A STUDY ON THE MACHINABILITY OF AL_2O_3 PARTICLE REINFORCED ALUMINIUM ALLOY COMPOSITE

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ABSTRACT

In this study, the machinability 2024Al/Al_2O_3 particle composite was investigated in terms of tool wear, tool life and surface roughness by turning specimens with TiN (K10) coated and HX uncoated carbide tools in different cutting conditions. The test results showed that tool life decreased with increasing cutting speed for both cutting tools and the tool life of TiN (K10) tool was significantly longer than that of the HX tool. It was observed that the major wear forms of the tools were the combination of rounding of nose and flank wear. The optimum surface roughness of the workpiece was obtained at the cutting speed of 160 m min^{-1}

KEYWORDS

Metal Matrix Composites; Machinability; Surface roughness; Tool wear; Tool life

INTRODUCTION

Metal-matrix composites (MMCs) have been increasingly used in industry because of their improved properties over those of non-reinforced alloys. Among the various types of MMCs, aluminium based composites have found in various engineering applications such as for cylinder block liners, vehicle drive shafts, automotive pistons, bicycle frames, etc. (Rohatgi, 1991; Dinwoodie, 1987; Joshi et al., 1995; Kocazac et al., 1993; Chadwich and Heath, 1990). High hardness aluminium oxide (Al_2O_3) or silicon carbide (SiC) particles are commonly used to reinforce aluminium alloys, but the full application of such MMCs is cost sensitive because of their high machining cost (Hung et al., 1995).

Machinability of MMCs has received considerable attention because of the high tool wear associated with machining. Although efforts have been made to produce near-net-shape MMCs products by casting or hot forging, the need for machining cannot be completely eliminated and the resulting near-net-shape products still have to be machined to the designed shape and dimension. MMCs reinforced with Al_2O_3 particles are extremely difficult to machine (turning, milling, drilling, threading) due to their extreme abrasive properties (Durante et al., 1997; Sahin et al., 2002). Therefore, the available literature has concentrated on the study of wear characteristics of various tool materials during machining aluminium alloy composites (Sahin et al., 2002; Lane, 1990; Monaghan and O'Reilly, 1992; Tomac and Tonnessen, 1992; Finn and Srivastava, 1996; Yanming and Zehna, 2000; Quan et al., 1999; Joshi et al., 1999; El-Gallab and Sklad, 1998; Hung et al., 1994;). MMCs cause extremely rapid wear of the cutting tools and consequently high tool cost. The reason for this is the presence of the hard Al_2O_3 particles in the aluminium matrix. Studies on machinability of light alloy composites reinforced with Al_2O_3/SiC fibres/particles (Chadwich and Heath, 1990; Lane, 1990; Tomac and Tonnessen, 1992; Cronjager and Meister, 1992; Saga and Ikeda, 1991; Chandrasekaran and Johansson, 1997) indicate poor machinability due to abrasive wear of tools. Moreover, quality of the machined surface also deteriorates with tool wear (Chadwich and Heath, 1990). With existing tools such as cemented carbides coated with titanium nitride (TiN) or titanium carbides (TiC), the wear rate of the tools is so high that machining is extremely expensive. With diamond tools, tool wear is very low but the price is very high and the shaping of the tool is very limited (Durante et al., 1997).

Several researchers have done experiments on machining of MMCs. Channakesavarao et al. (2000) have experimented with different cutting tools. They have reported that crater wear is not appreciable in K10 tools which have superior wear resistance and produce continuous chips. Hoecheng et al. (1997) have studied the effect of speed, feed, depth of cut, rake angle and cutting fluid on the chip form, forces, wear and surface roughness. Tool life, surface quality and cutting forces have been studied by Chambers (1996). Yuan and Dong (1993) have investigated the effect of percentage volume reinforcement, cutting angle, feed rate and speed on the surface integrity in ultra precision diamond turning of MMCs. El-Gallab and Sklad (1998) have used several tool materials to compare their effectiveness.

The main concern, when machining MMCs, is the extremely high tool wear due to the abrasive action of the ceramic fibres or particles. Therefore, tool materials of very high resistance to abrasive wear are often recommended (Cronjager and Meister, 1992; Chen, 1992). The High Speed Steel (HSS) tools are inadequate, cemented carbides tools are preferred for rough machining and Polycrystalline Diamond (PCD) tools for finish machining operations (Tomac and Tonnessen, 1992). The high cost of PCD tools increases the costs of machining MMCs so it is necessary to carry out basic machinability studies in order to find cutting conditions using carbide tools, which can increase productivity and minimise the tooling cost (Palanikumar and Karthikeyan, 2007).

