Investigation of Wear Anisotropy in a Severely Deformed Al-Al_3Ti Composite

SHIMAA EL-HADAD, HISASHI SATO, and YOSHIMI WATANABE

In the current investigation, Al-Al_3Ti composite was processed by equal channel angular pressing (ECAP). ECAP was carried out using routes A and B_C up to eight passes of deformation. It was observed that increasing the number of ECAP passes causes fragmentation of Al_3Ti platelet particles and decreases their sizes compared to their original sizes in the undeformed Al-Al_3Ti specimens. Moreover, the microstructure of route A-ECAPed Al-Al_3Ti composite samples showed a strong alignment of the fragmented Al_3Ti particles parallel to the pressing axis. On the other hand, ECAPed Al-Al_3Ti alloy specimens by route B_C have a relatively homogeneous distribution of Al_3Ti particles. Because of the platelet Al_3Ti particle fragmentation by ECAP, all the ECAPed specimens showed small anisotropy in their wear property in spite of this observed anisotropic microstructure induced by route A-ECAP.

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I. INTRODUCTION

ALUMINUM based composites containing aluminide particles were reported to possess higher wear resistance and lower friction with increasing volume fraction of the reinforcement particles. Compared to ceramic reinforcements, employing aluminide in Al matrix composites as wear resistant reinforcement has advantages.[1] In addition to the aluminide's high hardness, elastic modulus, melting temperature, and thermal stability, the thermal expansion coefficients of some of these intermetallics are much closer to those of Al alloys. This smaller difference in thermal expansion coefficients lowers the residual stresses at the reinforcements/matrix interfaces when the composite is exposed to thermal cycle and, hence, guarantees a lower degree of failure.[2]

Of these composites, Al-Al_3Ti composites containing Al_3Ti intermetallics are potential candidates as tribological materials.[3] Since the Al_3Ti particles in this composite are platelet in shape, it is expected that any deformation process aligning these particles in a certain direction would result in an anisotropic wear property.

Severe plastic deformation (SPD) of metals and alloys was reported to refine their structures by the intensive plastic strain imposed on the samples.[4] Moreover, some research revealed the influence of SPD intensive strain on the microstructure orientation in some metallic alloys.[5] This oriented microstructure may result in anisotropic mechanical properties in the deformed samples, as previously observed.[6] Therefore, if a severely deformed Al-Al_3Ti composite was selected for tribological applications, the anisotropy of its wear property should be carefully investigated.

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Equal-channel angular pressing (ECAP) (at present) is one of the developed SPD methods.[7] The ECAP process has the advantage that different slip systems can be introduced by rotating the samples.[8] In the case of route A, the sample is pressed repetitively without rotation, which results in accumulated unidirectional shear strain in the sample.[9] In contrast, route B_C is done by rotating the specimen 90 deg in the same sense, and a homogeneous strain can be imposed through four passes.[10] Therefore, route A forms an anisotropic structure, while route B_C develops a homogeneous structure.[11]

Zhang *et al*.[12] studied an ECAPed Al-5.7 wt pct Ni eutectic alloy processed through route B_C and route A methods. It was found that after ECAP processing by route B_C, fine Al_3Ni particles were homogeneously dispersed in the Al matrix and the samples showed no clear anisotropy in their tensile properties. After ECAP processing by route A, however, the eutectic textures containing α-Al and Al_3Ni fibrous dispersoids have highly anisotropic distribution and are proven to have significant anisotropy in tensile properties.

The microstructure and texture evolution of an Al-Al_3Ti composite ECAPed with routes A and B_C were investigated by Watanabe *et al*.[13] According to their study, the microstructure of ECAPed samples by route A has highly anisotropic distribution of Al_3Ti particles, while route B_C samples have homogeneous distribution of Al_3Ti particles.

Considering the wear property of the ECAPed Al-Al_3Ti composite based on the distribution of Al_3Ti particles, it is expected that route A-ECAPed Al-Al_3Ti composite will have anisotropy in its wear property. This is because the mechanical properties of the particle-reinforced composite depend on the distribution and orientation of the particles, as described earlier.[14,15]

In this study, Al-11 vol pct Al_3Ti composite was processed by ECAP with routes A and B_C up to eight passes. Using the ECAPed Al-Al_3Ti composites deformed with different routes, the anisotropy in the wear property of ECAPed Al-Al_3Ti composites was investigated. In spite of the alignment of Al_3Ti platelet particles to the shearing direction during ECAP, a small anisotropy in the wear property of the deformed Al-Al_3Ti composites was observed.

II. EXPERIMENTAL PROCEDURE

A. *Preparation of ECAPed Al-Al_3Ti Samples*

1. *Casting*

Prior to processing by ECAP, rod-shaped ECAP specimens of Al-5 mass pct Ti alloy with a diameter of 10 mm and a length of 60 mm were prepared by casting at 1023 K (750 °C) in a metallic mold. The as-cast specimens were then machined to obtain a smooth surface. In order to stand with the severe deformation during ECAP, the specimens were homogenized at 823 K (550 °C) for 1 hour and subsequently air cooled.

