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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF Al-6061/TiC METAL MATRIX COMPOSITES

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Summary: *In this study, manufacturing of Al-6061 matrix composites reinforced with 6 and 12% vol. of TiC particles was carried out by incorporating and diluting an Al/TiC/40p master composite. The composites were microstructurally and mechanically characterized in order to assess the effects of adding TiC particles into the Al-6061-T6 matrix. The master composite was fabricated by a flux assisted infiltration process. Powders of TiC (16.1 μm) and K-Al-F based flux (18.3 μm) were mixed in a 3:1 mass ratio. This mixture was uniaxially pressed and infiltrated with aluminium of commercial purity at 800ºC and held at temperature for 30 minutes under flowing Ar. The microstructural characterization revealed that the green compacts were fully infiltrated, however, a mass fraction of the flux was trapped within the matrix and the presence of* Al_3Ti *needles was observed. The fabricated Al/TiC/40p master composite was added into a molten Al-6061 alloy, targeting a reinforcement content of 6 and 12% vol. of TiC particles, at 750ºC for holding times of 10 and 18 minutes, respectively. The incorporation and dispersion of the TiC particles was successful and by using image analysis a yield of 93.4% and 89% for the Al-6061/TiC/6p and Al-6061/TiC/12p composites, respectively, was estimated. Moreover, the microstructural characterization showed a quite even distribution of the TiC particles with few clusters and free of reaction products for the Al-6061/TiC/6p composite. The microstructure of the Al-6061/TiC/12p samples also exhibited good distribution of the particles but with a larger number of particles agglomerated and with the presence of acicular* Al_3Ti *intermetallics. For both contents of reinforcement, the presence of entrapped flux was observed within the matrix, for the Al-6061/TiC/12p composite, these occurence was more evident. In the other hand, the monolithic alloy and the composites were subjected to a hot rolled process and subsequently to a T6 heat treatment. With respect to the Al-6061-T6 alloy, the composites exhibited a lower tensile strength but a larger elastic modulus. Fractography in the scanning electron microscope indicated that this behavior is due to the presence of flux in the matrix.*

1 INTRODUCTION

Manufacturing of metal matrix composites (MMCs) via the liquid routes challenges to overcome the difficulties imposed by the presence of oxides and the non-wetting nature in metal/ceramic systems. Survey of the literature shows that wetting in the Al/TiC system is good, with high dependence on temperature and contact time. Dynamic wetting in the Al/TiC couple is associated with the presence of an Al_2O_3 layer that prevents direct metal/ceramic contact and delays spreading of the liquid on the solid surface. This mechanical barrier induces reactive wetting in the Al/TiC system with the formation of Al_4C_3 at the interface. The good wettability in the Al/TiC system enables fabrication of MMCs with high ceramic content and near net shape at elevated temperatures under protective atmospheres [1,2].

The use of fluxes has been found an efficient alternative to disclose the real affinity in Al/ceramic systems in terms of wettability. In particular, a based K-Al-F flux dissolves the oxide layer in aluminum melts and enables spontaneous and instantaneous wetting in the Al/TiC system at temperatures as low as 660ºC in Ar or in air. This characteristic facilitates both; infiltration of TiC beds by molten Al and incorporation of TiC particles into Al melts [3-6]. In a previous work, the authors fabricated a master Al/TiC composite by a flux assisted infiltration method and successfully dispersed it into an Al melt [7]. In this work, the concept of the master composite was used to manufacture Al-6061-T6/TiC MMCs with low reinforcement contents.

2 EXPERIMENTAL PROCEDURE

Angular TiC particles with an average particle size of 16.1 μm were used as reinforcement for manufacturing MMCs. A master composite was fabricated by pressing a mixture TiC/Flux powders in a mass ratio 3:1 into cylindrical compacts. The flux powder, with an average particle size of 18.3 μm, was K-Al-F based with a composition close to the eutectic in the KF-AlF_3 system and a melting point of approximately 545ºC. The TiC/Flux compacts were placed into graphite crucibles and heated to 800 ºC, in a preheated tube furnace, with Al of commercial purity (99.7%) on top and held at temperature for 30 minutes under flowing Ar for infiltrating the liquid Al into the porous compacts.

