Revista de metalurgia

Fabrication and tribological properties of Al reinforced with carbon fibres(•)

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Abstract

The present work studies the manufacturing process of Al reinforced with Carbon Fibres (CF) by "Squeeze Casting", establishing the variables for obtaining an acceptable product with little Al_4C_3 at the interface. Friction and wear tests are performed and the necessary conditions for the formation of a tribofilm are established. The tests show an increasing resistance to abrasion due to their own wear mechanism. Certain design criteria for those components subjected to friction are recommended in order to maximise the mechanical performance of the tribological system.

Keywords

Carbon Fibres. Metal matrix composites. Squeeze casting. Friction. Wear. Tribofilm.

Fabricación y propiedades tribológicas de Al reforzado con fibras de carbono

Resumen

Este trabajo estudia el proceso de fabricación de composites Al reforzado con fibras de carbono mediante la técnica "*Squeeze Casting*", estableciendo las variables para obtener un producto aceptable que tenga poca cantidad de Al_4C_3 en la interfase. Se han realizado ensayos de fricción y desgaste y se han establecido las condiciones necesarias para la formación de la tribocapa. Se muestra la alta capacidad de resistencia a la abrasión de las piezas producidas debido a su propio mecanismo de desgaste y se recomiendan ciertos criterios de diseño para componentes mecánicos con el fin de optimizar las prestaciones mecánicas en un sistema tribológico.

Palabras clave

Fibras de carbono. Composites de matriz metálica. "*Squeeze casting*". Fricción. Desgaste. Tribocapa.

1. INTRODUCTION

The term Squeeze Casting is applied to various processes whereby pressure is imposed on a solidifying system, usually via a single hydraulically activated ram. The technique has certain advantages, such as the fine microstructure and low porosity levels in the product. It offers considerable potential for producing fibre-reinforced metals: bad wetting is overcome and shrinkage pores are eliminated so that high production rates and near-net shaping of parts are possible.

Due to its low cost, low density and ease of manipulation, aluminium is the most studied metal matrix for applications at temperatures below 450 °C. Carbon fibre is the most attractive reinforcing material due to its low density and high modulus, strength and thermal conductivity. Among composites, aluminium-carbon fibre (Al-CF) is considered one of the most promising composites. However, if the molten aluminium remains too long in contact with the carbon fibre during the fabrication process, the tensile strength of the final Al-CF composite is reduced due to the formation of aluminium carbide at the interface between the aluminium and the carbon fibre, although reaction is not detected below 550 °C[1]. For this reason squeeze casting is considered suitable for the production of this kind of composite because it allows a short contact time between the matrix and the fibres at high temperatures. In this case, the amount of aluminium carbide formed is minimised.

The infiltration process has been modelled mathematically by Mortensen for both pure metals[2] and alloys[3], while other authors, such as Yamouchi[4] and Long[5], have developed models that take into account factors based on the wetting of fibres by molten metals[6].

(•) Trabajo recibido el día 21 de febrero de 2000 y aceptado en su forma final el día 19 de septiembre de 2000.
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One of the most critical parameters in process design is the preform quality. Although De Bondt[7] obtained uniform preforms with a controlled volume fraction by using inter-spacing particles, it is more frequent to use preforms of short fibres with a high aspect ratio (length much larger than diameter) and a random orientation, since it is much simpler and less costly. The effect of compaction on this type of fibre preform and the deterioration of the preform during infiltration has been studied by Clyne[8] and Yamouchi[4].

The manufacturing process strongly influences the performance of the composite once in service. As regards mechanical resistance, it is generally accepted that reinforcement with ceramic fibres increases the ultimate tensile strength but decreases the yield strength and ductility[9]. However, this is not always the case, because it depends on the combination of materials used and the manufacturing process followed.

Rather than for their mechanical behaviour, Metal Matrix Composites (MMC's) have found applications because of their tribological properties. Their resistance to wear is a clear advantage over other materials[10]. This also happens when low volume fractions of reinforcement are used.

Different reinforcements have different wear mechanisms. For example, if the reinforcement is a hard ceramic material (such as the commonly used SiC_P, Al_2O_3), counterpart wear occurs through abrasion by the hard particles, while if the reinforcement is carbon fibre or another graphite-based material, tribological characteristics are improved by the formation of a very thin layer of graphite which acts as a solid lubricant at the interface. In this case, the worn part is the composite material and the counterpart hardly suffers any wear if it is sufficiently hard. Such a composite is suitable in a tribological system when the interchangeable part is made of this material.

This tribofilm can be observed and analysed by different procedures. Using Quinn's "twinning model"[11], for example, it is possible to determine the friction coefficient based on the slope between the graphite plates and the surfaces which are subjected to friction forces.

