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Research Article

Tool Wear, Surface Integrity and Dimensional Accuracy in Turning Al2124SiCp (45%wt) Metal Matrix Composite using CBN and PCD Tools

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Abstract: The focus of this study is the turning of Al2124SiCp (45% wt) Metal Matrix Composite using PCD, CBN-coated and CBN-uncoated tools. The machinability of Al2124SiCp (45% wt) Metal Matrix Composite is evaluated by measurement of tool wear, surface finish and dimensional accuracy of the work-piece. Wear mechanisms and patterns of tools in turning of Al2124SiCp (45% wt) Metal Matrix Composite are discussed. The experimental setup involved turning Al2124SiCp (45% wt) 78.0 mm long and 31.8 mm diameter on a precision lathe at fixed feed rate, different depth of cut and cutting speed using PCD, CBN-coated and CBN-uncoated tools. The reinforcement of the matrix consists of SiC 5-8 μm in diameter. Experimental results reveal that abrasion and adhesion presented the most prevalent mode of wear among all the tools. Fracture was observed among CBN tools while chipping on PCD tools. Flank and crater wear were observed in all tools with flank wear more prevalent in both CBN-coated and CBN-uncoated. Wear among PCD tools was low as compared to CBN tools. Further analysis reveal that the outer layer of the CBN-coated tools wear off fast creating a good platform for adhesion of matrix material on to the tool. This further increases wear of the tool due to adhesive wear as the built-up edge breaks off from the tool. PCD tool presented better surface finish than CBN tools with CBN-coated performing better than CBN-uncoated. Due to high SiC content, discontinuous chips are formed which are also curled due to increase in temperature at cutting zone causing bimetallic effect on the chip. On dimensional accuracy it was observed that PCD tool produced lowest diameter error followed by CBN-uncoated and finally CBN-Coated. It is concluded that in machining Al2124SiCp (45% wt) Metal Matrix Composite PCD tools are the best followed by CBN-coated and lastly CBN-uncoated.

Keywords: Diameter error, surface roughness, wears mechanism

INTRODUCTION

Metal Matrix Composites (MMCs) are endowed with superior properties but their full potential has not been realized yet over monolithic alloys. Key reason to this setback is their mach inability which still poses a significant setback (Persson, 2001; Muthukrishnan *et al*., 2008; Ciftci, 2009; Davim, 2003). The machining of MMCs is very difficult due to the highly abrasive and intermittent nature of the reinforcements. Presence of reinforcement phase in MMCs causes rapid abrasive tool wear (Ciftci, 2009; El-Gallab, 1998a; Muthukrishnan *et al*., 2007; Davim, 2012). MMC components are mostly produced using near net shape manufacturing methods and are subsequently finish machined to the final dimensions and surface finishes Muthukrishnan *et al*. (2007). Cemented carbide tools, widely used in metal cutting wear rapidly while cutting particulate MMCs and produce very poor surface finish due to the presence of hard reinforced SiC particles (Ciftci, 2009; Muthukrishnan *et al*., 2007).

Different classifications of tool wear mechanisms have been addressed in the literature. Basically, five wear mechanisms or any combinations of them are involved in tool wear. These are abrasion, adhesion, fatigue and dissolution/diffusion and tribochemical process. Attrition as a tool wear mechanism has also been reported. Holmberg and Mathews (1994) mention four main mechanisms of tool wear namely adhesive, abrasive, delamination and wear due to chemical instability, including diffusion, solution and electrochemical wear. Shaw (2005) mention eight mechanisms of tool wear as adhesive, abrasive, diffusion, fatigue, delamination, microchiping, gross fracture and plastic deformation. It is well accepted that the tool wear mechanisms in metal cutting involve more than one wear mechanism and it is difficult to predict the relative importance of any one of them. Predominance of wear mechanism depends on cutting conditions (Shaw, 2005).

