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Mechanical Properties of Functionally Graded Material Fabricated from Dilute Al-Cu Alloy

Tetsuro Ogawa and Yoshimi Watanabe*
Department of Functional Machinery and Mechanics
Shinshu University, 3-1-5 Tokida
Ueda 386-8567, Japan
* The author to whom correspondence should be addressed.
Fax: +81-268-21-5482, e-mail: yoshimi@giptc.shinshu-u.ac.jp

Al alloys are widely used as light ecomaterials. However, applications are limited when high hardness and high wear resistance are needed. It is well known that hardness of Al-Cu alloys can be increased on a large scale by heat treatments. Furthermore, the Al-Cu alloys with hardness and wear resistance gradients would probably have wide applications, based on the concept of functionally graded material (FGM). It is known that the Al based FGM rings can be fabricated by a centrifugal method that is an application of centrifugal casting technique. In many cases, however, the hardness and wear resistance gradients increase towards the ring's outer region. In the present study, novel method is proposed to fabricate an FGM ring, in which both mechanical property gradients increase towards the ring's inner region. For this purpose, dilute Al-Cu alloy is used as the initial master alloy for the centrifugal method. In case of dilute Al-Cu alloys, the density of the Al primary crystal is higher than that of the molten Al-Cu alloy. Therefore, the Al primary crystal particles migrate towards the outer region of the ring during the centrifugal method. Then, the Al_2Cu intermetallic compound will precipitate around ring's inner region. Consequently, the Al-Cu FGM ring with hardness and wear resistance gradients could be fabricated by combining the centrifugal method with heat treatments.

Key words: ecomaterials, resource economy, Al-Cu alloys, functionally graded materials (FGMs), heat treatment

1. INTRODUCTION

Since Al alloys have the attractive property of low density, they are widely used as light ecomaterials. Moreover, Al is one of the most desirable materials for recycling or re-using. This is because the energy costs involved in its production can be reduced by up to 95% by recycling Al scrap, as the production of Al from its ore is an energy consuming and very expensive process. However the performances of the Al alloys are limited when high hardness and high wear resistance are needed. This shortcoming can be overcome by the use of Al-Cu alloys, whose hardness can be increased on a large scale by heat treatments. From a viewpoint of resource economy, only the regions requiring higher mechanical properties should have a higher Cu concentration in the Al-Cu alloys. Furthermore, hardness and wear resistance gradients in the Al-Cu alloys would probably result in a better performance than that of a more homogeneous alloy, based on the concept of functionally graded materials (FGMs) [1, 2].

It has been shown that the FGM rings could be fabricated by a centrifugal method [3, 4]. In this method, a centrifugal force applied to a homogeneous molten composite, dispersed with particles, drives the formation of the desired gradation. The moving direction of the particles due to the centrifugal force is determined by the relative values of densities. In many cases, the volume fraction of reinforcement particles increases towards the ring's outer region, since the density of reinforcement particles is usually higher than that of the molten Al. Consequently, the gradient hardness and gradient wear resistance of Al based FGMs fabricated by the centrifugal method increase towards the ring's outer region [5, 6]. When the inner region of the ring is required to have high mechanical properties, the density of reinforcement particles should have a smaller value compared to that of the molten Al. However, since the above systems were limited, a new approach is needed to fabricate an FGM ring, in which both mechanical property gradients increase towards the ring's inner region.

Meanwhile, in the case of dilute Al-Cu alloys, the density of the Al primary crystal is larger than that of the molten Al-Cu alloy [7]. If this system is used for the initial master alloy of the centrifugal method, the Al primary crystal particles should migrate towards the outer periphery of the ring. After solidification, the

Al_2Cu intermetallic compound will form by precipitation around the ring's inner region. The volume fraction of the Al_2Cu intermetallic compounds would, therefore, increase towards the inner periphery of the ring. In the present study, the Al-Cu FGM ring with hardness and wear resistance gradients towards the ring's inner region was fabricated from dilute Al-3mass%Cu alloy by combining the centrifugal method with the heat treatments.

2. EXPERIMENTAL PROCEDURE

The Al-Al_2Cu FGM ring was fabricated by the centrifugal method from dilute Al-3mass%Cu initial master alloy. The alloy was melted in an argon gas atmosphere at 800°C. It was directly poured into a rotating mold that was heated at 750°C through an inlet. The applied G number was 120, where the G number is the centrifugal force in units of gravity [3, 4]. After casting, the mold was cooled in air. The fabricated FGM was cut into smaller specimens. The specimens were heated at 550°C for 20h, and then quenching into water (solution treatment). Some of these solution treatment specimens were aged at 160°C for 8h.