The master composite, with a content of 40% in volume of TiC particles, was added and diluted into molten baths of Al-6061 alloy (1.2%Mg, 0.75%Si, 0.30%Fe, 0.05%Cu), targeting a reinforcement content of 6 and 12% vol. of TiC particles, at 750ºC in atmospheric air for holding times of 10 and 18 minutes, respectively. Once the matrix of the master composite melted, the clay bonded SiC crucible cointainig the melt was removed from the furnace and lightly stirred to disperse homogeneously the TiC particles. The molten bath was cast into a preheated carbon steel mould prior surface cleaning of the liquid surface. A reference Al-6061 alloy and the MMCs manufactured were hot rolled at 450ºC, inducing a deformation of 28%, followed by solubilizing at 530ºC for 4 hours, water quench and artificial aging at 160ºC during 15 hours.

Samples for metallography were taken from the master composite and dilute composites and were mounted, ground, and polished. In this process, the use of water was ommited in order to preserve some Al_4C_3 that might had been present. The macroscopic particle distribution and the location of particles relative to the grain structure, were studied using optical and scanning electron microscopy (SEM). To reveal the grain structures, Al samples were anodised in a 4% solution of KBF_4 in water for 145 seconds at 14 V. All samples were then viewed in an optical microscope under crosspolarized light. Quantification of the particle fraction was performed using Scion Image analysis software on digitally captured images. Identification of the phases present was performed using energy dispersive X-ray analysis (EDX).

Specimens for tensile testing were obtaining by machining the reference Al-6061 alloy and the composites according to the ASTM E 08M standard for subsize specimens. Tensile testing was performed in a universal testing machine with a crosshead speed of 0.16 mm/s. Fracture of the tested specimens was observed in the SEM.

3 RESULTS AND DISCUSSION

3.1 Master composite

The TiC/Flux compacts were successfully infiltrated at 800ºC after holding for 30 minutes at temperature. Figure 1 shows the characteristics of the microstructure of the master composite. The digital images captured in the SEM in secondary electron mode reveal that most of the initial pores of the compact and the interstices left by the flux upon infiltration are occupied by aluminum. Although the majority of the flux was displaced to the outer surface of the infiltrated master composites, some flux was trapped within the matrix as indicated in Figure 1b). Scattered acicular Al_3Ti intermetallics were also observed in the matrix of the master composites, this means that a very light reaction occurred between TiC and liquid Al during the infiltration process. Under the resolution of the SEM, Al_4C_3 was not seen.

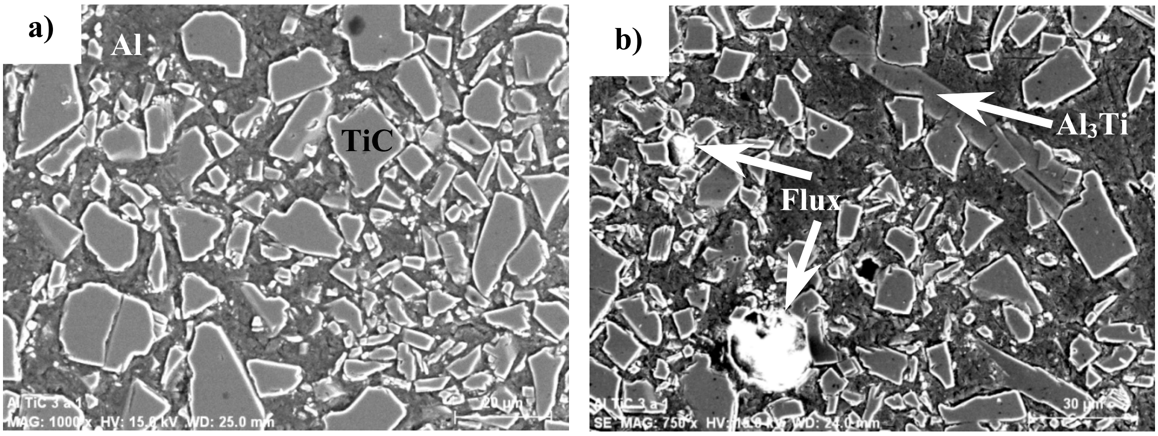

Figure 1: Microstructural details of the Al/TiC/40p master composite.

3.2 Incorporation and dispersion of the TiC particles into Al-6061 melts.

Metallography of the as-cast MMCs revealed that the incorporation and dispersion of the TiC particles into the Al-6061 melts was successful at 750ºC. Measurements by image analysis from digital images captured in the SEM in backscattered mode indicated that the yield of TiC particles into the matrices was of 93.4% and 89% for the targeted 6% and 12% in volume, respectively. Figure 2 shows the grain structure as observed in the optical microscope under polarized light for the Al-6061 reference alloy and the MMCs in both as-cast and as-hot rolled conditions. The incorporation of the TiC particles exhibits a noticeable grain refining effect in the matrix, as seen in the left column in Figure 2. Whereas the Al-6061 alloys solidifies with a vast cellular dendritic grain structure, the MMCs solidify with a fine equiaxed grain structure with a large number of particles engulfed within the grains after solidification meaning that these grains acted as substrates for nucleation of grains.