MMC's using graphite-based particles as reinforcement were investigated by Rohatgi[12], who studied many types of alloy and particle morphology combinations, together with the influence of the volume fraction on film thickness. Carbon fibre reinforced MMC's were studied by Amateau[13], who proposed a delamination theory for application to such a material in acceleration and deceleration intervals. Saka et al.[14] studied the effect of fibre orientation on tribofilm formation. Amateau[13] studied carbon fibre produced from polyacronitryl (ex-PAN) and observed that the low modulus type C-fibre showed better tribological behaviour. In a study of the pitch type, Saka also demonstrated the good behaviour of this composite. However, little attention has been paid to other fibre types, such as Vapour Grown Carbon Fibre (VGCF), or to the surface characteristics (finishing operations, roughness, etc.), which are very important in tribofilm formation.

In the present work, we study the manufacturing process of an Al-CF composite, and establish the variables for obtaining an acceptable product. Friction and wear tests are performed and the conditions necessary for tribofilm formation are established. In addition, we study that these MMC's support much higher pressure and velocity limits than other materials, which often present severe wear through seizure under similar conditions. They also show an increasing resistance to abrasion due to their own wearing mechanism. At the end of the paper, certain design criteria for components subject to friction are recommended in order to improve their behaviour and to maximise the mechanical performance of a tribological system.

2. SQUEEZE CASTING APPLIED TO Al-CF

The manufacturing process of this type of composite has certain characteristics which are important to take into account before the conditions applied to it are established. In the absence of computational models, some guidelines based on the physical mechanism of the high-pressure infiltration process follow:

- The process should be performed as quickly as possible. The reaction rate at the matrix-fibre interface is very high. The reaction products are prejudicial to the mechanical performance of the product. Al_4C_3 is crystalline and cracks easily. The chemical reaction to form this carbide is very slow for temperatures below 540 °C[1]. Squeeze casting is the most suitable technique since because it reduces the contact time between the molten metal and the fibre at high-temperature (more than 660 °C), thus considerably reducing the amount of carbides in the composite.

- The infiltration of preforms by the liquid metal is an irreversible process which occurs in a pressure range that depends on the materials to be mixed. To facilitate fibre wetting, the pressure can be increased[6], an alloy can be used instead of a pure metal[3], vacuum can be applied[6], or the fibre can be coated with Ni[15], although the last two options increase the complexity of the process and hence the cost.

It is important to characterise the preform (volume fraction, diameter, length and direction of the fibres) since the quality of the final product depends on the uniformity of these variables. Moreover, it is important to take into account the rigidity of the preform because compression during the infiltration process leads to an increased volume fraction in the final composite.

- The internal geometry of the preform at microscopic level is complex; there may be regions without infiltration, due to the high volume fraction and to the fact that the preform has very high porosity.
- Another important factor in the manufacturing process is the temperature of the different components. Carbon fibres oxidise at about 400 ºC and the aluminium liquid creates a small protective slag due to the surface oxidation of the molten metal.

The composite manufacturing technique used in the present work is a kind of squeeze casting. A fibre preform is placed in a crucible, into which liquid aluminium is poured and a high pressure is applied through a ram that provokes the infiltration. When infiltration is complete, the piece is extracted and cooled quickly. This is the Al-C composite. A critical step in the process, which is depicted in figure 1, is the manufacture of the preform from the VGCF fibres. Microscopic observation shows great variability in the diameters, although the fibres are not agglomerated in tows, which makes dispersion easier. However, the exPAN fibres are supplied in rolls, which are cut to produce tows of short fibres. To make the preform, short fibres are dispersed in a solution of sodium silica, leading to their random deposition of the same on a container.

The set of fibres is pressed until the predetermined volume fraction is reached; the

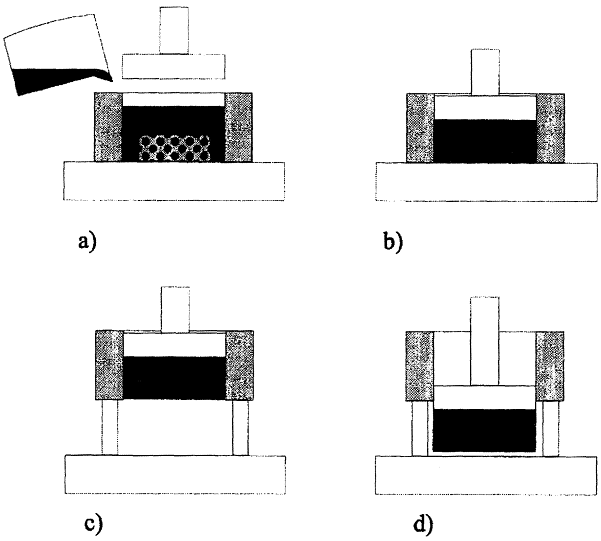

Figure 1. Squeeze Casting process: a) Pouring; b) Infiltration; c) and d) Extraction

Figura 1. Etapas del proceso Squeeze Casting: a) Colada; b) Infiltración; c) y d) Extracción

preform is then dried in a furnace for 3 hours. The volume fraction reached at this stage is about 20 %, but after infiltration, due to the high pressure, the preform is compressed and the volume fraction increases to 40 % or even to 60 % in some zones.