B. *Deformation*

An ECAP die fabricated from tool steel with two circular cross-sectional channels intersecting at 90 deg angle and a 36 deg outer arc of curvature was used, as shown in Figure 1. The ECAP was conducted with a pressing speed of 4 mm/min at room temperature using MoS_2 as lubricant. An equivalent strain of about 1.0 was introduced into the sample for each pass through die.[16] Using the rod-shaped Al-Al_3Ti composites, ECAP was carried out up to eight passes by route A and route B_C.

1. *Microstructure investigation of specimens after ECAP*

The ECAPed samples were cut along the pressing axis from its central position to obtain sections for microstructure and hardness investigations. Scanning electron microscopy (SEM) was used to observe the distribution of Al_3Ti particles in the ECAPed samples at random positions. The average length of Al_3Ti particles was calculated using the linear intercept method. The intercept lines were plotted horizontally and vertically on magnified SEM images taken randomly for the ECAPed samples. The particle's aspect ratio was determined using image analysis software. The aspect ratio is defined as the ratio of maximum and minimum lengths of the rectangle with smallest area that can be drawn around the particle. The angle between the fragmented Al_3Ti particle group and the deformation direction was measured at random positions in order to study the effect of ECAP on the particle alignment.

2. *Wear tests of ECAPed Al- Al_3Ti samples*

To study the anisotropy of the wear property of the ECAPed samples, two kinds of specimens were cut at different directions relative to the deformation axis. The short specimen has a wear plane parallel to the

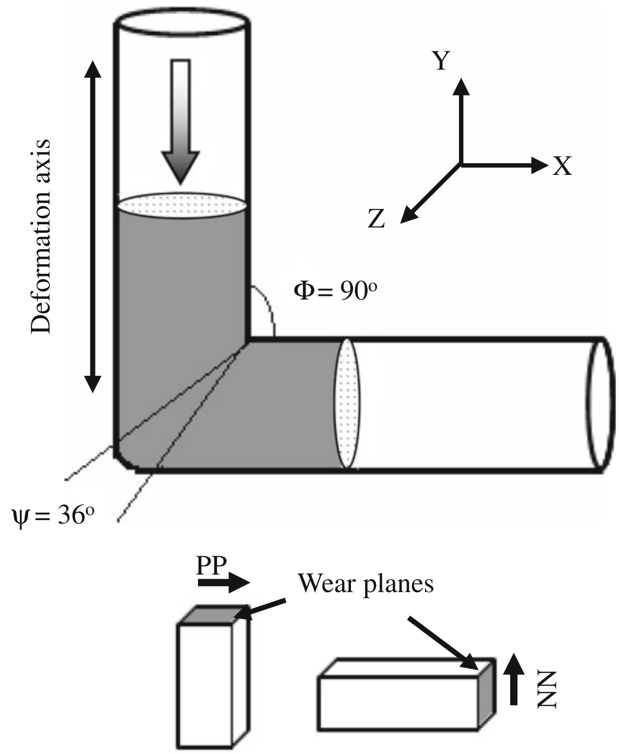

Fig. 1—Schematic illustration of ECAP showing the wear test samples and the wear directions: PP and NN.

deformation axis, while the long one was cut normal to this axis. The short and long samples have dimensions of 3.5 mm × 3.5 mm × 8 mm and 3.5 mm × 3.5 mm × 20 mm, respectively. The wear tests were carried out in X and Y directions, named PP and NN, respectively, as also shown in Figure 1. The wear tests were performed using block-on-disc type wear test. Dry wear test conditions were applied using S45C counter disc with 170 Hv hardness. The test was made under reciprocal line movement. The amplitude distance of the reciprocal movement was 26 mm and its frequency was 150 cycle/min. The load and total distance for the wear tests was 1.0 kgf and 0.468 km, respectively. The amount of wear was evaluated by weighing the samples before and after wear test.

III. RESULTS AND DISCUSSION

A. *Microstructure Aspects of ECAPed Al-Al_3Ti Composite*

Figure 2(a) is an SEM micrograph showing the original microstructure of Al-Al_3Ti composite, where coarse Al_3Ti platelet particles[17] were observed randomly distributed in the Al matrix. Figures 2(b) and (c) show the microstructure of Al-Al_3Ti composite ECAPed by routes A and B_C, respectively, at four and eight passes of deformation observed on the plane parallel to the pressing axis. The angle θ in these figures is the angle