Extensive studies have been conducted in machining of particulate MMCs with regard to wear

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Table 1: Alloying elements of Al2124 and their percentages

Element	Cu	Mg	Mn	Fe	Zn	Si	Cr	Ti and Zr	Others (Each)	Other (Total)	Al
Weight (%)	4.0-4.4	1.3-1.6	0.4-0.7	<0.3	0.25	0.2	0.1	0.2	<0.05	<0.2	Balance

and surface finish in relation to various machining parameters. Muthukrishnan *et al*. (2008) conducted experimental investigation on the machinability of fabricated aluminum metal matrix composite LM-25 (A356SiC/10p) involving continuous turning of composite rods using medium grade Polycrystalline Diamond (PCD) 1500 tools. Cutting conditions and parameters measured included surface roughness and tool wear. The researchers observed that higher cutting speeds result in relatively easier removal of the hard SiC particles, resulting in a better surface finish. El-Gallab and Sklad (1998b) carried out a study on surface integrity of machined AlSiC (20%vol) MMCs. In their experiments dry high-speed turning tests at different cutting speeds, feed rates and depths of cut were conducted using PCD tools in order to investigate their effect on the surface quality and the extent of the sub-surface damage due to machining.

In their research (Rajesh *et al*., 2010), studied effects of SiCp reinforcement to 7075 Al alloy and (10% wt) SiC (particle size 20-40 μm) MMC on surface roughness and tool wear during turning in terms of selected parameters as cutting speeds, feed rates and depth of cuts. From the experiments the researchers recommend that while using carbide tools, for optimum surface roughness in the work-piece, turning operation on Al alloy composite should be carried out at cutting speed within the range of 180 to 220 m/min, feed rate within range of 0.1 to 0.3 mm/rev and depth of cut within range of 0.5 to 1.5 mm. For minimum flank wear in the carbide tool, machining should be carried out at cutting speed of less than 200 m/min, feed rate of 0.1 mm/rev and depth of cut 0.5 mm. With respect to PCD tools the researchers recommend that turning operation on Al alloy composite should be carried out at cutting speed higher than 220 m/min but at a feed rate of less than 0.2 mm/rev and depth of cut less than 1.0 mm Rajesh *et al*. (2010).

In any turning operation, diameter error, Surface integrity and roundness are the key quality characteristics. Diameter error is the difference between the measured diameter and the designed diameter, where a positive error indicates undercutting of a cylindrical work-piece. It is an important quality characteristic of turned component parts, especially where cylindrical fits are involved (Rafai and Islam, 2009).

From the available literature involving machining particulate MMCs, it is evident that morphology, distribution and volume fraction of the reinforcement phase, as well as the matrix properties are among the factors that affect the overall cutting process. It is further observed that no literature is presented on machining Al2124SiCp (45% wt) MMC using CBN-coated, CBN-uncoated and PCD tools to assess surface roughness, tool wear and its mechanism as well as dimensional accuracy. This study therefore seeks to asses tool wear and wear mechanism, surface roughness as well as dimensional accuracy while machining Al2124SiCp (45% wt) MMC using PCD, CBN-coated and CBN-uncoated tools at a fixed feed rate, varying cutting speed and depth of cut.

