Tool Life And Surface Finish Evaluations In Dry Milling Of AISI D2 Tool Steel

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Abstract Good control and planning of cutting parameters and optimization of cutting conditions requires prediction of tool wear and surface finish. This paper presents a study of tool life and surface finish while machining AISI D2 tool steel. Milling tests were performed under dry cutting condition in order to avoid thermal shock on the brittle carbide tool. Various cutting speed and feed rates were tested while the axial and radial depth of cuts were set to be constant for all trials. Repetitions for each set of cutting condition were made three times and shortest tool life was taken. The results showed that the flank wear starts with an initial stage and it is followed by gradual stage and finally abrupt stage of wear. Mechanical wear or abrasion is typically dominant during the initial cutting. Majority of the tool wear modes were due to flank wear and excessive chipping on the tool edge. Maximum tool life is obtained at a cutting speed of 50 m/min and feed rate of 0.02 mm/rev. The effect of increasing feed rate on tool life is most significant and occurs at the lowest speed of 50 m/min. The life of the cutting tool does not reflect the state of the machined surface where the surface roughness value is still low at the end of the cut. Overall, the machined surface is very smooth with a R_a value of 0.10-0.37 µm. The surface defects identified during the test are voids, chatter marks, abrasion marks, built-up edges and distortions on the feed marks.

Keywords: flank wear, tool life, R_a, dry machining.

INTRODUCTION

In the engineering industry that involves manufacturing processes, milling is one of the important machining operations and end milling is the most frequently encountered metal removal operation (Lou et al., 1999; Poursafar et al., 2013). This operation uses a specific cutting tool, an end mill, to make an axial cut into the workpiece. Among the applications of this operation is in the production of die cavities, profiles, slots, contours, shoulders, and other milling parts. Tool steels are specially alloyed steels designed for high strength, impact toughness and wear resistance at room and elevated temperatures. They play an extremely important role in forming and machining of metals. To illustrate, tool steel designated by AISI D2 is commonly used for dies in cold extrusion, molds for plastics and rubber and press working in sheet metal forming. In fabricating tool steel for die and mold applications, high speed machining (HSM) has been employed widely as the most popular technique. In this technique, tool life and surface roughness are the prominent factors to be considered for achieving the goal in finishing product, which is to complete the machining process with the acceptable level surface finish without changing tool (Mason, 1995). For this purpose, it is urgent to know the performance of cutting tool in term of tool life and the quality of workpiece machined surface in term of surface roughness when machining under HSM technique.

Mold milling is often done dry because in addition to saving production costs, the use of cutting fluid can affect the integrity of the surface. Braghini Jr and Coelho (2001) state that the use of cutting fluids in end milling operations should be avoided as they increase the tendency of subsurface crack initiation. In producing the machined surface of component, most engineers would agree that tool wear is of crucial importance to be considered. Besides affecting the rate of production, tool wear has great influence in determining the quality of machined surface. Tool life refers to the duration a cutting or machining tool can effectively perform its intended function before becoming dull, worn, or otherwise unusable. It is a crucial factor in manufacturing and machining processes, impacting productivity, quality, and operational costs. Extending tool life involves proper maintenance, tool material selection and cutting conditions optimization. In addition to breakage, cutting tools wear in many different ways including flank wear, crater wear, chipping of the cutting edge and plastic deformation. Flank wear measurement is the most common method used to define the end of effective tool life (Karim et al. 2013).

For many engineering applications, the finish on a surface can have a big effect on the performance and durability of parts. Surface roughness is one of the most important characteristics of product quality which has a direct impact on product performance, aesthetic appearance, fatigue, corrosion resistance, etc (Jose et al. 2024). Surface roughness defines the vertical deviations of a measured surface from its ideal form. If these deviations are substantial, the surface is rough; if they are minor the surface is smooth. The overall performance and life span of machined component mainly rely on nature of surface attained during the machining process. It is well-known that surface integrity of a machined surface is influenced by numerous factors such as cutting speed, feed, and depth of cut and even it has a direct effect on functional performance of the component. In this study, wear of tool on its flank face is the focus to be examined and the results are related to the surface roughness of tool steel machined surface. Surface topography images are also presented to provide an overview of the surface texture and defects that exist after machining. For finishing milling, the parameters involved are cutting speed and feed rate, while the depth of cutting only has a very small influence on the surface (Sai et al., 2001;Kumbhar et al., 2013).

