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Machinability of Al-SiC metal matrix composites using WC, PCD and MCD inserts

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SUMMARY: The aim of this work is the study of the machinability of aluminium-silicon carbide Metal Matrix Composites (MMC) in turning operations. The cutting tools used were hard metal (WC) with and without coating, different grades and geometries of Poly-Crystalline Diamond (PCD) and Mono-Crystalline Diamond (MCD). The work piece material was AMC225xe, composed of aluminium-copper alloy AA 2124 and 25% wt of SiC, being the size of the SiC particles around 3 µm. Experiments were conducted at various cutting speeds and cutting parameters in facing finishing operations, measuring the surface roughness, cutting forces and tool wear. The worn surface of the cutting tool was examined by Scanning Electron Microscope (SEM). It was observed that the Built Up Edge (BUE) and stuck material is higher in the MCD tools than in the PCD tools. The BUE acts as a protective layer against abrasive wear of the tool.

KEYWORDS: Metal-matrix composites (MMCs); Machining; Particle-reinforcement; Turning; Wear

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RESUMEN: *Maquinabilidad de composites de matriz metálica Al-SiC usando herramientas de WC, PCD y MCD.* El objetivo de este trabajo es el estudio de la maquinabilidad del material compuesto de matriz metálica aluminio-carburo de silicio en operaciones de torneado. Las herramientas de corte utilizadas han sido de metal duro con y sin recubrimiento, diferentes grados de diamante policristalino (PCD) y diamante monocristalino (MCD). El material mecanizado ha sido AMC225xe, compuesto de la aleación de aluminio AA 2124 con un 25% en peso de partículas de SiC con un tamaño medio de 3 µm. Los experimentos se han realizado con diferentes velocidades de corte en una operación de refrentado, midiendo la rugosidad superficial, las fuerzas y el desgaste de la herramienta. La superficie desgastada de la herramienta ha sido examinada en el microscopio electrónico (SEM). Se ha observado que el filo recrecido y el material adherido son mayores en el caso de las herramientas de MCD que en las de PCD. El filo recrecido actúa como una capa protectora contra la abrasión.

PALABRAS CLAVE: Compuesto de matriz metálica (MMCs); Desgaste; Mecanizado; Reforzado con partículas; Torneado

1. INTRODUCTION

Advanced automotive and aerospace technology requires new materials to improve current performance. As a result, considerable research in the material science has been directed toward the development of new light-weight engineering materials providing high specific strength and stiffness at elevated temperatures, with good creep, fatigue and wear resistance. Particle reinforced aluminium alloys are an important group within the Metal Matrix Composites (MMCs), particularly those with ceramic particles, that improve the wear resistance and the mechanical properties. This kind of material is rapidly replacing conventional materials in various automotive and aerospace industries (Surappa, 2003). One of the most extended MMCs are the Al+SiC alloys that cause machining problems due to the high hardness of the reinforcement, which is significantly higher than the conventional tungsten carbide tools (Cronjager and Meister, 1992; El-Gallab and Sklad,1998a; Hung and Zhong, 1996).

Many researchers have investigated the tool wear and surface integrity during machining of MMCs, they found that the tool wear is excessive and surface finish is very poor when carbide tools are used for the machining of Al/SiC-MMC alloys (Looney et al., 1992; Weiner and Konig, 1993). It was also found that in most cases, the tool wear was due to abrasion by the hard reinforcement particles in the matrix material (El-Gallab and Sklad, 1998a; Hung and Zhong, 1996; Davim, 2012; Luliano et al., 1998). Li and Seah (2001) found that the abrasive wear of the tool was accelerated when the percentage of the reinforcement in the MMC exceeded a critical value, which varies with the density and size of the reinforcement particles. Moreover, most of the studies about the machinability of MMC's were carried out using materials with ceramic particles with a size of 25 microns or larger, resulting in bad performance of the hard metal (WC) tools, (Durante et al., 1997; Muthukrishnan et al., 2008a; Muthukrishnan et al., 2008b).