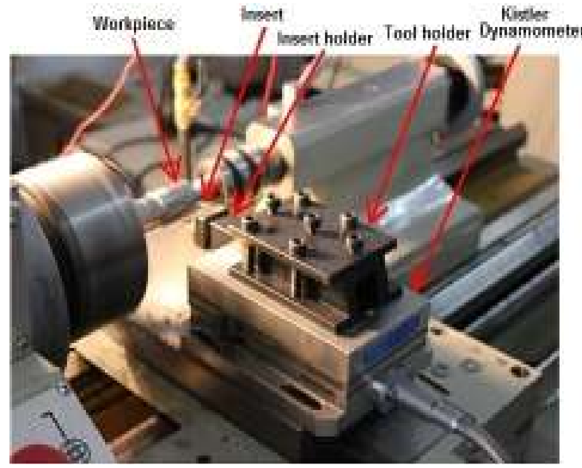

Fig. 1: Turning experiment set up

EXPERIMENTAL SETUP

Round bar of Al2124SiCp (45% wt) 31.8 mm diameter and 78.0 mm long was used for this study. The reinforcement consisted of particulate SiC of grain size 5 to 8 μm diameter. Table 1 shows alloying elements of Al2124 and their percentages. The percentage of particulate SiC in the metal matrix was 45% by weight. The machining of the MMC was performed at four different cutting speeds of 40, 60, 80 and 100 m/min. The lathe machine used for the turning test was High Precision Lathe Machine Model No: CG6125C with a span radius of 250 mm and length of 500 mm. The feed rate was set at 8.3 mm/min. The depths of cut used for machining were 0.1, 0.2 and 0.3 mm. All the tests were carried out under dry machining conditions. Figure 1 shows the experimental set up. Diameter error was measured with the aid of API Tracker 3 system set at a distance of 2.5 m from the work-piece. The cutting tools used were triangular shaped manufactured by Sumitomo Electric (Japan). They consisted of CBN-coated grade BNC 100 relief angle of 0° and rake angle of 0°. CBN-uncoated of grade BN 700 relief angle of 0^0, rake angle of 0° and PCD of grade DA2200 relief angle of 5° and rake angle 10°. The tools were mounted on a PTTNR2525-33 tool holder.

The surface roughness of the machined component was measured using a TR200 Portable Surface Roughness Tester by Time Group Inc (Australia) and

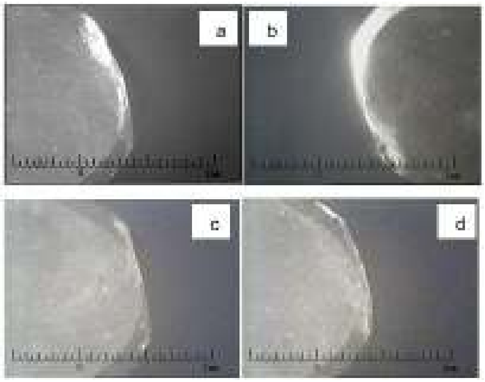

Fig. 2: Wear on CBN tool

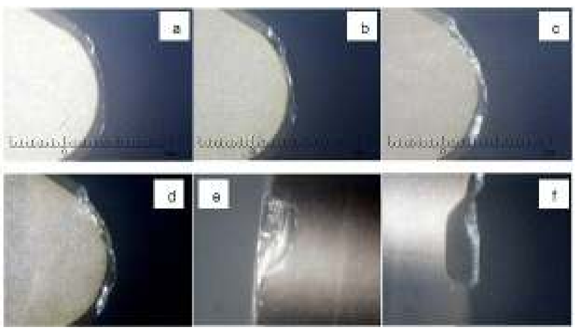

Fig. 3: Wear of CBNC tool

Form Talysurf PGI 1240 by Taylor Hobson Inc (USA). The worn tool tips were observed under CCD camera and the flank wear land was measured through use of integrated scale.

RESULTS AND DISCUSSION

Wear wechanism: There are many types of wear mechanisms that influence tool life. Under the current cutting conditions the main type of wear pattern physically observed was flank, crater, fracture and chipping wear. Figure 2, 3 and 4 show the various wear patterns on the three different tools. Comparing CBN-coated and CBN-uncoated tools it is observed that uncoated tools suffered more flank wear than coated tools. At low cutting speed the CBN-coated showed an amount of built-up edge Fig. 3a, b, c, d and f. At high cutting speed the flank wear of the tool increased tremendously with an increase in temperature at the tip. The wear of the tool also showed some fracture form of wear Fig. 3e. This could be attributed to the interaction between the tip and hard SiC particles. The rake surface of the tools suffered minimal damage since discontinuous chips were formed during the machining process. The rake surface suffered from abrasion wear by the hard SiC particles.

