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Effect of reinforcement coatings on the dry sliding wear behaviour of aluminium/SiC particles/carbon fibres hybrid composites

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ABSTRACT

Dry sliding wear of an AA 6061 alloy reinforced with both modified SiC particles and metal coated carbon fibres has been studied. SiC particles were used to increase the hardness of the composite while short carbon fibres are supposed to act as a solid lubricant. SiC particles were coated with a silica layer deposited through a sol–gel procedure to increase the processability of the composite and to enhance the particle–matrix interfacial resistance. The metallic coatings on carbon fibres were made of copper or nickel phosphorus which was deposited through an electroless process. The metallic coatings favoured the wetting of the fibres during processing and then dissolved in the aluminium matrix forming intermetallic compounds that increased its hardness. Wear behaviour of AA 6061–20%SiC and AA 6061–20%SiC–2%C was compared with that of the composites with the same reinforcement content but using coated particles and fibres. The influence that the modification of the matrix because of the incorporation of coatings on the reinforcements had on the mild wear behaviour was investigated. The wear resistance of the composites increased when carbon fibres were added as secondary reinforcement and when coated reinforcements were used.

1. Introduction

The wear behaviour of aluminium matrix composites exceeds by far than that of aluminium alloys because of the contribution of a hard ceramic phase incorporated in the aluminium matrix alloys. SiC and Al_2O_3 in the form of particles, whiskers or fibres reduce wear in aluminium alloys either by supporting the applied load or by restricting surface deformations at low loads and speeds under abrasive wear conditions [1]. However, these kind of brittle reinforcements are sensitive to cracking during severe wear conditions, reducing the wear resistance at relatively medium loads. Other problem associated with ceramic reinforcements is their tendency to be removed from the matrix. Under these conditions, fragment of reinforcement can act as a third body that increases the aggressiveness of the wear process [2].

Traditionally, the external addition of a lubricating substance is the easiest solution to the previous limitation. However, self-lubricating materials are more desired because they avoid the periodic application of external lubricants and allow the element to work at higher temperatures. Graphite is one of the most frequently used solid lubricants and its application as reinforcement in aluminium matrix composites has focused the attention of researchers [3–5].

The combination of hard ceramic particles, such as SiC ones, with self-lubricating reinforcements, such as carbon fibres, to produce a hybrid reinforcement system combines the main used strategies to improve the wear resistance of aluminium alloys. Some authors [6,7] have considered the manufacturing, the wear behaviour and the mechanical properties of Al/SiC/C composites, but most of these studies conclude that the main problem of these hybrid composites is associated with their fabrication processes and also with the role played by the matrix-reinforcement interfaces on the final behaviour of the composite.

Poor processability, especially for the most cost effective routes, i.e. casting, and low interfacial properties are usually consequence of the low wetting behaviour of SiC and graphite by molten aluminium. If high processing temperatures are used in the composites manufacturing, interfacial degradation reactions occur. These problems may cause the loss of particle and fibre reinforcements, and also favour the initiation of subsurface cracks at the interfaces, which is considered to be the main mechanism that reduces the positive contribution of reinforcements to the wear resistance of composites [8].

A common solution to both types of addressed problems can be adopted; it consists in the application of specially designed coatings on the reinforcements that improve wetting and avoid the formation of degradation products at the interfaces. However, different

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coatings must be used on SiC particles and carbon fibres because of their different nature.

Silica is one of the most successful coatings that prevent a direct reaction between SiC particles and molten aluminium, improving at the same time their wetting behaviour. Thin SiO_2 layers can be obtained either through direct oxidation of SiC particles [9] or via sol–gel [10]. This last alternative has shown that silica coatings on SiC particles produced by sol–gel methods can prevent the reactivity between the coating and molten aluminium; thus inhibiting the formation of degrading reaction products such as aluminium carbide and increasing the wettability during the Al–SiC composite casting manufacturing [11].

With similar purposes, many coatings of very different nature, i.e. metallic and ceramic ones, have been studied during the last years for the coating of carbon fibres. Among them, metallic coatings of nickel or copper are used to improve the wettability of carbon fibres by molten aluminium alloys. These metallic films have been deposited through many techniques, including electrolytic methods with current or by electroless techniques [12–14]. Previous studies have shown that electroless coatings deposited on short carbon fibres help to overcome the low wettability of graphite in molten aluminium while increasing at the same time the interfacial strength of the aluminium carbon composites [15].

The present research studies the effect on the wear behaviour of the incorporation and surface modification of two types of discontinuous reinforcements in an aluminium alloy: SiC particles and short C fibres. SiC particles have been coated by sol–gel SiO_2 with specific surfaces controlled by the heat treatments applied to the coatings [10,11]. Ni and Cu coatings produced by electroless have been deposited on carbon fibres, and both type of reinforcements have been analysed separately and combined in the same composite. The effect of the matrix/reinforcements interfaces and of the microstructure of the materials has been studied in all cases.

