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Effect of Reinforcement on the Machining of Aluminium Matrix Composites Obtained by Powder Metallurgy

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Abstract. Evaluation of the machining behavior of an aluminium matrix composite was undertaken. The composites were produced by hot extrusion of powder mixtures - AA 1100 reinforced with 5 %, 10 % and 15 % (by volume) of SiC particles. Experimental evaluation of the machining behaviour of the composites was carried out with tools of different materials (cemented carbide, ceramic and polycrystalline diamond). The results showed that the reinforcement impaired machining, mainly due to tool wear. Only polycrystalline diamond tools gave satisfactory results in terms of tool life and cutting speed, compatible with industrial requirements.

Introduction

Composites are advanced materials that can be defined as "a material system made of a mixture or combination of two or more macroconstituents, that differ in morphology and / or composition and are essentially insoluble among them"[1]. Composite materials were initially developed for specific applications in the aeronautic and aerospace industries. However, due to advantages such as high mechanical strength and elastic modulous, improved high temperature properties, low coefficients of thermal expansion and better wear resistance, these materials have found a series of more prosaic applications today and are replacing conventional materials in many well established components or are under consideration for new ones.

In a report published by the University of Michigan's Office for the Study of Automotive Transportation (Delphi IX), increase in the number of applications for metal matrix composites (MMC) in North American cars is expected during the next decade (2000-2010)[2]. Among the motor components, the report foresees use of of MMC in connecting-rods and pistons to the extent of 3 % and 5 % respectively by 2007.

A typical example of the application of MMCs in the car industry is the development of cylinder liners made from composites consisting of aluminium alloys with fine alumina particles dispersed in the matrix[3,4]. Cylinder liners made from this composite material are shown in Fig. 1 and have overall mechanical properties comparable to those made of cast iron. An additional advantage of the MMC liners is a 60 % weight reduction.

MMCs are generally difficult to machine. They require longer machining times and the use of more expensive wear resistant tools. Machining has a strong influence on the productivity of components and on the final production cost. Machinability, a derived term, is related to the degree of machining difficulty of certain materials and can be defined as "a technological quantity that expresses by means of a comparative value (index or percentage); the machining characteristics of a metal, in relation to another material taken as a standard" [5]. Machinability is a parameter that has to be considered in the development of new materials that would eventually be subject to some type of manufacturing process like machining.

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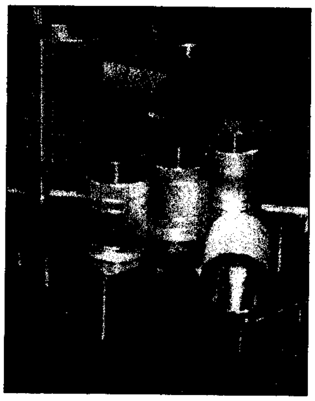


Figure 1. Cylinder liners made of aluminium alloy composites reinforced with fine alumina particles [3,4].

Experimental

Materials

The composite material used in this investigation had an aluminium matrix and was reinforced with silicon carbide particles. The composites were obtained by powder metallurgy and the production route has been described elsewhere [6]. AA 1100 aluminium powder used for making the composites had a median particle size of 22 μm. SiC particles with 6 μm median size was used to obtain composites with 0%, 5 %, 10 % and 15 % (by volume) of SiC.

Machining

Fourteen specimens 160 mm long and 31.75 mm in diameter were prepared for the machining tests. Three different types of tool materials were used: cemented carbide (CERMET); alumina based ceramic with addition of titanium carbide; and polycrystalline diamond (PCD). The inserts and tool-holders had the following characteristics: side rake angle (γ) = 0°; side-relief angle (α) = 11°; and position angle (X) = 90°, as shown in Fig. 2.

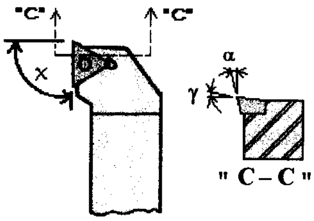


Figure 2. Illustration of geometric details of inserts and tool holders.

Equipment

A computerised numeric command (CNC) lathe was used. A programming routine in the language of the numeric command lathe was developed to carry out the tests. Four different cutting speeds were used for machining with carbide tools and only two different cutting speeds, for machining with the ceramic and diamond tools. The routine considered an initial block of roughing, for removing the aluminium layer used as canning during hot extrusion of the powder mixtures [6]. Once this layer was removed, the routine program considered regular stops for tool wear evaluation and change in cutting speed [7].

