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Aluminum matrix texture in Al-Al₃Ti functionally graded materials analyzed by electron back-scattering diffraction

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Al matrix functionally graded materials (FGMs) with oriented Al₃Ti platelets were fabricated by a centrifugal solid-particle method. The applied centrifugal forces were 30, 60, and 120 G (units of gravity). The orientation and volume fraction gradients of the Al₃Ti platelets within the samples were measured. Since a good lattice correspondence was reported for the close-packed directions and the close-packed planes between Al and Al₃Ti, the Al matrix in the Al-Al₃Ti FGMs fabricated by the centrifugal solid-particle method should have some texture. Al matrix texture was, therefore, analyzed by electron back-scattering diffraction (EBSD). Analysis of the resulting pole figures indicates a preferred orientation along the (200) plane for the Al matrix crystals. Furthermore, increasing the applied centrifugal force enhances the orientation effect. A correlation appears to exist between platelet orientation and the preferred texture of the Al matrix.
1. Introduction

The recent interest in materials with spatial gradients in composition and structure has been driven by the fact that these materials exhibit characteristics not attainable by conventional materials. Thus, there has been a considerable effort devoted to the development of functionally graded materials (FGMs). One of the promising methods for the fabrication of FGMs is the centrifugal method, which is an application of the centrifugal casting technique. The centrifugal force applied to a molten metal matrix and dispersed particles leads to the formation of a desired compositional gradient, where the gradient is controlled mainly by the difference in density between the matrix and the dispersed particles. The fabrication of the FGMs with dispersed particles made by the centrifugal method can be classified into two types on the basis of the melting point of dispersed particles or the liquidus temperature of the master alloy. When the melting point or liquidus temperature is significantly higher than the processing temperature, the dispersed phase remains solid in a liquid matrix; the method utilizing this phenomenon is named the centrifugal solid-particle method. On the other hand, when the melting point or liquidus temperature is lower than the processing temperature, centrifugal force is applied during the solidification of the dispersed phase and matrix; the method utilizing this phenomenon is called the centrifugal in-situ method.

In previous studies, ring-shaped Al-Al₃Ti FGMs with Al₃Ti platelets have been successfully fabricated from a commercial Al-5mass%Ti alloy, using the centrifugal solid-particle method. In this method, the master alloy is heated up to a temperature below the liquidus temperature, at which Al₃Ti intermetallic platelets remain solid in the molten Al matrix. The crystal structures and densities of the Al and Al₃Ti phases are shown in Fig. 1. The density of the Al₃Ti phase is higher than that of the molten Al matrix. Owing to this difference in density, upon casting under centrifugal force, the Al₃Ti platelets will segregate in the direction of the applied centrifugal force. This will lead to a graded distribution of the volume fraction of the Al₃Ti platelets in the Al matrix. It was also found that the solid Al₃Ti platelets in the molten Al matrix were oriented with their platelet planes nearly normal to the centrifugal force direction (radial direction). Then, Al matrix FGMs with oriented Al₃Ti platelets were fabricated by the centrifugal solid-particle method. A schematic representation of the arrangement of Al₃Ti platelets in FGMs is shown in Fig. 2.
Since there are some orientation relationships between the Al matrix and the Al₃Ti phase, it would be naturally expected that the crystallographic orientation of the Al grains in the FGMs is also affected by the orientation of the Al₃Ti platelets.

In this study, Al-Al₃Ti FGMs were fabricated by the centrifugal solid-particle method. The Al crystal texture as well as the Al₃Ti phase was then analyzed by electron back-scattering diffraction (EBSD). Although the crystal texture can be analyzed by X-ray diffraction, EBSD can evaluate both the crystal texture and the microstructure at the same measurement position. In addition, since the spatial resolution of EBSD analyzed using field emission scanning electron microscopy (FE-SEM) is less than 0.02 μm, it is possible to analyze local changes in crystal orientation. Hence, EBSD is an effective tool for evaluating the crystal texture and the crystal orientation relationship. Honda et al. have studied the nucleation of the primary Al phase on Al₃Ti during solidification by EBSD and reported the following orientation relationships between Al₃Ti and Al. The in-situ observation of butterfly-type martensite in Fe alloy during the tensile test could be carried out using EBSD. Therefore, EBSD results on the characteristics of Al₃Ti platelets and the Al matrix texture at the surface of the FGMs are presented. Although this study is based on our previous study of the Al-Al₃Ti FGMs analyzed by the Schulz reflection method, a detailed examination is carried out with new data analyzed by EBSD.