The Poly-Crystalline Diamond (PCD) tools provide a suitable tool life for high speed machining of MMC materials (Durante et al., 1997; Muthukrishnan et al., 2008a; Muthukrishnan et al., 2008b), thanks to their high hardness compared to conventional reinforcement materials like alumina (Al_2O_3) and silicon carbide (SiC). El-Gallab and Sklad (1998a) found that the Built Up Edge (BUE) formed during machining could protect the tool from abrasive wear. However, unstable BUE could cause tool chipping, resulting in poor surface finish. During machining the tool may fracture and pull out the reinforcement particles, resulting in a poor machined surface finish (El-Gallab and Sklad, 1998a; El-Gallab and Sklad, 1998b).

Advances in tool technology have resulted in the introduction of a variety of Polycrystalline Cubic Boron Nitride (PCBN) grades. PCBN tools have found wide applications, providing an alternative to conventional carbide and ceramic tools. PCBN tools are widely used in turning hard materials because they have reasonably long life owing to their good thermal resistance, high hardness and coefficient of thermal conductivity (similar to WC and half that of PCD) (Hung and Zhong, 1996; Davis, 1995). Ding et al. (2005) demonstrated that during machining with PCBN tools, the severity of transfer material on the tools increased significantly with cutting distance. This BUE was more apparent as cutting speed increases, resulting in a worse surface finish.

Cutting fluid is usually used to reduce cutting force and cutting temperature, so the tool life and machining efficiency are enhanced and the surface finish quality is improved. However, according to many studies, the use of cutting fluids with diamond tools doesn't improve the performance but leads to a greater tool wear (Ding et al., 2005; Hung et al., 1997). In fact, steam is the only fluid that is believed to improve the machinability of MMCs (Shetty et al., 2008), by reducing the presence of the BUE and the cutting forces while the surface roughness is lower.

Attending to the machining problems identified in the previous paragraphs, the aim of this paper is to study the influence of the reinforced SiC particles on the machinability of Al/SiC-MMC and tool life of different type of tool inserts during facing operations. The selected tools for these tests are Mono-Crystalline Diamond (MCD) tools as well as different grades of PCD. The influence of the PCD characteristics is analyzed. Despite the WC is not the most suitable material for the machining of this kind of materials (Davim, 2012), AMC225XE is normally produced by powder metallurgy, leading that the matrix can be reinforced with ultrafine SIC particles (2–3 microns), slightly lower than others MMCs reported in literature (Durante et al., 1997; Muthukrishnan et al., 2008b). Because a smaller particle size means less inertia force of the ceramic grains, it is expected that the abrasive wear will be reduced. In this regard, WC tools are also analyzed in order to observe if there is a relative impact on the tool wear.

2. EXPERIMENTAL PROCEDURE

The material used in the machining tests is AMC225xe (Muthukrisnan et al., 2008b) composed of aluminium-copper alloy AA 2124 and 25% on weight of SiC particles with average size of 3 µm. Table 1 shows the composition of the base aluminium alloy AA 2124 and Table 2 shows the characteristics of the composite material AMC225xe.

Table 1. Base material composition

Al024 composition (wt.%)									
Si	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Cr**	**Others**	**Al**
0.5	0.5	3.8–4.9	0.3–0.9	1.2–1.8	0.25	0.15	0.1	0.15	Bal.

The main alloying element of the base material is cooper, which is normally used because of its significant solubility in α-Al and its strengthening effect. Small ceramic particle size is used because it offers a significant benefit in terms of strength and fatigue performance, also allowing the use of processes such as forging, extrusion and precision machining (Materion, 2012).

