Wear Properties of Intermetallic Compound Reinforced Functionally Graded Materials Fabricated by Centrifugal Solid-particle and In-Situ Methods *

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Abstract

One of the functionally graded material (FGM) fabrication methods is a centrifugal method, which is an application of the centrifugal casting technique. The centrifugal force applied to a homogeneous molten composite assists the formation of the desired gradation. In this paper, the wear properties of two kinds of Al base FGMs, namely Al-Al$_3$Ti FGM and Al-Al$_3$Ni FGM, are reported. The former and the latter hold the oriented intermetallic compound platelets and the particle size gradient, respectively. Here, volume fraction, size, shape and orientation of the reinforcements in the composite play an important role in improving the mechanical properties of the materials, whereby FGMs with oriented platelets or particle size gradient may have special mechanical properties such as increased wear resistance. Based on the experimental results, the origin of anisotropic wear resistance and the effect of particle size on the wear properties are discussed.

Key words: Functionally Graded Materials (FGMs), Intermetallic Compound, Centrifugal Method, Wear, Anisotropy, Particle Size

1. Introduction

Functionally graded materials (FGMs) are new kinds of composites characterized by a compositional gradient from one component to another (1, 2). FGMs are promising candidates for obtaining properties unavailable in any one homogeneous monolithic material. The design of FGMs is intended to take advantage of certain desirable features of each of the constituent phases. For example, if an FGM is designed to be used in environments comprising separate regions of high and low temperature, it may consist of pure ceramic, which is heat-resistant, at the hotter end, and a metallic phase, which has better mechanical and heat-transfer properties, at the colder end. The distribution of the two phases is formed in a graded manner in order to utilize the desired properties based on the concept of material design.
A number of processes have been proposed for the fabrication of FGMs, including adhesive bonding, sintering, thermal spray and reactive infiltration, as well as the so-called centrifugal method. The centrifugal method allows for the creation of a gradient compositional distribution in metals containing powder or intermetallic particles, owing to the difference in density between the molten metal and the reinforcement. The fabrication of intermetallic particle-dispersed FGMs using the centrifugal method can be classified into two categories based on the liquidus temperature of the master alloy. The first type is the centrifugal solid-particle method, in which the processing temperature is lower than the liquidus temperature of the master alloy, whereby the dispersed intermetallic particles are stable inside a liquid matrix. The other method is the centrifugal in-situ method, in which the processing is implemented under temperatures higher than the liquidus temperature of the master alloy. As a result, in the case of the centrifugal in-situ method, the centrifugal force is applied to a completely liquid phase and the intermetallic compound particles crystallize from the liquid phase directly during the casting process.

One product of the centrifugal solid-particle method is Al-Al$_3$Ti FGM, which contains anisotropically oriented Al$_3$Ti platelets in the Al matrix. Figure 1 shows a schematic representation of the arrangement of the Al$_3$Ti platelets in an Al-Al$_3$Ti FGM ring, which is the typical shape of the finished product fabricated by the centrifugal method. The Al$_3$Ti particles are oriented with their platelet planes nearly perpendicular to the radial direction (the direction of the centrifugal force). In this case, anisotropic wear resistance is observed, dependent on the wear direction with respect to the alignment of the Al$_3$Ti platelet particles. The orientation of the Al$_3$Ti platelets, as well as the mean volume fraction of the particles, was found to be gradually distributed in the Al-Al$_3$Ti FGM. Therefore, the positional dependence of wear resistance is expected as a property in Al-Al$_3$Ti FGMs since it is known that volume fraction, size, shape and orientation of reinforcements in composite play an important role in improving the mechanical properties of the materials. The same reinforcement effects are also expected in FGMs.

