Particle distribution and orientation in Al-Al_3Zr and Al-Al_3Ti FGMs produced by the centrifugal method

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Abstract Al-Al_3Zr and Al-Al_3Ti functionally graded materials (FGMs) were produced by a centrifugal method from Al-5wt% Zr and Al-5wt% Ti alloys, respectively. Applied centrifugal forces were 30, 60 and 120*G* (units of gravity). Microstructural characterization was performed to evaluate the intermetallic particles' distribution and orientation. Knoop hardness tests were carried out, with the indenter's long diameter normal to the centrifugal force direction. Both the Al_3Zr and the Al_3Ti intermetallic particles are platelet in morphology. These platelets tend to be oriented normal to the centrifugal force direction. Higher applied centrifugal force increases both the intermetallic platelet volume fraction as well as their orientation in the outer regions of the fabricated FGM rings. Also higher orientation and volume fraction distribution are observed in the Al- Al_3Ti FGMs. Knoop hardness measurements in general follow the same trend as the intermetallic particle volume fraction for each sample.

Introduction

Aluminide intermetallic compounds are a promising class of lightweight structural materials. However, practical application is limited due to the material's poor ductility. An approach to overcome this shortcoming is to disperse the intermetallic compound in an aluminium matrix [1-4]. In this case, where the intermetallic compound has a higher density than the matrix, the centrifugal method is attractive due to the fact that there is a selective reinforcement of the surface of the component while gradually increasing the relative amount of ductile phases towards the inner region. This results in a higher wear resistance in the surface as well as maintaining high bulk toughness [5-8]. In fact, the presence of the reinforcing phase, in this case Al_3Ti or Al_3Zr platelets, has a strong influence on the local mechanical properties. The shape, size and spatial orientation of the reinforcing phase will also play an essential role on the wear performance of the material [9-13].

Particle segregation during casting with the centrifugal method occurs due to the difference in density between the particles and molten alloy [14], therefore, the study of two Al-intermetallic compounds systems where the intermetallic compounds have different density values, Al_3Ti and Al_3Zr have densities of 3.4 Mg/m^3 and 4.1 Mg/m^3, respectively, is of interest.

In the present study, novel experimental data was obtained for the Al-Al_3Zr system using the centrifugal method as well as extending the data available for the Al-Al_3Ti system from previous work [9, 10,15, 16]. Results indicate that an increase in the applied centrifugal forces increases both the particles' volume fraction as well as their orientation in the outer regions of the fabricated FGM rings. Also for lower applied centrifugal forces the Al_3Ti particles migrate faster than the Al_3Zr particles, a situation that is reversed for higher applied centrifugal forces.

Experimental Methods

Al-Al_3Ti and Al-Al_3Zr FGMs were produced by a centrifugal method, from Al-5wt % Ti and Al-5wt % Zr commercial alloys, respectively. The crystal structures and densities of the intermetallic compounds and of aluminum are presented in Table 1. Since the relative atomic masses of Al, Ti and Zr are 26.98, 47.88 and 91.22, respectively, the theoretical volume fraction of Al_3Ti in the master alloy was calculated to be approximately 11 vol% [9] and that of Al_3Zr as approximately 7 vol%.

In the centrifugal method the alloy is heated up to a temperature located between its *solidus* and *liquidus* temperatures, were most of the intermetallic platelets remain solid in a liquid Al-based matrix. It is then poured into a rotating mould in order to obtain ring-shaped samples. The temperature of the melting furnace was 1173 K and applied centrifugal casting forces were 30, 60 and 120*G* (units of gravity). A detailed description of the centrifugal method is available elsewhere [5-9]. Samples were cut, polished and divided into ten regions of equal width along the centrifugal force direction. The outer surface of the ring is therefore represented as the position 1.0 of the normalized distance and the inner surface by the position 0.0.

Optical micrographs were taken and from those intermetallic particles size, distribution and orientation were measured along two planes, perpendicular to the rotating axis (referred as OP1 in the subsequent text) and perpendicular to the rotating direction (OP2), as seen in Fig. 1. Knoop hardness tests were performed, with the indenter’s long diameter normal to the centrifugal force direction.