The purpose of the present work, therefore, was at different cutting conditions on a CNC lathe machine; using TiN (K10) coated carbide tools and HX uncoated carbide tools to:

(a) machine the 2024 Al alloy matrix material and the Al_2O_3 particle-reinforced 2024 aluminium alloy composite

(b) investigate the wear of each cutting tool; and

(c) evaluate the surface roughness values of the matrix and composite materials,.

Tool wear in the turning of composite was investigated with special attention paid to the effects of material structures, by scanning electron microscope (SEM). The experimental results were used to compare both cutting tools and materials.

EXPERIMENTAL PROCEDURE

1. Material Details

In this study, 2024 aluminium alloy with the theoretical density of 2800 kg/m^3 was used as the matrix material while α-Al_2O_3 (alumina) particles with an average particle size of 32 μm, and a density of 3950 kg/m^3 were used as reinforcement. The Al_2O_3 particles supplied by Treibacher, are short particles with a white colour. The grain size of Al_2O_3 particles was determined using a Malvern Laser Size Analyser.

The materials used in the present work were 2024 Al alloy composites reinforced with 30 wt. % Al_2O_3 particles, having a composition by wt of >93% α-alumina, ~1.8% TiO_2, and maximum 0.8% Fe_2O_3, 1.1% CaO and 0.2% other magnetic materials. Composites were fabricated by the vortex method with subsequently applied pressure, using a 2 kW power resistance-heated furnace under argon gas. Composites were shaped in the form of cylinder of 40 mm outer diameter and height of 140 mm. Production process parameters were selected to be as follows: Pouring temperature 700 ^oC, preheated mold temperature 550 ^oC, stirring speed 900 rev min^{-1}, stirring time after the completion of particle feeding 5 min, particle addition rate 5 g min^{-1} and applied pressure 6 MPa (Kok, 2005). Unreinforced 2024 Al matrix alloy sample was also produced by the same method. The chemical composition of the 2024 Al alloy matrix by wt was 3.23% Cu, 0.81% Mg, 0.74% Si, 0.54% Mn, 0.13% Zn with balance being Al. Details of the experimental set-up and production processes are reported in the previous studies (Sahin et al., 2002; Kok, 2005).

For microstructural investigations the test samples were prepared by standard metallographic techniques. Microscopic examinations of the specimens were carried out using a scanning electron microscope (SEM). The typical microstructures of 2024 Al alloy and the Al_2O_3/2024 Al alloy composite are shown in Fig. 1 whilst the associated material properties are given in Table 1.