On the other hand, in the case of FGMs fabricated by the centrifugal in-situ method, the centrifugal force is applied to a completely liquid phase, whereby the intermetallic compound particles crystallize from the liquid phase directly during the casting process. Therefore, the size of the crystallized particles in such FGMs is affected by the solidification process under the centrifugal force. Figures 2 (a), (b) and (c) show schematic illustrations of the microstructure of the Al-Al$_3$Ni FGM fabricated by the centrifugal in-situ method, where (a), (b) and (c) represent the inner, interior and outer peripheral regions of the ring.
Peripheral regions of the ring, respectively. It is clear that the volume fraction of the Al$_3$Ni primary crystal particles follows a gradient distribution in the Al-Al$_3$Ni FGM. It is important to note here that the size of the primary Al$_3$Ni crystal particles varies depending on their position in the ring. Since FGM rings fabricated by the centrifugal \textit{in-situ} method have gradient distributions of secondary particles, they display gradient wear resistance. Such wear properties can be expected to extend the application fields of FGMs.

Considering the above points, Al-Al$_3$Ti FGMs with different Al$_3$Ti platelet orientations and Al-Al$_3$Ni FGMs with different particle size distributions\textsuperscript{(13)} have been systematically fabricated using the centrifugal solid-particle and \textit{in-situ} methods, respectively, and the wear properties of Al-Al$_3$Ti and Al-Al$_3$Ni FGMs have been explored\textsuperscript{(17,18)}. In this article, the microstructure and wear properties of intermetallic reinforced Al base FGMs, fabricated by both the centrifugal solid-particle and \textit{in-situ} methods, have been reviewed. Moreover, the origin of anisotropic wear resistance in the Al-Al$_3$Ti FGMs and the effect of particle size on the wear properties in the Al-Al$_3$Ni FGMs have been described, and the merits of FGMs as wear-resistant materials are discussed.

2. Wear Properties of Al-Al$_3$Ti FGMs Fabricated by the Centrifugal Solid-Particle Method\textsuperscript{(17)}

Al-Al$_3$Ti FGMs were fabricated using the centrifugal solid-particle method in a similar manner to that of previous studies\textsuperscript{(7-10)}. The master alloy ingot was a commercial aluminum alloy containing 5mass\% Ti. The ingot was melted under an argon gas atmosphere at a temperature of solid-liquid coexisting state. The applied \( G \) were 10, 30 and 50, where \( G \) indicates the centrifugal force in units of gravity.

A block-on-disc type wear apparatus was used for the wear tests. Specimens for wear tests were cut into 5 mm x 5 mm x 20 mm sized blocks. The Al-Al$_3$Ti FGMs were machined from the outer or inner region of the FGM thick-walled ring, and the specimens were tested without any additional heat treatment. The anisotropic wear resistances in the Al-Al$_3$Ti FGMs were measured in three directions based on the expectation that most of the Al$_3$Ti platelets were arranged with their platelet planes aligned approximately perpendicular to the radial direction of ring (centrifugal direction). The sliding directions were along the longitudinal direction on outer surface of the ring (A), along the radial direction on the radial plane (B), and along the hoop direction on the radial plane (C). In the case of direction (A), therefore, the worn plane nearly coincides with the Al$_3$Ti platelet face plane, as shown in Fig. 3. In the cases of directions (B) and (C), on the other hand, the worn planes coincided with the platelets’ two edge planes, and the wear directions were along the

![Fig. 3](image)

Fig. 3 Three types of wear specimens were prepared taking into account the morphology of the Al$_3$Ti platelets in the thick-walled FGM ring. The sliding directions were along the longitudinal direction on the ring outer surface (A), along the radial direction on the radial plane (B), and along the hoop direction on the radial plane (C).
thickness direction and the longitudinal direction of the Al₃Ti platelets, respectively (Fig. 3). The counterdisc for the wear tests was S45C steel heat-treated to achieve hardness of 185 Hv. The relative sliding speed and sliding distance were 1 m/s and 1 km, respectively. All wear tests were performed under rotary movement conditions at room temperature and in laboratory air environment, without the use of any lubricants. The initial loading stress was set to 1.0 MPa and was kept constant during the entire wear test. The morphology of the Al₃Ti platelet-particles in the Al matrix before the wear tests was observed using an optical microscope.