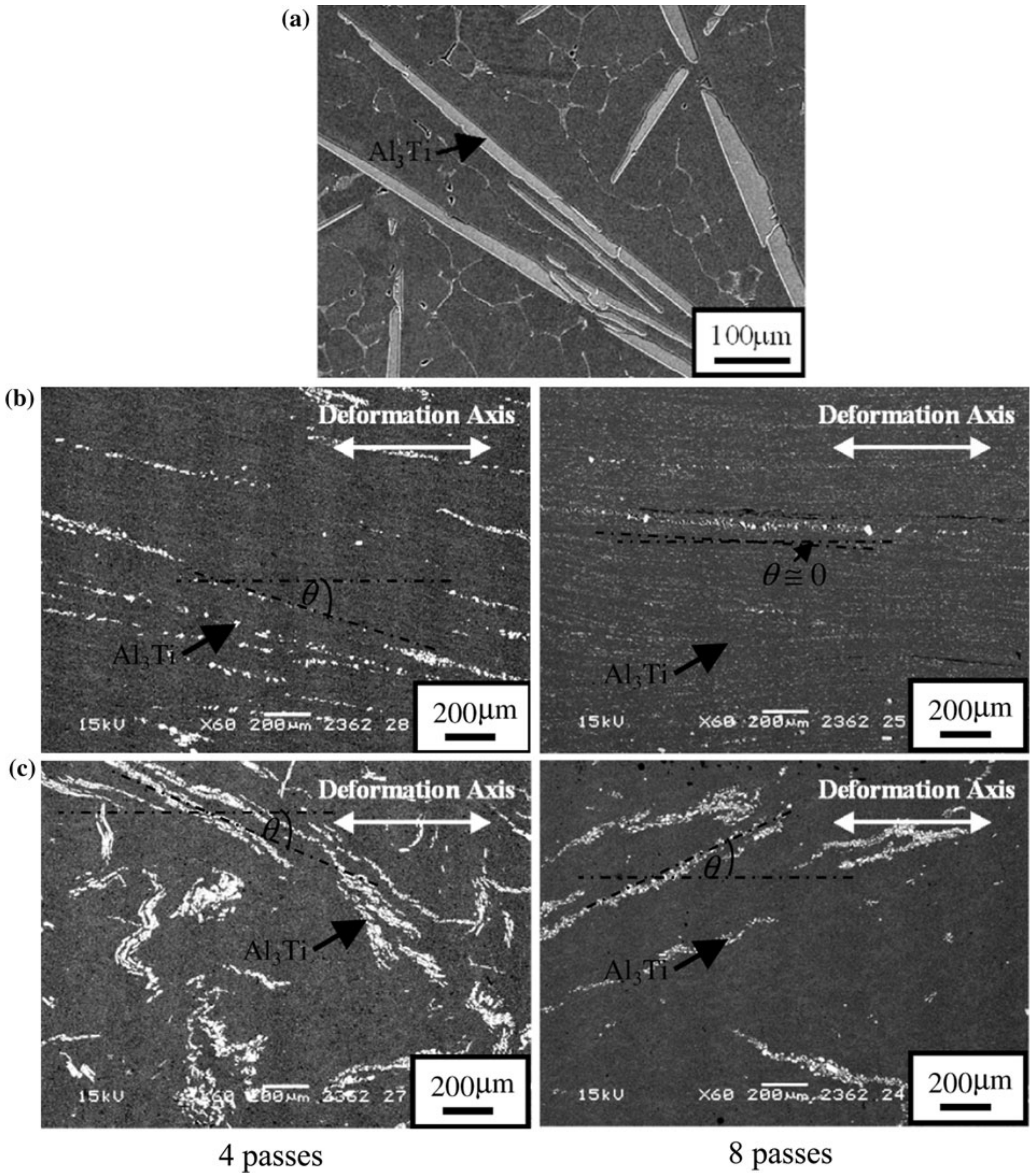

Fig. 2—SEM photographs showing microstructures of (*a*) as-cast Al-Al_3Ti composite, (*b*) route A, and (*c*) route B_C ECAPed samples.

between the deformation axis and the axis of an Al_3Ti particle group. After the as-cast Al-Al_3Ti composite samples were deformed under the large strains of ECAP, the Al_3Ti platelet particles were severely fragmented and granular Al_3Ti particles were observed. Consequently, the particles' sizes and their aspect ratios are expected to show a remarkable decrease when the deformation proceeds to higher strains.