EXPERIMENTAL TECHNIQUE

Cutting tools

The tools used were CVD coated carbide grade T250M (Figure 1), manufactured by Seco Tools with ISO designation of XOMX120408TR-D14. This cutting tool is coated with 13 layers of coating consisting of TiCN, TiN and Al_2O_3 with a total thickness of 5 µm. The cutting tool is rigidly mounted on an end milling tool holder (standard ISO R217.69-2020.3-12-2A, provided by SECO Tools) which is 20 mm in diameter and can hold two inserts with the maximum axial depth of cut 11 mm (Figure 2). The substrate of the insert consists of WC-10%Co alloy and its grain size is less than 1 micron. The mechanical properties is given in Table 1 and the assembled tool geometry of the insert are shown in Table 2.

Figure 1: Indexable carbide tool

Figure 2: Tool holder

Table 1: Mechanical properties of the insert

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

Table 2: Cutting tool geometry

Nose radius (mm)	0.8
Chamfer width (mm)	0.16
Chamfer angle	14^0
Axial rake angle	8^0
Radial rake angle	-7^0
Peripheral relief angle	7^0
Face cutting edge angle	17^0
Face clearance angle	15^0
Peripheral clearance angle	$1^0 – 15^0$
Blade setting angle	$90^0 8'$
Helix angle	15^0

Workpiece material

The cutting performance is tested on AISI D2 tool steel bars (Figure 3) that have been hardened to 62 HRC. The dimension of the workpiece material provided is 305 x 70 x 53 mm^3 to comply with the provisions of ISO 8688-2. The composition and properties of the workpiece materials can be seen in Table 3 and 4, respectively.

Figure 3: Workpiece

Table 3: Chemical composition of AISI D2 tool steel

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

Table 4: Physical properties of AISI D2 tool steel at room temperature

Density (kg/m^3)	Modulus of Elasticity (N/mm^2)	Thermal Conductivity (W/m^0C)	Hardness (HRC)	Specific Heat (J/kg^0C)
7700	193000	20.2	60-62	460

The workpiece material is cleaned by removing the surface layer at a certain thickness to ensure that there is no hard skin layer compared to the bulk material formed as a result of oxidation and during the forming process.

Machining tests

All machining trials were performed dry on a Saber 750 vertical CNC milling machine from Cincinnati. Cutting speed and feed rate were selected as the machining parameters to analyze their effect on tool life and surface roughness while radial and axial cutting depths of 20 mm and 1 mm respectively were maintained. Combinations of cutting parameters are presented in Table 5. End milling is done in full engagement as shown in the Figure 4. To avoid premature failure, 10 mm of pre-machining was done on the workpiece at one end of the bar before testing for each new insert while the other end of the bar was left uncut. Machining for each set of cutting conditions is repeated three times so that more accurate results are obtained. Each test is started with a fresh cutting edge and the milling operation is stopped when the insert exceeds 0.3 mm flank wear.

Table 5: Setting of machining parameters

Machining parameters					
Feed rate, f_z (mm/rev)	Cutting speed, V_c (m/min)				
0.02	50	65	72	80	95
0.04	50	65	72	80	95
0.06	50				
0.08					
0.10					