Procedure

The specimens were machined at cut depth (p), feed (f) and nose radius (r) of 0.875 mm, 0.1 mm/rot and 0.4 mm, respectively; according to standard ISO 3685 specifications (Fig. 3) [8]. The cutting speeds used were, 273, 229, 185 and 141 m/min, for machining with the carbide tool, and 273 and 229 m/min for machining with the ceramic and diamond tools. At each cutting speed, six stops were made for wear analysis. After each stop, the insert was removed from the support (tool-holder), to measure flank wear (Vb) and to register it using an optical microscope (Fig. 4).

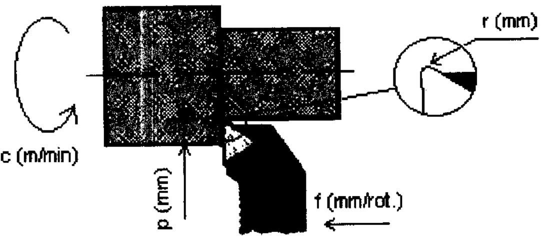


Figure 3. Schematic representation of the machining parameters used.

The worn cutting edge of the tool was substituted with a fresh one at each change in cutting speed, starting thereby, a new cycle of measurements. All the tests were performed with a 5 % aqueous cutting fluid, at a flow rate of 2000 l/h.

The tests allowed the wear of each tool material to be evaluated The results obtained with carbide tools were used for the determination of the machinability index of each material and the machining length method was used [5,9]. This is a relatively quick method that does not require large amounts of material. This method was chosen because of the limited amount of material available.

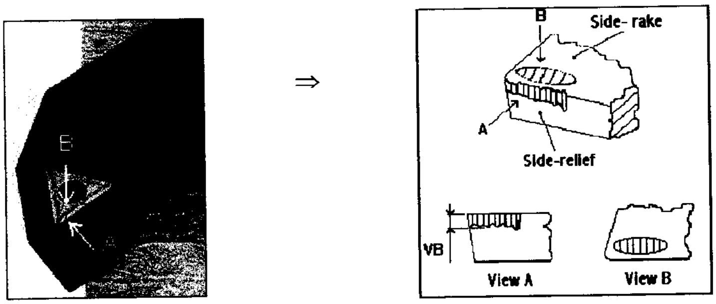
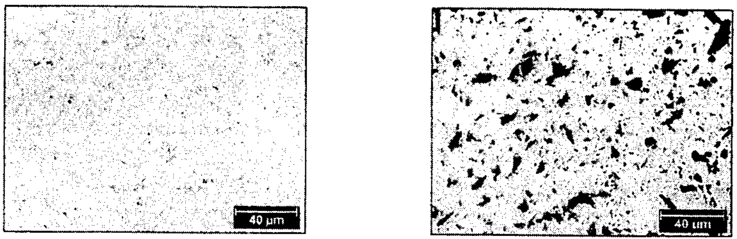


Figure 4. Schematic illustration of wear location. A - flank wear (side-relief) and B - crater wear (side-rake).

Results and discussion

Microstructural characterisation

In the material without reinforcement (Al/SiC 0 %), small voids and homogeneously distributed inclusions were observed. These probably had their origin in the powder mixing stage during material processing (Fig. 5 (a)). In the composite with 10 % reinforcement, SiC agglomerates were observed. These SiC agglomerates may have due to the differences in size between the aluminium and SiC powders (Fig. 5 (b)).

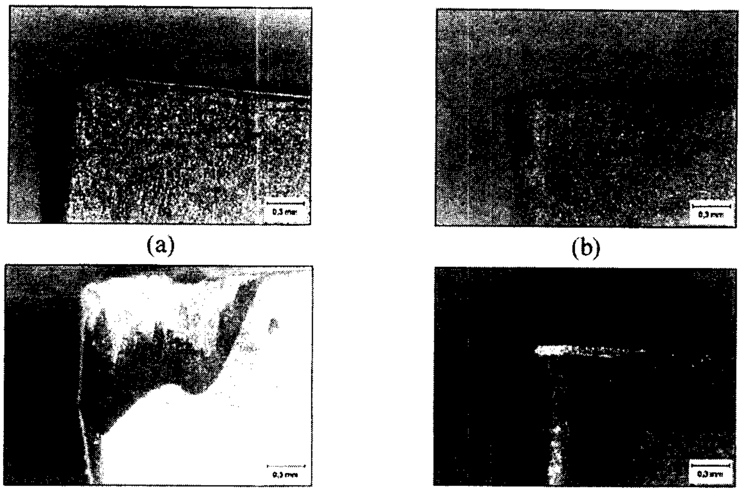


(a) (b)

Figure 5. Optical micrographs showing the microstructure of the composite material. (a) Al/SiC 0 % - transverse section showing aluminium and some dark particles, mainly oxides. (b) Al/SiC 10 % - transverse section showing SiC particles and agglomerates.

