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Tribocorrosion Studies in Centrifugally Cast Al-matrix SiC_p-reinforced Functionally Graded Composites

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Abstract. The present work reports results obtained from a series of preliminary experiments aiming at complementing the current knowledge about the wear behaviour of centrifugally-cast FGM Al/SiCp composites, through concurrent corrosion processes. Precursor MMC's were prepared by rheocasting, using 118.8 μm SiC particles and an Al-10Si–2.2 Mg alloy. Those MMC's were then molten and centrifugally cast in order to produce cylindrical FGMMC's. Discs machined from the top surface of each sample were tested against nodular cast iron pins, using an inverted configuration pin-on-disc tribometer. Sliding tests took place at room temperature, over a 50000 m sliding distance, with a sliding speed of 0.3 m s^{-1}, under a 5 N normal load; both dry-sliding and water-lubricated tests were performed. In order to elucidate the mechanisms involved, the wear coefficients were calculated for each condition, and the samples were subjected to morphological characterization *via* SEM/EDS. Concurrently, in the case of the water-lubrication tests, the corrosion potential of the tribological pair was monitored. The results obtained show an increase in material loss for the water-lubricated cases, although variations are registered depending on reinforcing particle volume fraction. At the same time, the open circuit potential response of the tribological pair may be correlated with the events of formation/destruction of the tribolayers.

Introduction

Al-matrix composites reinforced with SiC particles have attracted a growing interest from the automotive, aeronautical and aerospace industry, due to their advantageous toughness to weight ratios, combined with the possibility of employing conventional casting technologies. Furthermore, through an adequate control of the ceramic particles distribution from the part surface down to its core, the conventional MMC may become a functionally graded metal matrix composite (FGMMC) in which the wear resistance is expected to be improved at the surface whilst a high global toughness is preserved throughout the bulk of the component [1]. Centrifugal casting is one of the most effective methods for processing SiCp-reinforced Al-based FGMMC's [2]. Previous research has been done in order to study the dry sliding behaviour of these materials against cast iron counterfaces, a situation commonly found in practical applications [3-4]. Less attention, however, has been devoted to the behaviour under lubricated conditions, where corrosion is liable to intervene as a complicating factor. In fact, despite the fact that corrosion studies and wear behaviour of Al-based SiC-reinforced MMC's are separately available in the literature, published works dealing with wear corrosion are rather limited in number [5]. The interaction between both kinds of phenomena is, however, of the utmost importance for engineering applications.

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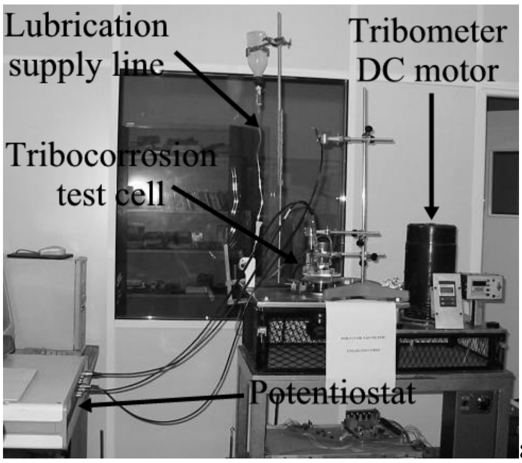
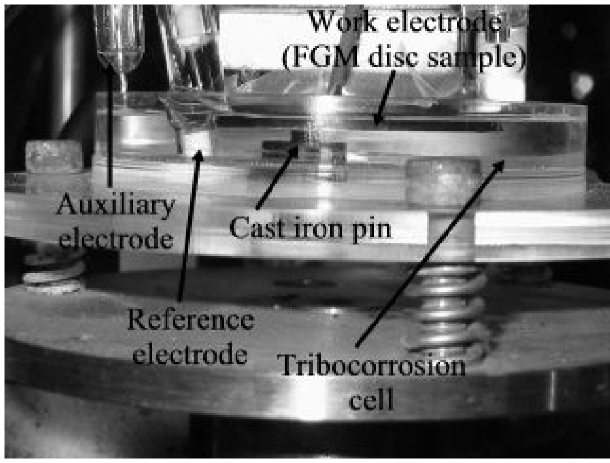
Materials and Testing Procedure