2. Experimental

2.1. Materials

The matrix of the aluminium composites fabricated consisted of an AA 6061 alloy supplied by ALPOCO in the form of powder with an average size of 75 μm and with the following nominal composition (wt.%): 95.5Al, 1.47O, 1.23Mg, 0.94Si, 0.43Cu, 0.38Cr and 0.062Fe. The reinforcements used were SiC particles (SiCp) and carbon fibres. SiCp had an average size of 26 μm and were supplied by Navarro SiC. Carbon fibres of the type AS4 were supplied by Hexcel Composites with an average diameter of 7.2 μm as continuous fibres. They were cut down using a grinder and fibres between 100 μm and 1 mm were fabricated with a mean length of 800 μm.

2.2. Sol–gel coating of SiC particles

SiO_2 coatings deposited on SiCp were produced by a sol–gel procedure using tetraetoxisilane (TEOS) as precursor, ethanol as solvent in an 11:1 rate, and distilled water in a molar rate of 5:1. The hydrolysis was carried out under acid pH conditions for 2 h at room temperature and the sol concentration was 204 g/L. Afterwards, the SiC particles were aggregated to the sol under agitation for 2 h and were left inside the solution for a further 30 min without stirring. Coated particles with fresh SiO_2 were washed in ethanol and dried in a furnace at 120 °C for 1 h.

In order to condensate the silica layer, coated particles were heat treated for 1 h at temperatures of either 500 °C or 725 °C, obtaining silica coatings with different structures and chemical characteristics. Isothermal desorption BET tests indicated that the 500 °C treated coating was highly porous, with a specific surface of 74.64 m^2/g, while the 725 °C treated one was much more compact, having a specific surface of 1.74 m^2/g.

2.3. Electroless Ni and Cu coatings of carbon fibres

Short carbon fibres were coated using a multiple stage procedure [16,17]. First, fibres were cleaned with acetone and afterwards were dried at 120 °C for 15 min. Prior to metallization, fibres were oxidized to create some surface roughness that favoured coating deposition. Surface metallization consisted of the following stages: the first stages, common for the two types of metallic coatings deposited (Cu and Ni), consisted of a sensibilization operation by immersion in a solution of 12 g/L of $SnCl_2{\cdot}2\,H_2O$ and 40 mL/L of HCl for 15 min in a ultrasonic bath, followed by a distilled water wash and activation by immersion in a 0.2 g/L $PdCl_2$ solution with 2.5 mL of HCl.

Metallization solutions were different for each coating material. For copper coatings, the solution composition was 10 g/L of $CuSO_4{\cdot}5\,H_2O$, 45 g/L of ethylenediaminetetraacetic acid (EDTA), 20 g/L of NaCOOH, 16 mL of HCHO at 36%, with NaOH added to adjust the pH to 13; this last stage was carried out by immersion for 3 min in the solution at 40 °C.

Nickel coatings were produced by using the following solution: 40 g/L $NiSO_4{\cdot}2\,H_2O$, 20 g/L $NaH_2PO_2{\cdot}H_2O$, 100 g/L $Na_3C_6H_5O_7{\cdot}2\,H_2O$, 50 g/L NH_4Cl with NH_3 used for pH control up to 9. This stage was carried out for 4 min at 80 °C.

2.4. Composite manufacturing

Composite specimens were prepared by means of melting tests of cold compressed (520 MPa during 5 min) powder pellets of 13 mm diameter and 3 mm height. Pellets of 1 g were constituted by a homogeneous manual mixture of AA 6061 powders with 20 vol.%. of SiC particles and 2 vol.%. of carbon fibres. Composites with coated and uncoated reinforcements were produced to evaluate the influence of coatings on the wear behaviour. Materials with only SiC or carbon fibres were also manufactured for comparative purposes. Melting tests were carried out on compacted pellets in a vacuum furnace (4×10^{-5} mbar) at 750 °C for 30 min. The different types of composites manufactured are described in Table 1.

2.5. Wear tests

The pin-on-disc method was tested on grounded composite specimens with a load of 10 N and sliding velocity of 0.08 m/s up to a total sliding distance of 150 m. The counterface was a 6 mm diameter ball made of SAE 1042 quenched steel.

The total weight of three specimens for each type of composite was measured before and immediately after the wear test. Volume loss was determined for each specimen from the penetration of the pin inside the composite surface and it was continuously measured using a LVDT. The friction coefficient was continuously recorded during the test.

Table 1
Manufactured composites and codes used for their identification.

Code sample	SiC coating	C fibres coating
SiC	Uncoated particles	–
500 SiC	Sol–gel treated at 500 °C, 1 h	–
725 SiC	Sol–gel treated at 725 °C, 1 h	–
SiC/C	Uncoated particles	Uncoated fibres
500 SiC/Ni–C	Sol–gel treated at 500 °C, 1 h	Ni coated fibres
500 SiC/Cu–C	Sol–gel treated at 500 °C, 1 h	Cu coated fibres
725 SiC/Ni–C	Sol–gel treated at 725 °C, 1 h	Ni coated fibres
725 SiC/Cu–C	Sol–gel treated at 725 °C, 1 h	Cu coated fibres