Machining and machinability

The machining tests showed that the addition of hard ceramic particles to the aluminium matrix affected considerably the machining characteristics of the material. In all the tests, the carbide tool exhibited the worst wear resistance, followed by the ceramic tool and finally, the diamond tool. The extent of wear of the diamond tool was negligible (Fig. 6). The carbide tool wear values were very high to be acceptable. Further, the resistance of the carbide, ceramic and diamond tools to wear decreased with increasing reinforcement volume fractions.



(a) (b)

(c) (d)

Figure 6. Aspect of tool surfaces subject to flank wear. (a) Fresh carbide tool. (b) Carbide tool after machining Al/SiC 0 % - Vc = 273 m/min. (c) Carbide tool after machining Al/SiC 10 % - Vc = 273 m/min. (d) Diamond tool after machining Al/SiC 10 % - Vc = 273 m/min.

The superior wear resistance of the diamond tool makes it evident that this tool material is the most adequate for machining abrasive reinforcement containing composite materials. In machining Al/SiC 15 % composite material, the diamond tool had a flank wear 22 times lower than that of the carbide tool, under identical conditions. Several other papers reported similar conclusions concerning the machining of similar materials [10-16].

Machinability

The machining length method indicates that, for a given cutting speed and a pre-established flank wear value (Vb = 0.6 mm in this investigation); there is a certain machined length in meters, that is related to the tool life. The machinability indices determined in this paper are based on the carbide tool wear as already mentioned.

In the case of composite materials, when the above concept was applied at each of the four cutting speeds used in the tests, (see Fig. 7 and Table 1, the former shows an example for Vc = 273 m/min.). It was verified that the machining length relationship was maintained in a certain range.

The results showed that the choice of Al/SiC 0 % (material without reinforcement) as a standard reference for determination of the machinability index was inappropriate. The wear generated in the tool by machining Al/SiC 0 % was very small. Therefore, extrapolation of these results to a tool life criterion equal to 0.6 mm (Fig. 7) was incorrect. Hence, the material with 5 % SiC was taken as the standard reference for the machinability index determination. Its machinability was taken as 100 %. The machinability of the material with 10 % SiC was 48 %, compared to the new standard reference (5 % SiC). This value was the mean value from data obtained at three cutting speeds, 273, 229, and 141 m/min. (Table 1). For the material with 15 % SiC, the machinability was 29 % and this value was the mean value for the three cutting speeds; 273, 229 and 185 m/min. The values for Al/SiC 10 % (Vc 185 m/min) and Al/SiC 15 % (Vc 141 m/min) were not considered as data were quite disperse (Table 1).

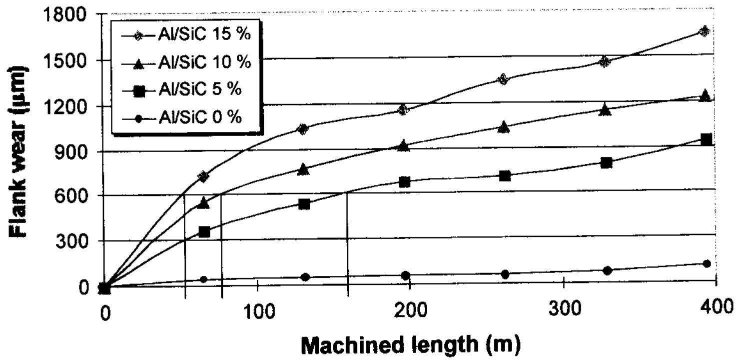


Figure 7. Evolution of tool wear along the machined length for composite materials with 0 %, 5 %, 10 % and 15 % of reinforcement. Carbide tool and cutting speed of 273 m/min. were used.

Table 1. Values of machined length for a flank wear (Vb) equal to 0.6 mm and their respective machinability index. Composite materials machined with carbide tool.

