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Wear Analysis of Silicon Nitride (Si_3N_4) Cutting Tool in Dry Machining of T6061 Aluminium Alloy

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Abstract. Dry machining is an eco-friendly machining process and its importance in the manufacturing industries should be taken seriously. Machining without the use of any cutting fluid is becoming increasingly more popular due to concerns regarding the safety of the environment and reducing cost. Dry and wet turning of T6061 aluminium alloy was performed on a lathe by using Silicon Nitride (Si_3N_4) inserts as the cutting tool. Tool wear behaviour of Si_3N_4 cutting tool were studied with the aim of finding the optimum cutting conditions for both dry and wet machining. Machining was performed at four different cutting speeds; 292, 388, 518 and 689 m/min using two different cutting parameters (feed rate, f = 0.2 mm/rev, depth of cut, d = 0.1 mm and f = 0.4 mm/rev, d = 0.2 mm). Material removal rate (MRR) was also obtained and the temperature at the tool-chip interface were measured using an infrared (IR) thermometer as to see the effect of temperature rise during machining. Dry machining with smaller cutting parameters resulted in lower wear rates by 37 to 48% for all four cutting speeds. Nevertheless, reduction of wear rate by 38 to 57% was found from wet machining. The optimum cutting speed for both dry and wet machining of T6061 aluminium alloy using Si_3N_4 cutting tool was found to be 518 m/min for both cutting parameters. However, the optimum cutting parameters are apparently with the feed rate of 0.4 mm/rev and depth of cut of 0.2 mm. At the optimum cutting speed, the tool tip temperature for dry machining was higher than wet machining by 40 and 51% for f = 0.2 mm/rev and f = 0.4 mm/rev respectively. Dry machining of T6061 Aluminium alloy can be more suitable particularly at higher cutting speed with interrupted cutting operations.

Introduction

It is well known that coolants can improve tool performance to a great extent and always maintain the machined material at ambient temperature. In manufacturing industries, cutting fluids play an important role in removing the heat generated due to friction during cutting; achieving better tool life, surface finish and dimensional tolerances; preventing the formation of built-up edge as well as to minimize wear rates and in removing the chips formed [1]. However, the coolants produce problems in the working environment and also create problems in waste disposal. This creates many ecological problems and results in more economical overheads for manufacturing industries. Used coolant from machining processes is harmful to both environment and human health. The chemical substances that are found in lubricants are toxic to the environment if the cutting fluid is released to soil and water.

Moreover, workers who are exposed to the coolant in both liquid and mist form have experienced serious health problems [2]. Besides that, as the number of extensiveness of environmental protection laws and regulations increase, the cost of using coolants is on the rise. The costs connected with the use of cutting fluids are estimated to be a few times more than the labor and overhead costs; about 15% of the operation costs are attributable to the use of coolants which are three to four times the cutting tool costs [3]. Furthermore, the maintenance and management costs are also increasing because of the chemical disintegration of some coolants. The used coolant however should be treated before releasing it to the environment; resulting in another burden to the manufacturing industries. Therefore, dry machining is the future trend for metal cutting industries due to both health problems and financial burdens created by wet machining [4].

According to Shaw [2], aluminium and its alloys are considered to be the most critical materials with regards to dry machining; since it possesses a high thermal conductivity, the workpiece absorbs considerable amount of heat from the machining process and may cause deformation due to its higher thermal expansion capabilities. Aluminium alloys also may cause problem related to chip formation due to its high ductility. T6061 Aluminum alloy has a wide range of mechanical and corrosion resistance properties as well as having most of the good qualities of aluminum. It is used in many applications from aircraft structures, yacht construction, truck bodies, bicycle frames to screw machine parts.

Cutting fluids normally are not necessary when machining most aluminum alloys because of the relatively low cutting temperatures. Several studies on dry machining have been performed using various tools and work materials [5-7]. One of the most recent studies on dry machining of T6061 aluminium alloy was performed by Tasnim *et. al*. [8], but no research has been done particularly on dry machining of T6061 Aluminum alloy using Si_3N_4 tools. This paper aims to obtain the optimum cutting speed for dry machining of T6061 aluminium alloy using Si_3N_4 tool inserts by studying the wear rates, tool life and material removal rates.

Experimental Procedure

Work Material Preparation. The raw T6061 Aluminum alloy rod (diameter 120 mm) was fixed into the 3 jaw chuck of the lathe machine (HARRISON M600). Then, the aluminum alloy rod was straight turned several times to perform the skinning operation. Finally, the work material was measured to 82 mm apart and grooved into 5 equal sections.