The following infiltration variables can now be set:

- Volume fraction of the preform. During infiltration this value is doubled, but if it increases more, there is a risk that infiltration will be incomplete.
- Temperature of the preform, mould and aluminium at the beginning of the process:
  - The molten metal must be sufficiently overheated, so that it does not solidify at the moment of contact with the crucible or the fibre.
  - The preform must be heated to reduce the effect of solidification during contact, but not too high to avoid oxidation of the fibre.
  - The crucible must be heated to avoid cooling of the liquid metal, although there are practical limitations, since the crucible forms part of a system with difficult access to the heaters.
- The chemical reaction, the temperature gradient, the solidification and, therefore, the microstructure of the composite, depend on the operation times.
- Three time intervals have to be controlled:

- The time from the beginning of pouring into the crucible until the application of pressure by the piston, which must be kept to a minimum in order to reduce the quantity of Al_4C_3 formed.
- The time during which pressure is applied and during which infiltration and solidification occur.
- The time during which the piece is extracted and cooled.

The maximum available pressure is used. As a practical limitation, there must be a compromise between the pouring time and the pressure applied to the liquid metal, since, depending on the pressure supplied by the hydraulic pump, the smaller the diameter of the hydraulic cylinder used is, the faster the process will be, considerably reducing the force applied to the piston.

After cooling, the thermal treatment is continued in order to relax residual stress and to render the microstructure more uniform.

As a summary, the values of the parameters used in this manufacturing process are:

- Preheating of the preform: 300 ºC
- Preheating of the crucible: 300 ºC
- Temperature of molten aluminium: 760 ºC
- Infiltration pressure: 22 MPa
- Time of pouring: 20 s
- Pressurisation time: 10 s
- Extraction time: 20 s

Different materials were obtained with the same mean volume fraction of 40 %, but using different type of fibres:

- Al-VGCF. Pure aluminium (99 %) and Vapour Grown Carbon Fibres.
- Al-exPAN. Alloy of aluminium (5 % Si) with high modulus exPAN carbon fibres.

3. STUDY OF THE PRODUCT

The MMC's obtained through this process were analysed metallographically by Light Optical Microscopy (LOM) and Scanning Electron Microscopy (SEM). The tribological properties were also studied.

From figures 2 and 3, which depict samples with a similar volume fraction, the following characteristics can be observed

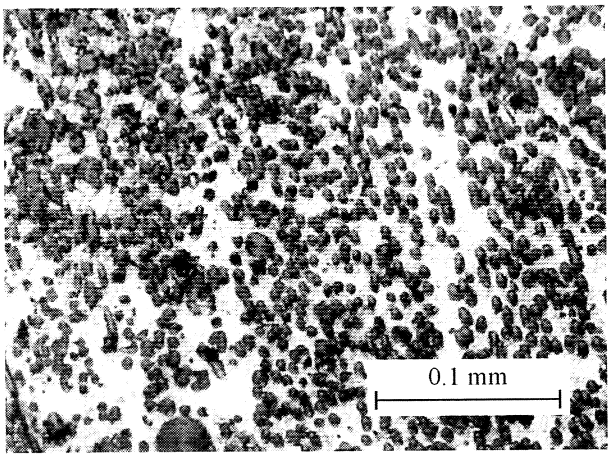

Figure 2. Metallographic image of Al-VGCF

Figura 2. Metalografía de Al-VGCF

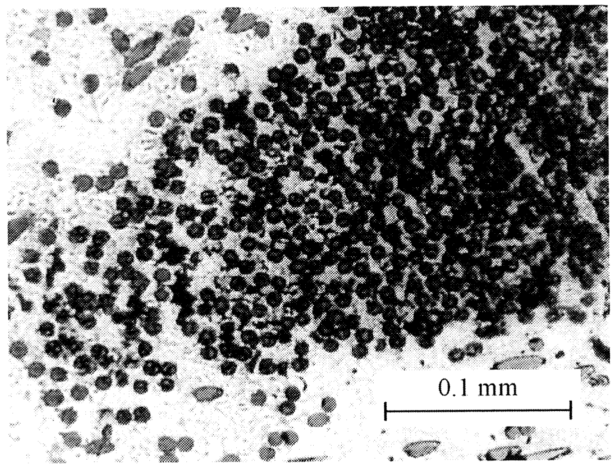

Figure 3. Metallographic image of Al-exPAN

Figura 3. Metalografía de Al-exPAN

- The fibre diameter of the composites with VGCF varies, between 1 µm and 25 µm, as shown in figures 2 and 4. However, the distribution and direction of the fibres can be considered sufficiently uniform.
- The exPAN fibres vary very little in diameter (by around 5 µm), as shown in figures 3 and 5. However, the fibres are very segregated, since they are supplied in bundles and are not able to disperse during the manufacture of the preform.