Figure 4 shows the distribution of Al₃Ti platelets in FGMs fabricated using the centrifugal method. Here, the abscissa represents the position of the platelets in the thickness direction of the ring, normalized by the thickness, i.e., 0.0 and 1.0 correspond to the inner and outer surfaces, respectively. It is clear that the volume fraction of Al₃Ti platelets increases towards the ring’s outer edge. In addition, a steeper distribution of Al₃Ti platelets was observed in the specimens manufactured using greater values for G. In this way, FGMs comprising dispersed platelet particles may be fabricated by the centrifugal method, similar to the case in which spherical particles are present.

![Figure 4](image)

**Fig. 4** Distributions of volume fraction (a) and the Herman’s orientation parameter (b) for Al₃Ti platelets in the FGMs. The abscissa in this figure is the position of the particles in the thickness direction normalized by the thickness; i.e., 0.0 is the inner surface and 1.0 is the outer surface of the ring (17).

![Figure 5](image)

**Figs. 5** (a), (b) and (c) Wear volumes of the FGMs fabricated for G=10, 30 and 50, respectively. The result for a pure Al specimen made by the same process is also shown in (c) for comparison (17).
The positional dependence on the orientation along the radial direction is also shown in Fig. 7. Here, one of the ordinates shows the Herman’s orientation parameter, \( f_p \) \(^{9, 10, 19, 20}\), which ranges between values of \( f_p = 0 \) (for a random distribution of the planes) and \( f_p = 1 \) (for a perfect alignment). It is clearly seen that the orientation parameter increases proportionally to the normalized thickness. Thus, both the orientation of the Al\(_3\)Ti platelets and the volume fraction of particles are gradually distributed in the Al-Al\(_3\)Ti FGM. It was also noted that a steeper gradient distribution for the orientation parameter was formed for specimens created using greater values for \( G \). Therefore, the positional dependence of wear properties might be expected in Al-Al\(_3\)Ti FGMs.

The wear volumes of FGMs fabricated for \( G = 10, 30 \) and \( 50 \) are shown in Figs. 5 (a), (b) and (c), respectively. The results for a pure Al specimen made by the same process are also shown in the figure for comparison. The wear volumes in the Al-Al\(_3\)Ti FGMs are much smaller than those of pure Al. It is also seen from these figures that the wear volume at the ring’s outer region is smaller than that at the inner region. The positional dependence of the wear resistance is emphasized by an increase in the value of \( G \).

It should be mentioned here that in the case of the ring’s outer region, considerable anisotropy exists in the wear volume among the three platelet orientations tested, where direction (B) shows the worst wear resistance among the three orientations. In contrast, directions (A) and (C) show relatively better wear resistance, and the wear volume of direction (C) is slightly smaller than that of direction (A). Moreover, greater anisotropy of the wear resistance is found for specimens with larger orientation parameters. Although not presented here, anisotropic wear resistance was not observed at the ring’s inner region.

Figure 6 shows the mean wear-volume as a function of volume fraction of Al\(_3\)Ti platelet-particles. It is seen that the mean wear-volume decreases proportionally to the increase in the volume fraction of the Al\(_3\)Ti platelet-particles. Thus, the wear resistance is significantly improved by introducing Al\(_3\)Ti platelets-particles into the Al matrix.

In order to express the anisotropic wear resistance quantitatively, the wear volume ratios (wear volume of direction (B) / wear volume of direction (A) or (C)) were calculated. We have considered that the larger the value of wear volume ratio, the larger the anisotropy of wear resistance. Figure 7 shows the wear volume ratios plotted against the orientation parameter of the Al\(_3\)Ti platelets. It is obvious that since the wear volume ratio increases together with the orientation parameter, we can conclude that the anisotropy of wear resistance is emphasized with an increase in the orientation parameter of the Al\(_3\)Ti platelets. The origin of anisotropic wear resistance in Al-Al\(_3\)Ti FGMs will be discussed later.
In order to investigate the microstructural features near the worn surface, cross-sections of specimens parallel to the sliding direction were observed. The results are shown in Fig. 8. Damaged layers containing broken Al₃Ti platelets are found in (a) and (b). Particularly, in the case of direction (B), the wear tests led to fracture and bending of the Al₃Ti platelets along the wear test direction. This result is similar to that of Si particles in the damaged layer reported for the case of Al-Si alloy wear tests (21). In contrast, damaged Al₃Ti platelets were not observed for direction (C) (Fig. 8 (c)).

