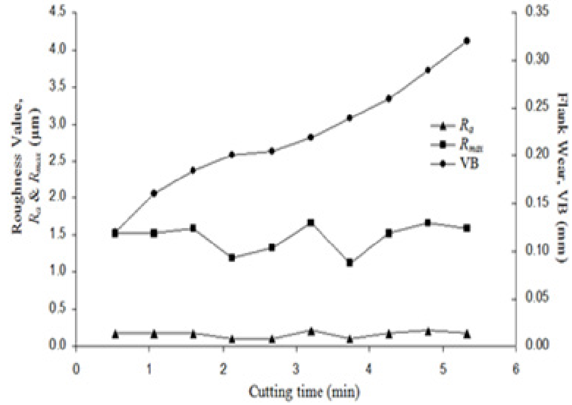

Figure 7a. Ra, Rmax and VB against cutting time at Vc = 95 m/min and f = 0.02 mm/rev.

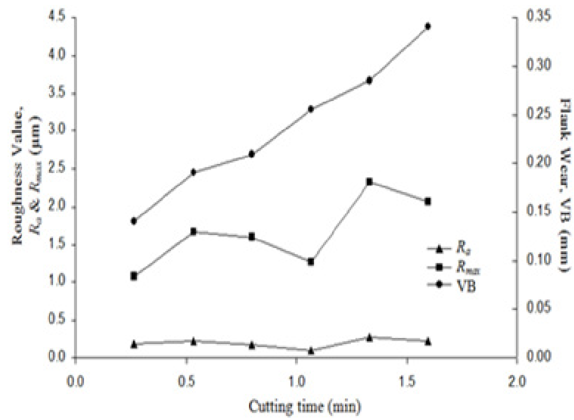

Figure 7b. Ra, Rmax and VB against cutting time at Vc = 95 m/min and f = 0.04 mm/rev.

The graphs involving only the lowest cutting speed and the highest cutting speed for both feeds as the assumption of other cutting speeds, which are between the speeds that shows curve behaviour pattern that almost the same with graphs which has been plotted before. Generally, based on the graphs, it was found that surface roughness does not play an important role in controlling the tool life. Apart from that, on all cutting conditions, surface roughness variation in relation to flank wear is not important. During cutting session, the development of flank wear nearly proportional to the cutting time. Somehow, the R_a and R_{max} values are stable and oscillate in a horizontal range.

Ghani et al.[20] also obtained similar results as above as they found that the surface roughness is almost constant with development of flank wear for all cutting conditions. Many researchers have studied the relationship between surface roughness and flank wear find that value of R_a and R_{max} oscillate in constant range, meanwhile flank wear continued to increase during the cutting passes. It also found that the last value of surface roughness corresponds with the end of life of the tool still shows the small value within the range of swing values of surface roughness. This condition illustrates that surface roughness does not determine by the establishment of flank wear only. It also stresses that flank wear alone is not enough to explain the changes of surface roughness connected with cutting time.

Based on the plotted graphs, it shows that R_{max} values more turbulent compared to R_a values as it provide a clearer picture of the changes taking place on surface roughness during cutting situation. Somehow, the curve pattern of R_{max} values still tallies to R_a values curve pattern as there are minor changes in R_a values.The R_{max} values also experienced the same changes, but R_{max} value involves in large amount differences. However, the graph in Figure 7(b) shows that there is R_a and R_{max} values tendency to increase at the end of the cutting. So, it may be said that the tendency increase the surface roughness values which initially only applies to the precarious state cuts as in these cases is of the highest cutting speed and feed which is 95 m/min and 0.02 mm/rev. This fact is clearly supported by the statement that the development of flank wear cannot explain the machined surface roughness changes and vice versa. Eventually, both flank wear and crater wear cause enlargement roughness.

Flank wear does not provide much distinction to the surface roughness formation. Viera et al.[21] expressed that cutting tool that used in machining shows the flank wear only applies to the main cutting edge, whereas no wear at the edge of the secondary cutting as it is responsible in generate surface roughness. From all the graphs plotted in Figures 6 and 7, the VB curve pattern against cutting time is the same as the beginning value and end value of flank wear that is about the same. On the contrary, the tendency of R_a and R_{max} values increasing as shown in Figure 7(b) curves. There are others phenomenon existed that are dominant in determining machined surface roughness which related to the higher cutting conditions. Apart from flank wear, there are higher cutting speed and/or higher feed that contribute to other frictions such notch wear and crater wear as it can rougher the surface. However, the presence of good coating can prevent the establishment of notch wear and crater wear as the condition experienced in Figure 7(b). It can link to vibration or instability of cutting process which caused by high dynamic load result from high cutting speed and feed. If compared to R_{max} curves in four graphs shown, it is clear that changes in cutting speed from 50 m/min to 95 m/min can produce a smoother surface with smaller R_{max} swing values and the situation is applicable for both feeds. On the other hand, the changes of feed from 0.02 mm/rev to 0.04 mm/rev is also constructing smoother surface. The conflict with the general expectation happened to both cutting speeds. Otherwise, the impacts of cutting speed still meet the general expectation as higher cutting speed helps in smoother the surface. However, the optimal cutting conditions can be determined which the cutting speed is 95 m/min and feed 0.02 mm/rev based on the roughness values that is much smaller and more stable compared to other conditions.

4. Conclusion

Wear rate is much higher at the feed of 0.04 mm/rev than 0.02 mm/rev. The flank wear of the cutting tool grows faster at the feed of 0.04 mm/tooth. The dominant wear modes are flank wear, abrasion and chipping at tool edge. The generated surface on the entire experiment is very smooth with average roughness value, R_a at the range of 0.10 µm to 0.37 µm. Cutting speed increases the range of 50 m/min to 95 m/min and also feed changes from 0.02 mm/rev to 0.04 mm/rev showed no clear effect towards variations in the roughness value produced. On all cutting conditions, the surface roughness value oscillates in a narrow value of range. This research also finds that surface roughness does not necessarily worsen from time to time as the increasing of flank wear as well as the elapsingoftool life.

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