No Al_4C_3 was detected in either composite, which indicates that the speed of the process was sufficient to avoid the appearance of this undesirable product. Infiltration was complete, except in certain areas of the bundles of exPAN fibres, where the molten metal could not totally penetrate.

To determine the strength of the material a three point bending test was performed, according

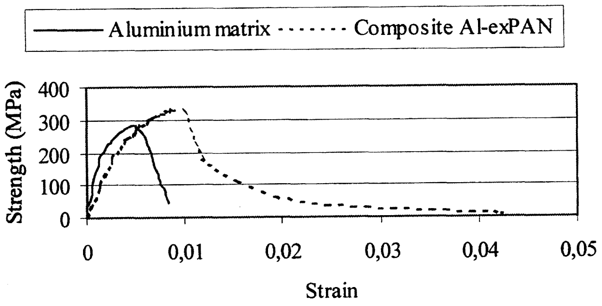

Figure 4. SEM image of Al-VGCF fracture

Figura 4. Imagen SEM de la fractura de Al-VGCF

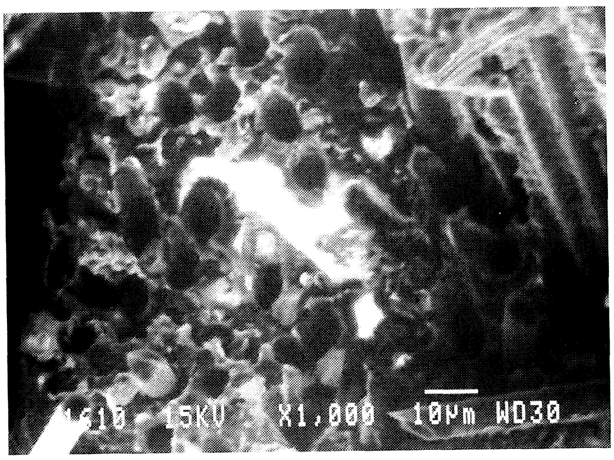

Figure 5. SEM image of Al-exPAN fracture

Figura 5. Imagen SEM de la fractura de Al-exPAN

to the standard ASTM E855-84 METHOD B for metallic materials. In most cases the strength was slightly below that of the matrix material. However, in some cases both the strength and ductility where higher (see figure 6), which is usual since an increase in strength is usually combined with a loss of ductility.

The UTS of the resulting samples vary due to the following reasons: the residual stresses originating from the quick cooling, the porosity arising from lack of infiltration, separation between fibres that produces weak areas, and the low adhesion strength of the fibre to the matrix. The last point can be observed by fractographical analysis, which reveals pull-out, especially in the Al-exPAN composites (Fig. 5) due to the lack of infiltration into the tows.

Figure 4, shows the fracture surface of an Al-VGCF sample. Note how the fibres have broken in the same plane as the matrix, indicating good fibre-matrix adhesion.

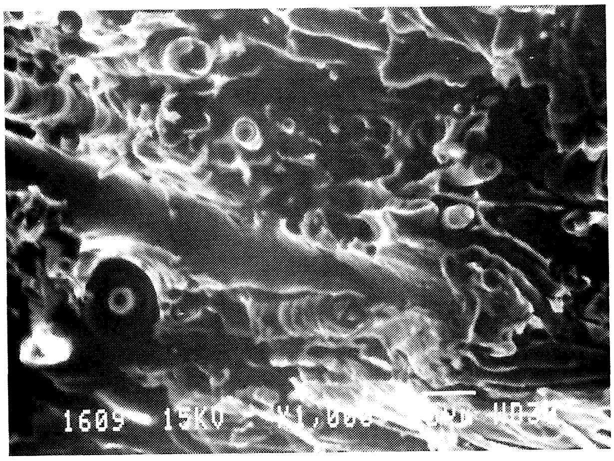

Figure 6. Three-point bending test of Al 5% Si (UTS_{max}=282.1 MPa), and its composite with exPAN (UTS_{max}=331.4 MPa)

Figura 6. Ensayo de doblado por 3 puntos de la matriz de aluminio con 5%Si (UTS_{max}=282.1 MPa) y su compuesto con exPAN (UTS_{max}=331.4 MPa)

4. TRIBOLOGY OF THE PRODUCT

The produced samples show good mechanical properties although a total reliability has not been obtained yet. The tribological properties seem more promising in the short term since, in addition to their high specific resistance, the carbon fibres degrade into graphite powders when they are worn, adhering to the sliding surface to form a third body. This tribofilm between the two surfaces acts as lubricant and reduces the friction coefficient (graphite is a widely used solid lubricant) and the wear coefficient (stopping the wear mechanisms of abrasion and adhesion) between the surfaces.

During tribological tests, several aspects must be considered:

- Wear mechanisms occur on a very small-scale for their study and can only be observed at microscopical level, so that statistical approach is needed.
- A multitude of variables are involved in the wear mechanism[16], but only the most important have been chosen for study.
- A wear mechanism does not appear in isolation, but coexists with other mechanisms. In dry contact intervene, for example, physical phenomena such as abrasion, oxidation of the surfaces, local heating, etc.
- There is no universal test system of wear. The results cannot easily be extrapolated to a real situation. The contact geometry, the complex tensional fields generated, vibrations and other

environmental features such as temperature, humidity, etc., are very difficult to simulate.