CBN-coated tool showed a relatively stable Built Up Edge (BUE) which enabled the tool to have longer tool life. However the BUE has an effect on the surface

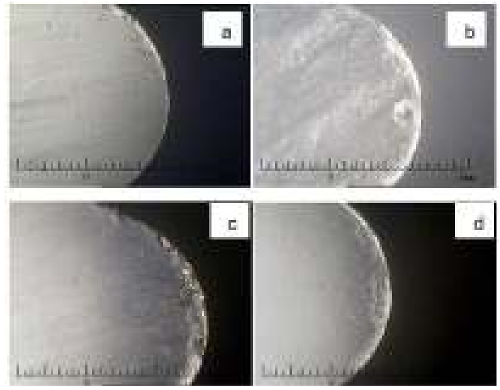

Fig. 4: Wear on PCD tool

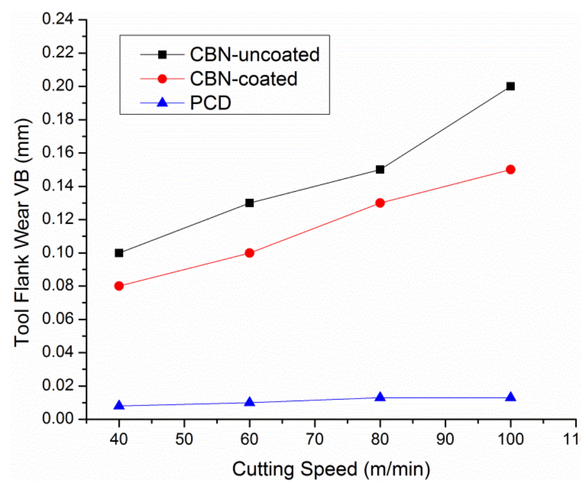

Fig. 5: Tool Wear at feed 8.3 mm/min and depth of cut a = 0.1 mm

quality as some of the matrix material is deposited of the work surface hence lowering surface quality. Abrasion is the dominant mode of wear of the tool where the first layer of coating is fast worn out in the initial machining. The worn tool reveals BUE on the cutting edge as shinny aluminum matrix material. In CBN-uncoated the tool shows BUE edge as the shinny part Fig. 2. The mode of wear is abrasion form of wear where the sharp cutting edge is worn off by the hard abrasive particles of SiC. For PCD tools dominant wear observed is flank wear Fig. 4. This wear is quite minimal and the tool retains the cutting edge for a long time as compared to CBN tools. Chipping is also evident in PCD tool which shows the worn cutting edge in form of a rugged edge Fig. 4. PCD tool further shows abrasive wear of the rake face in form of crater wear (Fig. 4a, b and c) this could be due to the rake angle of the PCD tool where the chips slide over the rake surface gouging out tool material. Among the three tools the shinny part shows built up edge on the cutting surface. It is observed that among the three tools PCD tool suffers lowest wear in the machining process and retains its cutting edge.