SiC_p-reinforced FGMMC dowels were produced by centrifugal casting from stir-cast precursor MMC's. Details of the stir-casting apparatus and technique pertain to previous works [1], while a detailed description of the centrifugal casting furnace, its operation and material processing conditions can be found elsewhere [6]. Discs for pin-on-disc tests (disc free surface area 12.6 cm^2) were then machined from the cast dowels, in order to test the top surface, which presents the highest SiC_p content in each FGMMC. Those tests were performed with nodular cast iron (NCI) pins as a counterface, using a privately-built tribometer, which was instrumented through the use of a *Radiometer Analytical Voltalab PGZ100* potentiostat. Due to constraints imposed by electrical signal collection, the tribometer had to be converted to an inverted configuration, and a purposely-designed tribocorrosion cell was built. Before the start of those tests involving water lubrication, the system was kept stationary for a period of time sufficient to reach a steady state from the corrosion point of view. All the tests were performed with a sliding speed v = 0.3 m s^{-1} and a sliding distance x = 50000 m, under a normal load of 5 N. After the tests, the FGMMC samples and corresponding NCI pins were analysed by SEM/EDS in order to study their morphology and chemistry at selected locations. Fig. 1 shows the layout of the tribocorrosion experimental setup, while Table 1 summarizes the matrix composition, delay time $t_{\gamma MAX}$ to reach the maximum centrifugal acceleration of 240.4 m s^{-2}, median particle size D_V (measured by laser interpherometry), reinforcement fraction f_A (measured from optical micrographs by quantitative image analysis), and lubrication condition of the pin-on-disc tests. Additionally, it contains the chemical composition of the NCI pins.



a)



b)

Fig. 1 – a) General layout of the tribocorrosion experimental setup, showing the relative positions of tribometer, potentiostat and ancillary sub-systems; b) tribocorrosion cell details, showing the positioning of the FGMMC disc sample, NCI pin and potentiometry electrodes (Pt auxiliary electrode, saturated calomel reference electrode, and work electrode).

Table 1 – Material composition, delay time $t_{\gamma MAX}$ for centrifugal casting of FGM samples, SiC particle median size D_V, reinforcement fraction f_A and tribocorrosion tests lubrication conditions.

Sample	Composition [wt%]	$t_{\gamma MAX}$ [s]	D_V [μm]	f_A [%]	Lubrication
C59	Al – 10Si – 2.2Mg	17	118.8	12.6	Water
C60		5	118.8	35.7	Dry sliding
C61		5	118.8	35.7	Water
NCI	Fe – 3.3 C – 2.0S i – 0.5 Mn – 0.08 S (max) – 0.2 P (max)				

Results and Discussion

Table 2 summarizes the wear coefficient values determined for the various samples. Those values show that the NCI pins always suffer a much more pronounced degradation than the FGMMC discs, although K_P is not much sensitive to lubrication conditions or SiC particle content. However, water-lubrication seems to play a key role in determining the extent of degradation of the FGMMC, since K_D rises almost 40 times from sample C60 to C61. Under water-lubricated conditions, FGMMC SiC particle content also seems to play an important role, since K_D decreases more than 10 times when f_A goes from 35.7 (C61) to 12.6 % (C59). This behaviour is similar to that reported in the literature for the case of dry-sliding of FGMMC's centrifugally cast from a *Duralcan*™ precursor MMC reinforced by smaller SiC particles ($D_V \approx 12$ μm) [3], when a critical threshold in the amount of SiC reinforcing particles was found, above which severe composite wear occurred, due to lack of fatigue strength, leading to metal/ceramic interface fracture and eventually to particle pull-out.

Table 2 –Disc (K_D) and pin (K_P) wear coefficients.

Sample	C59	C60	C61
K_D [mm^3 N^{-1} m^{-1}]	12.66 x 10^{-6}	3.77 x 10^{-6}	145.02 x 10^{-6}
K_P [mm^3 N^{-1} m^{-1}]	3.55 x 10^{-4}	3.56 x 10^{-4}	2.33 x 10^{-4}

Fig. 2 shows selected SEM images representative of the morphology of the surface observed in the different tests.