- The appearance of a third body makes the study more complex. However, it is necessary, in many cases, to reduce the wear.

The composites obtained have been tested in a pin-on-disk tribometer, which is represented in figure 7. The test fulfils the requirements established by the ASTM G99-90 standard.

The pin of composite material (Fig. 8) is a rectangular prism, which is supported in the tribometer so that both edges form an angle of 90º. It is placed perpendicular to the disk of cemented steel (hardness 55 HRC).

Tribological tests were carried out with normal forces of 1 N, 2.5 N and 5 N, and different finishes on the disk, which was grounded with different grain sizes of SiC to provide the following surface roughnesses R_a: 0.17, 0.12, 0.07, 0.04 μm. The average friction coefficient (in steady state running) for each of the tested conditions was obtained. The range of speed studied was small because of limitations of the tribometer. Two speeds were applied, 0.15 m/s and 0.3 m/s.

In the test involving Al-exPAN no tribofilm was formed, and the coefficients of friction and wear were similar to those of the matrix aluminium. The worse behaviour of this composite was due to the graphitic structure of this type of fibre, which is not transformed into graphite powder. Similar phenomena were observed by Amateau et al.[13]. When tests were carried out in other reference materials, such as steel and brass, none could withstand the high pressures applied to the pin, resulting in seizure. Therefore, the test described was only performed on the composite Al-VGCF, because it alone could withstand these conditions of pressure and speed.

Below, we describe how the friction coefficient varies as a function of load and surface roughness, for different test speeds. When the tribofilm is

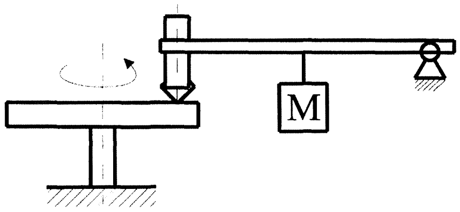

Figure 7. Diagram of tribometer

Figura 7. Esquema del tribómetro

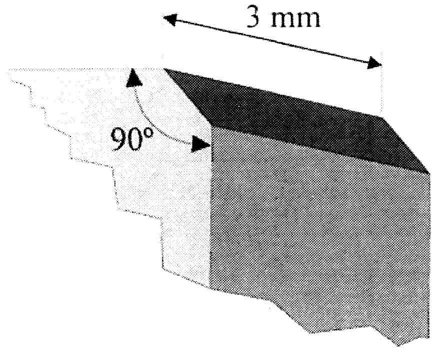

Figure 8. Pin shape

Figura 8. Forma del pin

formed, the friction coefficient is always about 0.4. In the range of parameters studied, it can be deduced that the friction coefficient falls when the load and surface roughness rises. In most cases, the friction coefficient increases with speed. Therefore, the tribofilm is formed when a high load is applied and the surface roughness of the disk is enough.

From figures 9 and 10 it can be observed that, for a very rough surface finish, the friction coefficient decreases when the load is increased. This shows the influence of the roughness on tribofilm formation. The increase in the friction coefficient when the speed is increased is possibly due to local heating.

This tendency changes for lighter loads, when the friction coefficient increases with increasing loads. At high speeds, however, the load has less influence on the friction coefficient, as can be observed in figure 10.

On the disk polished with a mirror finish (surface roughness of Ra = 0.04 μm), the tribofilm is not well formed and the friction coefficient are

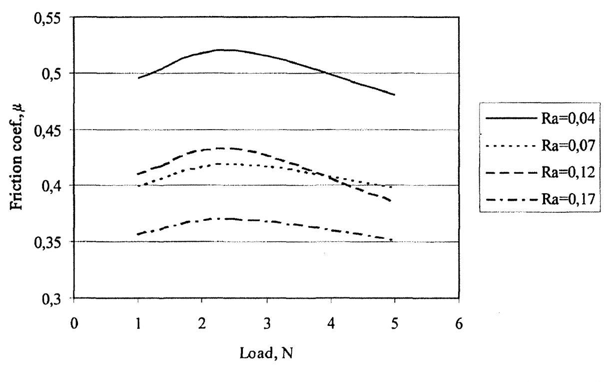

Figure 9. Variation of friction coefficient with load, v= 0.15 m/s

Figura 9. Variación del coeficiente de fricción con la carga, v= 0.15 m/s

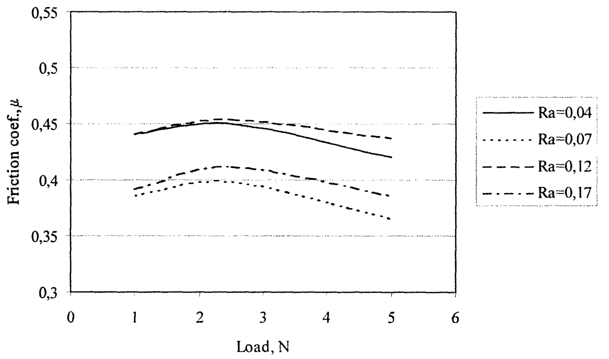

Figure 10. Variation of friction coefficient with load, v= 0.30 m/s

Figura 10. Variación del coeficiente de fricción con la carga, v= 0.30 m/s

very high. In this case, the load has little influence on the value of the friction coefficient.