Figures 3(a) and (b) show the average sizes of Al_3Ti particles and their aspect ratios as a function of the number of ECAP passes. It is remarked that the size of Al_3Ti particles in both of the specimens deformed with routes A and B_C decreased with increasing the number of ECAP passes, as shown in Figure 3(a). In addition, the aspect ratio of Al_3Ti particles steeply decreased when they were deformed using both ECAP routes

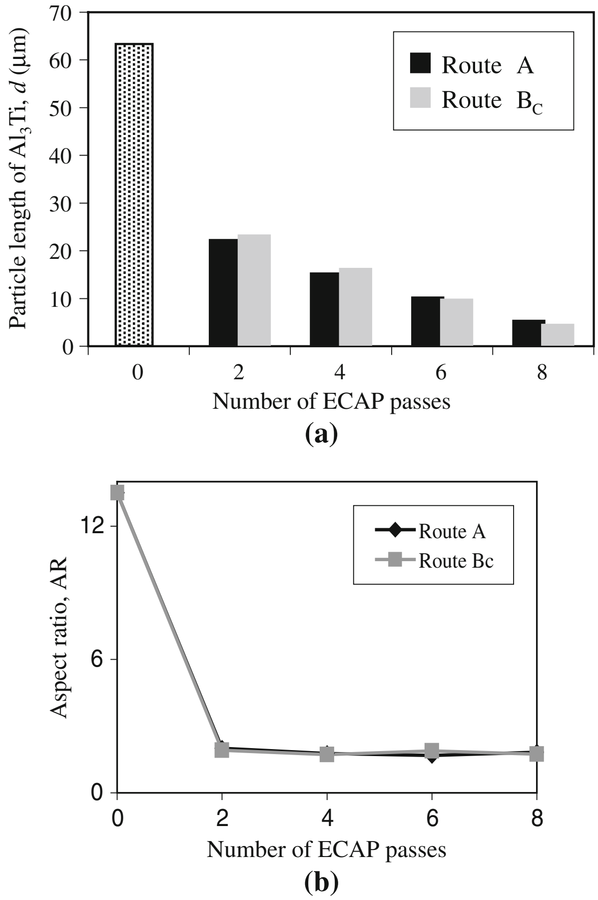

Fig. 3—Quantitative measurements of (*a*) mean size and (*b*) aspect ratio of Al_3Ti particles *vs* number of ECAP passes on the plane parallel to the pressing axis.

(Figure 3(b)). Moreover, the common shape of the Al_3Ti particle is changed from platelet to granular shape, as can be observed from the magnified micrograph of the route A sample after four passes of deformation, as shown in Figure 4.

Comparing the microstructure of route A and B_C samples at eight passes of deformation, micrographs of route A (Figure 2 (b)) showed fine granular Al_3Ti particles strongly aligned along the deformation axis, and the initial shape of these Al_3Ti particles was not observed anymore. On the other hand, in ECAPed specimens with route B_C, the alignment of the Al_3Ti particles remained unchanged when the strain increased from 4 to 8. This difference of microstructure comes from the type of strain induced by ECAP. Route B_C accumulates a multidirectional shear strain in the samples, while route A deforms it through a unidirectional strain.[8] Therefore, the ECAPed microstructure will be different.

Similar to short-fiber-reinforced composites, the orientation of Al_3Ti platelet particles is expected to play an essential role in establishing the behavior of the composite. Although the intent of most processing procedures is to produce random fiber orientation, fabrication

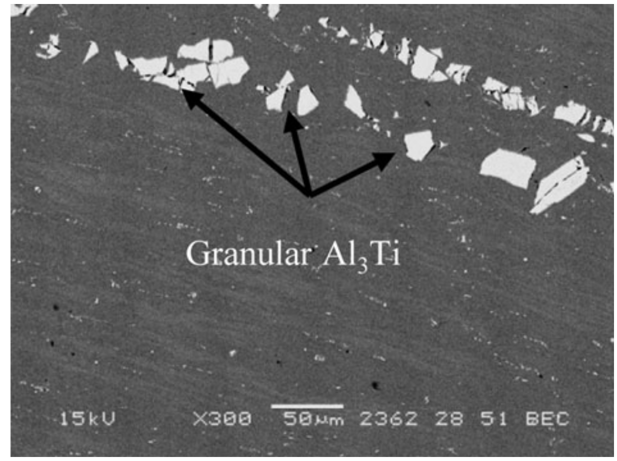

Fig. 4—Magnified SEM micrograph of the ECAPed Al-Al_3Ti samples after four passes A.

kinetics can induce partial orientations, which give rise to anisotropic (*i.e.*, directionally dependent) properties.[18] This degree of anisotropy may vary depending on the fabrication conditions. In the current ECAPed Al-Al_3Ti composite samples, the microstructure showed different degrees of anisotropy when different processing routes were used. The sensitivity of the properties of short-fiber-reinforced composites to processing induced fiber orientation led some researchers to quantitatively calculate the degree of fiber orientation. A Herman's orientation parameter, f_p, proposed by McGee and McCullough[18] was used in the current experiments to evaluate the microstructure anisotropy after ECAP:

$$f_p = [2 < \cos^2\theta > -1], \langle \cos^2\theta \rangle = \int_{-\pi/2}^{\pi/2} \cos^2\theta\, n(\theta)\, d\theta \quad [1]$$