Figs. 8 (a), (b) and (c)  Cross-sections parallel to the sliding directions (A), (B) and (C), respectively (17).

The present Al-Al₃Ti FGMs exhibit anisotropic wear resistance, as shown in Fig. 5. The main difference between directions (A), (B) and (C) is the orientation of the Al₃Ti platelets in the Al matrix. In direction (A), the wear plane is nearly parallel to the Al₃Ti platelet face planes, while in directions (B) and (C) the wear planes are parallel to the platelet edge planes along the thickness and longitudinal directions, respectively. Transmission electron microscopy (TEM) revealed that the Al₃Ti platelets are several micrometers thick (22), and that Al₃Ti is brittle in nature. Based on these facts, it can be concluded that the shear flow stress for forming a damaged region in direction (B) should be lower than that in directions (A) and (C). This is supported by the evidence that Al₃Ti platelets for direction (B) break easily during the wear test (Fig. 8 (b)), whereas the platelets for directions (A) and (C) are more difficult to break. Thus, direction (B) shows a lower wear resistance, while directions (A) and (C) show better wear resistance.

The volume fractions of Al₃Ti in direction (A) and (C) specimens, both of which were tested along the longitudinal direction of the Al₃Ti platelets, are the same. However, direction (A) exhibits worse wear resistance compared to direction (C). The wear plane of the Al₃Ti platelets is different for the two specimens, namely the platelet face for direction (A) and the edge plane for direction (C). The Al matrix for direction (A) is easier to
deform around the worn surface compared to direction (C) because the Al matrix forms layers parallel to the wear plane where nothing prevents the deformation. Thus, the wear rate for direction (A) is faster than that for direction (C).

3. Wear Properties of Al-Al$_3$Ni FGMs Fabricated by the Centrifugal In-Situ Method

Six Al-Al$_3$Ni FGM rings were systematically fabricated by the centrifugal in-situ method. Master alloy ingots comprised Al-13 mass% Ni and 20 mass% Ni alloys. Liquidus temperatures of both Al-Ni alloy ingots were lower than the processing temperatures. Consequently, the centrifugal force can be applied during the solidification of the Al$_3$Ni intermetallic compound and Al matrix. The applied centrifugal forces were $G=30$, 50 and 80. The FGM rings have an outer diameter of 90mm and a thickness of roughly 25mm. The casting conditions and notifications for each specimen are summarized in Table 1. The volume fraction and the particle size of the Al$_3$Ni particles at each position were measured by optical microscopy.

<table>
<thead>
<tr>
<th>Initial master ingot (mass% of Ni)</th>
<th>Pouring temp. ($^\circ$C)</th>
<th>Mold temp. ($^\circ$C)</th>
<th>$G$ number/ Cooling rate ($^\circ$C/s)</th>
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<tbody>
<tr>
<td>Specimen R1 13 900 600 30 / 0.27</td>
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<tr>
<td>Specimen R2 13 900 600 50 / 0.29</td>
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<tr>
<td>Specimen R3 13 900 600 80 / 0.37</td>
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<tr>
<td>Specimen R4 20 900 600 30 / 0.27</td>
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<tr>
<td>Specimen R5 20 900 600 50 / 0.29</td>
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<tr>
<td>Specimen R6 20 900 600 80 / 0.37</td>
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Sample plates 5.5mm in thickness were cut from the outer, interior and inner parts of the Al-Al$_3$Ni FGM rings. Using these specimens, wear tests were carried out using a ball-on-disc machine (Rhesca Co., Ltd., FPR-2100) under reciprocal movement. A stainless steel sphere was used as a counter ball in the wear tests. Both the wear specimens and the counter balls were cleaned before the tests with acetone using an ultrasonic cleaner.

Fig. 9 Volume fraction distributions of Al$_3$Ni particles in Al-Al$_3$Ni FGMs.
The wear tests were conducted under a load of 19.6N at sliding velocity of 15mm/s for a sliding distance of 150m.