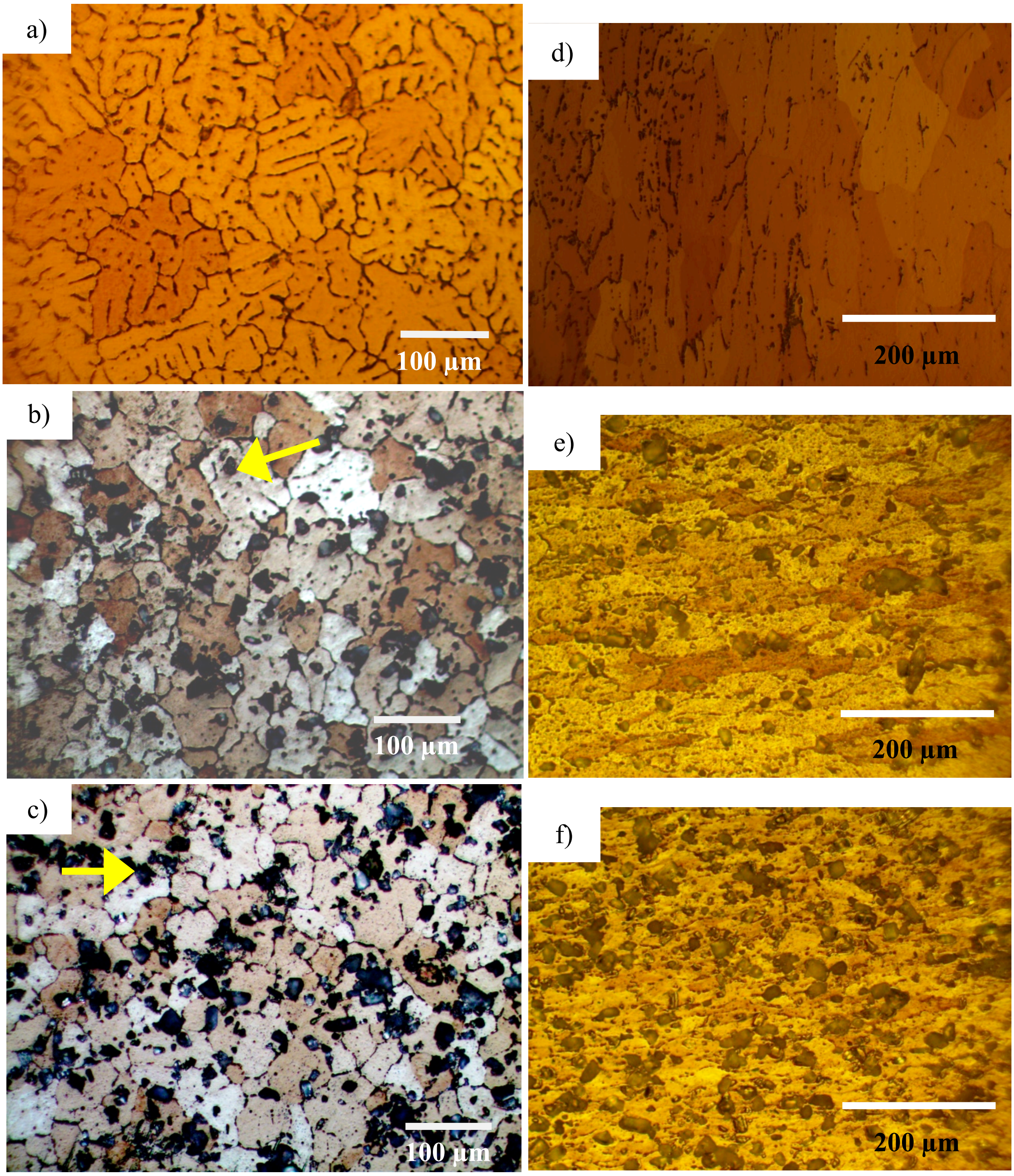

Figure 2: Grain structure of a) and b) Al-6061 alloy, c) and d) Al-6061/TiC/6p and e) and f) Al-6061/TiC/12p. Left; as cast and right; as-hot rolled.