2. Origin of Al matrix texture

In previous studies, the crystallographic relationship between the Al matrix and the Al₃Ti platelets in Al-Al₃Ti FGMs was studied by transmission electron microscopy (TEM). Selected-area diffraction (SAD) taken along a low-index direction provided useful information for determining the orientation between the Al matrix and the Al₃Ti platelets. The diffraction patterns taken at the Al-Al₃Ti interface are shown in Fig. 3. The orientation relationship between the Al (fcc) and Al₃Ti (D₀₂₂) phases is given by

\[
(112)_{\text{Al/Al₃Ti}} // (111)_{\text{Al}}, \quad [110]_{\text{Al/Al₃Ti}} // [1\bar{1}0]_{\text{Al}}
\]

(1)
A good lattice correspondence was found for the close-packed directions and the close-packed planes between two crystals. Since the solid Al\textsubscript{3}Ti platelets in the molten Al matrix were oriented with their platelet planes nearly normal to the centrifugal force direction, the Al\textsubscript{3}Ti platelets in the FGMs should exhibit orientation. Moreover, since it was reported that the plane normal direction of the Al\textsubscript{3}Ti platelets corresponded to the [001\textsubscript{Al\textsubscript{3}Ti}] direction\textsuperscript{22,23}, it is considered that the [001\textsubscript{Al\textsubscript{3}Ti}] direction on the surface of the FGMs would be parallel to the centrifugal force direction. Therefore, it would be naturally expected that the crystallographic orientation of the Al grains in Al-Al\textsubscript{3}Ti FGMs is affected by the orientation of the Al\textsubscript{3}Ti platelets. The origin of the Al matrix texture in Al-Al\textsubscript{3}Ti FGMs fabricated by the centrifugal solid-particle method is summarized in Fig. 4. However, no detailed studies on the texture of the Al matrix in Al-Al\textsubscript{3}Ti FGMs have been performed.

3. Experimental methods

Since the relative atomic masses of Al and Ti are 26.98 and 47.88, respectively, the theoretical volume fraction of Al\textsubscript{3}Ti in the master alloy was calculated to be approximately 11 vol.\%. Figure 5 shows an Al-Ti phase diagram.\textsuperscript{24,25} In this study, an Al-5 mass\% Ti commercial alloy with Al\textsubscript{3}Ti platelets is used as the initial material. If the temperature of the melting furnace was set at 900 °C, the Al\textsubscript{3}Ti platelets could remain in the solid state in a liquid Al matrix during heating at 900 °C. Therefore, Al-Al\textsubscript{3}Ti FGMs could be fabricated by the centrifugal solid-particle method. The molten alloy was poured into a rotating mold, in which the applied centrifugal casting forces were 30, 60 and 120 $G$ (units of gravity). The fabricated FGMs are ring-shaped with an outer diameter of 90 mm, a height of 25 mm, and a thickness in the range of 20-25 mm. A detailed description of the centrifugal solid-particle method is available in previous reports.\textsuperscript{6,8,9,12}

Samples for microstructural observation were taken from the ring’s outer region and observed by optical microscopy. The particle distribution and orientation of Al\textsubscript{3}Ti platelets were measured along three observation planes: perpendicular to the rotating axis (hereafter referred to as OP1), perpendicular to the rotating direction (OP2), and perpendicular to the centrifugal force direction (OP3), as shown in Fig. 2.

The texture of the Al matrix, as well as the Al\textsubscript{3}Ti phase, in the Al-Al\textsubscript{3}Ti FGMs produced at 30 and 120$G$ was also analyzed at the outer surface (OP3) of the rings using FE-SEM with
EBSD equipment. As the reference material, a pure Al sample was produced by the centrifugal method at an applied centrifugal force of 80 G, and the texture of OP3 was measured by EBSD. Although the plane on OP3 is curved, the OP3 plane was mechanically and electrically polished and flattened. The dimensions of EBSD specimens were approximately 5 x 5 mm² in a cross section and 2 mm in thickness. The EBSD measurements were carried out in step sizes of 3.0 μm for pure Al sample and 2.0 μm for Al-Al₃Ti FGMs. The acceleration voltage of FE-SEM for the EBSD measurement was 15kV. The grid for data collection was hexagonal. The data collected by EBSD were analyzed using TSL-OIM 6.1.