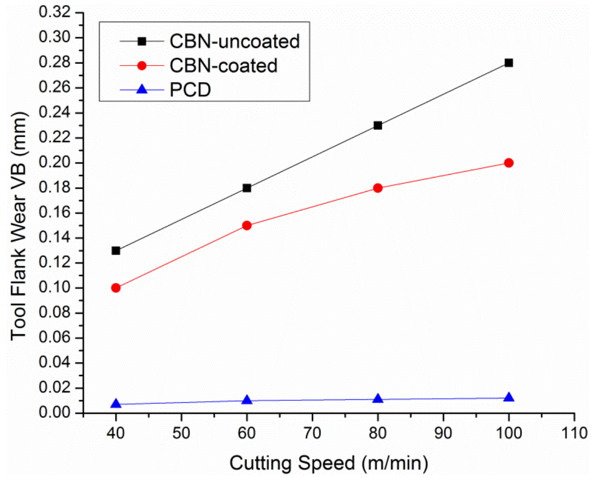

Fig. 6: Tool Wear at feed 8.3 mm/min and depth of cut a = 0.2 mm

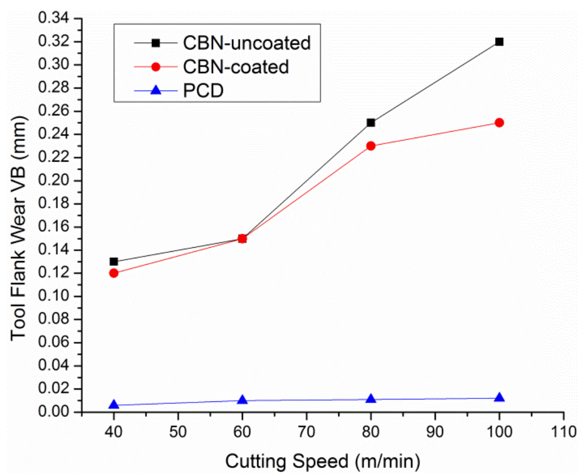

Fig. 7: Tool Wear at feed 8.3 mm/min and depth of cut a = 0.3 mm

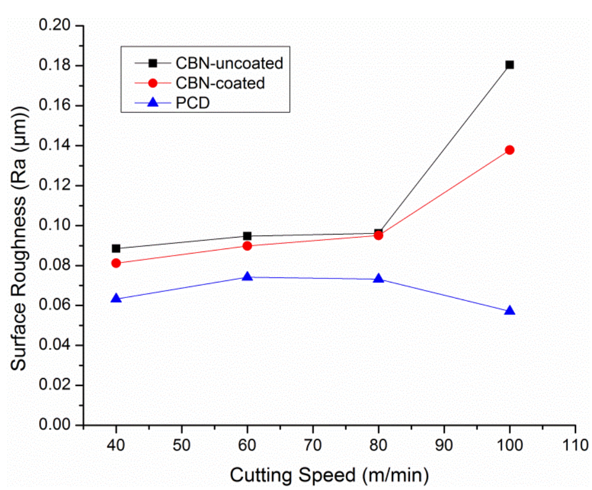

Fig. 8: Surface roughness at feed 8.3 mm/min and depth of cut a = 0.1 mm

Tool flank wear: Figure 5 to 7 show the influence of cutting speed on flank wear of CBN-uncoated, CBN-coated and PCD tools during turning of turning of Al2124SiCp (45% wt) MMC. From the figures it is observed that at any particular feed an increase in cutting speed and depth of cut cause a corresponding increase in flank wear.

From Fig. 5, it can be observed that at depth of cut of 0.1 mm and feed of 8.3 mm/min flank wear for CBN tool is 0.1 mm at 40 m/min cutting speed which increases to 0.25 mm at cutting speed of 100 m/min. For the same depth of cut and feed the flank wear for CBNC is 0.08 mm at 40 m/min cutting speed which increases to 0.18 mm at 100 m/min. the flank wear for the PCD at all the speed is quite negligible ranging from 0.008mm at 40 m/min cutting speed increasing to 0.013 mm at 100 m/min cutting speed. A similar trend can be observed with an increase in depth of cut while maintaining the same feed rate. At the depth of cut of 0.2 mm and feed of 8.3 mm/min (Fig. 6) flank wear for CBN-uncoated tool is 0.13 mm at 40 m/min cutting speed which increases to 0.28 mm at cutting speed of 100 m/min. For the same depth of cut and feed the flank wear for CBN-coated is 0.1 mm at 40 m/min cutting speed which increases to 0.2 mm at 100 m/min. The flank wear for the PCD at all the speed is quite negligible ranging from 0.007 mm at 40 m/min cutting speed increasing to 0.012 mm at 100 m/min cutting speed. At the depth of cut of 0.3 mm and feed of 8.3 mm/min (Fig. 7) flank wear for CBN-uncoated tool is 0.13 mm at 40 m/min cutting speed which increases to 0.32 mm at cutting speed of 100 m/min. For the same depth of cut and feed the flank wear for CBN-coated is 0.12 mm at 40 m/min cutting speed which increases to 0.28 mm at 100 m/min. The flank wear for the PCD at all cutting speeds is quite negligible ranging from 0.006 mm at 40 m/min cutting speed increasing to 0.012 mm at 100 m/min cutting speed. It is observed that an increase in depth of cut causes an increase in flank wear which increase with increasing cutting speed. In all the cutting parameters it can be observed that PCD tool presents lowest flank wear over the total cutting time. From the findings it can be concluded that the depth of cut and cutting speed are significant on the tool flank wear during machining of Al2124SiCp (45% wt) MMC.