The work piece is a cylindrical bar of 175 mm diameter. The machining operation is a facing from 175 mm to 50 mm diameter with constant cutting speed and without cutting fluid (see Figure 1). The tests are performed in a CNC CMZ TL-15M lathe (5000 rpm, 14 kW). The cutting forces are measured using a three-component dynamometer (KISTLER 9257BA) attached to the lathe turret, and the data is recorded using a DAQ system. The flank wear of the tool (VB) is controlled with a contact microscope (KEYENCE VHX-500F), the tool surface is controlled with a SEM microscope (FEG-SEM Zeiss Ultra Plus equipped with EDS) and the surface roughness is measured with a tester (MITUTOYO SJ-201PR). The cutting tools material and geometries are summarized in Table 3; the rake angle corresponds to the angle measured with the tool mounted in a tool holder with ISO reference STFCL2525M16.

The cutting conditions used in the experimental tests are summarized in Table 4. WC tools with and without coating are tested under two different cutting speeds (v_c), 200 and 500 m min^{-1}. Instead, when PCD (coarse and fine grain) and MCD diamond tools are analyzed, the cutting speed has been gradually increased from 200 m min^{-1} to 800 m min^{-1} with increments of 100 m min^{-1}. Point out that every test is divided in many cuts in order to observe the evolution of the tool wear. Between facing passes the tools are cleaned to remove the BUE from the tip of the tool, dissolving the aluminium in a sodium hydroxide solution.

Table 2. Composite material characteristics

AMC225XE characteristics	
Composition	Al2024 + 25% (vol) SiC
Average SiC particles size	3 µm
Heat Treatment	T4
Ultimate Strength	680 MPa
Yield Strength	480 MPa
Elastic Modulus	115 GPa
Hardness	130 HBW 2.5/62.5 + /−3.1%

3. TEST RESULTS AND DISCUSSION

Among all the tested tool inserts, WC tools are analyzed first. For instance, Figure 2 and Figure 3 show the uncoated and coated WC tools, respectively, after only a single facing cut at 200 m min^{-1}. It can be noticed the lost geometry in the cutting edge where flank and crater wear are present. There is also stuck material around the wear zones in the flank face. These failure modes are more aggressive at 500 m min^{-1}.

Observing the results, the main conclusion is that the SiC particles produce a fast wear when machining with WC cutting tools, so they are not suitable to machine AMC225xe.

On the other hand, the PCD tools with positive rake angle (+6°) (Fig. 4a) also show that the material is bonded to the clearance face of the tool acting as a protective barrier against flank wear (Fig. 4b). In fact, the wear phenomenon occurs again at the rake face (Fig. 4c) where the main wear type is the crater wear. It is also observed that as this tool wear becomes more severe the cutting forces and surface roughness increase. Comparing PCD and WC tools

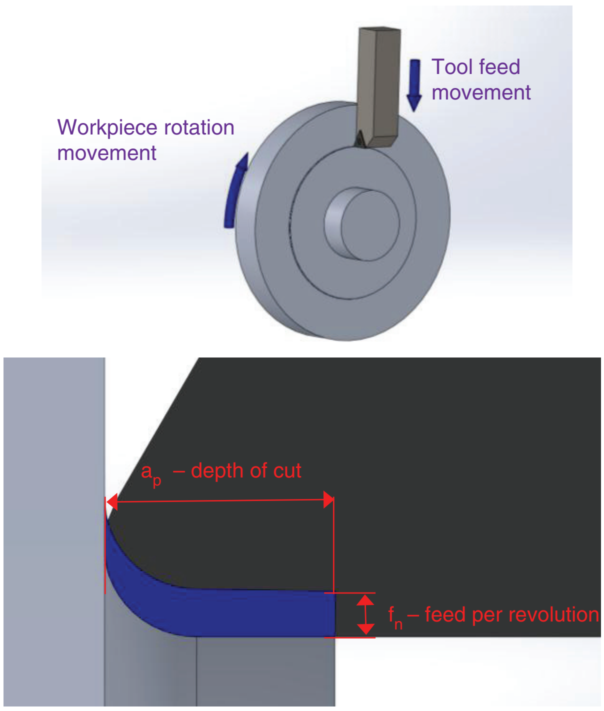

Figure 1. Scheme of the machining operation.