where θ is the angle between the deformation axis and the axis of an Al_3Ti particle group, as shown in Figure 2. The term n (θ) is the orientation distribution function that specifies the fraction of particles within the angular element $d\theta$. The parameter f_p becomes 0 for a random distribution, and it becomes 1 for perfect alignments with the axis of Al_3Ti particle groups parallel to the deformation axis.[19] Figure 5 shows the variation of f_p as a function of the number of ECAP passes evaluated on the plane parallel to the deformation axis. It is clear that the behavior of f_p for ECAPed Al-Al_3Ti samples is different between routes A and B_C. In both of the ECAPed specimens at two passes, f_p was around 0.4 and then this value continuously increased with further deformation by route A. The alignment of Al_3Ti particles becomes almost parallel to the deformation axis at eight passes of ECAP. This is because of the reported unidirectional shear strain provided by ECAP deformation using route A.[20] When the number of passes increases, this unidirectional strain accumulates and can be translated to microstructural anisotropy, as shown in the microstructure of route A ECAPed samples of Figure 2.

In the case of route B_C, f_p at two and six passes showed relatively larger f_p, while at four and eight passes, smaller f_p was observed. However, a relatively constant trend can be considered for the overall f_p values from two to eight passes of ECAP. This result is in accordance with the reported microstructural homogeneity of route B_C ECAPed samples.[21] Since ECAP using route B_C induces a multidirectional shear strain,[20] increasing the number of ECAP passes results in homogeneous distribution of the fragmented Al_3Ti particles in the Al matrix.

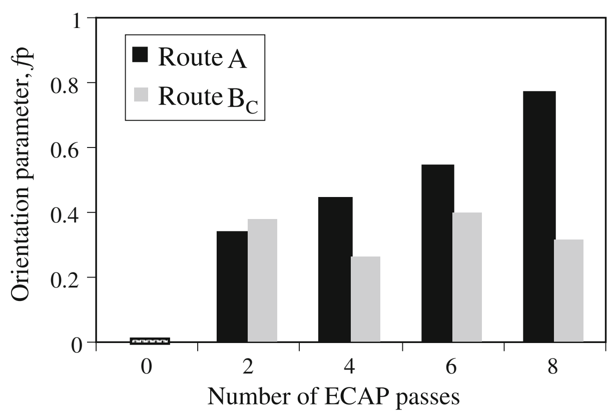

Fig. 5—Change in the calculated orientation parameter of the ECAPed Al-Al_3Ti samples with increasing number of ECAP passes.

B. *Wear Anisotropy and Particles Orientation*

According to Zmitrowicz *et al.*,[22] the anisotropic friction induces anisotropic wear; *i.e.*, the intensity of the removed mass depends on the sliding direction. This anisotropy may result from the anisotropy of mechanical properties of materials with microstructures (crystals, composites, polymers, *etc.*). Based on this, the wear resistance of a composite can show some anisotropy depending on the processing induced fibers/particles orientation.

The anisotropy in the wear property was reported for Al-Al_3Ti functionally graded materials (FGMs) with aligned Al_3Ti particles.[23] In this study, the anisotropic wear property of the FGMs was dependent on the applied wear direction relative to Al_3Ti particles. A greater anisotropy in wear resistance was found for specimens with a larger orientation parameter. This is because Al_3Ti particles were groups of coarse platelet particles aligned normal to the centrifugal force direction and distributed gradually in the fabricated FGMs. The schematic illustration of the Al-Al_3Ti FGM sample is shown in Figure 6(a), where the coarse aligned Al_3Ti platelet particles can be observed on planes (OP1 and OP2) of the sample.