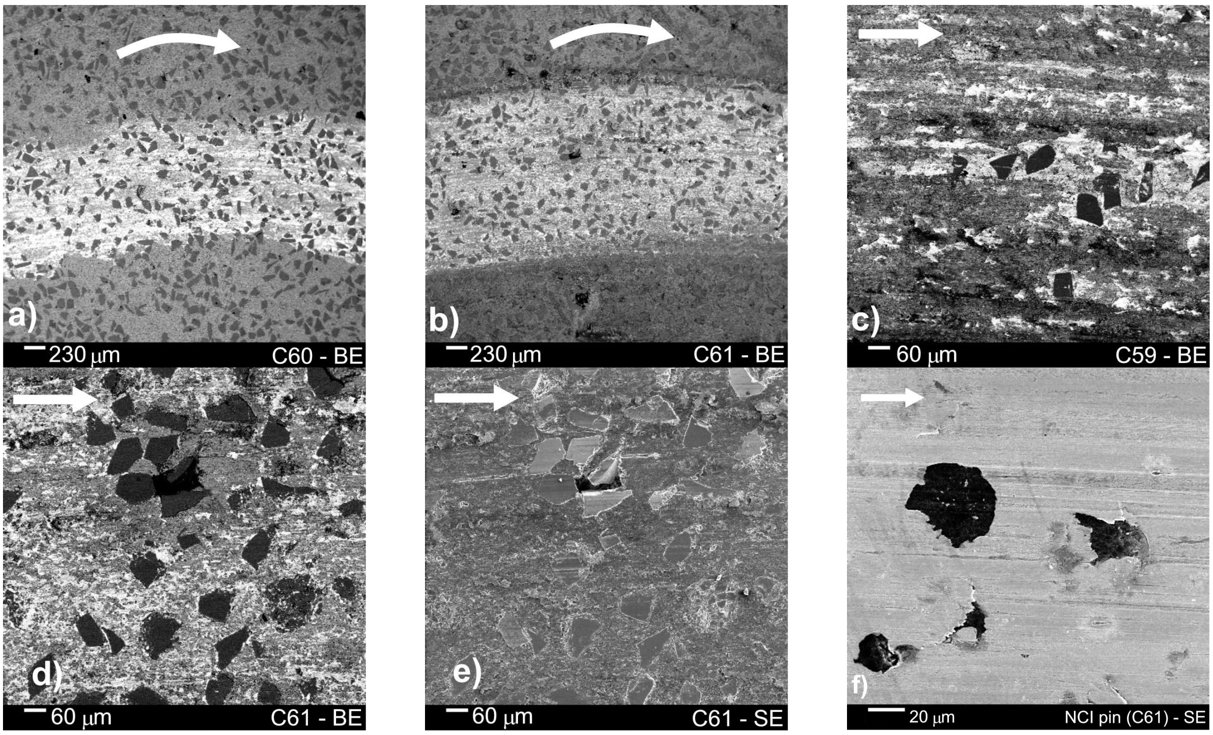


Fig. 2 – SEM images representative of the tested samples. In every image, the arrow indicates the sliding motion of the counterbody. a) Sample C60 and b) sample C61, BE images showing the respective wear tracks; c) sample C59 and d) sample C61, BE detailed images from the wear track; e) sample C61 SE detailed image from the wear track; f) SE image from the NCI pin used to test sample C61.

In every case, in accordance with earlier reports [3-4], an Fe-rich protective tribolayer, with slight oxidation signs, as revealed by EDS, was present on the wear track, corresponding to the lighter-shaded areas in the backscattered electrons (BE) images in Figs. 2a) and 2b). Also, this Fe-rich tribolayer always showed a more regular contour on water-lubricated samples than in the case of dry-sliding. In fact, the presence of water, acting as a carrier, seems to facilitate the deposition of the tribolayer. This mechanism should lead to enhanced protection of the FGMMC, but, as shown by the K_D values presented in Table 2, it seems to be counterbalanced by the degradation due to the corrosion effects of water. Looking at the BE images shown in Figs. 2c) and 2d), corresponding to the wear tracks of samples C59 and C61 respectively, one observes that the SiC particles seem to act as anchoring sites for the transferred Fe protective tribolayers. This anchoring effect seems to be more pronounced in sample C59 (lower f_A) than in sample C61 in which the tribolayer seems to be more uniformly distributed throughout the wear track. Also, in the secondary electrons (SE) image from sample C61 in Fig. 2e), the SiC particles exhibit a smooth abraded surface, indicative of their load-carrying protective role, a feature observed in all samples. Both traits are in accordance with earlier observations [3-4].However, in the present work, it was generally observed that SiC particles were prone to be catastrophically pulled out from the matrix, thus obviating to their roles as load-carrying elements and anchoring sites. Particle pull-out was mainly observed in water-lubricated samples, and was more common for high SiC content, which is consistent with the K_D values reported in Table 2. As suggested by Bai *et al*. [7], water tends to react with Al preferentially at the Al/SiC interface, thus provoking chemically induced fracture, which in turn may be responsible for SiC particle pull-out under sliding conditions. Furthermore, the relative abundances of reinforcing particles in samples C59 and C61 would explain why particle pull-out was less common in the former case (less Al/SiC interface total area, hence less chemical attack sites).

Water-lubricated samples exhibited signs of a slight deposition of oxidized iron outside the wear track, a trait not found in the dry-sliding sample, which again indicates the role of water as a carrier for transferred material.

As to the NCI pins (Fig. 2f)), they always exhibit aligned grooves along the sliding direction, as well as damage and pull-out of the graphite nodules, these aspects being more noticeable with samples C59 and C60, which concurs with the higher K_P values found. There were no signs of Al deposition or SiC particles inclusions; on the other hand, formation of a very fine oxide network occurred with water-lubrication.