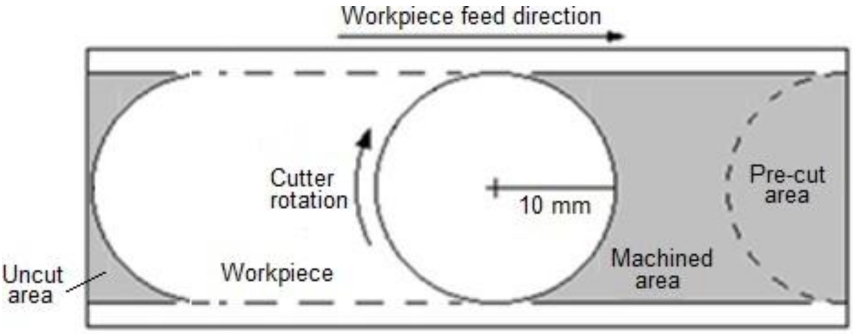


Figure 4: Cutter position and condition of workpiece

Tool Wear and Surface Roughness Measurement

Tool wear was observed and measured by using a digital vernier microscope with the magnification power ranging from five to ten times. Tool rejection or failure was determined based on the following criteria: (a) average flank wear = 0.3 mm (average of two inserts); (b) maximum flank wear, VB_{max} = 0.7 mm (on any of the inserts) (SIRIM, 1989). Flank wear was observed and measured at various cutting intervals throughout the milling test until the tools failed and smooth increment of it was the major concern. 2D surface roughness measurement, R_a (SIRIM, 1982) was performed on a Mitutoyo Surftest 420 surface profilometer. Readings are taken at least three times at three different places with a straight movement of the stylus tip in a direction parallel to the direction of the feed movement at various cutting intervals for all cutting conditions. Surface roughness measurements are made at certain cutting length intervals based on flank wear measurements to obtain uniform and accurate flank wear readings. The length of this cut is different for different cutting conditions based on the flank wear condition. To ensure the accuracy of the data taken, observations are made on a special table that is free from movement and vibration. In addition, the profile meter is calibrated before readings are performed for each set of tests.

Machined Surface Analysis

The workpiece material was cut to a specific shape and size using a special carbide saw to obtain a sample of the machined surface. Two samples are taken for each cutting condition, namely the initial sample taken on the first pass for the start of machining and the final sample taken when the tested insert reaches 0.3 mm flank wear where the tool is considered to be absolutely blunt. 2D topography were examined under a laser scanning microscope (Leica Industrial Confocal Microscope) and photographs were taken for the purpose of topographical analysis of the machined surface.

RESULTS AND DISCUSSION

Tool life

Table 6 gives the life data of multi-layer CVD coated carbide cutting tools that have been tested. Under particular machining conditions tested, this investigation of tool behaviour in milling fully hardened tool steel found that cutting tools did not performed well at the feed rate of 0.04 mm/rev but it performed very well at the feed rate of 0.02 mm/rev.

Table 6: Experimental results for tool life

Cutting speed (m/min)	Feed rate = 0.02 mm/rev		Feed rate = 0.04 mm/rev	
	Tool life (min)	Wear rate (mm/min)	Tool life (min)	Wear rate (mm/min)
50	20.00	0.015	5.00	0.060
65	15.24	0.020	3.90	0.077
72	13.91	0.022	3.48	0.086
80	10.24	0.029	2.51	0.120
95	5.33	0.056	1.60	0.188

From Table 6, the longest tool life achieved with the feed rate of 0.02 mm/rev is 20 minutes when machining at the cutting speed of 50 m/min and compared with the same cutting speed, longest tool life achieved at the feed rate 0.04 mm/rev is just 5 minutes. Almost all the tool life when machining with the feed rate of 0.02 mm/rev are four times longer than machining with the feed rate of 0.04 mm/rev except at the cutting speed of 95 m/min. At the cutting speed of 95 m/min and feed rate of 0.02 mm/rev, tool life was achieved at 5 minutes. It is the lowest range of tool life that required by the standard of ISO 8688-2 and it is the upper limit of the application ranges for the feed rate of 0.02 mm/rev since futher increase of cutting speed will cause the result of extremely short tool life. But in the other way round, all the cutting speeds performed with the feed rate of 0.04 mm/rev achieved tool life in between 1.6 and 5 minutes which are under the minimum requirement of ISO 8688-2. Generally, at lower feed rate (0.02 mm/rev) and lower cutting speeds gives the better tool life which is shown in Figure 5. Table 6 also shows that at higher cutting speeds, the flank wear rates were high for both feed rates tested. Increasing the feed rate from 0.02 mm/rev to 0.04 mm/rev increased the wear rate more than three times at all cutting speeds. Once the tool started to experience wear, the rapid rise could be attributed to high heat generated at the cutting edge of the tool-chip and tool-workpiece interface. At higher cutting temperature, faster uneven flow would be generated at the cutting edge of the tool at higher feed rate which may have led to chipping or fracture at the cutting edge and also accelerate tool wear with the consequent reduction in tool life.