The microstructures of the fabricated Al-Al_2Cu FGM ring and the heat-treated specimens (solution treatment and aging) were observed using an optical microscope (OM) and a scanning electron microscope (SEM) along the plane perpendicular to the rotating axis. Both quantitative energy dispersive X-ray (EDX) and X-ray diffraction (XRD) analyses were performed in order to identify the structure of the second phase. For the mechanical property characterization, the hardness and wear distributions were measured. The wear resistance was measured using an Okoshi-type wear machine [8, 9], in which the hard peripheral surface of a rotating disc is pressed against the specimen plane with load increasing in proportion to the square root of the sliding distance to maintain a constant stress during the wear test.

3. RESULTS AND DISCUSSION

Figure 1 shows typical microstructures of the Al-Al_2Cu FGM ring fabricated from dilute Al-3mass%Cu alloy by centrifugal method. Figures. 1 (a), (b) and (c) were taken at the ring's outer, ring's interior and ring's inner region, respectively. In these figures, an arrow indicates the direction of centrifugal force. White regions are identified to be the Al_2Cu intermetallic compound and black regions are the Al by EDX analysis. From the microscopic observation, we noticed that volume fraction of Al_2Cu phase increases towards the ring's inner position (opposite the centrifugal force direction). This is because the Al primary crystal particles migrate towards the outer periphery of the ring under the application of the centrifugal force, since the density of the Al primary crystal is larger than that of the molten Al-Cu alloy. After solidification, the Al_2Cu intermetallic compound formed by precipitation, which increases towards the ring's inner position. Consequently, the volume fraction of Al_2Cu intermetallic compound increases towards the inner region of the ring.

(a)

(b)

(c)

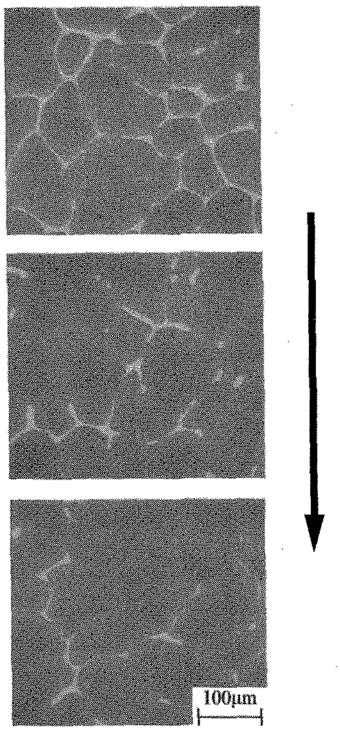

Fig. 1 The typical SEM microstructures of the Al-Al_2Cu FGM ring. An arrow indicates the direction of centrifugal force.
(a) ring's inner region, (b) ring's interior region,
(c) ring's outer region.

In order to express this phenomenon quantitatively, the distribution of Cu concentration in the Al-Al_2Cu FGM ring was measured. Results are shown in Fig. 2. The abscissa in this figure represents the position of normalized thickness of the ring; *i.e.* 0.0 is the inner surface and 1.0 is the outer surface. As can be seen, the Cu concentration increases towards the ring's inner position. It was quantitatively confirmed that the volume fraction of the Al_2Cu increases towards the inner periphery of the ring.

Figure 3 shows the XRD patterns of the Al-Al_2Cu FGM before and after the heat treatments (solution treatment and aging). It is seen that, although the Al and Al_2Cu peaks co-exist before the heat treatments, the Al_2Cu peaks disappear after the heat treatments. Namely, only the Al phase is detected after heat treatments. The supersaturated solid solution and/or GP zones would be formed after the solution treatment and aging.

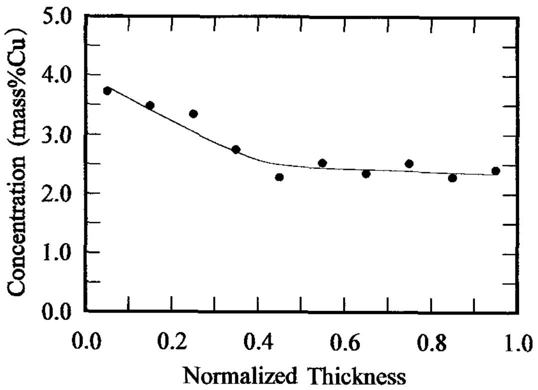

Fig. 2 Cu concentration distribution of the Al-Cu FGM. The abscissa in this figure represents the position of normalized thickness of the ring; i.e. 0.0 is the inner surface and 1.0 is the outer surface.