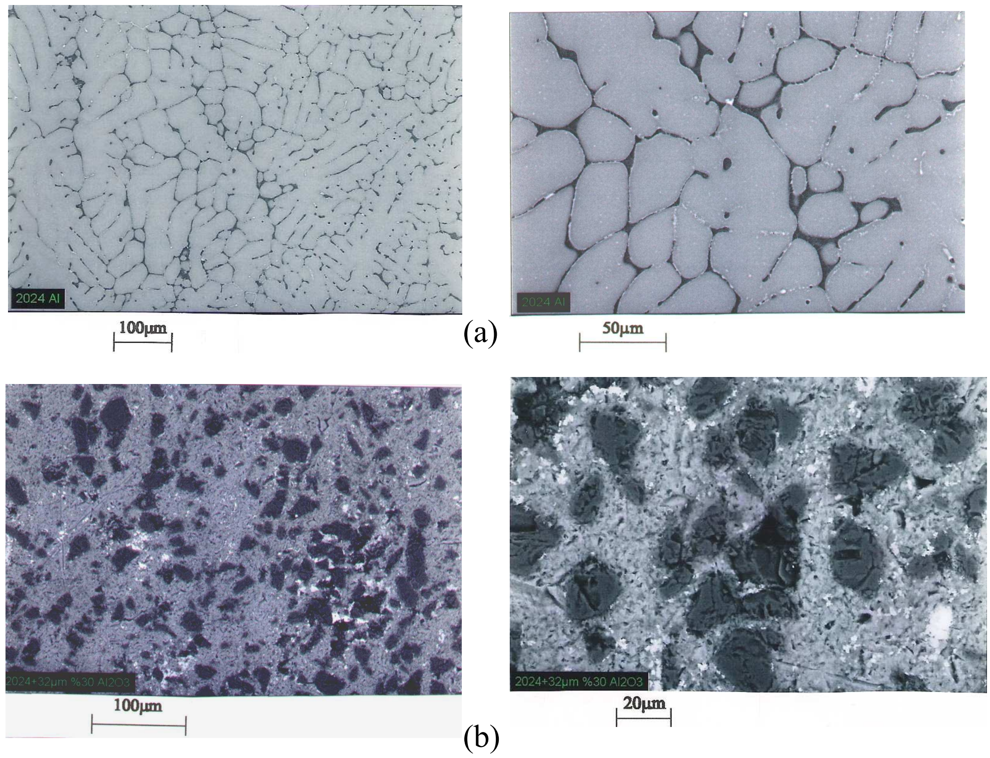


Figure 1. Scanning electron micrographs of: (a) the 2024 Al alloy, (b) the 30 wt. % Al_2O_3 particle-reinforced composite with 32 µm particle size, polished, black regions are Al_2O_3 particles.

Table 1. Material properties of 2024 Al and Al_2O_3/2024 Al alloy based composite

Material	Ultimate tensile strength (MPa)	Brinell hardness (BHN)	Density (kg/m^3)
2024 Al	68	89	2766
Composite	105	128	2925

2. Cutting Conditions

Machining tests were carried out without coolant and at a constant depth of cut equal to 2 mm and feed rate of 0.1 mm rev^{-1}. The cutting conditions and experimental specifications in the experiment are given in Table 2. Turning tests were conducted to determine the tool wear and tool life under different cutting conditions using a 2.2 kW stepless-controlled Boxford 250 CNC lathe machine when cutting one type of composite and its alloy matrix. Two types of cutting tools, including a TiN coated on K10 carbide grade denoted by the term of K10 tool, and uncoated HX carbide grade denoted by the term of HX cutting tool in this study, have been used. All tools are commercially available inserts, according to ISO code, CCMT09T304R-95HX and CCMT09T308-41 were supplied by Seco and Widia, respectively, for machining tests. Tool geometry used is listed in Table 3.

Table 2. Experimental specifications and cutting conditions

Cutting parameters	Specifications
Cutting tool materials	K10 and HX
Cutting speed (m min^{-1})	100, 160 and 210
Feed rate (mm rev^{-1})	0.1
Depth of cut (mm)	2.0
Work materials	2024 Al + Al_2O_3 composite including 30 wt. % of Al_2O_3 and 2024 Al alloy matrix

After each test the worn cutting tool were measured with an optical tool microscope to determine the degree of flank wear. For these tests, 0.3 mm flank wear (VB) was taken as the tool life criterion. The wear characteristics of the cutting tools were also examined by SEM. The surface roughness of the materials was measured by the aid of a stylus instrument. The conventional method of representing surface roughness was shown by center-line average (R_a) and peak-to-valley maximum (R_t) to provide a quantitative evaluation of the influence of cutting parameters on the surface finish of each workpiece.

Table 3. Cutting tool geometry

Tool type	Manufacturer	Rake angle	Clearance angle	Approach angle	Nose radius
K10 cutting tool (K10 coated with TiN)	Widia	0^o	7^o	80^o rhombic	0.8mm
HX cutting tool (uncoated)	Seco	0^o	7^o	80^o rhombic	0.4mm

RESULTS AND DISCUSSION

Fig. 2 shows the variation of tool life as a function of cutting speed for both K10 and HX cutting tools. It can be seen that the logarithm of tool life decreased linearly with increasing the cutting speed in all cutting conditions while the rate of change for the composite was much smaller than that of the matrix alloy. The result showed that tool life of the K10 cutting tool was longer than that of the HX tool for both materials, and the tool life difference between the cutting tools in machining the composite was much smaller than that in machining the matrix alloy. The least tool life was obtained in machining of the composite due to the having hard abrasive Al_2O_3 particles in the matrix while the highest tool life was found in machining of the 2024 Al matrix alloy.