Several pins were subjected to a wear test in the pin-on-disk tribometer. Periodic measurements of the worn volume on steel disks were made with surface finishes of Ra=0.17 μm, Ra=0.12 μm and Ra=0.04 μm at a speed of 0.2 m/s, and two loads of 2.5 N and 5 N. The worn volume was measured by image analysis after every 1000 m of sliding distance. Figure 11 shows a calibrated photograph, in which the area of the triangle ABC was measured. The results are given in figure 12. Multiplying the area by the width of the pin (3 mm) gives the wear volume. A pressure of about 15 MPa in the final period of the test was calculated by dividing the load by the contact area.

When the contact area increases, the pressure decreases and the wear volume ratio maintains constant. In addition, it was seen that the variation in worn volume with wear distance was linear which justifies the use of Kragelsky's wear coefficient:

$$K = \frac{V}{N \cdot L}$$

where V is the worn volume, N is the normal load and L is the sliding distance.

When measuring the worn volume, the initial flattening of the edge and formation of the tribofilm, which occur in the first few meters of sliding, were discounted. At this stage, the worn volume is greater as roughness and load increasing. The reason for this large initial wear is the irregular surface at the start and the wear of the pin as abrasion fills the holes. In figure 13 a delaminated matrix is observed because of the small volume

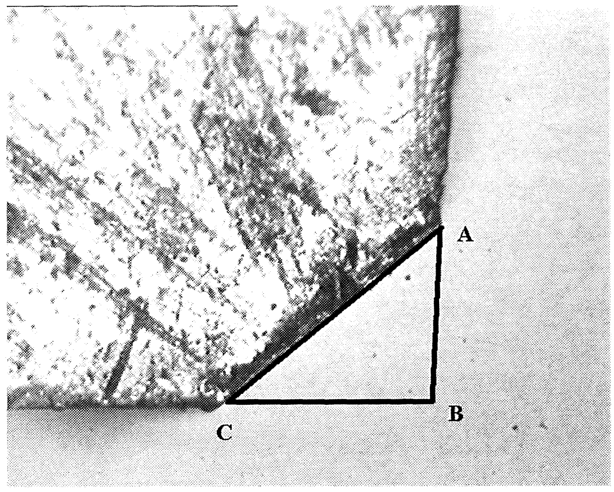

Figure 11. Measurement of wear with image analysis

Figura 11. Medida del desgaste con el analizador de imagen

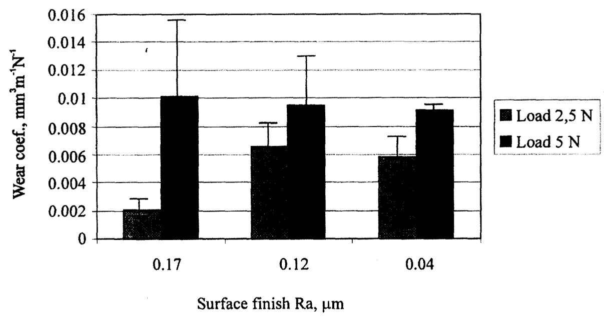

Figure 12. Wear coefficient for different loads and surface finishes

Figura 12. Coeficiente de desgaste según la carga y la rugosidad superficial

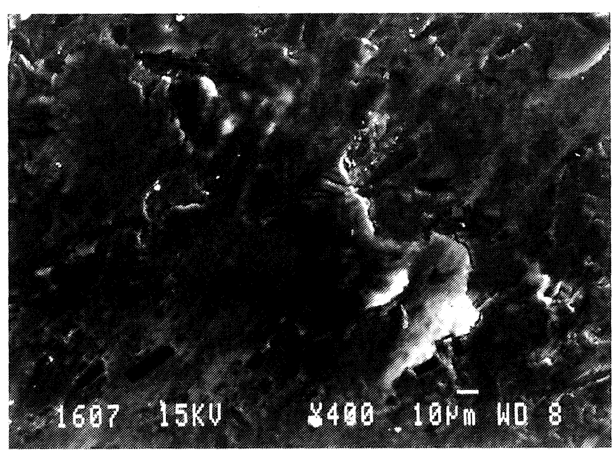

Figure 13. SEM image of the tribofilm and matrix delamination on the pin of Al-VGCF