4. Results and discussion

4.1 Characterization of the Al₃Ti platelets

In Fig. 6, the typical microstructures of the Al-Al₃Ti FGMs produced at 30, 60 and 120 G are shown. The microstructures on the OP1 and OP2 planes for the three FGMs are very similar, whereas those on the OP3 plane were not. This is due to the fact that the planes of Al₃Ti platelets tend to be oriented perpendicular to the centrifugal force direction. The OP1 and OP2 planes intersect Al₃Ti platelets along their edges, whereas the OP3 plane intersects the platelet face.

Figure 7 shows the volume fraction of Al₃Ti platelets in the FGMs as a function of ring position normalized by the ring thickness, where 0.0 and 1.0 correspond to the ring’s inner and outer surfaces, respectively, as shown in Fig. 2. The volume fraction of Al₃Ti platelets increases from the inner to the outer surface of the ring. This is because the density of Al₃Ti is higher than that of molten Al. It is also observed that, at the outer surface, the volume fraction of Al₃Ti platelets increases with applied centrifugal force. By comparing between the 60 and 120 G specimens, we found only a very small increase in the volume fraction at the ring’s outer region. From this finding, it is deduced that the maximum particle volume fraction packing is approximately 40 vol.%.

 Orientations of Al₃Ti platelets were measured from the micrographs by the same method as that described in previous reports. The centrifugal force direction, the A3 direction in Fig. 2, was chosen as the reference axis, and the orientation angle θ between this axis and the normal direction of the Al₃Ti platelets observed in the OP1 and OP2 planes was measured.
The orientation histograms of the OP1 and OP2 planes in the FGMs ring’s outer region are presented in Fig. 8 as an example. It is clear that Al\textsubscript{3}Ti platelets tend to have the perpendicular direction of their planes within orientation angles of -15 to 15 ° to the centrifugal force direction along the OP1 and OP2 planes.

To express this tendency, Herman’s orientation parameter, \( f_p \), is calculated.

\[
fp = [2<\cos^2 \theta>-1],
\]

is calculated. The orientation parameter \( f_p \) becomes 0 for a random distribution of Al\textsubscript{3}Ti platelets, and it becomes 1 for perfect alignments with their planes perpendicular to the centrifugal force direction. The gradient distributions of \( f_p \) within the FGMs fabricated at 30 and 120 G are shown in Fig. 9. It is seen that a \( f_p \), as well as the volume fraction of Al\textsubscript{3}Ti, was graded within the FGMs. The \( f_p \) values calculated for the outer region of three FGMs rings are listed in Table 1. As can be seen in Table 1, an increment in the applied centrifugal force leads to the enhancement of the orientation of the Al\textsubscript{3}Ti platelets.

4.2 Crystal orientation analysis of Al matrix using Schulz reflection method

The Al matrix texture of the outer surface of the Al-Al\textsubscript{3}Ti FGMs along OP3 was studied by the Schulz reflection method. The (200) pole figures of each specimen determined by this method are presented in Fig. 10. Nonrandom patterns appear in all the pole figures, indicating a preferred orientation along the (200)\textsubscript{Al} plane for the Al matrix crystals. In particular, the area with a high intensity (more than 1) becomes narrower with increasing centrifugal force. Therefore, increasing the applied centrifugal force enhances this orientation effect.