Fig. 3 (a)-(c) shows the variation of tool flank wear with cutting time for each of the tools and the machined materials under various cutting speeds up to 210 m min^{-1} keeping the other machining parameters unchanged. From this figure, it can be observed that cutting time decreased with increasing cutting speed and hence, increasing cutting speed produced a faster tool wear. This is similar to machining of any conventional material in that the cutting tool wears faster at higher cutting speed. Fig. 3 shows that in all cutting conditions, the TiN-coated K10 cutting tool had a lower tool wear compared with uncoated HX tool. The coating of the cutting tool helps in reducing wear on the flank face because the coating makes the tool surface harder than its normal surface (Kılıçkap et al., 2005). Thus the K10 tool sustained the least flank wear due to the extreme hardness and high wear resistance of this material, whereas HX was found to be very unsatisfactory and sustained the most severe flank wear. There was an appreciable reduction at higher cutting speeds for both of the cutting tools life. For example, the HX tool lasted 1.46 and 0.46 min, while K10 tool gave approximately 1.8 and 0.6 min life when the tests conducted at cutting speeds of 100 and 210 m min^{-1} respectively, for machining the composite.

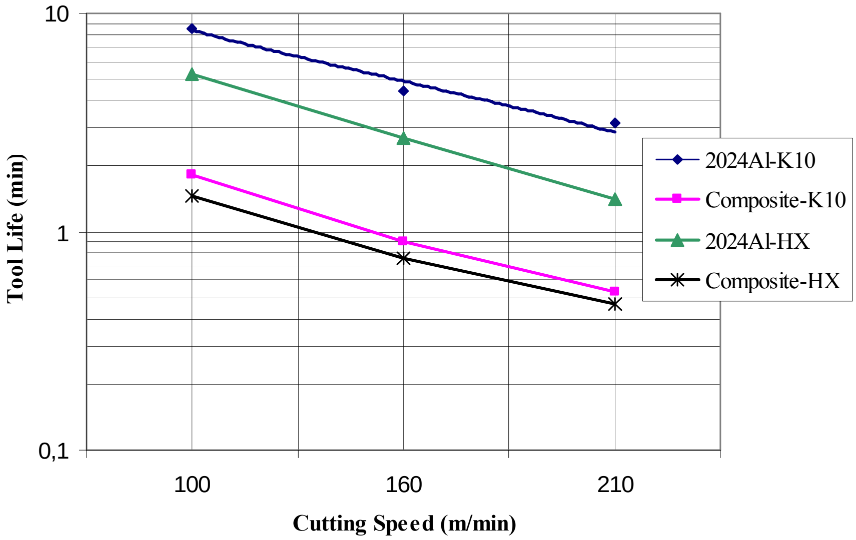


Figure 2. Tool life versus cutting speed

Typical SEM micrographs of wear patterns of K10 and HX cutting tools are shown in Fig. 4 (a)-(d) when machining the 2024 Al matrix alloy under similar test conditions. It can be seen that for the K10 cutting tool, a smooth and uniform flank wear and nose wear were associated with the removal of the coated layer on both flank face and rake face (Fig. 4 (a) and (c)), while the flank wear was observed to be associated with fairly uniform and close-packed abrasion marks for the HX cutting tool (Fig. 4 (b) and (d)). However, adhesion of the workpiece material was more pronounced for the K10 insert than for the HX insert. At the low cutting speed, of 160 m min^{-1} speed, a built-up-edge (BUE) formed on the rake face of the K10 tool as shown in Fig. 4 (a) whereas, as shown in Fig. 4 (d), a BUE formed on the rake face of the HX tool at 100 m min^{-1} cutting speed.

Fig. 5 (a) and (b) also indicate the flank wear surfaces for both cutting tools when machining the Al_2O_3 particle reinforced composites, tested at 100 m min^{-1} and 160 m min^{-1} cutting speed respectively. From Fig. 5 (a), it can be concluded that a smooth flank wear and nose wear were evident for the K10 tool. The grooves observed on the flank face of the K10 tool could have formed by loss of coated layer and sintered particles through aluminium seizure and pull-out process, however, as shown in Fig. 5 (b), for the HX cutting tool nose wear was similar but chipping on the flank face was dominant for this test condition. The flank wear observed in Fig. 5 (a) and (b) was caused by the abrasive nature of the hard Al_2O_3 particles present in the workpiece material. When machining MMCs with coated carbides the coating was removed from the tools, and the dominating wear occurred on the flank faces of the tools, particularly for K10 coated tools.