Material	Machined length (m)							
	Vc = 273 m/min		Vc = 229 m/min		Vc = 185 m/min		Vc = 141 m/min	
Al/SiC 5 %	160	100 %	199	100 %	224	100 %	298	100 %
Al/SiC 10 %	77	48 %	98	49 %	134	60 %	143	48 %
Al/SiC 15 %	52	33 %	54	27 %	60	27 %	58	20 %

The values obtained from the tests, were plotted on a logarithmic graph of cutting speed versus tool life (for a tool life criterion Vb = 0.6 mm), (Fig. 8). Appraisal of the results, according to Annex F, item F.2 - ISO 3685 [8], permitted the constants C and n of Taylor's equation, given in Equation 1 to be calculated. This equation allows the extraction of ideal values for cutting speed, which are in agreement with the expected tool life, or vice-versa, for the feed and cut-depth conditions used in the tests.

$Vc = C / t^n$ (1)	where: Vc is the cutting speed (m/min); C and n are constants; t is time (min).

For the graph shown in Fig. 8, n is the slope of the straight line and C is the cutting speed for a tool life equal to 1 minute. Consequently, for each case, a specific configuration of Taylor's equation is obtained as shown in Table 2. Thus, for a tool life of 15 minutes, the cutting speed was determined as shown in Table 3. The 15 minutes tool life was established as the reference value. It has been adopted by some toolmakers as a recommendation for the development of new products.

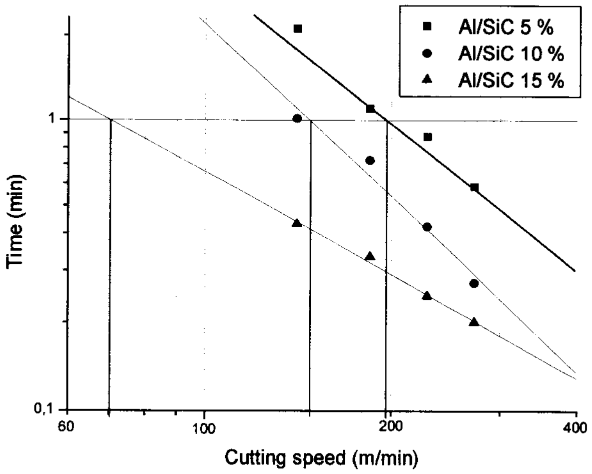


Figure 8. Logarithmic graph of the cutting speed versus tool life (Vb = 0.6 mm) for the composite materials with 5 %, 10 %, and 15 % SiC and machined with carbide tools.

From an industrial point of view, the results shown in Table 3, are considered extremely low. Tomac and Tønnessen [16] working with similar materials also obtained low cutting speed values, ranging from 20 to 50 m/min. They pointed out that the use of carbide tools was only applicable in the case of a small production lot.

Table 2. General forms of the Taylor equation for composite materials with different SiC volume fractions.

Al/SiC 5 %	Al/SiC 10 %	Al/SiC 15 %
$Vc = 190 / t^{0.50}$	$Vc = 142 / t^{0.51}$	$Vc = 75 / t^{0.81}$

Table 3. Values of cutting speed extracted from Taylor's equation for a tool life of 15 minutes for the carbide tool.

Al/SiC 5 %	Al/SiC 10 %	Al/SiC 15 %
Vc = 49 m/mim	Vc = 36 m/mim	Vc = 8 m/mim

The value of "n" is quite high for the three composite materials considered in this paper. This indicates that the variation in the value of the cutting speed has little influence on tool life. Other researchers [11,16] also arrived at similar conclusions when machining identical materials with carbide tools. If cutting speed, which usually has a large influence on tool life of conventional materials, has a reduced effect on composites, another factor has to be responsible for the drastic decrease in tool life in the case of composites. This factor is the presence of extremely hard and abrasive particles in the material, that is, the reinforcement.

Conclusions

- The results have shown that machining metal matrix composites with carbide tools is unacceptable from the industrial and production point of view. An acceptable tool life for carbide tools is only achieved at low cutting speeds.
- Diamond is the tool material that performed best. It was 22 times superior to carbide tool, under similar machining conditions.
- The reinforcement particles had a great influence on machining characteristics of composites. The SiC particles reduced the tool life drastically when machining parameters adopted for conventional materials were used. Application of Taylor's equation to data obtained during machining showed that variation of the cutting speed in the machining of composites had a reduced effect on tool life. The drastic reduction of tool life in this case, can be attributed to the presence of extremely hard and abrasive particles in the material.
- The machinability indices for composites with 10 % and 15 % SiC, upon taking the 5 % composite as a standard reference, was around 48 % and 29 %, respectively. These values are very low and indicate the difficulty in machining composites, compared to conventional materials.

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