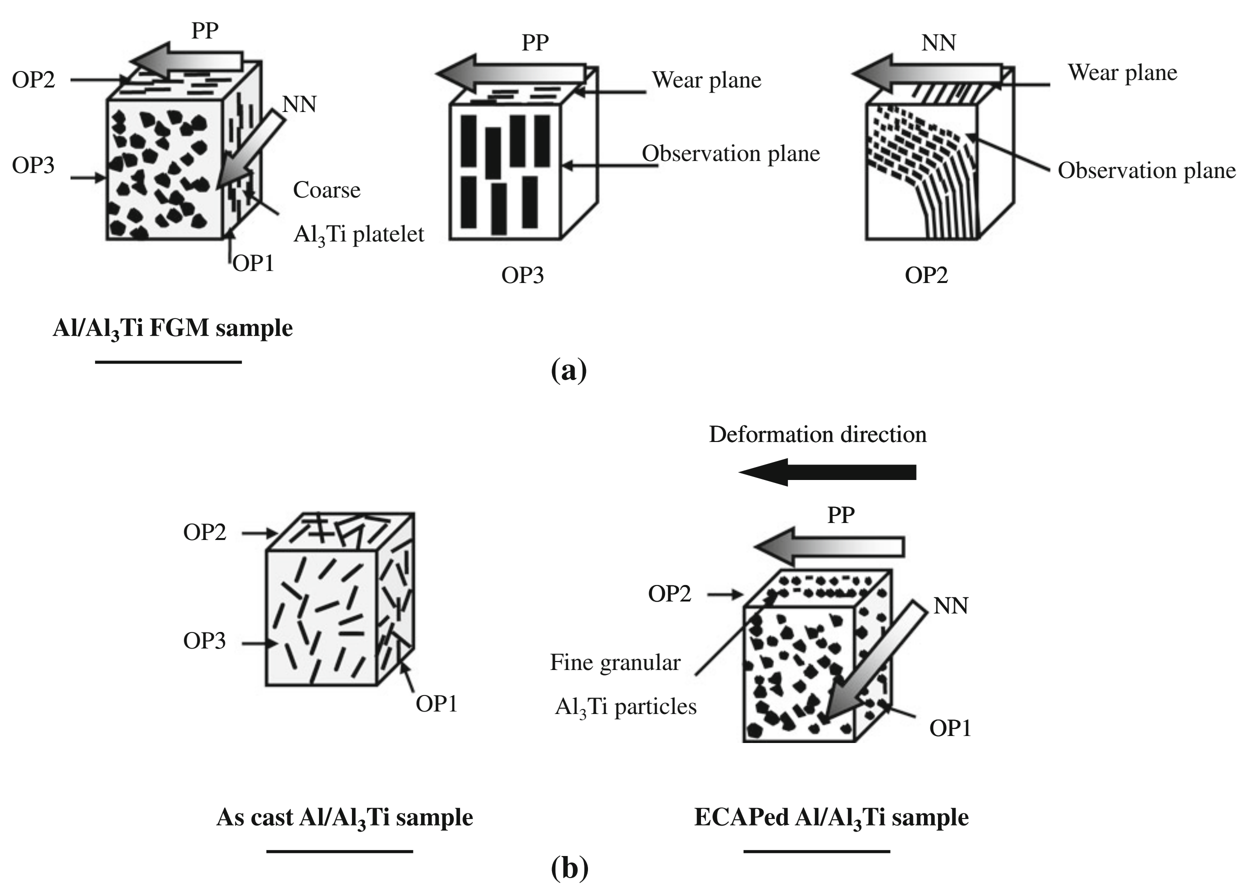

Fig. 6—Schematic illustration of (*a*) Al-Al_3Ti FGM, (*b*) ECAPed Al-Al_3Ti composite, and the description of wear test directions.

In the current ECAPed Al-Al_3Ti composite, Al_3Ti particle groups were aligned in a direction close to the deformation direction. However, the fragmentation of Al_3Ti platelet particles by the large strain of ECAP refined their size and changed their shape to the granular morphology, as obvious on planes (OP1 and OP2) shown in Figure 6(b). Comparing the reported microstructure of Al-Al_3Ti FGMs[23] with the current ECAPed Al-Al_3Ti composite, small anisotropy can be expected in the wear property of ECAPed Al-Al_3Ti samples when tested on the PP and NN directions.

The variations in weight loss by wear of routes A and B_C ECAPed samples using the block-on-disc wear test are shown in Figure 7. In the nondeformed samples, the very large intermetallic particles act as load-supporting elements preventing the soft Al matrix from becoming directly involved in the wear process, similar to particulate-reinforced Al matrix composites.[24] Upon further deformation, with a continued reduction in the size of Al_3Ti particles and their alignment in bands along the deformation direction, a decrease in the wear resistance is observed in the PP direction up to four of ECAP. This is due to the loss of load bearing capabilities of the particles, which caused an increased wear rate accordingly. However, with increasing the applied strain to 6, the particles will be further refined and show their strengthening effect on the matrix, reducing the weight loss in the direction parallel to the deformation direction.[1] This was not the case for the NN direction, where the wear rate increased at two passes of deformation and then remained almost constant with increasing applied strain. This can be attributed to the observed banded microstructure shown in Figures 2(b) and (c), which in turn makes the contact between the sample block and the disc, which occurs in successive bands of reinforced and nonreinforced regions.

Comparing the weight loss for the two test directions shown in Figure 7, it is observed that the wear property in the deformation direction, PP, is consistently better than that for the NN direction for both route A and B_C samples. However, these differences in the wear property between NN and PP directions are small considering the error bars for the plotted points. Therefore, it can be said that the ECAPed samples do not have a large anisotropic wear property regardless of the processing route.

With the preceding in mind, it is concluded that there are two main factors influencing the anisotropy in the ECAPed Al-Al_3Ti samples: the particle shape (coarse platelet/fine granular) and the particle alignment to a certain direction. Figures 8(a) and (b) shows the relationship between the weight loss and the orientation parameter in the parallel and normal wear test directions, respectively. It is observed that increasing *fp* up to (~0.4) resulted in increased weight loss in both the PP and NN directions. However, the weight loss value decreased with further increase of the orientation parameter. This is because of the associated decrease in the particle size and aspect ratio with increasing the number of ECAP passes, as shown in Figure 3.