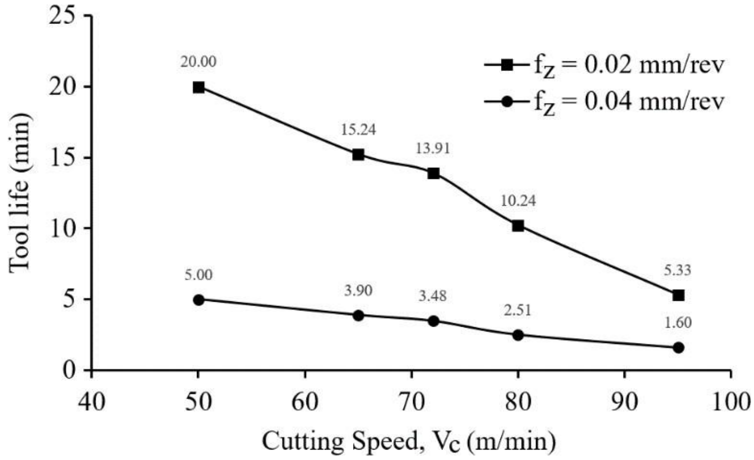


Figure 5: Tool life of coated carbide tools at various cutting speeds and feed rates.

Figure 5 shows the comparison of tool life for both the feed rates of 0.02 and 0.04 mm/rev in the range of cutting speeds from 50 to 95 m/min. From this figures, it is clearly seen that XOMX120408TR-D14 tool performed well in the feed rate of 0.02 mm/rev instead of 0.04 mm/rev and also the lower cutting speeds. These experiment results obtained also show that cutting speeds and feed rates have significantly affected the tool life of the carbide cutting tool when milling hardened tool steel.

Surface roughness

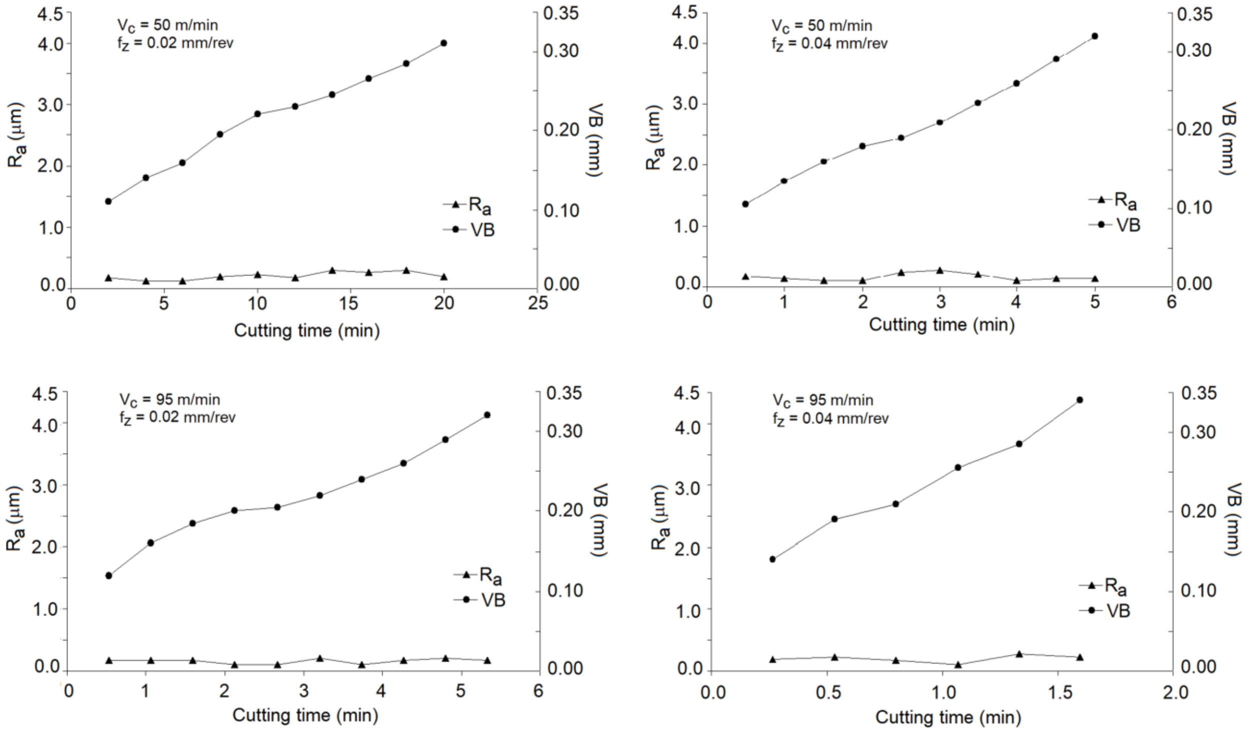
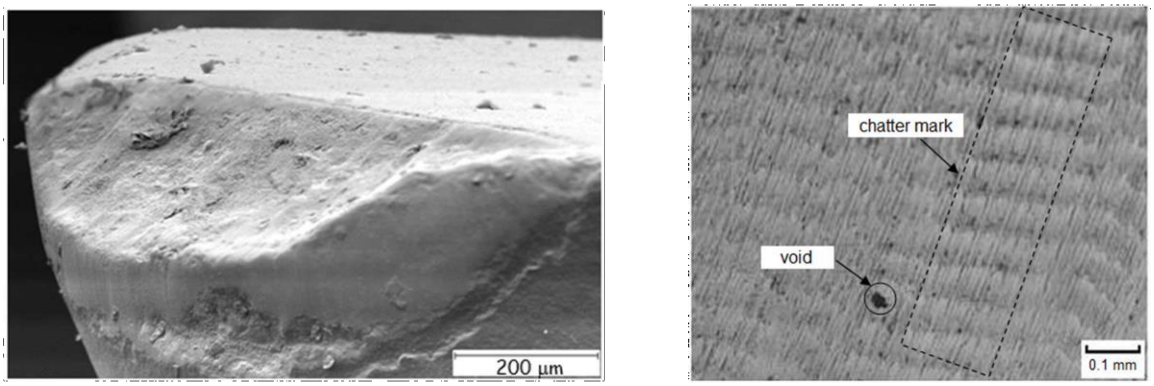