Figure 9 shows the volume fraction distributions of the Al$_3$Ni primary crystal particles in the FGM rings (13). The volume fraction of the Al$_3$Ni primary crystal particles increases towards the outer surface along the direction of the centrifugal force. Comparing the volume fraction distribution of Al$_3$Ni particles among specimens R1, R2 and R3, the gradient of the volume fraction of the Al$_3$Ni particles in FGM ring becomes steeper as $G$ increases. The same phenomenon is observed for specimens R4, R5 and R6. This result agrees with that reported in previous studies (4, 9). Moreover, specimens R1 through R3 display a steeper gradient of volume fraction of Al$_3$Ni particles than specimens R4 through R6 due to the fact that the viscosity of the Al-Ni alloy melts during the casting process increases together with the volume fraction of the Al$_3$Ni particles. Since the nominal volume fraction of the Al$_3$Ni particles in specimens R1 through R3 is smaller than that in R4 through R6, the viscosity of the melt of the former is lower than that of the latter. Owing to this difference in the viscosities of the Al-Ni alloy melts, the volume fraction distribution of Al$_3$Ni particles in R1 through R3 becomes steeper than in specimen R4 through R6 (13).

Figure 10 shows the variation of the average three-dimensional diameter of the Al$_3$Ni primary crystal particles as a function of their normalized position. The size of the Al$_3$Ni primary crystal particles was measured under the assumption that the shape of the Al$_3$Ni particles is spherical. It can be inferred from Fig. 10 that there is a gradient distribution of both particle size and volume fraction in Al-Al$_3$Ni FGMs. Moreover, it is clear that larger values of $G$ and lower Ni content in the master alloys result in a smaller particle size. The particle size distribution within the FGM is also affected by the cooling rate (13).

In this way, the effects of Al$_3$Ni particle distribution on the wear properties of Al-Al$_3$Ni FGMs were investigated. The results of the wear tests for Al-Al$_3$Ni FGMs are shown in Fig. 11. As can be seen in this figure, the wear resistance of the Al-Al$_3$Ni FGMs changes from place to place. The weight loss by wear at the outer region is smaller than that at the inner region. This result shows the Al-Al$_3$Ni FGM gradient wear resistance along the ring thickness (the centrifugal force direction). Moreover, since the mean volume fraction of the Al$_3$Ni particles within specimens R4 through R6 are larger than that within specimens R1 through R3, better wear resistances are observed for the former. Another remarkable finding from Fig. 11 is that better wear resistance was observed for specimens manufactured under greater $G$. 

![Figure 10: Particle size distributions of Al$_3$Ni particles in Al-Al$_3$Ni FGMs (13).](image-url)
Gradient distribution of both particle size (Fig. 10) and volume fraction (Fig. 9) is observed for the present Al-Al$_3$Ni FGMs. Therefore, one question arises about which gradient distribution has a more pronounced effect on the wear resistance. In order to answer this question, the wear volumes of each specimen were re-plotted against both the particle size and the volume fraction, and the results are shown in Fig. 12. It is important to note here that superior wear resistance is obtained by increasing the volume fraction of Al$_3$Ni particles as well as by reducing the particle size. In other words, each parameter has an inherent effect on wear resistance.

It was shown that, in the case of FGM fabricated by the centrifugal solid-particle method, the particle size at the outer region is larger than that at the inner region (24) which is different from the present Al-Ni system. This is because the motion of solid particles during the implementation of this method can be qualitatively explained by Stokes' law (4, 24, 25). In other words, the particle size gradient in FGMs fabricated by the centrifugal solid-particle method will de-emphasize the mechanical property gradient in comparison to FGMs with the same volume fractional gradient but without the particle size gradient. On the other hand, in the case of the FGM fabricated by the centrifugal in-situ method, the size of the particles was smaller at the outer ring region. Therefore, the particle size gradient of Al-Al$_3$Ni FGM may emphasize the gradients in mechanical properties, which may be one of the advantages of FGMs fabricated by this method.