In order to understand the difference in wear anisotropy among the Al-Al_3Ti FGMs and ECAPed Al-Al_3Ti composite, theoretical wear models discussed in Reference 25 can be helpful. Archard[26] formulated the wear equation of the form

$$W = \frac{p_n s}{H} \quad [2]$$

where the volume of the material removed (W) is directly proportional to the sliding distance (s), the normal pressure (pn), and the dimensionless wear coefficient (k), and inversely proportional to the hardness of the surface being worn away (H). By analogy to Archard's law, in the simplest case, wear velocities (Eq. [3]) can be defined as functions of the normal pressure (p_n) and the sliding velocity (V_{AB}); *i.e.*,

$$v^+ = -i_A\left|p_n^A\right|\left|V_{AB}\right| \quad \text{and} \quad v^- = -i_B\left|p_n^B\right|\left|V_{BA}\right| \quad [3]$$

where

$$\left|p_n^A\right| = \left|p_n^B\right|, V_{AB} = -V_{BA} \quad [4]$$

The coefficients i_A and i_B used in Eq. [3] are defined as dimensional wear constants or the specific wear rates.[27] If i_A and i_B are multiplied by the hardness of bodies,

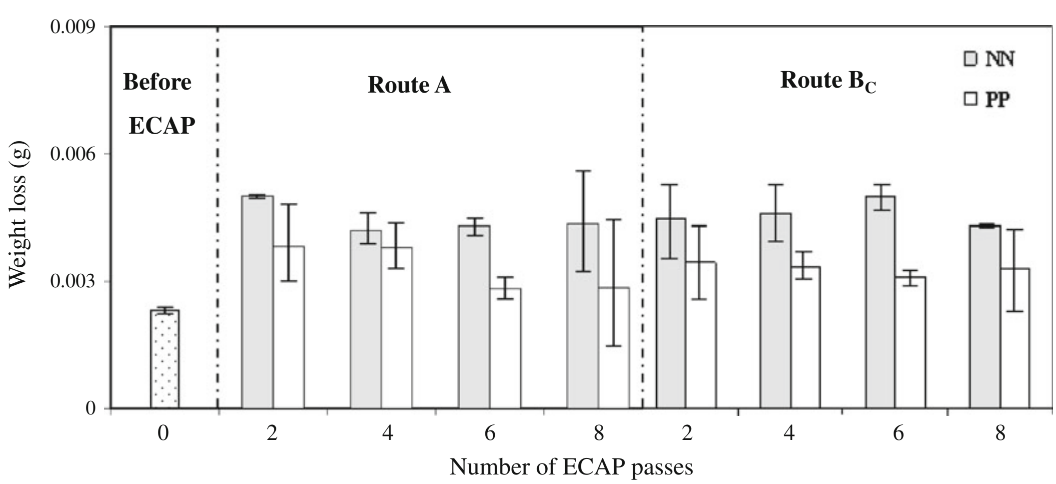

Fig. 7—Weight loss during block-on-disc wear test of routes A and B_C ECAPed Al-Al_3Ti alloy samples.

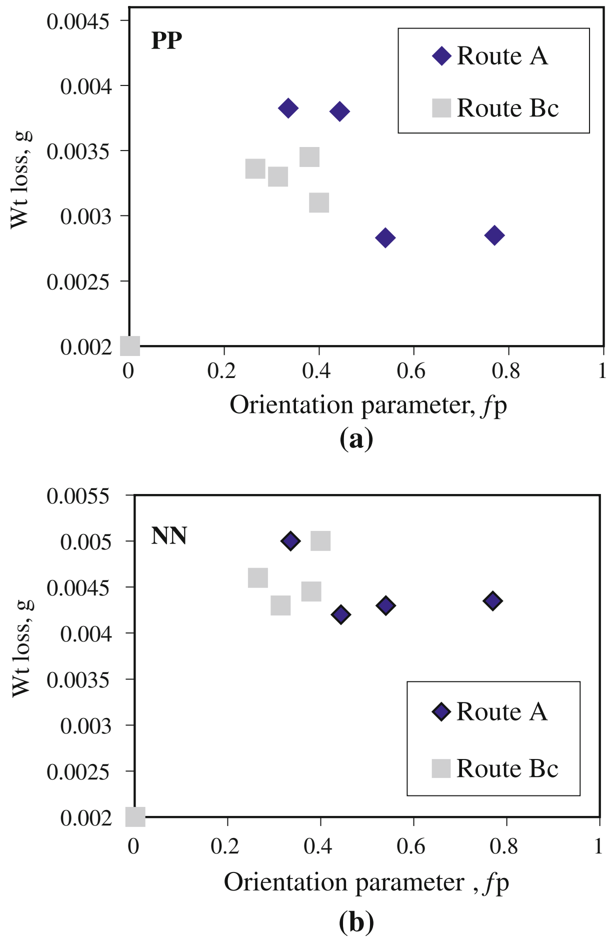

Fig. 8—Weight loss of ECAPed Al-Al_3Ti samples in (*a*) PP and (*b*) NN directions *vs* the particle's orientation parameter.