Figura 13. Imagen SEM de la tribocapa y la delaminación sobre el pin de Al-VGCF

fraction in this zone. However, most surface is covered by a thin film of graphite which acts as a lubricant (Fig. 14). Figure 15 shows a pin of

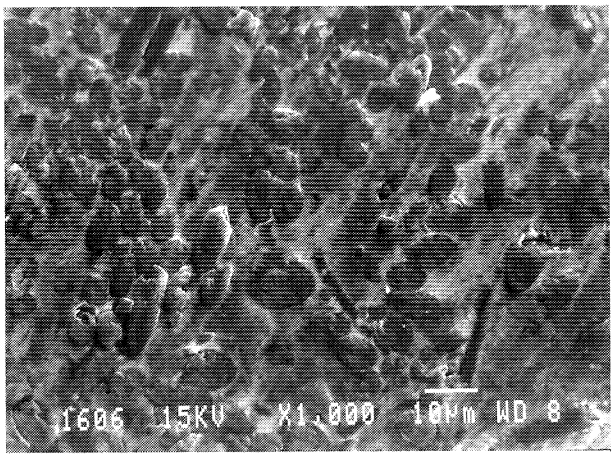

Figure 14. SEM image of the tribofilm formed on the pin of Al-VGCF

Figura 14. Imagen SEM de la tribocapa sobre el pin de Al-VGCF

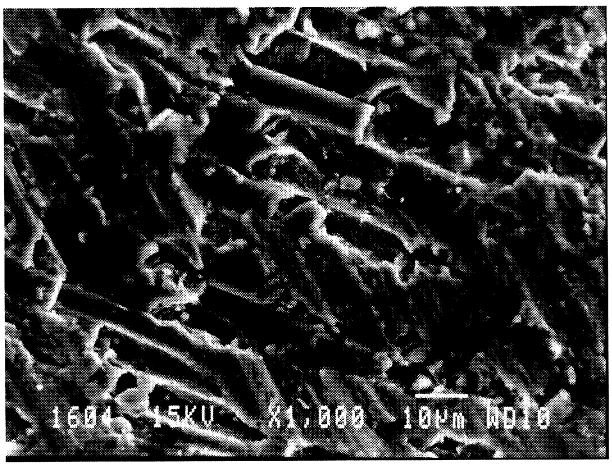

Figure 15. SEM image of the tribofilm formed on the pin of Al-exPAN

Figura 15. Imagen SEM de la tribocapa sobre el pin de Al-exPAN

Al-exPAN composite, where the matrix material adheres to the disk, and the degraded fibre does not cover the matrix as in the case of Al-VGCF.

5. DISCUSSION

The properties of an MMC are superior to those which could otherwise be obtained with the element alone. This can be seen from figure 6, where the composite has better in strength and ductility than the base aluminium alloy.

Figure 14 shows that a tribofilm is formed on Al-VGCF through degradation of the graphite of the carbon fibre, whose residues adhere to the surface of the matrix of the composite as well as to the surface of the disk, thus changing the colour of both surfaces (Fig. 12). In steady state, the fibre is degraded and covers part of the surface of the matrix, while plastified zones of aluminium are formed in small points (Fig. 13). The wear mechanism is determined by the roughness and relative hardness of the surface of the disk against which the pin slides. The initial wear mechanism is abrasive, the roughness of the hard material (in our case a steel disk) breaking off microchips from the composite material and filling the valleys of the roughness until they are full. At the same time, the pressure between the disk and the pin deforms the top of the pin plastically because it cannot sustain the pressure. If sufficient volume is not lost due to abrasion, it will be ploughed on the surface resulting in severe delamination, until a sufficient contact surface is created to sustain the load.

Thereafter, the wear curve decreases when the tribofilm begins to be formed as consequence of degradation of the carbon fibre in the form of graphite, until it is stabilised once the tribofilm is completely formed (see figure 14).

This process is similar to that which occurs in a grinding operation. In the actual case studied, due to the very high pressure at the beginning, there is the production of abrasion in the contact zone as a result of the roughness of the disk. When the valleys of the roughness are filled so that the contact surface increases, the pressure is reduced, until no more abrasion is produced. To form a good substrate on the disk covered by the tribofilm, certain pressure threshold must be surpassed for the carbon deposited in the valleys to be sufficiently compact and stable. This explains why the friction coefficients obtained with polished surfaces are greater than that obtained with coarse surfaces, since the tribofilm cannot adhere well to the disk. This is due to the absence of surface roughness.

The wear mechanism in the pin, therefore, consists of a succession of steps:

- Loss of material from the matrix by delamination.
- Degradation of the fibre that has been lightly exposed and scattered on the surface of the matrix and of the disk to form the tribofilm, thus avoiding direct contact between metals and reducing the friction and wear coefficient.
- Loss of the tribofilm and exposure of the matrix, leading to metallic delamination.

Thus, the wear mechanism is really a mixture of abrasive and adhesive wear.

The whole contact area does not suffer each of these steps simultaneously. Rather, they occur locally, thus preventing completely separation of the matrix and tribofilm. The duration of the tribofilm formed on the composite material (second step) mainly depends on the quality of adhesion of the graphite to the disk.