Table 1 presents the results of grain size measurements in the as-cast Al-6061 alloy and MMCs. These measurements were performed in pieces taken from the top and bottom of the castings. It is observed that, irrespective of the presence or not of the TiC particles, there is not a significant variation of the average grain size with respect to the position of the sample. It is evident that the incorporation of the TiC particles significantly reduced the grain size in the Al-6061 matrix of the MMCs from 81.9 to 55.8 and 35.1 µm for 6 and 12% in volume of TiC particles incorporated and dispersed into the melts, respectively. A reduction in the standard deviation with the addition of particles indicates that the grain structure is more homogeneous throughout the casting and means also that the distribution of particles is equally uniform.

Sample	Average grain size (µm)		Estandard deviation		Average grain size (µm)	Estandard deviation
	B	T	B	T		
Al-6061	81.06	83.05	±30.66	±31.97	81.97	±31.71
Al-6061/TiC/6p	54.18	59.04	±16.77	±16.09	55.87	±16.70
Al-6061/TiC/12p	35.69	34.57	±9.60	±9.35	35.12	±9.48

B = bottom and T = top of the casting.

Table 1: Average grain size of the as-cast Al-6061 and MMCs manufactured (µm).

The optical micrographs in the right column in Figure 2 show the deformation experienced by the matrix after hot rolling. Noticeable banding of the TiC particles in the rolling direction is not observed.

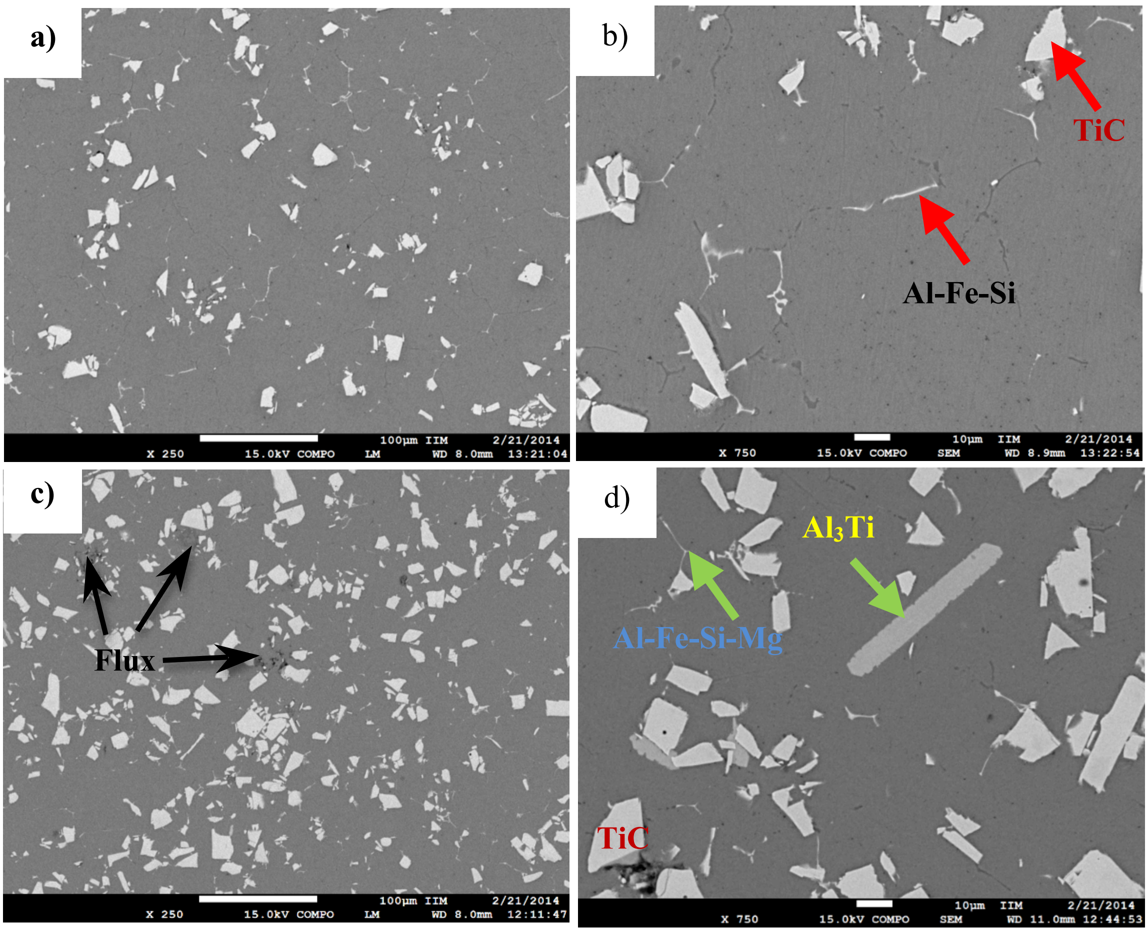

Figure 3: SEM backscattered images of the a) and b) Al-6061/TiC/6p and c) and d) Al-6061/TiC/12p as-cast MMCs.