Machining. The Si_3N_4 triangular tool insert (SANDVIK COROMANT) was inserted into the tool holder (MTJNR 2525 M16K) at the tool post. Prior to machining, the initial diameter of the aluminum alloy rod was measured each time. Machining was performed using four different cutting speeds; 292, 388, 518 m/min and 689 m/min with two different cutting parameters; (d = 0.1 mm, f = 0.2 mm/rev and d = 0.2 mm, f = 0.4 mm/rev). Machining was performed in both dry and wet conditions (using traditional straight oil cutting fluid). Time to machine each slot was recorded using a stop watch.

Temperature and Wear Measurement. During the machining process, tool tip temperature was measured using an Infrared pyrometer (ST-677 HDS) focusing mainly at the tool-chip interface. Temperature measurements were repeated 5 times. After machining each segment, the tool was removed from the tool holder to measure the wear. Wear measurement was done using an Optical Microscope (Nikon MM-400). Data were extrapolated (up to maximum flank wear of 0.3 mm), graphs were plotted, tool life for Si_3N_4 tool was analyzed and optimum cutting conditions were found.

Results And Discussion

Wear Analysis. Wear measurements for the Si_3N_4 tools are shown in Figs. 1-2. For the dry machining using the lower parameters (d = 0.1 mm, f = 0.2 mm/rev), Si_3N_4 tool has shown to have similar wear rates for the first three cutting speeds (292, 388 and 518 m/min); (0.008, 0.012 and 0.014 mm/min) and (0.008, 0.011, 0.014 mm/min) for dry and wet machining respectively. However, there is significant difference in the wear rates at the highest cutting speed, V = 689 m/min which is 0.021 mm/min for dry machining and 0.015mm/min for wet machining. When the cutting parameters have been doubled (d = 0.2 mm, f = 0.4 mm/rev), similar observation was noticed. Similar wear rates were found for both dry and wet machining (0.013 and 0.019 mm/min) and (0.013 and 0.018 mm/min) at the first two cutting speeds 292 and 388 m/min. While at the two highest cutting speeds (518 and 689 m/min), the wear rates are slightly different for dry and wet machining; (0.026 and 0.040 mm/min) and (0.023 and 0.035 mm/min).

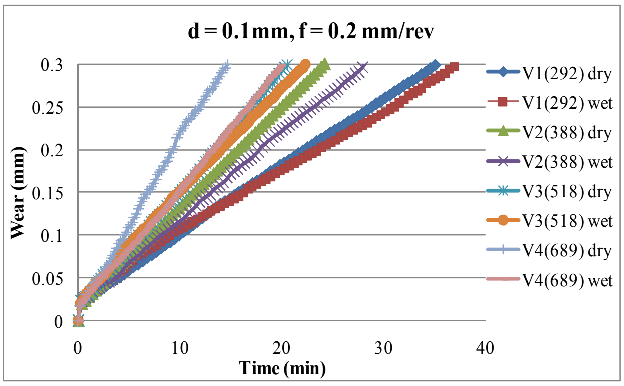

Fig.1: Flank Wear Measurements using d=0.1 mm and f= 0.2 mm/rev for Wet and Dry Machining

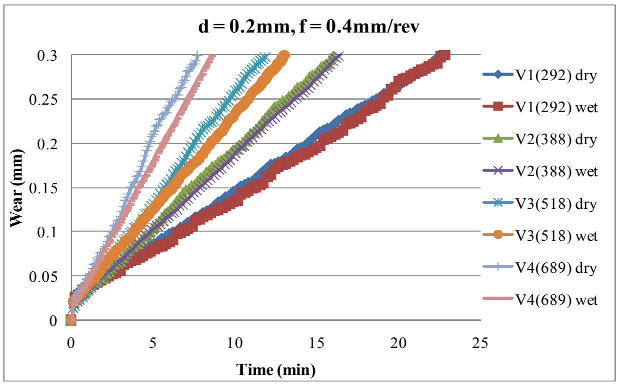

Fig. 2: Flank Wear Measurements using d=0.2 mm and f= 0.4 mm/rev for Wet and Dry Machining

Additionally, for dry machining, when the cutting parameters were doubled (d = 0.2 mm, f = 0.4 mm/rev), the wear rates have shown to increase by 63 - 90 % for all four cutting speeds. Meanwhile, the percentage increase of wear rates for wet machining is in the range of 63 - 133 %. Obviously, the lower cutting parameters (d = 0.1 mm, f = 0.2 mm/rev), has shown to have lower wear rates for both wet and dry machining. However, for the wet machining, there is a reduction of 0 - 28.5 % and 0 - 12.6 % in tool wear intensity of Si_3N_4 tool for the lower and higher cutting parameters respectively (Fig. 3).