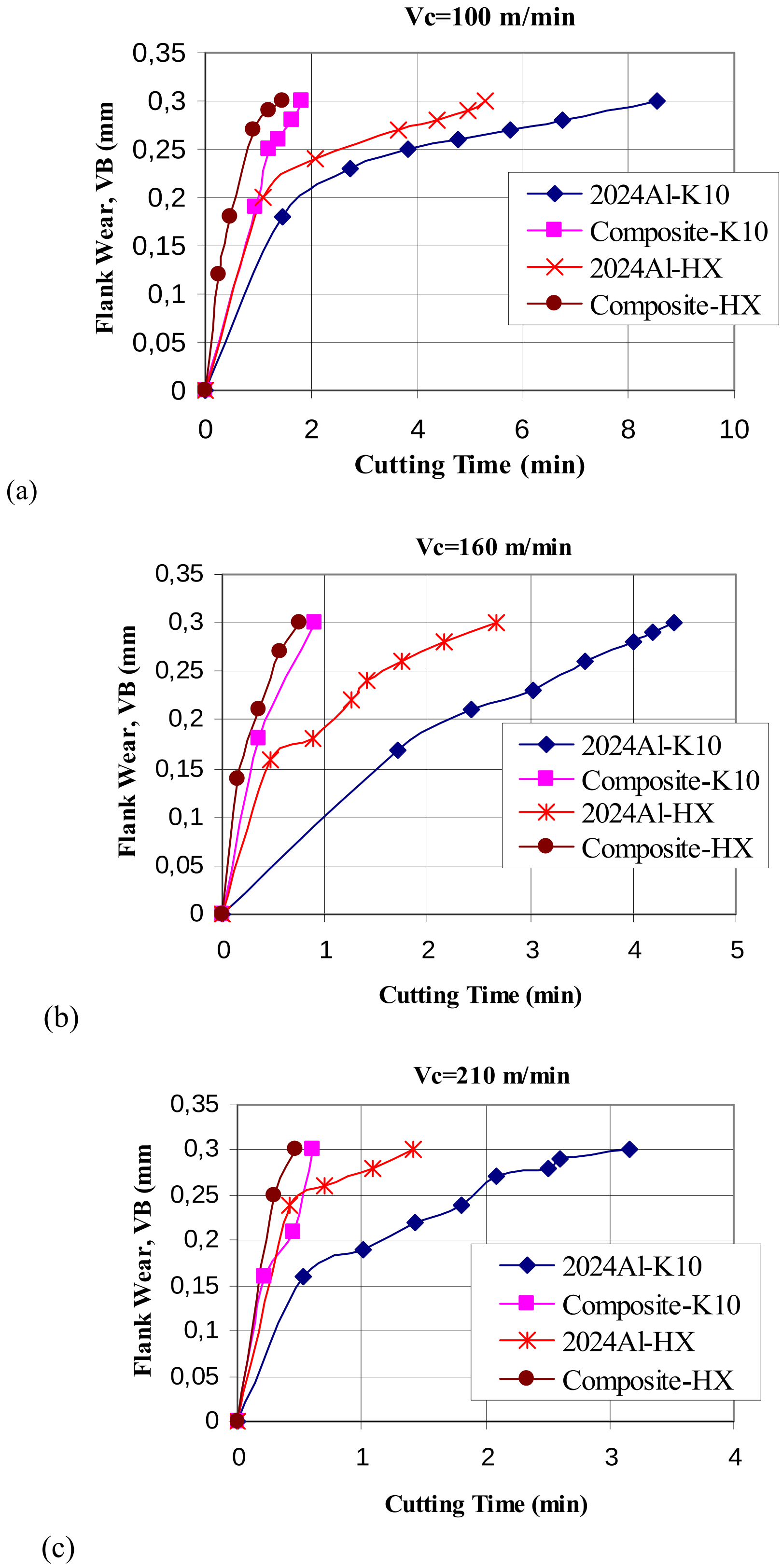
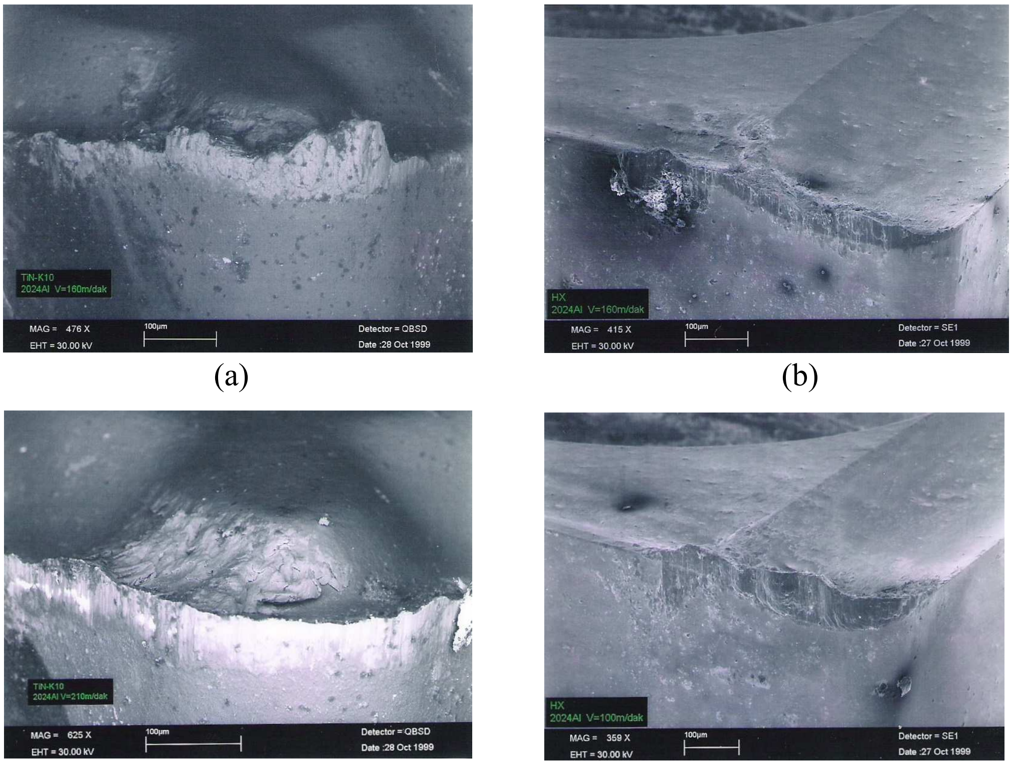