Figure 6: Graph of surface roughness, R_a (µm) and flank wear, VB (mm) against cutting time (minute) at four different cutting parameters

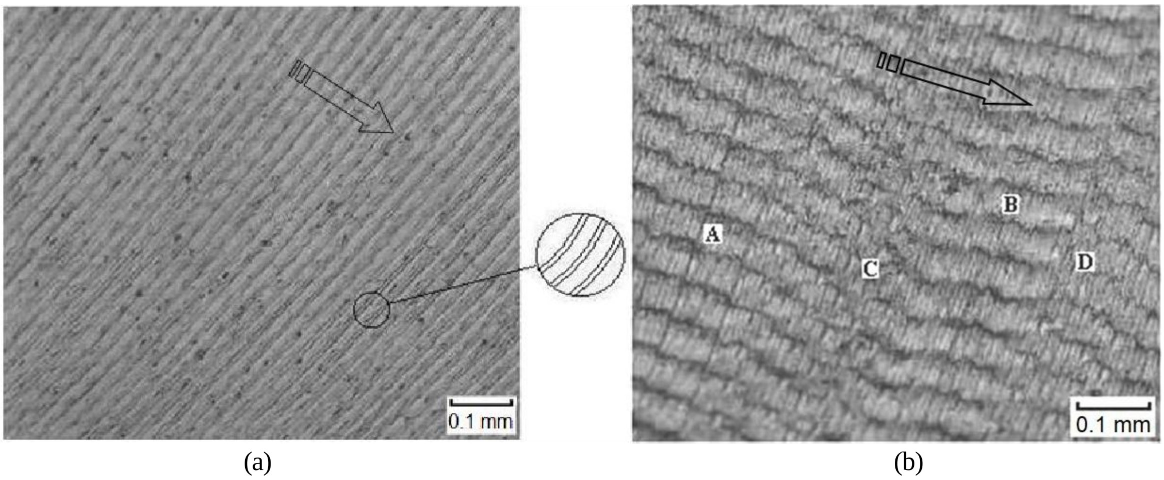
Generally, based on all the graphs, it is found that the surface roughness does not play an important role in controlling tool life. Moreover, at all cutting conditions, the variation of surface roughness with respect to flank wear is insignificant. Throughout the cutting process, the development of flank wear is almost directly proportional to the cutting time, but the values of R_a are stable and oscillate in a horizontal range. Ghani et al. (2002) also obtained the same results as above where they found that the surface roughness is almost constant with the development of flank wear at all cutting conditions. In fact, according to Bonifacio and Diniz (1994), many researchers who studied the relationship between surface roughness and flank wear found that the values of surface roughness R_a oscillate around a constant value while flank wear continues to increase throughout the cutting process. It was found that the final value of the surface roughness corresponding to the end of the tool life still shows a small value and is in the range of oscillation of the surface roughness values. This situation gives the impression that surface roughness is not determined by the formation of flank wear alone. From the curves that have been plotted, it is found that at a cutting speed of 50 m/min and a feed rate of 0.02 mm/rev, the minimum and maximum R_a values are 0.13 µm and 0.3 µm respectively while at a feed rate of 0.04 mm/rev, the minimum and maximum R_a values are 0.1 µm and 0.27 µm. These recorded R_a values are still in the very smooth range, but increasing the feed rate gives a smoother surface. This situation may be caused by the chatter that occurs due to the sudden breaking of the cutting edge.