Table 3. Specifications of the tools

Geometry	Material	Rake angle (0)
TCGT16T304	Uncoated WC (AZHT110)	+30
TCMW16T304	CVD Coated WC (UC5105: Alumina+TiCN)	0
TCMT16T0304	PCD (fine grain, 2 μm)	+6
TCMW16T0304	PCD (fine grain, 2 μm)	0
TCMW16T0304	MCD	0
TCMW16T0304F-L1	PCD (coarse grain, 10 μm)	0

Table 4. Cutting conditions

Cutting Speed (v_c) (m min^{-1})	Feed rate (f_n) (mm rev^{-1})	Depth of cut (a_p) (mm)
200 – 800	0.1	0.5

results, in both cases the flank wear is negligible, and this is probably a consequence of the protective layer of stuck material. Therefore, it can be supposed that this adhered material acts as a protective layer that reduces abrasive, adhesive and diffusive wear mechanisms on the flank face.

Machining with MCD and PCD diamond tools with 0° rake angle there is no presence of abrasive wear (Fig. 5, bottom row) led by SiC abrasive particles. BUE is presented as the most important problem for this kind of tools. This fact is because the adhered material (Fig. 5, top row) protects the rake and flank faces. However, the machining using PCD tools with fine grain results in chipping phenomena or small edge cracks for cutting speed of 400 m min^{-1} (Fig. 5f) and higher. It is believed that the reason is the tool material breaks away with the stuck material of the BUE. Figure 5 shows the stuck material layer on the tip of the different tools and the wear after being cleaned in sodium hydroxide solution.

Regarding the volume of the stuck MMC material to the tool tip, it is noticed that more material is adhered to the MCD tools than to the PCD tools. It is believed that this happens due to MCD's a greater effective surface (free of binder) with free carbon atoms that can combine with silicon particles of the base material (Chen et al., 2005; Coscia et al., 2005). The similarity of their characteristics and their position on the periodic table, originates an affinity between carbon and silicon.

In addition, the rake faces of the tools are analyzed by Scanning Electron Microscope (SEM) after chemical cleaning to remove the stuck aluminum. For instance, in Figure 6 the presence of bonded silicon particles is noticed for MCD (Fig. 6a) and PCD (Fig. 6b) tools. Precisely, the silicon particles are adhered to the diamond grains of the contact zone (Fig. 6a, circled area) due to the affinity between the carbon and silicon, but not to the binder as it is observed in the spectrums of the PCD tool (Fig. 6b). The analysis for the rest of the rake faces showed no presence of any silicon particle adhered.

Going deeper in the analysis, small cracks are observed in the cutting edge of the tools. It is thought that these happen at the beginning of machining and can be the origin of the fractures at 400 m min^{-1}. The reason of this fact might be the impacts of the ceramic particles against the tool or the removal of grains and agglomerates led by the stuck aluminium in the early stages of the formation of the BUE. Anyway, this point is difficult to verify because the adhesion occurs very quickly.

The case of fine grain PCD, damaged at 400 m min^{-1} cutting speed, is further studied to analyze the influence of the BUE on the cutting forces and the final surface finish. As shown in Figure 4, the tool has been cleaned after being tested at 400 m min^{-1}. Afterwards it has been tested at a cutting speed of 500 m min^{-1}, both cleaned and with initial BUE. Table 5 shows the values of cutting forces and surface roughness obtained in facing operations at 400 m min^{-1} before breakage and

