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# Formation of a wear-induced layer with nanocrystalline structure in Al–$Al_3Ti$ functionally graded material

Hisashi Sato [a,b,*], Takashi Murase [b], Toshiyuki Fujii [b], Susumu Onaka [b],
Yoshimi Watanabe [a], Masaharu Kato [b]

[a] *Omohi College, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan*
[b] *Interdisciplinary Graduate School of Science and Engineering, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama 226-8502, Japan*

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## Abstract

A new severe plastic deformation (SPD) process to obtain nanocrystalline (NC) structure by wear is reported. An Al–$Al_3Ti$ functionally graded material fabricated by a centrifugal method is wear tested to investigate the microstructure of the wear-induced layer. When the sliding distance of the wear exceeds $l = 100$ m, the wear-induced layer is obtained just below the worn surface. The microstructure of the wear-induced layer consists of fine $Al_3Ti$ fibrous particles and an NC solid-solution matrix containing a partly amorphized phase. The NC matrix has fine grains with a mean diameter of 16 nm and is a supersaturated solid-solution in which Ti is dissolved in the Al matrix. From the microstructure, it is estimated that the wear-induced layer is formed at a nominal shear strain of more than 90 and an effective shear strain of more than 52. An NC structured wear-induced layer is generated by the SPD process.

*Keywords:* Al–$Al_3Ti$ alloy; Functionally graded material (FGM); Wear; Severe plastic deformation (SPD); Nanocrystalline (NC) structure

## 1. Introduction

Wear causes large plastic strain on the surface of materials. The effective plastic shear strain $\overline{\delta}$ induced in oxygen-free high-conductivity copper by wear, which is calculated from nominal strain, has been reported to be as large as $\overline{\delta} = 10–100$ [1]. Since the worn surface of materials is thus severely deformed by wear, marked microstructural changes and resultant fracture occur on the worn surface. Therefore, the wear behavior of materials has frequently been the subject of investigation in efforts to improve wear resistance [2–9]. One example of materials with excellent wear resistance are a metal matrix composites (MMCs) containing solid particles [2–8]. Since the solid particles improve the strength and wear resistance of materials, such composites are often used in automobiles and airplanes [2,4–6].

Recently, titanium–aluminide intermetallic particles have attracted attention as solid particles for use in MMCs [10]. Among the Ti–Al particles, $Al_3Ti$ is particularly promising. This is because $Al_3Ti$ particles have a low density, high hardness and phase stability at high temperatures. However, the ductility and fracture toughness of the $Al_3Ti$ intermetallic particles are not sufficiently large. For this reason, when $Al_3Ti$ particles are used, they are often dispersed in a ductile matrix to form a composite with reasonable strength and wear resistance [10].

Watanabe et al. have proposed an Al–$Al_3Ti$ functionally graded material (FGM) as a composite containing $Al_3Ti$ particles [7,11–13]. FGMs are materials in which the composition and/or the microstructure vary in one specific direction [7,11–16]. Watanabe et al. fabricated Al–$Al_3Ti$ FGM in a ring shape using a centrifugal method

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[*] Corresponding author. Address: Omohi College, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan. Tel./fax: +81 52 735 5293.
*E-mail address:* sato.hisashi@nitech.ac.jp (H. Sato).

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[7,8,11–13]. This method enables creation of a gradient compositional distribution in metals containing ceramic powder or intermetallic particles. A larger number of $Al_3Ti$ particles in the Al–$Al_3Ti$ FGM are gradually distributed around the outside of the ring along the centrifugal force direction since $Al_3Ti$ has a higher density than Al [7,8,11–13]. As a result, the surface region of the FGM ring has better wear resistance and higher strength compared with those at the inner region. Using such an Al–$Al_3Ti$ FGM, Watanabe et al. have investigated microstructural evolution near the surface during a wear test of the Al–$Al_3Ti$ FGM [7]. They found that a wear-induced layer with a thickness of about 100 μm is formed just below the worn surface [7]. In addition, when subjected to heat treatment, the wear-induced layer is decomposed into Al and small $Al_3Ti$ particles [8,17]. On the basis of these results, Watanabe et al. identified the wear-induced layer as a supersaturated solid-solution in which Ti is dissolved in an Al matrix [7,8,17]. However, details of the microstructure and formation process of the wear-induced layer are still unknown.