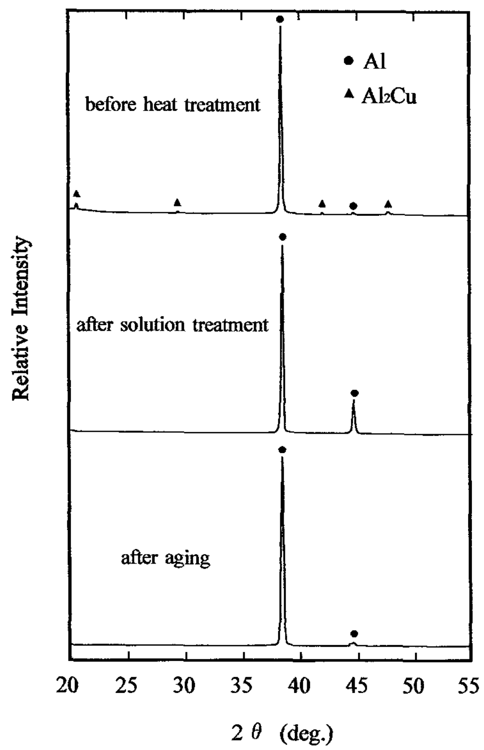

Fig. 3 XRD patterns of the Al-Cu FGM ring both before and after heat treatment (solution treatment at 550℃ for 20h and aging at 160℃ for 8h).

In order to study the mechanical properties required as light ecomaterials, hardness tests were performed. The Al-Al_2Cu FGM without a heat treatment has a dual phase structure (Al and Al_2Cu), and the coarser Al_2Cu intermetallic compound is found, as shown in Fig. 1. Therefore, hardness measuring using a small indenter is not the best method to evaluate the hardness of the whole specimen. In this study, the Brinell hardness test with a large indenter, whose diameter is 10mm, was adopted. In contrast, the Al-Cu FGMs with the heat treatments have a mono phase structure. The micro Vickers hardness test was carried out on the heat-treated specimens, since the detailed hardness distributions could be obtained.

Figure 4 shows the distribution of the Brinell hardness in the Al-Al_2Cu FGM ring before the heat treatments. As can be seen, the Brinell hardness of the ring's inner region is larger than that of the ring's outer region. This is because the content of Al_2Cu intermetallic compound increases towards the ring's inner position, and the hardness of the Al_2Cu intermetallic compound is larger than that of the Al. In this way, the Al-Al_2Cu FGM rings with a hardness gradient can be successfully fabricated by the centrifugal method from dilute Al-Cu alloy, where the hardness increases towards the inner region of the ring.

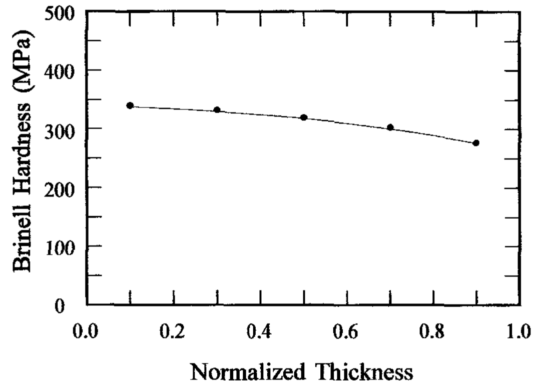

Fig. 4 The Brinell hardness distribution of the Al-Al_2Cu FGM ring.

Figure 5 shows the distributions of the micro Vickers hardness in the solution-treated specimen and the aged specimen. It is apparent that the higher micro Vickers hardness value was found around the inner region of the ring. Similar gradient could be observed among the hardness distributions and the Cu concentration. The micro Vickers hardness of the specimens at inner region of the ring increases in a large scale by aging. Although there is no evidence, GP zones should form by aging. Currently, transmission electron microscope (TEM) observation is being carried out to observe the GP zones, and results will appear in a future report.