4.3 Crystal orientation analysis of Al matrix using EBSD

In general, the structure of a cast metal contains the 1) chill cast zone, 2) columnar zone, which contains elongated crystals with certain crystallographic directions aligned in the direction of heat -flow or crystal growth, and 3) interior equiaxed zone. A relatively strong texture is usually associated with columnar grains. This is attributed to a preferred direction of growth. The <001> direction is the preferred growth direction of the solidification of pure Al. Moreover, during centrifugal casting, the heat flow is parallel
to the A3 direction of the ring. Then, there is a possibility of casting texture in the pure Al sample fabricated by centrifugal casting. The texture of the Al matrix in pure Al sample produced at 80 G was, therefore, analyzed at the outer surface (OP3) of the rings using FE-SEM with EBSD equipment. Figure 11 shows the inverse pole figure map and inverse pole figure of the centrifugally cast pure Al sample along OP3 fabricated at an applied centrifugal force of 80 G. These inverse pole map and figure show the crystal plane orientation on the plane observed from the A3 direction. As seen in the inverse pole figure in Fig. 11, <001>Al directions of pure Al sample are distributed randomly. Although this measurement area includes about only 15 Al grains, it is believed that the crystal orientation of the Al grains is randomly distributed owing to the stirring of the Al melt by the centrifugal force applied. Therefore, no texture is observed in the pure Al sample fabricated by centrifugal casting.

Figures 12(a) and 12(b) are the inverse pole figure maps and inverse pole figures of the Al3Ti phase in the Al-Al3Ti FGMs fabricated under the applied centrifugal forces of 30 and 120 G, respectively, also along OP3. Similarly to Fig. 11, these inverse pole figures show crystal plane orientation on the plane observed from the A3 direction. In the case of the Al-Al3Ti FGMs, a concentration of data points is seen in the inverse pole figures near the (001) corner, indicating the development of a strong texture in OP3. It is also shown in Fig. 12 that the orientation of the Al3Ti platelet face is (001)Al3Ti, which is in agreement with previous studies. Thus, the [001] Al3Ti direction of the Al3Ti phase is aligned perpendicular to the Al3Ti platelets. Note that the concentration of Al3Ti near the (001) corner in the FGMs sample at 120 G is higher than that in FGMs sample at 30 G. This is because an increment in applied centrifugal force leads to an enhancement of the orientation of the Al3Ti platelets, as shown in Fig. 9.

The inverse pole figure maps and inverse pole figures of the Al matrix in the Al-Al3Ti FGMs also along OP3 fabricated under applied centrifugal forces of 30 and 120 G are shown in Figs. 13(a) and 13(b), respectively. It can be seen from Figs. 12 and 13 that not only the Al3Ti phase but also the Al matrix has texture. Since texture is not observed in the pure Al sample fabricated by centrifugal casting, the texture in the Al matrix does not originate from the centrifugal casting itself. Similarly to the Al3Ti phase, since the concentration of the data points near the (001) corner of the Al matrix in the FGMs sample at 120 G is much higher than that in the FGMs sample at 30 G, the formation of the texture of crystal
orientations of the Al matrix and Al$_3$Ti is clearer on the FGMs sample at 120 $G$ than on the FGMs sample at 30 $G$. Figure 14 shows a set of 200 pole figures of the centrifugally cast pure Al sample and the Al matrix in the Al-Al$_3$Ti FGMs under centrifugal forces of 30 and 120 $G$. As seen in these figures, the texture of the Al matrix is formed in the Al-Al$_3$Ti FGMs and the texture becomes stronger as the centrifugal force increases. This result is in good agreement with the results shown in Fig. 10. In this way, an increment in the applied centrifugal force leads to a stronger texture. In the comparison of the texture of the Al phase with that of the Al$_3$Ti phase, however, one can notice that the former is somewhat limited. In the following, we will discuss why the Al matrix has a weaker texture than the Al$_3$Ti phase.

4.4 Discussion

Taking into account the results for the Al$_3$Ti platelet orientation described in the previous section, a correlation appears to exist between the Al$_3$Ti platelet orientation and the preferred orientation of the Al matrix crystals. This correlation is in agreement with the lattice correspondence found between the Al matrix crystals and the Al$_3$Ti phase in previous studies.\textsuperscript{20,21} Considering that Al$_3$Ti platelets remain solid during the centrifugal solid-particle method and have reached their position as the solidified matrix engulfs them, it is believed that the Al crystals’ preferred orientation is dependent on the platelets’ orientation.