Considering that large shear strain is imposed on a worn surface, the wear-induced deformation can be regarded as a severe plastic deformation (SPD) processes. Recently, it has been reported that SPD of metals by equal-channel angular pressing (ECAP) [18,19], accumulated rolling bonding (ARB) [20], high-pressure torsion (HPT) [21], drilling [22], milling [23,24], etc. produces an ultrafine grain (UFG) or a nanocrystalline (NC) structure without heat treatment. Therefore, a wear-induced layer is also expected to have an UFG or NC structure. Moreover, such a wear-induced layer would be easily obtained by the wear on the surface region of an Al–$Al_3Ti$ FGM ring. This is because local deformation occurs on the surface region due to condensation of $Al_3Ti$ particles. Although it is well known that it is difficult to obtain an UFG and NC structure in Al and Al alloys, the huge strain induced by the local deformation in Al–$Al_3Ti$ FGM is expected to generate an UFG or NC structure.

In this study, wear tests for an Al–$Al_3Ti$ FGM were performed to obtain a wear-induced layer, and the microstructure of this layer was investigated using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). As will be shown later, very interesting experimental results on the microstructure of the wear-induced layer with NC structure were obtained.

## 2. Experimental procedure

### 2.1. Preparation of Al–$Al_3Ti$ FGM

A commercial Al–5 mass% Ti alloy containing $Al_3Ti$ platelet particles was used as the master alloy ingot. Because the relative atomic masses of Al and Ti are 26.98 and 47.90, respectively, the volume fraction of $Al_3Ti$ in this alloy is calculated to be about 11 vol.%. Using the Al–5 mass% Ti alloy, an Al–$Al_3Ti$ FGM was fabricated by the following centrifugal method.

The Al–5 mass% Ti alloy ingot was melted at 900 °C under an argon gas atmosphere. Since the liquidus temperature ($L \leftrightarrow L + Al_3Ti$) is significantly higher than the processing temperature, the $Al_3Ti$ particles remained solid in the liquid Al matrix during the centrifugation [7,13]. The melt of Al–5 mass% Ti alloy was poured into a rotating cylindrical mold with an inner diameter of 90 mm at a rotational speed of 1260 rpm. The applied centrifugal force by rotating the mold was $G = 80$, where $G$ is expressed in units of standard gravity. The Al–$Al_3Ti$ FGM fabricated by the centrifugal method had a ring shape with an outer diameter of 90 mm, a wall thickness of approximately 20 mm and a length of 30 mm. Detailed descriptions of the centrifugal method have already been presented elsewhere [7,14–16].

### 2.2. Wear tests for Al–$Al_3Ti$ FGM

Fig. 1 is a schematic illustration of a specimen used for wear tests. Using a spark-cut machine, the wear test specimens (10 mm × 10 mm in cross-section and 16 mm in height) were cut from the outer region of the Al–$Al_3Ti$ FGM, where $Al_3Ti$ platelet particles were more condensed. In each specimen, the wear plane coincided with the outer surface of the FGM ring. The sliding direction for wear was parallel to the longitudinal direction of the FGM ring.

Wear tests were performed using a block-on-disc-type wear machine under rotary movement. An S45 C steel disc with a diameter of 80 mm and a hardness of 190 Hv was used as a counterdisc. The surface of the counterdisc was mechanically polished using SiC paper and liquid $Al_2O_3$ before the wear tests. The wear tests were performed with an initial applied stress of 0.5 MPa and a sliding speed of

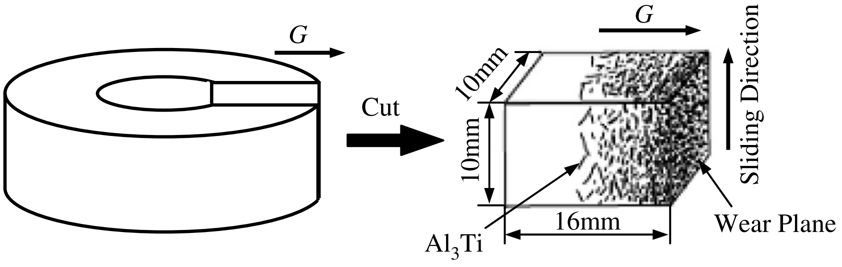

Fig. 1. Schematic illustrations showing an Al–$Al_3Ti$ FGM specimen for wear tests. Left and right illustrations show an Al–$Al_3Ti$ FGM ring and a wear specimen, respectively.