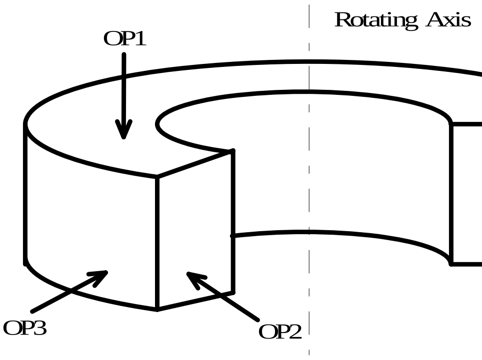

Fig. 1 Schematic drawing of the FGM ring.

Table 1 Cystal Structure and density

Element or compound	Crystal Structure	Density [Mg/m^3]
Al	*fcc*	2.7
Al_3Ti	$D0_{22}$	3.4
Al_3Zr	$D0_{23}$	4.1

Results and Discussion

Intermetallic compounds area faction and Knoop hardness distribution. As seen in Figs. 2 and 3 in all samples the volume fraction occupied by Al_3Ti or Al_3Zr particles decreases from the outer (1.0 position in the abscissa of the figures) to the inner regions (position 0.0) of the FGM rings. In fact, with samples cast under 60 and 120*G* there is an absence of particles from around the middle to the inner region of the rings in both the Al-Al_3Ti and Al-Al_3Zr FGMs.

From Fig. 2, relating to the Al-Al_3Ti FGMs, an increase in the applied centrifugal force does not appear to significantly increase the intermetallic particle fraction at the outermost region of the rings, which remain around 20-25%, but does increase the particle fraction in the adjacent regions. Overall the Al-Al_3Zr FGMs present lower volume fraction than the Al-Al_3Ti FGMs, as expected due to the initial lower theoretical volume fraction.

At applied centrifugal force of 30*G* the Al-Al_3Zr FGM exhibits a very low gradient when compared to the Al-Al_3Ti sample. The samples from both systems cast at 60*G* display a very similar trend while, for the samples subjected to a centrifugal force of 120*G*, a higher relative clustering of particles on the outermost regions is found for the Al-Al_3Zr FGM.

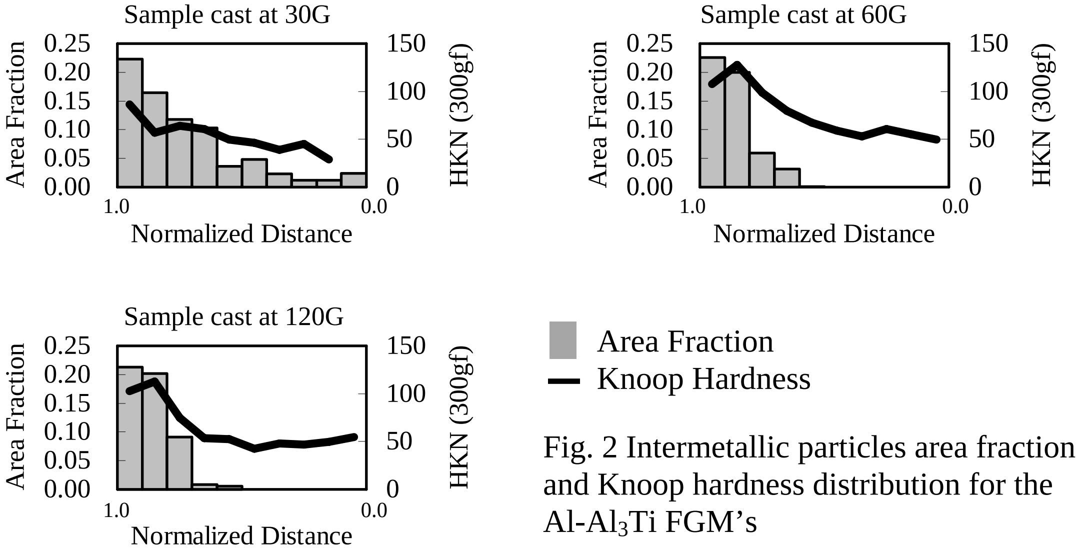

Fig. 2 Intermetallic particles area fraction and Knoop hardness distribution for the Al-Al_3Ti FGM's