Figure 13 shows the Brinell hardness distribution of the Al-Al$_3$Ni FGMs as a function of the specimen position. As can be seen in Fig. 13, all of the Al-Al$_3$Ni FGMs fabricated from Al-20%Ni alloy (specimens R4 through R6) have greater hardness than those fabricated from Al-13%Ni alloy (specimens R1 through R3). Moreover, the hardness of Al-Al$_3$Ni FGMs increases towards the outer surface of the specimens. From this result, it is found that the hardness distribution in FGMs is closely related to the Al$_3$Ni particle distribution, as well as to the wear resistance distribution.

Fig. 11 Results of the wear tests for Al-Al$_3$Ni FGMs. The “in”, “mid” and “out” labels represent the inner, interior and outer parts of Al-Al$_3$Ni FGMs, respectively (18).

Fig. 12 Distribution of wear property as functions of the volume fraction and the particle diameter of Al$_3$Ni particles in Al-Al$_3$Ni FGMs (18).
4. Merits of FGMs as a Wear Resistance Material

The properties of aluminum alloys can be improved through the addition of aluminum-transition metal intermetallic phases \(^{(26)}\). In this study, it was found that the wear properties are improved through the addition of Al\(_3\)Ti and Al\(_3\)Ni intermetallic compound particles. As already mentioned, volume fraction, particle size and orientation distributions in the FGMs, which strongly affect the wear properties of the materials, can be controlled in both the centrifugal solid-particle and \textit{in-situ} methods through the processing parameters such as the value of \(G\) and the cooling rate gradient during the fabrication process of the FGMs. Therefore, tailored microstructures with suitable wear properties can be obtained by using the centrifugal solid-particle and \textit{in-situ} methods.

In the case of Al-Al\(_3\)Ti FGMs, the significant anisotropy observed in the wear properties was found to be dependent on the direction of the wear relative to the Al\(_3\)Ti platelet orientation. Therefore, the wear properties of FGMs along one direction are better than those of composite materials with random orientation. Moreover, it was shown in a previous study that a wear-induced supersaturated solid solution layer (supersaturated layer) was formed near the worn surface region, roughly 100 \(\mu\)m in depth \(^{(8)}\). Since this layer does not cause severe damage to the counter surface, the Al-Al\(_3\)Ti FGMs are suitable for wear-resistant material.

It was shown that both volume fraction and particle size have gradient distributions within the FGMs fabricated using the centrifugal method. In the case of FGMs fabricated using the centrifugal solid-particle method, the particle size at the outer region is larger than that at the inner region \(^{(24)}\), and the particle size gradient de-emphasizes the wear property gradient, which is mainly affected by the volume fractional gradient. In contrast, in the case of FGMs fabricated by the centrifugal \textit{in-situ} method, the size of the particles was smaller at the outer ring region, where the volume fraction of the Al\(_3\)Ni particles is increased. Therefore, the particle size gradient emphasizes the gradients in mechanical properties. This may be one of the advantages of FGM rings fabricated using this method.

By implementing the concept of FGMs, the wear properties of a material can be improved at a designed place for a designed amount along a designed direction, resulting in both resource efficiency and the improvement of the reliability of industrial products.

5. Summary

In this article, the wear properties of Al-Al\(_3\)Ti FGMs with different Al\(_3\)Ti platelet orientations, as well as the wear properties of Al-Al\(_3\)Ni FGMs with different particle size distributions, were studied. The results are summarized as follows.
Anisotropic wear resistance was found to be dependent on the direction of the wear test relative to the Al$_3$Ti platelet orientation. Specimens tested along the Al$_3$Ti platelets thickness direction show the smallest wear resistance among the three orientations due to the ease with which the Al$_3$Ti platelets broke.

A greater anisotropy in wear resistance was found for specimens with larger orientation parameters.

Al-Al$_3$Ni FGMs display a wear resistance gradient along the ring thickness (the direction of the centrifugal force). It was found that the wear resistance increases together with the volume fraction and with reducing the particle size.

The particle size gradient within the FGM fabricated using the centrifugal in-situ method emphasizes the gradients in mechanical properties.

It is possible to improve the wear resistance of FGMs so that improved wear properties could be achieved by considering the volume fraction, particle size and orientation distributions of the reinforcements within the FGMs.

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