Furthermore, Si_3N_4 cutting tool was found to have better wear resistance when compared to Titanium Nitride (TiN) and Titanium Carbonitride (TiCN) coated tools from a recent research done by Tasnim *et. al.* (2012) for the machining of T6061 Aluminium alloy in dry and wet conditions. This is because Si_3N_4 cutting tool has properties which lead to excellent thermal shock resistance, ability to withstand high structural loads to high temperature. This type of tool also has superior wear resistance when compared to the both tools (TiN and TiCN) even though they are better in wear resistance. Besides that, Si_3N_4 cutting tool is particularly suited for rough-machining and even under unfavorable cutting conditions such as heavily interrupted cuts and varying depth of cut.

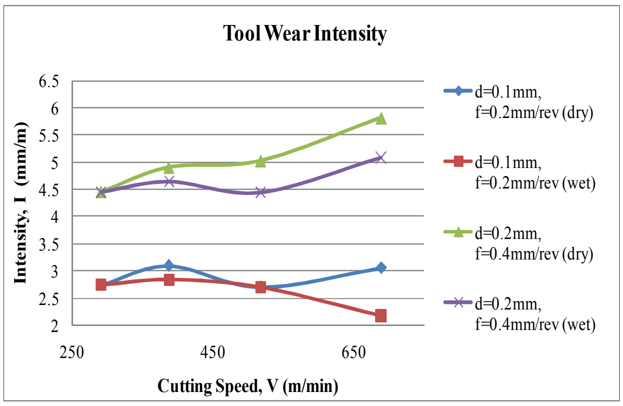

Fig.3: Graph of Tool Wear Intensity for Si_3N_4 tool

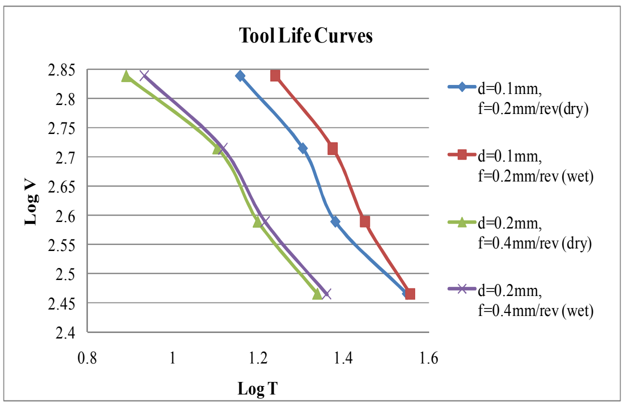

Fig. 4: Graph of Tool Life For Si_3N_4 Tool From Wet and Dry Machining

Tool life graph for Si_3N_4 cutting tool was obtained (Fig.4) for both machining conditions. The exponential values (n) were found from the slopes of the tool life curves based on the Taylor's tool life equation Eq. (1),

$$V\,T^{n} = C; \tag{1}$$

where V is the cutting speed, T is the tool life and C is the constant value. The n values for both cutting conditions were found to be around 0.8. Dry machining using Si_3N_4 cutting tool has resulted in a slight decrease in tool life by 1- 10% when the cutting speed increased from 292 to 689 m/min for both cutting parameters (Table 1). Longer tool life is observed generally by an increase of 1 – 9.4 % for wet machining by using Si_3N_4 cutting tool as compared to dry machining. Nevertheless, largest tool life percentage difference was observed for 689 m/min. Material removal rates were calculated using Eq. (2),

$$MRR = \pi D_{avg} d f N; \tag{2}$$

where D_{avg} is the average diameter, d is the depth-of-cut, f is the feed and N is the spindle speed used in rpm. The data for MRR values can be seen in Table 1.

Table 1: Tool Life and MRR Values For Si_3N_4 Cutting Tool From Wet and Dry Machining

Cutting speed, V (m/min)	Cutting parameters	MRR (mm^3/ min)	Tool life (min) (dry)	Tool life (min) (wet)	Difference in Tool Life (%)
V1(292)	d = 0.1 mm and f = 0.2 mm/rev	5875.33	35.55	36.09	1.50
V2(388)		7812.66	26.14	28.22	7.37
V3(518)		10435.11	20.75	22.25	6.74
V4(689)		13875.79	15.82	17.43	9.24
V1(292)	d = 0.2 mm and f = 0.4 mm/rev	23501.32	22.77	23	1.00
V2(388)		31250.65	16.18	16.49	1.88
V3(518)		41740.46	12.76	13.13	2.82
V4(689)		55503.15	7.7	8.5	9.41