Surface roughness: Figure 8 to 10 show the influence of cutting speed and depth of cut on surface roughness Ra of CBN-uncoated, CBN-coated and PCD tools during turning of Al2124SiCp (45% wt) MMC. From the figures it is observed that at any particular feed an increase in cutting speed causes a corresponding increase in surface roughness with exception of PCD tool.

From Fig. 8, it can be observed that at depth of cut of 0.1 mm and feed of 8.3 mm/min surface roughness

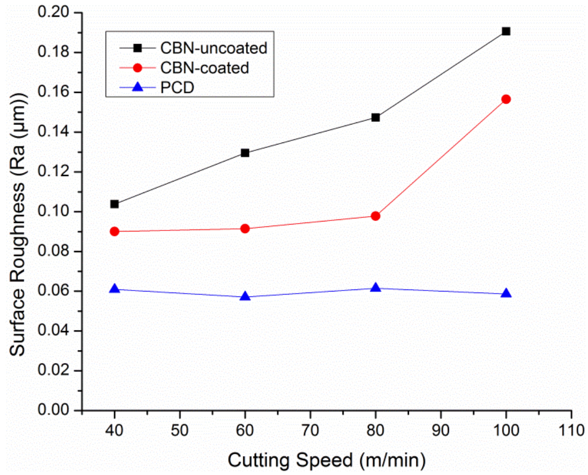

Fig. 9: Surface roughness at feed 8.3 mm/min and depth of cut a = 0.2 mm

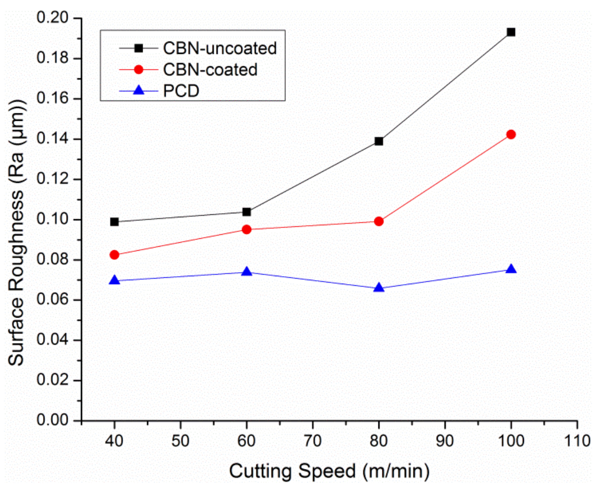

Fig. 10: Surface roughness at feed 8.3 mm/min and depth of cut a = 0.3 mm

for CBN-uncoated tool is 0.0885 µm at 40 m/min cutting speed which increases to 0.1804 µm at cutting speed of 100 m/min. For the same depth of cut and feed the surface roughness for CBN-coated is 0.0812 µm at 40 m/min cutting speed which increases to 0.1378 µm at 100 m/min. The surface roughness for the PCD at all the speed is relatively low ranging from 0.0632 µm at 40 m/min cutting speed decreasing to 0.0571 µm at 100 m/min cutting speed. At the depth of cut of 0.2 mm and feed of 8.3 mm/min (Fig. 9) surface roughness for CBN-uncoated tool is 0.0989 µm at 40 m/min cutting speed which increases to 0.1931 µm at cutting speed of 100 m/min. Surface roughness for CBN-coated is 0.0825 µm at 40 m/min cutting speed which increases to 0.1423 µm at 100 m/min. The surface roughness for the PCD is quite negligible ranging from 0.0695 µm at 40 m/min cutting speed decreasing to 0.0751 µm at 100m/min cutting speed. At the depth of cut of 0.3 mm and feed of 8.3 mm/min (Fig. 10) surface roughness for