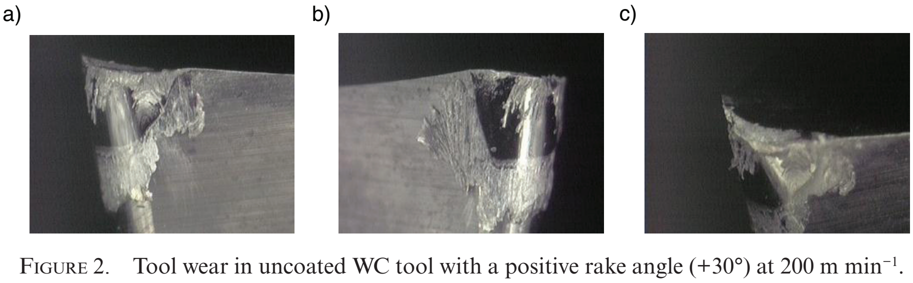

Figure 2. Tool wear in uncoated WC tool with a positive rake angle (+30°) at 200 m min^{-1}.

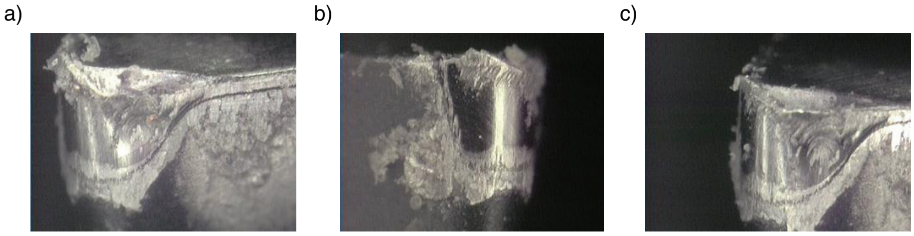

Figure 3. Tool wear in coated WC tool with a neutral rake angle (0°) at 200 m min^{-1}.

at 500 m min^{-1} after breakage. It can be seen that BUE doesn't affect the cutting forces or the surface finish, even when the tool is broken any trend is not noticed. Again, it is believed that the absence of differences in cutting forces and surface roughness values comes from the rapid formation of the BUE in the cleaned tools and thus, this performs as a tool already with BUE.

On balance, the main conclusion achieved is that the adhered material (BUE) protects the tool edge against the wear effect produced by SiC particles. Anyway, the benefits of the BUE can cause damage to the cutting edge due to the removal of grains and agglomerates leading to small cracks and finally to catastrophic failure (Sandvik Coromant, 2005).

4. CONCLUSIONS

The WC tools suffer rapid flank and crater wear leading to an ineffective machining process. Neither CVD (Al, TiN) coatings have provided good enough performance. The positive PCD tools suffer gradual increase of the crater wear leading to a deterioration of the surface roughness and increasing cutting forces. The neutral (0°) rake angle diamond tools, PCD and MCD, offer the best performance. Their higher cutting pressure on the rake surface of the tool, compared to the positive tools, results in a protective layer of stuck material in that face, i.e., the BUE. Consequently, the direct contact of SiC particles against the rake

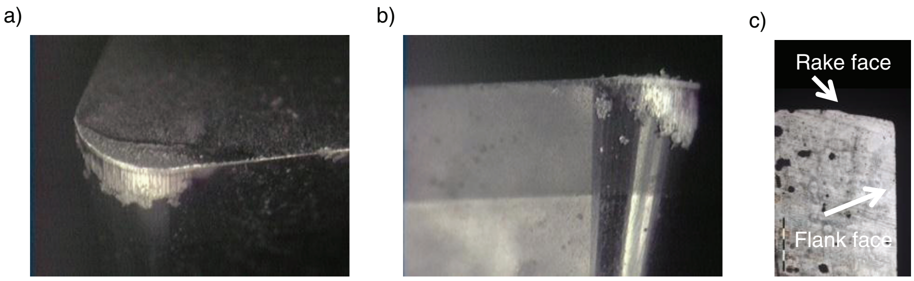

Figure 4. Tool wear in PCD tool with a positive rake angle (+6°) at 500 m min^{-1}.