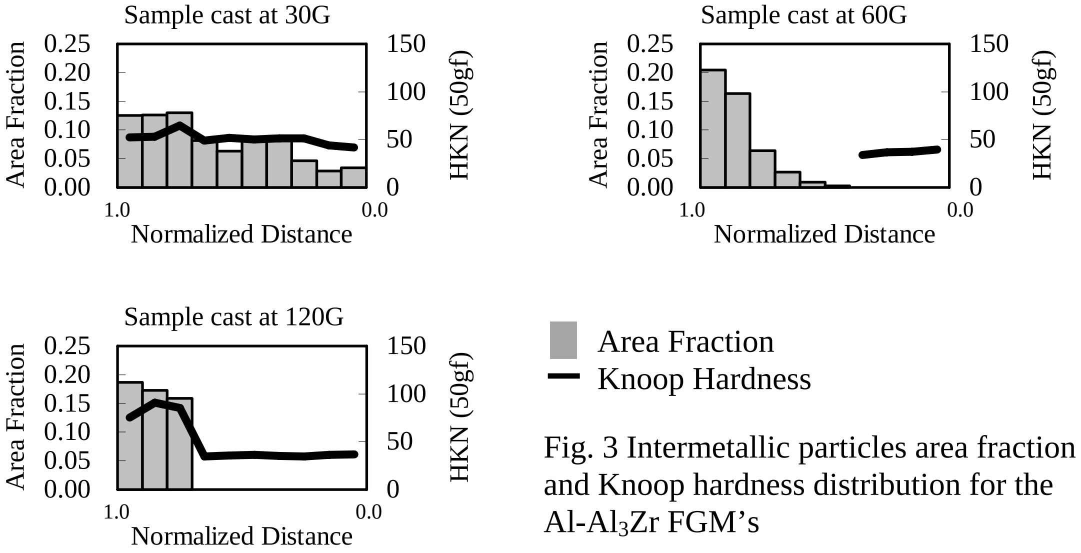

Fig. 3 Intermetallic particles area fraction and Knoop hardness distribution for the Al-Al_3Zr FGM's

Table 2 Mean intermetallic particle area

Al_3Ti		Al_3Zr	
Applied *G* force	Area (μm^2)	Applied *G* force	Area (μm^2)
30*G*	10.59	30*G*	6.07
60*G*	10.76	60*G*	12.94
120*G*	8.17	120*G*	19.97

Al_3Ti particles have a higher segregation rate with lower applied centrifugal forces than the Al_3Zr particles; a situation that is reversed for higher applied centrifugal forces. Several factors are involved in the segregation rate of particles during the centrifugal solid-particle method, namely, density difference between the particles and the molten alloy, viscosity of the liquid matrix through which the particles migrate and particle shape and size, among others [14]. In both the Al-Al_3Ti and Al-Al_3Zr systems the intermetallic particles are platelet in shape, alsoAl_3Zr density is higher than that of Al_3Ti. As can be seen in Table 2, at applied centrifugal force of 30*G* the mean particle area for the Al- Al_3Zr

sample is lower than in the comparable Al-Al_3Ti FGM, which can account for its lower gradient. As applied centrifugal force is increased so does the mean particle area for the Al- Al_3Zr samples leading to the observed higher segregation rate.

Knoop hardness measurements for the Al-Al_3Ti FGMs (Fig. 4) in general follow the same trend as the volume fraction for each sample, with values around 50 in the regions without particles and over 100 in areas with the higher intermetallic content. Knoop hardness measurements for the Al-Al_3Zr FGMs (Fig. 5).