(a) (b)

Figure 7: The sudden chipping of the cutting edge causes chatter at the beginning of the cut. Cutting conditions: V_c=50 m/min; f_z=0.04 mm/rev (t=0.500m). R_a=0.17 µm

Yuan Ning et al. (2001) stated that chattering may be caused by periodic breakage that starts at the tip of the cutting tool. Any change in the cutting edge as a result of wear or chipping (Figure 7a) will cause the contact of the cutting point between the cutting edge and the workpiece material to become non-smooth or unstable, then this will start the occurrence of chatter on the cutting tool and subsequently affect the machined surface. An overview of the situation as stated can be seen in Figure 7b. At a cutting speed of 95 m/min and a feed rate of 0.02 mm/rev, the minimum and maximum R_a values were 0.1 µm and 0.2 µm respectively, while at a feed rate of 0.04 mm/rev recorded a minimum and maximum R_a value of 0.1 µm and 0.27 µm respectively. This data shows that the machined surface is still smooth even at maximum cutting conditions. The machined surface actually contains various defects when observed at certain magnification factors under the microscope eventhough it appears very smooth, clean and shiny. In milling, the generated surface topography consists of a series of cutting tool edge path or so-called feed marks. This feed marks vary for different cutting conditions but more significant differences can be observed when comparing the topography of the surface at the beginning and end of cutting. To examine the effect of end milling on the surface of the workpiece, two sample photographs have been included as can be seen in Figure 8. The topography at the beginning of the cut (Figure 8a) generated by the still sharp cutting tool is clean with the lines of feed marks clearly visible. Chipping at the beginning of cutting is believed to be the cause of the existence of black spots on the surface topographies in Figure 7b and Figure 8a.



(a) (b)

Figure 8: The condition of the workpiece surface after milling at the highest cutting condition which is V_c = 95 m/min and f_z = 0.04 mm/rev; (a) initial cut (b) final cut

This chipping is also the cause of the prominent and wide feed marks in Figure 8a. It can be seen that there are two series of feed marks for a series of cutting edge paths. The problem of surface finish defects and high wear rates in steel machining is always associated with the existence of very hard alloy carbide particles on a large scale and dispersed in the microstructure of the workpiece. Chou and Evans (1997) stated that carbides that are very hard on a large scale in the workpiece will increase friction on a fine scale through micro-fracture and fatigue resulting in higher wear rates. In this study, the AISI D2 tool steel used contains relatively high carbon and chromium. According to Koshy et al. (2002), the high volume of insoluble chromium carbide particles in D2 tool steel is responsible for providing good wear resistance for this material and also promotes frictional wear of cutting tools and makes this material very difficult to machine. Braghini Jr and Coelho (2001) in their research stated that extreme wear on the cutting edge can be linked to the concentration and high density of hard particles present in the workpiece material. The black spots that can be seen on the topography of the surface in Figure 7b and Figure 8a may be voids resulting from the removal of hard carbide particles from the surface of the workpiece during milling (Stephenson et al., 2001). Hard carbide abrasive particles are pulled out and dragged on the surface due to the cutting edge not being able to cut perfectly because it has chipped. These particles may continue to adhere and solder to the surface after being dragged due to the high surface temperature of the freshly machined surface. These particles may also stick to or deposited on the area of tool chipping (Figure 9) and then grow causing it to become unstable at some point and then break. Some of these built-up edges are removed by the cutting tool while the rest will be deposited or soldered randomly on the surface of the workpiece.