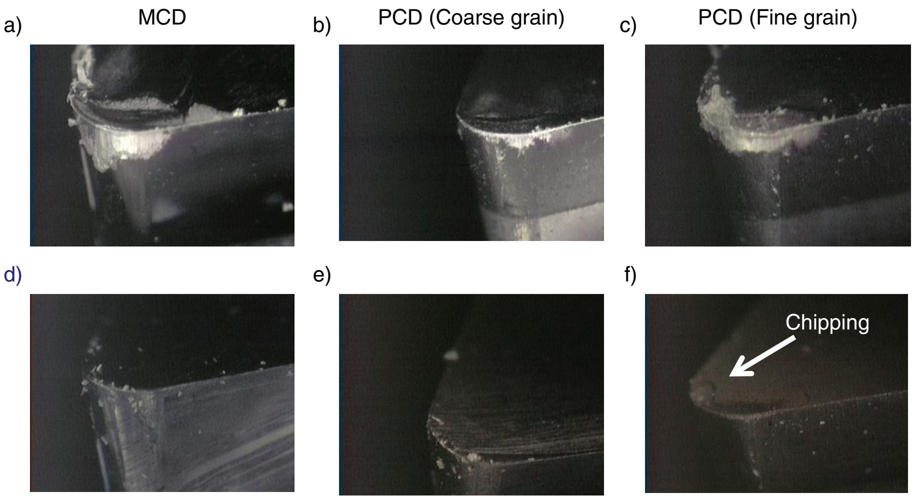

Figure 5. Top row, tools after machining. Bottom row, tools after chemical cleaning to remove the BUE. 400 m min^{-1}. Rake angle 0°.

Table 5. Cutting force and surface roughness values with fine grain PCD insert

Cutting Speed (m min⁻¹)	Initial BUE	Cutting Force (N)	Feed Force (N)	Radial Force (N)	Surface Roughness (µm)
400	No	60	22	25	0.90
400	Yes	62	21	28	0.93
500	No	70	22	27	1.49
500	Yes	62	14	28	1.01

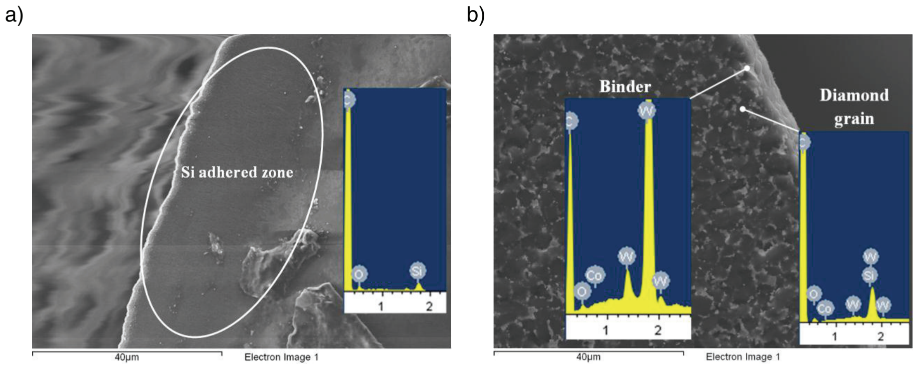

Figure 6. SEM image of the MCD surface : (a) where it can be seen a shaded area that contains silicon; (b) the fine grain PCD surface.

face of the tool is avoided reducing the crater wear. The conclusions of the comparison between fine grain PCD (2 µm), coarse grain PCD (10 µm) and MCD tools are:

Fine grain PCD tools suffer edge breakage at lower cutting speed than other cutting materials. It is believed that the reason is the tool material breakaway with the welded material of the BUE.

The volume of stuck material in the diamond tools is a consequence of the affinity between the surface free carbon atoms and silicon of the workpiece material. Using PCD tools is lower than that noticed with MCD tools. This is a consequence of the lower effective surface of the PCD tools due to the presence of bonding material.

Regarding the machinability of the material, the optimum cutting speed to obtain a suitable tool life is between 400 and 500 m min^{-1} using PCD tool with small grain size. This allows to avoid the abrasive wear in the tool and the minimization of the adhered material.

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