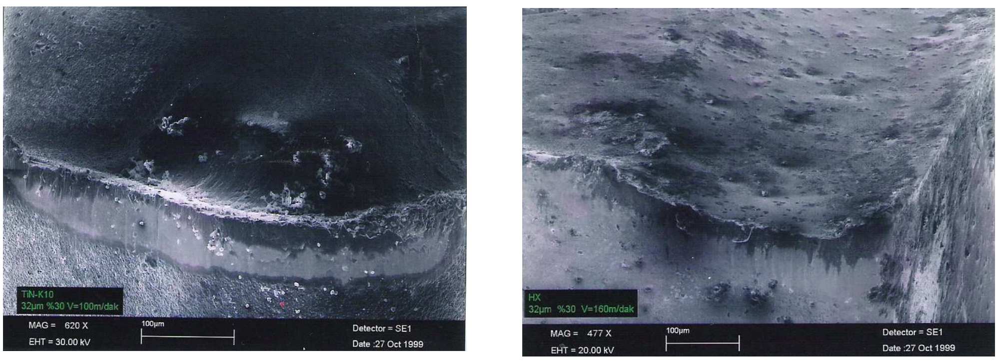
Figure 3. Variation of flank wear as a function of cutting time under cutting speeds of: (a) 100 m min^{-1}; (b) 160 m min^{-1}; (c) 210 m min^{-1}.



(a) (b)

(c) (d)

Figure 4. Flank wear of cutting tools in the machining of the 2024 Al alloy: (a) K10 tool, tested at 160 m min^{-1} cutting speed; (b) HX tool, tested at 160 m min^{-1} cutting speed; (c) K10 tool, tested at 210 m min^{-1} cutting speed; (d) HX tool, tested at 100 m min^{-1} cutting speed.



(a) (b)

Figure 5. Flank wear of cutting tools when machining of the 30 wt. % Al_2O_3 particle-reinforced composites with 32 µm particle size: (a) K10 tool, tested at 100 m min^{-1} cutting speed; (b) HX tool, tested at 160 m min^{-1} cutting speed.