The optimum cutting parameters can be found by basing on the relationship of tool life and MRR values. Larger amount of material removal are found with the larger cutting parameters (d = 0.1 mm, f = 0.2 mm/rev) compared to the lower cutting parameters (d = 0.1 mm, f = 0.2 mm/rev) for both dry and wet machining as can be seen from the bar chart in Fig.5. The largest volume removal of material for Si_3N_4 cutting tool is found from the second highest cutting speed, V3 = 518 m/min for both cutting conditions. Even though, the first cutting speed, V1 = 292 m/min has longer tool life (35.55 min) compared to the highest cutting speed, V3= 518 m/min (20.72 min); apparently the volume material removal is highest at V3 = 518 m/min because it has larger MRR (10435.11 mm^3/min) compared to the lowest cutting speed (5875.33 mm^3/min) for the depth-of-cut, d = 0.1 mm and feed rate, f = 0.2 mm/rev. Similarly for the depth-of-cut, d = 0.2 mm and feed rate, f = 0.4 mm/rev, the highest volume material removal is also found at V3 = 518 m/min. Thus, V3 = 518 m/min can be said as the optimum cutting speed in dry and wet operation for both cutting parameters.

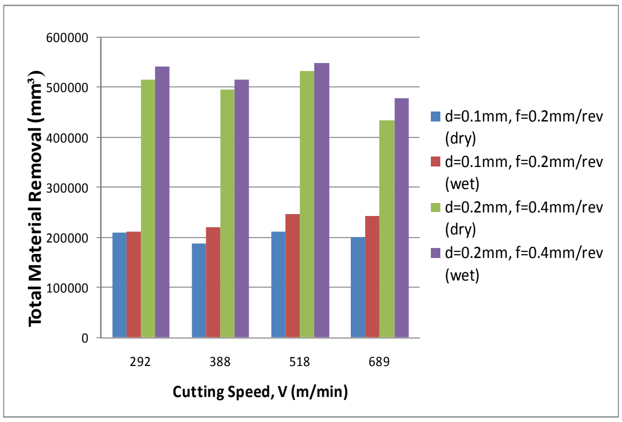

Fig. 5: Total Material Removal For Si_3N_4Tool

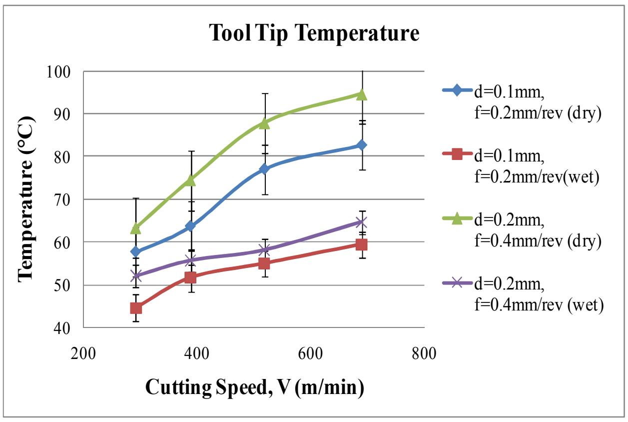

Fig.6: Tool Tip Temperature Measurements For Si_3N_4Tool

Temperature Analysis. The differences in the tool tip temperature also can be seen in Fig. 6 where the dry machining has higher temperature than the wet machining for both cutting parameters (d = 0.1 mm, f = 0.2 mm/rev and d = 0.2 mm, f = 0.4 mm/rev). The tool tip temperature for the Si_3N_4 cutting tool has shown to have increased by 23 - 40 % and 21 -51 % when machined dry for the lower and higher cutting parameters respectively when machined from 292 – 689 m/min. This is due to the absence of coolant during machining the T6061 Aluminium alloy which causes higher frictional forces at the tool-chip interface, thus resulting into larger cutting forces.

At the optimum cutting speed, V = 518 m/min, the tool tip temperature for dry machining was higher than wet machining by 40 and 51% for f = 0.2 mm/rev and f = 0.4 mm/rev cutting parameters respectively. Meanwhile, at the highest cutting speed (689 m/min), the tool tip temperature rise was slightly smaller; about 39 and 46 % for the lower and higher cutting parameters respectively. The temperature build up overall for both cutting parameters at both cutting conditions is below than 100 °C due to the fact that interrupted cutting operations at high speed was employed, i.e, short machining time. Therefore, less heat from the chip is penetrated into the tool.

Conclusions

The Si_3N_4 tools are suitable for dry machining at high speed. The optimum cutting speed for both cutting parameters using Si_3N_4 tool for both wet and dry conditions is found to be 518 m/min. However, the optimum cutting parameters were found to be from using the depth of cut of 0.2 mm and feed rate of 0.4 mm/rev for both wet and dry conditions. The tool tip interface temperature for dry machining was higher than wet machining for both cutting parameters by 40 and 51% at the optimum cutting speed, V = 518 m/min. However, this temperature rise is too small to have an influence on the tool wear measurements since it is performed at interrupted cutting process. Dry machining of T6061 Aluminium alloy by using Si_3N_4 as the cutting tool can be a more environmental friendly and an economical machining process particularly at higher cutting speed with interrupted cutting operations.

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