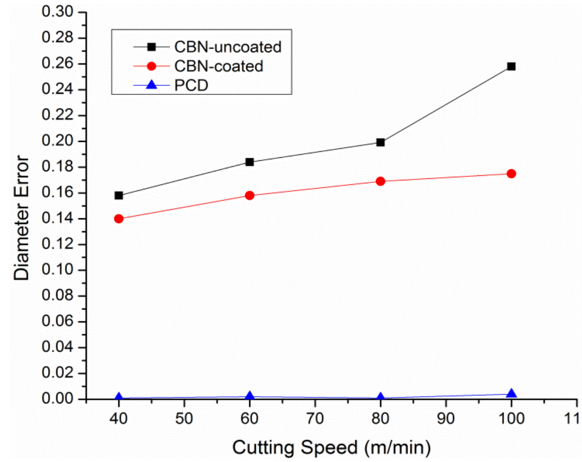

Fig. 11: Diameter error at feed 8.3 mm/min and depth of cut a = 0.1 mm

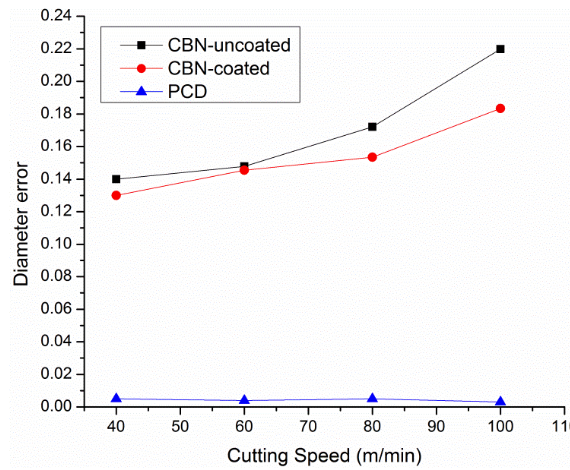

Fig. 12: Diameter error at feed 8.3 mm/min and depth of cut a = 0.2 mm

CBN-uncoated tool is 0.1038 µm at 40 m/min cutting speed which increases to 0.1906 µm at cutting speed of 100 m/min. That for CBN-coated is 0.0901 µm at 40 m/min cutting speed which increases to 0.1565 µm at 100 m/min. For PCD, surface roughness is quite negligible ranging from 0.0609 µm at 40 m/min cutting speed decreasing creasing to 0.0586 µm at 100m/min cutting speed. It is observed that an increase in depth of cut causes a corresponding increase in surface roughness which increases with increasing cutting speed. However this is not the case observed with PCD tool where at an increase in cutting speed shows an improved surface finish. In all the cutting parameters it can be observed that PCD tool presents lowest surface roughness over the total cutting time. From the results it can therefore be concluded that the depth of cut and cutting speed are significant on the surface roughness during machining of Al2124SiCp MMC.