A worn flank encourages adhesion of the workpiece material because of the high pressure generated at the tool-workpiece interface with increasing friction. The tool flank face is thus often covered with an aluminium alloy film as evidenced in Fig. 4 (a) and (c) and Fig. 5 (a) since aluminium alloy is an active metal. It is suggested that flank wear of tool is caused by both abrasive and adhesive wear mechanisms. However, each time an aluminium alloy film is scratched and gauged away by the Al_2O_3 particles, the grooves that formed on the tool face are filled with the workpiece material. Thus the adhering layer somewhat protects the tool's flank face against further abrasion. However, from Fig. 5 it can be also observed that adhesion of the workpiece material in machining the aluminium alloy composite was greater for the K10 tool than for the HX tool. As shown in Fig. 5, flank wear was associated with BUE formation in addition to damage to the layer of TiN coating material of the K10 coated tool. For the HX tool, however, smooth flank wear and small amount of adhering material on flank face were observed and no such a BUE was formed although chipping on the flank face was evident in Fig. 5 (b).

As a result, the Al_2O_3 particles in the composites also microcut these tools randomly and densely in the space between the workpiece and the tool, so that the abrasive wear occurred in these tools in addition to rounding of the nose. Furthermore, adhesion wear also appeared on the tool face since the aluminium alloy tended to seize on the rake face or flank face of the tool. One of the problems encountered at lower cutting speed was the formation of BUE on the TiN coated tool while removal of the coated layer on the rake face was also evident. However, edge chipping with small sizes on the main cutting edge and rounding of nose were the predominant wear mechanisms for the HX tools.

A series of preliminary tests was conducted to observe the effect of tool material on tool wear and surface quality in turning the Al_2O_3 particle-reinforced composites. In investigations of the machined surface roughness, two parameters namely the average surface roughness (R_a) and the maximum peak-to-valley height of roughness (R_t) were considered. The average surface roughness and the maximum peak-to-valley height of roughness values with respect to the different cutting speeds are shown in Fig. 6 and 7 respectively for the matrix alloy and its composites. From Fig. 6, it can be seen that increasing the cutting speed from 100 to 210 m min^{-1} resulted in a remarkable improvement in the surface finish of the aluminium alloy matrix which is what would be expected for the alloy matrix. While average surface roughness values generated by the K10 cutting tools for the composite, were found to be much less than those of the HX tools, it is observed that the R_a value of the K10 tool at 100 m min^{-1} cutting speed was a little bit more than that of the HX tool. This suggests the HX cutting tool is more suitable for machining composites at lower cutting speed than 100 m min^{-1} As shown in Fig. 6, the maximum surface roughness value was obtained in the machining of 2024 Al alloy matrix with HX tool at 100 m min^{-1} cutting speed, whereas the minimum value was found when machining of the composite with K10 cutting tool at 160 m min^{-1} cutting speed. Generally, for the matrix alloy the average surface roughness values decreased with increasing the cutting speed, while for the composite they decreased up to the 160 m min^{-1} and thereafter increased sharply with increasing the cutting speed. It was noticed that the coating played an important role on surface quality. In general, the coated K10 cutting tool provided a lower surface roughness in all machining conditions.

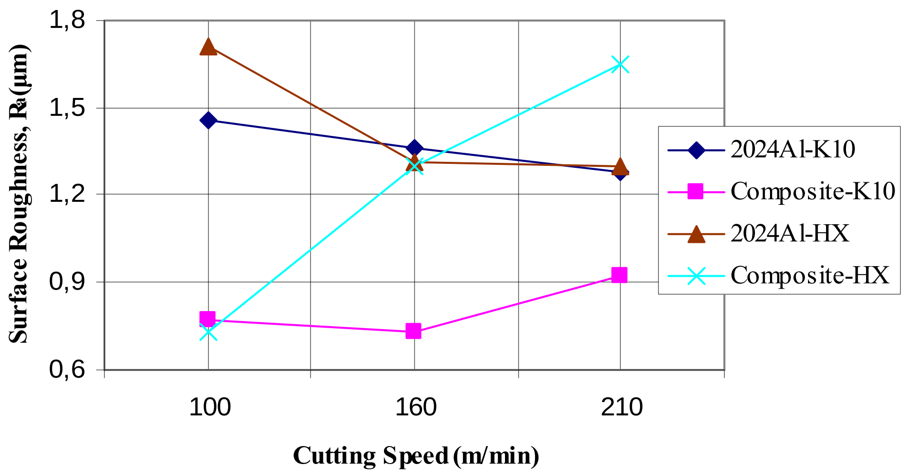


Figure 6. The effect of cutting speed on the average surface roughness (R_a).