Figure 3 shows the distribution of the TiC particles in the Al-6061 matrix as observed in the SEM in backscattered electron mode. A reasonably even distribution of the reinforcement is appreciated with some clustering of the particles for the Al-6061/TiC/12p composite. After the addition of the master composite into the Al-6061 melts and upon dissolution of it, a dark scrap floated in the surface of the molten bath. This scrap corresponded to the flux trapped in the master composite. Although the melt was cleaned before casting, the matrix of the composites with low reinforcement contents still exhibited some presence of entrapped flux. The Al-6061/TiC interfaces were found to be free of Al_4C_3 but some needles of Al_3Ti were seen in the composites with a larger presence for the addition of 12% TiC particles.

3.3 Tensile properties of the MMCs.

Table 2 lists the results of the tensile test. The Al-6061-T6 alloys presents the typical behavior expected for the T6 heat treatment of this alloy. However, the MMCs did not achieve even the strength of the monolithic alloy. Certainly, the presence of the stiff TiC particles increased the elasticity modulus but a reinforcement effect was not registered and the loss of ductility was dramatic. The fractured surfaces of the tensile specimens as seen in the SEM explain this behavior. The fracture path was dictated by the presence of entrapped flux in the MMCs leading to premature failure with a lower strength.

Sample	Elasticity modulus (GPa)	Yield stress (MPa)	Maximun strength (MPa)	% Elongation
Al-6061-T6	72.1	290	312	10.2
Al-6061/TiC/6p-T6	87.9	279	299	5
Al-6061/TiC/12p-T6	99.1	269	286	4

Table 2: Tensile properties of the Al-6061-T6 reference alloy and the MMCs subjected to a T6 heat tretament after hot rolling.

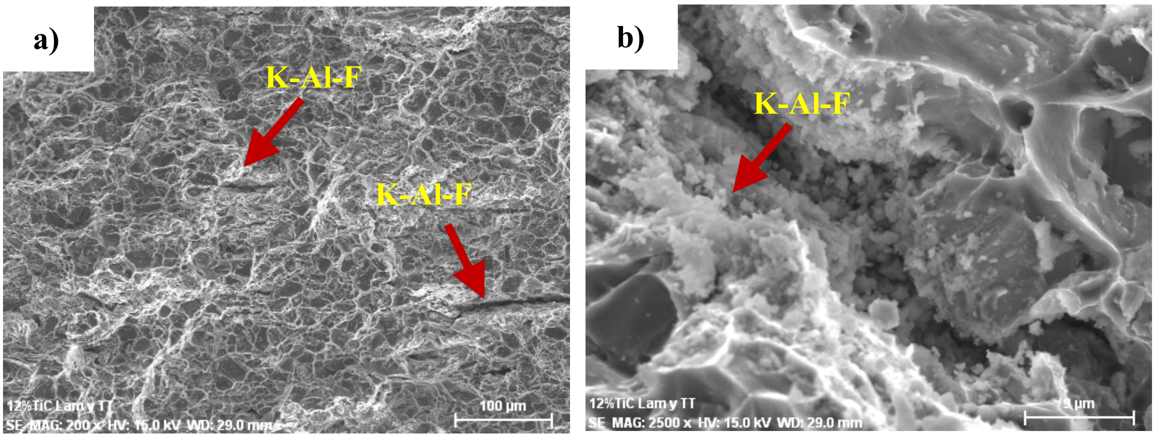

Figure 4: Fractography of the Al-6061/TiC/12p-T6 MMC.

4 CONCLUSIONS

Flux-assisted infiltration enabled fabrication of a master composite with 40% TiC particles. This was used as an additive to produced Al-6061 MMCs reinforced with 6 and 12% TiC particles following standard Al casting practice. Quite even distribution of the TiC particles in the Al-6061 matrix was observed with some clustering of the TiC particles for the 12% TiC composites. No bulk reaction was detected, only Al_3Ti needles were found in the MMCs. The TiC particles acted as nucleants during solidification leading to a significant grain refinement of the matrix. Even though the TiC particles in the Al-6061-T6 matrix increased the elasticity modulus, the tensile strength properties were not improved due to the presence of entrapped flux in the matrix.

5 ACKNOWLEDGMENTS

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