Although very strong orientation effects of Al$_3$Ti platelets were observed in the ring’s outer region of the FGMs, especially for the sample fabricated at larger $G$ values, the texture of the Al matrix of the FGMs is somewhat limited. Here, we would like to discuss this phenomenon. Since an Al$_3$Ti particle in an Al melt plays a role as the heterogeneous nucleation site of pure Al grains,\textsuperscript{16,34-33} the solidification of the Al matrix around Al$_3$Ti particles would proceed under epitaxial phenomena. However, not all Al grains may solidify on Al$_3$Ti platelets, since the Al$_3$Ti platelets in the Al melt are large and the number density of Al$_3$Ti platelets is low. Another reason for this is the multiple orientation relationships between the Al and Al$_3$Ti phases.\textsuperscript{16,34}

The crystal orientation relationship between pure Al and Al$_3$Ti has often been investigated by X-ray diffraction (XRD) and TEM.\textsuperscript{20,21,35} As previously mentioned, Al and Al$_3$Ti have a good lattice correspondence for the close-packed directions and the close-
packed planes between these crystals. Recently, Honda et al. have reported the following multiple orientation relationships between Al$_3$Ti and Al investigated by EBSD$^{16}$:

\[
\begin{align*}
(001)_{\text{Al/Ti}} & \parallel (001)_{\text{Al}}, \ [100]_{\text{Al/Ti}} \parallel [100]_{\text{Al}} \\
(100)_{\text{Al/Ti}} & \parallel (001)_{\text{Al}}, \ [001]_{\text{Al/Ti}} \parallel [100]_{\text{Al}} \\
(102)_{\text{Al/Ti}} & \parallel (110)_{\text{Al}}, \ [201]_{\text{Al/Ti}} \parallel [110]_{\text{Al}} \\
(110)_{\text{Al/Ti}} & \parallel (110)_{\text{Al}}, \ [110]_{\text{Al/Ti}} \parallel [110]_{\text{Al}}
\end{align*}
\]

which indicate that the primary Al phase grows epitaxially from the nuclear Al$_3$Ti phase.$^{16}$ Crystallographic studies of the Al-Al$_3$Ti system using the edge-to-edge matching model were carried out by Zhang et al.$^{36}$ They predicted the following orientation relationships between Al and Al$_3$Ti:

\[
\begin{align*}
\text{OR1:} & \quad (112)_{\text{Al/Ti}} \parallel (111)_{\text{Al}}, \ [110]_{\text{Al/Ti}} \parallel [110]_{\text{Al}} \\
\text{OR2:} & \quad (112)_{\text{Al/Ti}} \parallel (111)_{\text{Al}}, \ [201]_{\text{Al/Ti}} \parallel [110]_{\text{Al}} \\
\text{OR3:} & \quad (200)_{\text{Al/Ti}} \parallel (200)_{\text{Al}}, \ [021]_{\text{Al/Ti}} \parallel [011]_{\text{Al}} \\
\text{OR4:} & \quad (200)_{\text{Al/Ti}} \parallel (200)_{\text{Al}}, \ [010]_{\text{Al/Ti}} \parallel [010]_{\text{Al}}
\end{align*}
\]

The atomic arrangements of the (112)$_{\text{Al/Ti}}$ and (200)$_{\text{Al/Ti}}$ planes of Al$_3$Ti are shown in Figs. 15(a) and 15(b), respectively. The atomic arrangements of Al of OR1 to OR4 are also superimposed on Fig. 15. Since \{111\}_Al is composed of stacks of closed-packed planes, namely, ABCABCA⋯ or ACBACBA⋯, OR1 shows normal stacking of the ABCABCA type at the interface between Al$_3$Ti and Al, whereas OR2 has a twin structure at the interface, i.e., ABCACBA stacking. Therefore, there are other possible orientation relationships between Al and Al$_3$Ti for OR1 and OR2, as shown in Fig. 16.