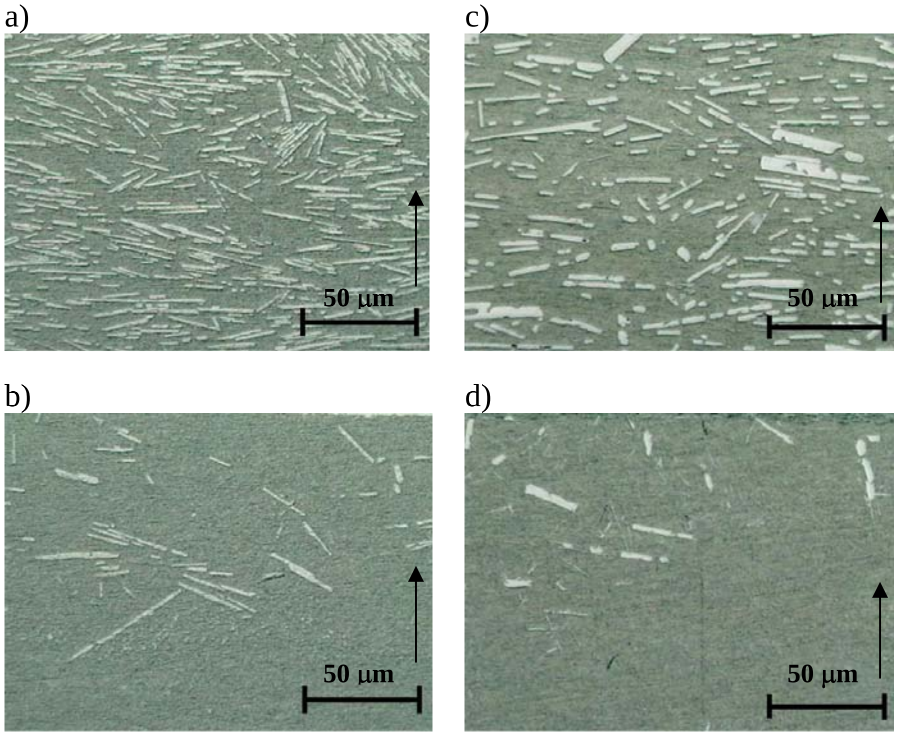

Fig. 4 Optical micrographs, brighter areas are the intermetallic particles.
a) and b) are from the Al-Al_3Ti FGM cast at 60G at the outer (position 1.0) and interior regions (position 0.6) , respectively.
c) and d) are from the Al-Al_3Zr FGM cast at 60G at the outer (position 1.0) and interior regions (position 0.6) , respectively.
The arrow indicates the direction of applied centrifugal force.

Orientation distribution of Al_3Zr and Al_3Ti platelets. The Herman´s orientation parameter, *fp*, is used to quantitatively express platelet orientation, taking the radial direction (normal to the centrifugal force direction) as the reference axis, *fp*=1 represents a perfect alignment with the radial direction while *fp*=0 corresponds to a totally random distribution [18-19]. From previous studies of Al-Al_3Ti FGMs it is known that the platelets tend to be oriented normal to the centrifugal force direction and also that orientation parameters along the OP1 and OP2 directions are similar [16], therefore in figures 5 and 6 the results presented are an average of the Hermann's orientation parameter for both observation planes.

As seen in Figs. 5 and 6 the orientation of platelets in the outer regions is increased with the increase in applied centrifugal force, although, as with the volume fraction values, the increase of applied centrifugal force from 60 to 120*G* does not affect significantly the orientation parameter for the outermost region but does increase it for the adjacent regions, a similar effect is observed for the Al-Al_3Zr FGMs. Also higher orientation parameter values are obtained for the Al-Al_3Ti FGMs. The higher volume fraction of Al_3Ti platelets leads to the necessity of a closer packing between them, which is facilitated by their shape and size. As for the behavior of the Al_3Zr platelets, a very low orientation parameter is found in the outer regions of the sample cast under 30*G* and an essentially essentially random orientation in the interior regions. At applied centrifugal forces of 60 and 120*G*, the Al-Al_3Zr FGMs follow the same trend as the Al-Al_3Ti FGMs although with a lower overall value, in this case the lower volume fraction allows for a greater freedom of movement of the Al_3Zr platelets, leading to lower orientation parameter values (see Table 2 and 3).