The wear resistance is one of the important mechanical properties determining the service lifetime of products. Thus, Okoshi-type wear test was carried out for the fabricated FGM. The test results are shown in Figs. 6. It is clear from this figure that the specimens show the superior wear resistance in the inner region of the rings, since the wear volume at inner region is small. Therefore, the wear resistances could be improved by the proposed fabrication method. Moreover, it is interesting to note that the wear volume of the Al-Al$_2$Cu FGM ring is smaller than that of the aged specimen. One of the possible reasons for the above difference is the existence of the coarser Al$_2$Cu intermetallic compound. When the superior wear resistance is needed, the Al-Al$_2$Cu FGM without a heat treatment should be used. On the other hand, the Al-Al$_2$Cu FGM with the heat treatments should be used when high hardness is required.

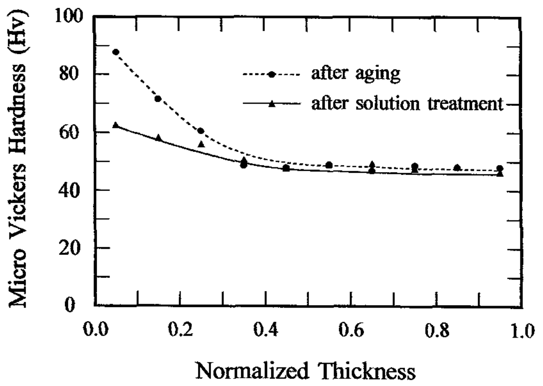

Fig. 5 The micro Vickers hardness distributions of the Al-Cu FGM ring after solution treatment (at 550℃ for 20h) and aging (at 160℃ for 8h).

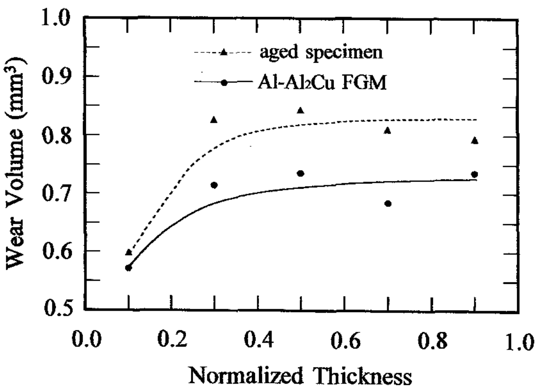

Fig. 6 The wear volume distributions of the Al-Al$_2$Cu FGM ring and the aged specimen.

As already mentioned before, the Al-Al$_2$Cu FGM ring with hardness and wear resistance gradients could be fabricated by the centrifugal method in which the superior mechanical properties were found around the inner region of the ring. Therefore, the fabricated Al-Cu FGM ring can save resources and extend the service lifetime, as well as being available as ecomaterials.

4. CONCLUSIONS

In this study, the Al-Cu FGM ring with the hardness and wear resistance gradients were fabricated from dilute Al-3mass%Cu initial master alloy by combining the centrifugal method with the heat treatments. It was found that the Al-Al$_2$Cu FGM ring with hardness and wear resistance gradients could be fabricated by the centrifugal method in which both mechanical properties increase towards the inner region of the ring.

Moreover, the hardness of the fabricated specimens at the inner region of the ring increases in a large scale by the heat treatments, since GP zones would form by aging. The wear resistance of the Al-Al$_2$Cu FGM ring is better than that of the aged specimen. When the superior wear resistance is needed, the Al-Al$_2$Cu FGM without heat treatments should be used. In contrast, the Al-Al$_2$Cu FGM with heat treatments should be used when high hardness is required.

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References

[1] S. Suresh and A. Mortensen, "Fundamentals of Functionally Graded Materials, Processing and Thermomechanical Behaviour of Graded Metals and Metal-Ceramic Composites", IOM Communications Ltd, London, (1998).

[2] Y. Miyamoto, W. A. Kaysser, B. H. Rabin, A. Kawasaki and R. G. Ford (Eds.), "Functionally Graded Materials: Design, Processing and Applications", Kluwer Academic Publishers, Boston (1999).

[3] Y. Fukui, *JSME Inst. J. Series III*, **34**, 144-148 (1991).

[4] Y. Watanabe, N. Yamanaka and Y. Fukui, *Composites Part A*, **29A**, 595-601 (1998).

[5] Y. Watanabe and Y. Fukui, *Aluminum Trans.*, **2**, 195-209 (2000).

[6] Y. Watanabe and T. Nakamura, *Intermetallics*, **9**, 33-43 (2001).

[7] K. Bornemann and F. Sauerwald, *Z. Matallk*, 14, 145-159 (1922).

[8] M. Okoshi, T. Sata and M. Mizuno, *Trans JSME*, **21**, 555-561 (1955).

[9] R. Takagi and Y. Tsuya, *Wear*, **5**, 435-445 (1962).

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