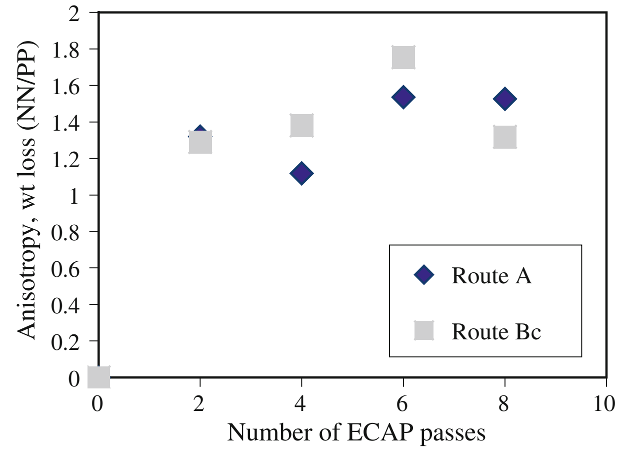

Fig. 9—Variation of wear anisotropy of ECAPed Al-Al_3Ti samples with number of ECAP passes.

then we get dimensionless intensities of wear $i_A H_A$ and $i_B H_B$. Therefore, the hardness can be easily included in the quantitative estimation of the dimensional wear intensity coefficients i_A and i_B.

Zmitrowicz *et al.*[22,27] assumed that the wear intensity i_A is a function of the sliding direction. Following his assumption, the orientation parameter, *fp*, defined in Eq. [1] as the degree of the platelet particle orientation should relate to the wear intensity i_A. Using the extension of Archard law described in Reference 25, i_A and *fp* can be related as follows:

$$i_A = i_A(fp),\ fp \in (0,1) \quad [5]$$

By substituting in Archard law (Eq. [2]), the anisotropy of wear can be explained by

$$W = \frac{p_n s}{H(fp)} \quad [6]$$

And the velocity Eq. [3] will be accordingly changed to

$$v^{+} = -i_A(f_p)\left|p_n^A\right|\left|V_{AB}\right| \text{ and } v^{-} = -i_B(f_p)\left|p_n^B\right|\left|V_{BA}\right| \quad [7]$$

Equations [6] and [7] can be roughly applied to the case of FGM, where the platelet particles are present and the influence of *fp* on the wear anisotropy is quite important. In the current ECAPed samples, however, this equation is not applicable since the particle shape was altered to fine nonplatelet particles. Thus, even if the orientation parameter apparently increased, no significant change will really occur. Therefore, it is recommended in the case of ECAPed Al-Al_3Ti to calculate the average hardness in the two test directions and then substitute to Archard law (Eq. [2]) separately. Representing the wear anisotropy *via* mathematical models and thus calculating the volume loss (*W*) in both Al-Al_3Ti FGMs and ECAPed Al-Al_3Ti using the precedent equations should be a topic for future work.

In order to quantitatively explain the anisotropic wear resistance, the weight loss ratio (weight loss of direction (NN)/weight loss of direction (PP)) was calculated. We have considered that the larger the value of the weight loss ratio, the larger the anisotropy of wear resistance. Figure 9 shows the anisotropy (weight loss ratio) against the number of ECAP passes. From this figure, it is evident that the anisotropy increases with increasing the deformation up to six passes and hence increasing the particle alignment to the deformation direction. Upon further deformation, the anisotropy of the Al-Al_3Ti samples decreased at eight passes of ECAP using route A and route B_C. The significant increase of *fp* value from six to eight passes using route A, which resulted in a banded structure, as shown in Figure 2(b), was expected to increase the wear anisotropy. However, the smaller size and the lower aspect ratio of the Al_3Ti particles observed at eight passes A limited the effect of increasing *fp* on the anisotropy of the ECAPed samples. Therefore, the samples did not show larger anisotropy at eight passes of ECAP.

IV. CONCLUSIONS

In this study, microstructure and wear anisotropy of Al-Al_3Ti composite ECAPed by routes A and B_C were investigated. Fine Al_3Ti particles homogeneously dispersed in Al matrix were observed in case of route

B_C-ECAPed samples. In contrast, the microstructure of route A-ECAPed samples showed a highly anisotropic distribution. In spite of this observation, all the ECAPed specimens showed small anisotropy in their wear property. Concluding, ECAP, as one of SPD processes, can alter the shape of the platelet Al_3Ti particles and fragment it to very small sized granular particles. As a result, limited anisotropy of the wear property in the Al-Al_3Ti composite containing platelet particles can be achieved regardless of the ECAP processing route.

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