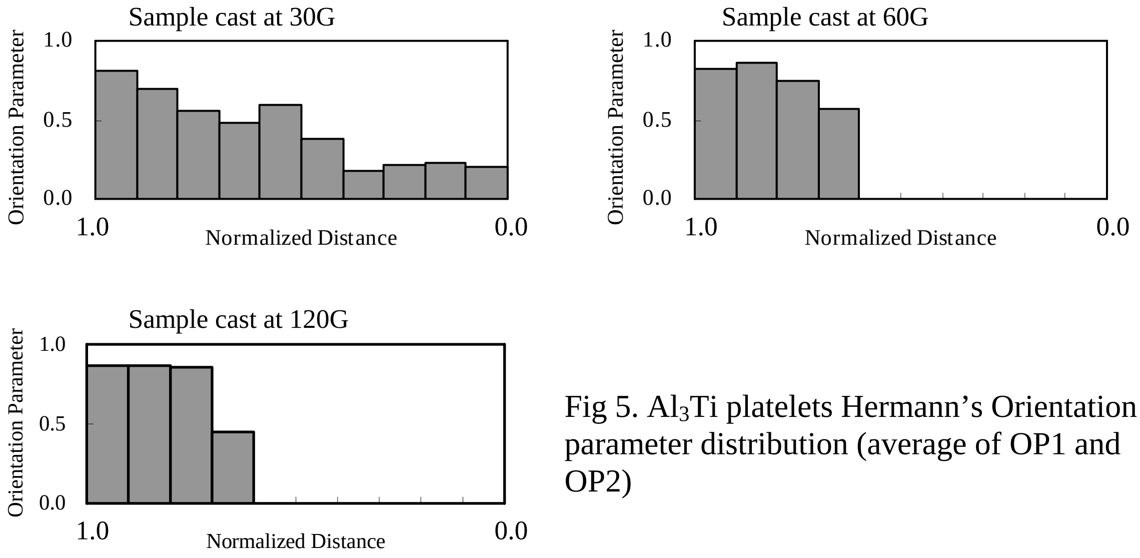

Fig 5. Al_3Ti platelets Hermann’s Orientation parameter distribution (average of OP1 and OP2)

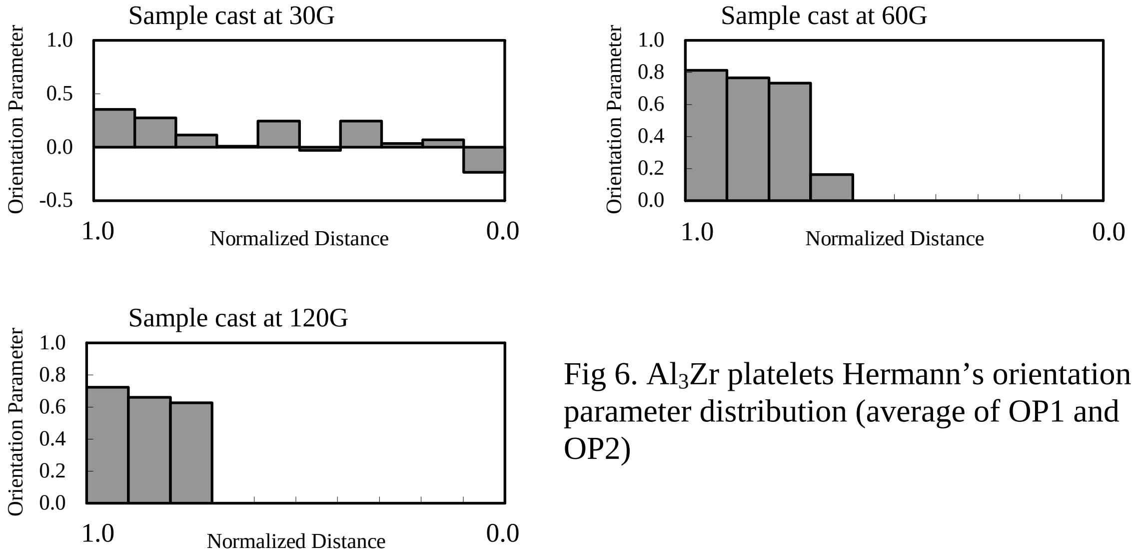

Fig 6. Al_3Zr platelets Hermann’s orientation parameter distribution (average of OP1 and OP2)

Table 3 Mean elongation (Relationship between the major axis length and minor axis legth) of the intermetallic particles

Al_3Ti	
Applied *G* force	Elongation
30*G*	5.54
60*G*	7.28
120*G*	8.00

Al_3Zr	
Applied *G* force	Elongation
30*G*	5.95
60*G*	4.56
120*G*	4.80

Conclusions

In the present study Al-Al_3Ti and Al-Al_3Zr functionally graded materials (FGMs) were fabricated by the centrifugal solid-particle method. Intermetallic compound volume fraction and orientation distribution were measured.

1) Higher applied centrifugal force increases both the intermetallic particles volume fraction as well as their orientation in the outer regions of the FGMs.

2) The increase of applied centrifugal force from 60 to 120*G* does not affect significantly the volume fraction or the orientation parameter distribution for the outermost region of the FGMs but does increase it for the adjacent regions

3) Al_3Ti particles have a higher segregation rate with lower applied centrifugal forces than the Al_3Zr particles; a situation that is reversed for higher applied centrifugal forces.

4) Higher orientation values for the intermetallic platelets are found in the Al-Al_3Ti FGMs.

5) Mean intermetallic particle size increases significantly in the Al-Al_3Zr samples with an increse in applied centrifugal force.

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