\[
\begin{align*}
\text{OR1':} & \quad (112)_{\text{Al/Ti}} \parallel (111)_{\text{Al}}, \ [110]_{\text{Al/Ti}} \parallel [110]_{\text{Al}} \quad \text{with a twin structure} \\
\text{OR2':} & \quad (112)_{\text{Al/Ti}} \parallel (111)_{\text{Al}}, \ [201]_{\text{Al/Ti}} \parallel [110]_{\text{Al}} \quad \text{without a twin structure}
\end{align*}
\]
Describing these orientation relationships on a stereographic projection of Al<sub>3</sub>Ti, the <001> <sub>Al</sub> directions of the Al matrix can be plotted as shown in Fig. 17. Figure 17 was constructed by superimposing the stereoprosjections of Al and Al<sub>3</sub>Ti with OR1-4 and OR1’-2’. The <001> <sub>Al</sub> directions of OR1, OR2’, OR3, and OR4 are close to the [001] <sub>Al<sub>3</sub>Ti</sub> direction. However, only OR4 has an exact crystal orientation of [001] <sub>Al<sub>3</sub>Ti</sub> // <001> <sub>Al</sub>, and other ORs have some scatters. On the other hand, the <001> <sub>Al</sub> direction of OR1’ is rotated between 47 and 72° from the [001] <sub>Al<sub>3</sub>Ti</sub> direction and OR2 is rotated 47, 50, and 67° from the [001] <sub>Al<sub>3</sub>Ti</sub> direction. However, the frequency of the appearance of OR1’ or OR2 with the twin structure at the interface may be lower than that of OR1 or OR2’, because the stacking fault energy of aluminum is high. Nevertheless, there is no one-to-one correspondence between the [001] <sub>Al<sub>3</sub>Ti</sub> and <001> <sub>Al</sub> directions because of multiple orientation relationships between the Al<sub>3</sub>Ti and Al phases. Therefore, a strong texture could not appear for the Al matrix, even in the FGMs with the perfect alignment of Al<sub>3</sub>Ti platelets, i.e., Herman’s orientation parameter, ŵ<sub>p</sub>, is 1.

5. Conclusions
In this study, Al-Al<sub>3</sub> Ti FGMs with oriented Al<sub>3</sub> Ti platelets were fabricated by the centrifugal solid-particle method. The Al matrix texture, as well as the orientation of Al<sub>3</sub> Ti platelets, was studied by electron back-scattering diffraction (EBSD) and/or microscopic observation. The obtained results are summarized as follows.
1) The planes of Al<sub>3</sub>Ti platelets in the FGMs tend to be oriented perpendicular to the centrifugal force direction
2) The Al matrix in the FGMs also shows a texture structure, since there is a good lattice correspondence between the Al<sub>3</sub>Ti phase and the Al matrix.
3) An increment in the applied centrifugal force leads to a stronger texture in both the Al<sub>3</sub>Ti phase and the Al matrix.
4) A weaker texture appears in the Al matrix than in the Al<sub>3</sub>Ti phase, since there are multiple orientation relationships between the Al<sub>3</sub>Ti and Al phases.
5) It is concluded that a strong texture could not appear in the Al matrix, even in the FGMs with the perfect alignment of Al<sub>3</sub>Ti platelets.
Acknowledgments

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References


Figure Captions

**Fig. 1.** Crystal structures and densities of Al and Al\(_3\)Ti phases.

**Fig. 2.** (Color online) Schematic representation of the arrangement of Al\(_3\)Ti platelets in the Al-Al\(_3\)Ti FGMs. Definitions of the observation planes OP1, OP2, and OP3, directions A1, A2, and A3, orientation angle \(\theta\), and normalized thickness are also shown in this figure.

**Fig. 3.** Diffraction pattern at the Al-Al\(_3\)Ti interface.\(^{20,21}\)

**Fig. 4.** (Color online) Summary of origin of Al matrix texture in Al-Al\(_3\)Ti FGMs fabricated by the centrifugal solid-particle method.

**Fig. 5.** (Color online) Al end of the Al-Ti equilibrium phase diagram.\(^{24,25}\)

**Fig. 6.** Typical microstructures observed on OP1, OP2, and OP3 of the Al-Al\(_3\)Ti FGMs produced at 30, 60, and 120 G.\(^{18}\)

**Fig. 7.** Volume fraction gradients of Al\(_3\)Ti platelets in the FGMs as a function of normalized thickness. The normalized thickness shows the ring position normalized by the ring thickness, where 0.0 and 1.0 correspond to the ring’s inner and outer surfaces, respectively.