Open-circuit potential (OCP) curves registered during the water-lubricated tests are presented in Fig. 3. It should be noted that OCP under the conditions employed in these tests represents the potential of the galvanic couple formed between the disc (FGMMC) and the pin (NCI). In addition, it also reflects simultaneously the state of the unworn disk material and that of the material in the wear track. As reported by Ponthiaux *et al.* [8], galvanic coupling between worn and unworn parts is likely to occur, being dependent on the OCP's of the materials in the worn and unworn areas, the ratio and relative positions of these areas, as well as the mechanism and kinetics of the anodic and cathodic reactions in both areas. So, it should be emphasised that, whereas wear phenomena solely regard the wear track area, corrosion phenomena may occur over the whole free surface of the samples. Thus, measured mass variations (and resulting K_D values) will contain contributions from both types of phenomena. With this in mind, one can nevertheless observe that the curves in Fig. 3 seem to agree with the calculated K_D values and the SEM observations.

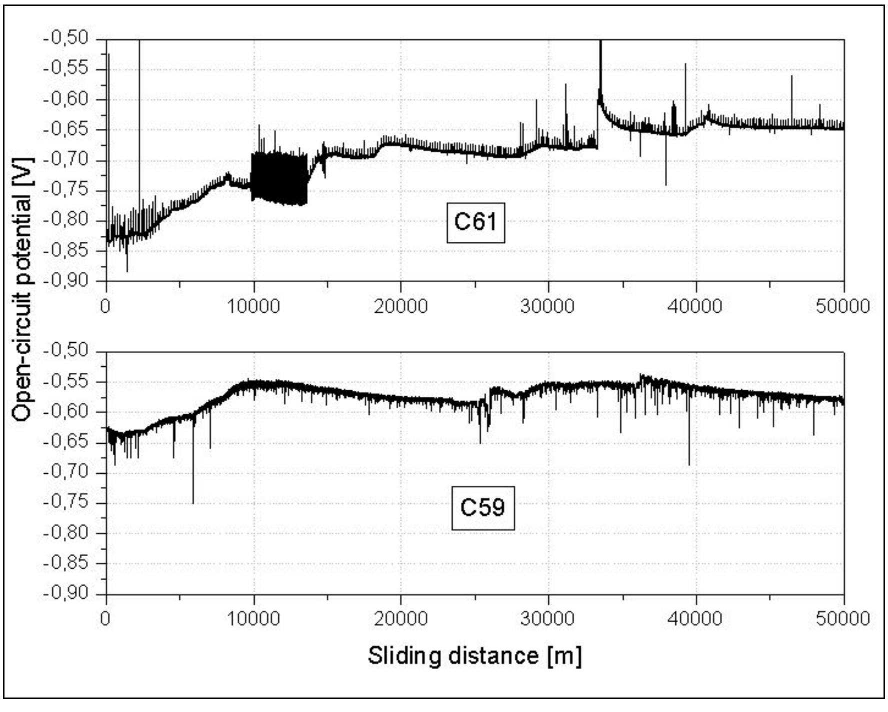


Fig. 3 – Open-circuit potential (OCP) curves corresponding to the water-lubricated tests.

In all cases there is a period corresponding to x ≈ 10000 m, during which a regular increase in OCP suggests a gradual build-up of a protective layer. After that period, OCP values basically stabilize, except for randomly spaced abrupt changes. This behaviour could be indicative that, although a steady-state seems to be achieved, the system is sometimes disturbed by sudden episodes of catastrophic material removal, due to SiC particle pull-out, and/or destabilisation of the tribolayers anchored to them, followed by the build-up of a new film. Again, sample C59, was less prone to sudden variations in OCP than C61, most probably because of the lower number of particle pull-out episodes occurred during sliding, as discussed before. In other words, this behaviour is also indicative of the presence of a more stable tribolayer formed at the wear track in sample C59, corroborating the lower wear coefficients found in that sample.

Conclusions

During tribological contact between Al/SiC_p reinforced FGMMC's, water plays a part as a carrier agent for transferred material. Nevertheless, water lubrication significantly increases wear of FGMMC's, by facilitating catastrophic SiC particle pull-out, thus obviating the load-carrying and anchoring role of the reinforcements. At the same time, by exposing a fresh surface to the environment, water enables the galvanic coupling of worn and unworn areas, these effects outweighing its role as a carrier.

Under water-lubricated conditions, an increase in reinforcing particles content led to poorer FGMMC wear performance. Regarding the effects on the NCI pins, these always suffered more generalized damage than the FGMMC counterfaces, although, as wear coefficients are concerned, there seemed to be no measurable effect resulting from lubrication conditions, and only a slight one from SiC particle content in the FGMMC.

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