The surface roughness plays an important role in the formation of this substrate on the disk. The grooves of rough surfaces which are perpendicular to the direction of the movement favours the filling of the troughs with debris. On the other hand, when the grooves are along the same direction as the movement, very little deposition is observed.

On one hand, the degree of roughness is important, as can be observed from the wear tests carried out for the different roughnesses of the disks. For the disk with a finish of Ra = 0.17 μm (Figs. 9 and 10), the friction coefficient decreased with increasing loads, because higher loads facilitate adhesion of the graphite on the substrate and therefore the stability of the tribofilm. The roughness must be sufficiently high for the substrate to adhere well, keeping the friction coefficient at a value below 0.4. The effect of speed is much less pronounced. There tends to be a slight increase in the friction coefficient with increasing speeds. This may be due to the vibrations originated from the different friction coefficients at different points of the contact path.

When the roughness of the disk is Ra=0.12 μm, the tribofilm is of worse quality than in the previous case, due to the smaller valleys, to which the tribofilm must attach. As a rule, the friction coefficient decreases as the load increases from 1 N to 2.5 N, because the higher pressure facilitates the adhesion of the tribofilm on to the disk.

With a roughness of Ra=0.07 μm, the friction coefficient grows to 0.44, which is significantly above the values obtained in the previous cases. In this case, the friction coefficient increases with the load because of the difficulty which the tribofilm has in order to adhere to this surface. The load, therefore, does not contribute to improving the establishment of a tribofilm, while the increases in load lead to an increase in the friction coefficient.

With respect to the disk with finely polished surface (Ra=0.04 μm), the friction values are higher, since it is more difficult to form the tribofilm.

More interesting is the wear coefficient obtained for different surface roughness values and loads (Fig. 12). For a high surface roughness and light loads, the substrate is well formed, thus reducing not only the friction but also the wear coefficient due to the relationship that exists between the surface roughness and formation of the tribofilm.

6. CONCLUSIONS

In the present work we describe the manufacturing process of aluminium matrix composites with carbon fibre, and the designing of squeeze casting equipment for their production. During the process, a preform of carbon fibres is infiltrated at a pressure of 22 MPa, so that the composites have no pores, and the microstructure is of small grain size.

In order to avoid mechanical degradation of the reinforcement by chemical reaction, several recommendations must be followed: minimum contact time between molten metal and fibre, and maximum cooling rate of composite after solidification. Several infiltrations were carried out using different parameters for the production of two types of composite (Al-VGCF, and Al-exPAN).

When high pressure friction tests were carried out on steel, brass and Al-exPAN seizure resulted. It was seen that the tribological properties of the Al-VGCF depend on the quality on the tribofilm. In order to produce a stable tribofilm that last the life of the composite, it is necessary the operation parameters to be perfectly controlled for the initial stages of the formation of substrate on the surface of the disk. Besides a minimal volume fraction of reinforcement[12], the following recommendations are proposed:

- A certain degree of surface roughness with a texture perpendicular to the sliding direction to encourage correct adhesion of the tribofilm to the metal. Since the degree of roughness influences the formation of the tribofilm there has to be a minimum value (around Ra= 17 μm).
- A high pressure between the bodies, without exceeding an upper limit (around 15 MPa in our test, as calculated from measurements of the wear volume).
- A limited speed to avoid undesirable dynamic effects.

The interesting point of the manufacturing process described and the type of fibre used is the selflubricating capacity of Al-VGCF. The exPAN fibres are supplied in bundles that are difficult to disintegrate during preparation of the preform. For this reason, fibre distribution in the preform is not uniform, and some zones with a maximum concentration of fibres are not fully infiltrated, leading to porosity. The resulting behaviour is irregular and a lubricated tribofilm cannot be formed. This does not occur with VGCF, which is supplied in the form of short fibres of different diameters. So that they are easily surrounded by the aluminium matrix. In this way a more uniform tribofilm is obtained, providing lower friction and wear coefficients.

Tribofilm formation does not depend on a very fine surface roughness either of the pin or of the material against which it will slide, meaning that the cost of finishing the pieces is considerably reduced.

The fibre prevents delamination of the matrix since it acts as an obstacle and constitutes a limit to the size of the platelets which are characteristic of this wear mechanism. A well formed tribofilm considerably increases the pressure and speed limits attainable before seizure results, since the third body prevents direct metal - metal contact.

A study of the tribological properties of the Al-VGCF shows that the composite is of considerable industrial interest, because its low friction and wear coefficients under high-pressure contact, provided that the tribofilm be well formed.

Since the wear is produced in the composite with no abrasion of the hard part (the disk), the piece of composite material is ideal for use as the interchangeable part in a tribological system.

Acknowledgement

The work has been performed within the framework HCM-network program CHRX-CT94-0457 titled: "Production and applications of Vapour Grown Carbon Fibres".

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