**Fig. 8.** Orientation histograms observed on OP1 and OP2 planes in FGMs ring’s outer region.\(^{18}\)

**Fig. 9.** Gradient distributions of orientation parameter \(f_p\) within the FGMs fabricated at 30 and 120 G.

**Fig. 10.** (Color online) Al matrix texture (200) pole figures for the outer surface of the Al-Al\(_3\)Ti FGMs along OP3 determined by Schulz reflection method.\(^{18}\)
Fig. 11. (Color) Inverse pole figure map (a) and inverse pole figure (b) of the centrifugally cast pure Al sample along OP3 fabricated at applied centrifugal force of 80 G. These figures present the crystal plane orientation on the plane observed from A3.

Fig. 12. (Color) Inverse pole figure maps and inverse pole figures of the Al$_3$Ti phase in the Al-Al$_3$Ti FGMs along OP3. The FGMs were fabricated at applied centrifugal forces of 30 G (a) and 120 G (b). These figures present the crystal plane orientation on the plane observed from A3.

Fig. 13. (Color) Inverse pole figure maps and inverse pole figures of the Al matrix in the Al-Al$_3$Ti FGMs along OP3. The FGMs were fabricated at applied centrifugal forces of 30 G (a) and 120 G (b). These figures present the crystal plane orientation on the plane observed from A3.

Fig. 14. 200 pole figures of (a) the centrifugally cast pure Al sample under centrifugal force of 80 G and the Al matrix in the Al-Al$_3$Ti FGMs under the centrifugal forces of 30 G (b) and 120 G (c).

Fig. 15. (Color online) Atomic arrangements of Al of OR1 to OR4 superimposed on atomic arrangements of (112)$_{Al_3Ti}$ (a) and (200)$_{Al_3Ti}$ (b) planes of Al$_3$Ti.

Fig. 16. (Color online) Stacking of closed pack planes (112)$_{Al_3Ti}$ and (111)$_{Al}$ at interface between Al$_3$Ti and Al for OR1 type and OR2 type.

Fig. 17. Composite inverse pole figure of 001$_{Al}$ poles in the Al$_3$Ti coordinate. The 001$_{Al}$ poles with OR1-4 and OR1’ and 2’ are superimposed.

Table I. Herman’s orientation parameter $fp$ calculated for outer region of three FGMs rings. [18]
Fig. 1. Crystal structures and densities of Al and Al₃Ti phases.

<table>
<thead>
<tr>
<th>Crystal Structure</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Al_fcc" /></td>
<td>2.699 Mg/m³ solid Al at 20 °C, 2.315 Mg/m³ molten Al at 900 °C</td>
</tr>
<tr>
<td><img src="image" alt="Al₃Ti_D022" /></td>
<td>3.36 Mg/m³</td>
</tr>
</tbody>
</table>

Fig. 2. (Color online) Schematic representation of the arrangement of Al₃Ti platelets in the Al-Al₃Ti FGMs. Definitions of the observation planes OP1, OP2, and OP3, directions A1, A2, and A3, orientation angle θ, and normalized thickness are also shown in this figure.
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Fig. 7. Volume fraction gradients of Al₃Ti platelets in the FGMs as a function of normalized thickness. The normalized thickness shows the ring position normalized by the ring thickness, where 0.0 and 1.0 correspond to the ring’s inner and outer surfaces, respectively.

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Fig. 16. (Color online) Stacking of closed pack planes (112)_{Al_3Ti} and (111)_{Al} at interface between Al_3Ti and Al for OR1 type and OR2 type.
Fig. 17. Composite inverse pole figure of 001$_{Al}$ poles in the Al$_3$Ti coordinate. The 001$_{Al}$ poles with OR1-4 and OR1’ and 2’ are superimposed.

**Table I.** The Hermans orientation parameter $f_p$ calculated at outer region of three FGMs rings.

<table>
<thead>
<tr>
<th>Applied centrifugal force</th>
<th>Herman’s orientation parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OP1</td>
</tr>
<tr>
<td>30 G</td>
<td>0.839</td>
</tr>
<tr>
<td>60 G</td>
<td>0.808</td>
</tr>
<tr>
<td>120 G</td>
<td>0.876</td>
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