The influence of the cutting speed on the maximum peak-to-valley height of surface roughness (R_t) is given in Fig. 7. It is clear from this figure that although R_t values of the K10 cutting tools were again much less than those of the HX tools for the composite, for the matrix alloy generally the HX cutting tools gave a better surface finish. Only at 100 m min^{-1} cutting speed, the HX tool produced a worse surface finish than the K10 tool. For the matrix alloy, while the difference between R_t values of the K10 tools was not so much, those of the HX tools decreased remarkably up to 160 m min^{-1} and thereafter a small decrease was achieved, with increasing cutting speed. So, it can be observed that HX cutting tools were more satisfactory than the K10 tools for machining of the matrix alloy. For the composite, R_t values of the K10 tools decreased very little up to 160 m min^{-1} and then increased sharply while those of the HX tools increased considerably, with increasing the cutting speed. As a result, it can be said that K10 tools were more suitable than HX tools for use in the machining of the composite because the difference between R_t values of the K10 and HX tools was so much.

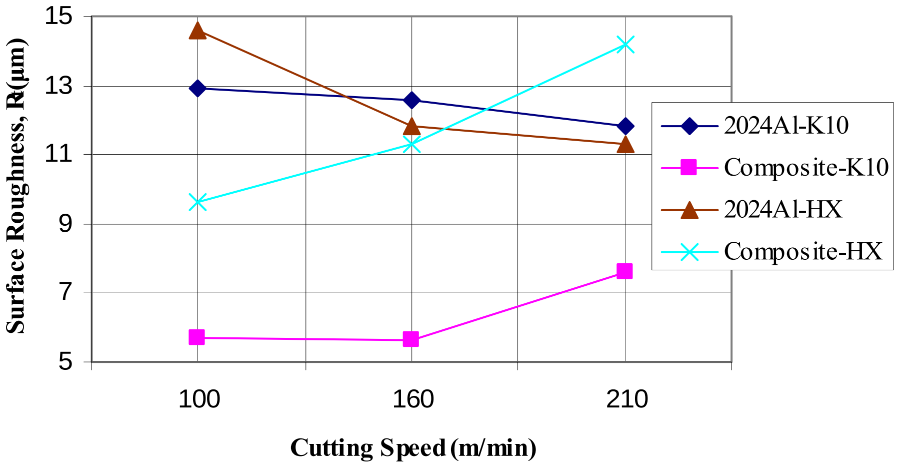


Figure 7. The effect of cutting speed on the maximum peak-to-valley height of surface roughness (R_t).

CONCLUSIONS

The following conclusions have been drawn from the results of this study:

1. The tool life of the TiN coated K10 tool was significantly longer than that of the HX tool. However, in the machining of the matrix alloy the tool life difference between cutting tools was larger than that in the machining of the composite. The tool life decreased with an increase in the cutting speed for both tools in all cutting conditions.
2. It is observed that the major tool wear forms were the combination of flank wear and rounding of the nose. For the K10 tools, removal of coated layer from the substrate material and BUE formation appeared when machining composites at lower cutting speed. For the HX tools, however, edge chipping and nose rounding was evident due to high temperature and stresses at the cutting edge.
3. It was shown that cutting speed was the influential machining parameter on the tool wear. The tool wear increased considerably with increasing cutting speed.
4. For cutting tools, the TiN coated K10 cutting tool showed better performance than that of HX tool. The coating decreased tool wear and produced a smoother surface finish.
5. The surface roughness of the workpiece was mostly affected by cutting speed. The optimum surface roughness in the machining of MMCs was obtained at a cutting speed of 160 m min^{-1} for K10 tool while the maximum surface roughness values appeared in the machining of the aluminium matrix alloy at the cutting speed of 100 m min^{-1} for HX tool. For the matrix alloy, the surface roughness values of both cutting tools decreased with increasing the cutting speed. For the composite, surface roughness values for the HX tool increased while those of K10 tool decreased a little up to 160 m min^{-1} cutting speed and thereafter increased sharply, with increasing the cutting speed.

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