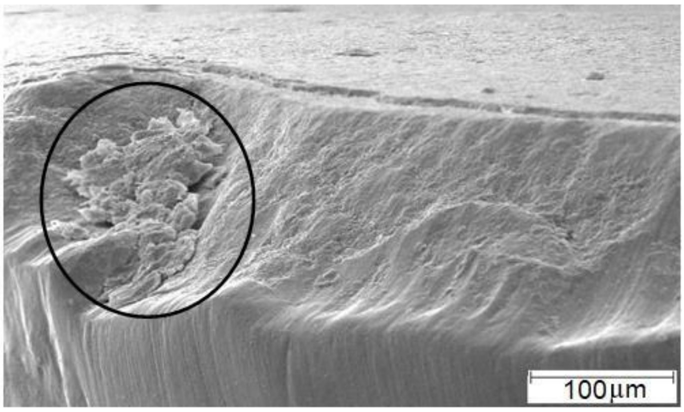


Figure 9: The material of the workpiece that adheres and remains on the chipping area of cutting tool (t=1.600m). Cutting conditions: V_c = 95 m/min; f_z = 0.04 mm/rev

Che Haron et al. (2000) have found some built-up edges forming on the tool nose area during machining. A situation like this has already been discussed by Bailey & Jeelani (1974) where the built-up edge formation covers the nose area of the tool. At the end of the cut (Figure 8b) where it is done by tools that have become dull or have reached a certain level of wear, although the feed marks still exist, they are no longer clear and the feed lines are also seen to be non-uniform due to the change of dark and light colors that uncertain. From the letters given on this topography, it is found that areas A and B show significant chatter marks on a larger scale while areas C and D show faint chatter marks on a smaller scale. This indicates the occurrence of cutting edge vibrations at different amplitudes in a short tool path distance. Chatter or self-excited vibration as can be seen in Figure 8b begins with disturbances in the cutting zone, especially when using less homogeneous workpiece materials (Kalpakjian, 1995) as in this experiment. The less homogeneous structure of the workpiece will cause a change in the morphology of the chips which is also caused by the wear process of the cutting tool. According to Ismail et al. (1993), the vibrations occurring in milling may be caused by random variations in the microhardness of the workpiece material. This causes the cutting edge to be subjected to non-uniform forces so it tends to vibrate. Apart from that, chattering in this condition may also be caused by interference at the cutting edge and changes in friction conditions at the tool-workpiece interface, especially when cutting is done in a dry condition.

CONCLUSION

Wear progression of coated carbide tool is similar in nature with initial stage, followed by the gradual stage and finally the abrupt stage of wear. Cutting speed above 95 m/min are considered the upper limit of the application ranges for the feed rate of 0.02 mm/rev since futher increase of cutting speed will cause the result of extremely short tool life. The dominant wear modes for the carbide tool are flank wear, abrasion and chipping at tool edge. Increasing the cutting speed in the range of 50 mm/min to 95 m/min and changing the feed rate from 0.02 mm/rev to 0.04 mm/rev did not show a clear influence on the variation of the surface roughness value produced. At all cutting conditions, the surface roughness value remains oscillating in a small range while the flank wear continues to increase and is directly proportional to the cutting time. In this case, the life limit of the cutting tool cannot be determined by the surface roughness. The surface generated in the entire experiment was very smooth with an average roughness value, R_a in the range of 0.10-0.37 µm. The surface defects identified during the test are voids caused by the removal of carbide particles, chatter marks, abrasion marks, built-up edges, burn marks and distortions on the feed marks. In general, it is suggested that the main factor in determining the roughness value and quality of the surface topography is vibration or chatter and other changes in the cutting tool such as chipping and built-up edges in addition to flank wear. The microstructure factor of the workpiece material needs to be emphasized because it is an important factor that affects the wear rate of the cutting tool and the quality of the surface finish. Wet machining should be reconsidered as it may help to extend tool life at high cutting speeds and feed rates in addition to flushing abrasive particles from interfering with the cutting zone or adhering to the machined surface. Taking into account the results of cutting tool life and surface roughness covering all series of tests, the optimal cutting speed and feed rate are 95 m/min and 0.02 mm/rev respectively.

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