Dimensional accuracy: Figure 11 to 13 show the influence of cutting speed and depth of cut on diameter

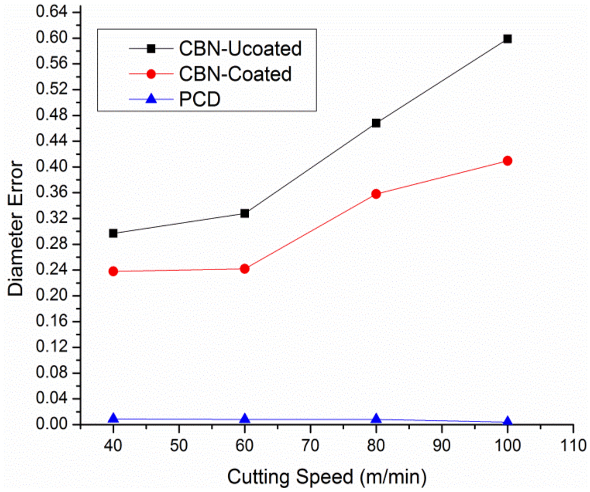

Fig. 13: Diameter error at feed 8.3 mm/min and depth of cut a = 0.3 mm

error of CBN-uncoated, CBN-coated and PCD tools during turning of Al2124SiCp (45% wt) MMC. From the figure it can be observed that at any particular feed an increase in cutting speed causes a corresponding increase in diameter error with exception of PCD tool.

From Fig. 11, it can be observed that at depth of cut of 0.1 mm and feed of 8.3 mm/min diameter error for CBN-uncoated tool is 0.158 at 40 m/min cutting speed which increases to 0.258 at cutting speed of 100m/min. For CBN-coated tool it is 0.14 at 40 m/min cutting speed which increasing to 0.175 at 100 m/min. For the PCD tool the error is negligible at all cutting speeds ranging from 0.001 at 40 m/min cutting speed increasing to 0.004 at 100 m/min cutting speed. At the depth of cut of 0.2 mm and feed of 8.3 mm/min (Fig. 12) diameter error for CBN-uncoated tool is 0.14 at 40 m/min cutting speed which increases to 0.1721 at cutting speed of 100 m/min. For CBN-coated tool it is 0.13 at 40 m/min cutting speed which increases to 0.1535 at 100 m/min. For the PCD tool it is negligible ranging from 0.005 at 40 m/min cutting speed decreasing to 0.003 at 100 m/min cutting speed. At the depth of cut of 0.3 mm and feed of 8.3 mm/min (Fig. 13) diameter error for CBN-uncoated tool is 0.297 at 40 m/min cutting speed which increases to 0.5989 at cutting speed of 100 m/min. For the CBN-coated tool it is 0.238 at 40 m/min cutting speed which increases to 0.4097 at 100 m/min. For the PCD tool it is negligible ranging from 0.002 at 40 m/min cutting speed increasing to 0.004 at 60 and 80m/min cutting speed but at 100 m/min the error decreases to 0.002. In all the cutting parameters it can be observed that PCD tool presents lowest diameter error over the total cutting time. From the experimental results it can be concluded that the depth of cut and cutting speed are more significant on the diameter error during machining of Al2124SiCp (45% wt) Metal Matrix Composite.

CONCLUSION

The wear mechanism of CBN-coated CBN-uncoated and PCD tools on turning of Al2124SiCp (45% wt) Metal Matrix Composite was investigated. The dominant wear mechanism included abrasion and adhesion while fracture and chipping were also observed. The wear type that is dominant in all the tools is flank wear. However, crater wear was observed in PCD tool which was attributed to the presence of rake angle of the tool. It was further observed that a high level of Built Up Edge (BUE) formation occurred in all the tools with highest coating in CBN-coated and CBN-uncoated tools. In the coated CBN-uncoated tool it is observed that the coating is worn out fast creating a platform for embedding of matrix material which increases wear through adhesion. This is also observed in CBN-uncoated. PCD tool present chipping of the cutting edge in form of craters. CBN-uncoated is observed to have the highest flank wear among the three tools followed by CBN-coated while PCD has the lowest flank wear.

PCD tool produced the best surface finish followed by CBN-coated while uncoated CBN-uncoated tool produced the worst surface finish.

On dimensional accuracy it was observed that PCD tool has the lowest diameter error followed by CBN-coated and lastly CBN-uncoated. This was due to PCD retaining sharp edge throughout the machining time while CBN tools loosing cutting edge as cutting progresses.

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