Electro-Migration Effect of Titanium Structure under High Magnetic Field

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Abstract. It is well known topic that electro-migration accompanies the transport of atoms, ions and holes in a material. Then we can say that both electro-migration and strong magnetic field have potential to control crystal alignment. In this study, an electric current and/or a static magnetic field were applied to a titanium sample parallel to each other to investigate the effects of the electric current and the static magnetic field on crystal alignment in the titanium. Using XRD analysis, it was understood that titanium crystals having a c-axis perpendicular to the electric current direction increased under the imposition of only the electric current and under the simultaneous imposition of the electric current and the magnetic field. On the other hand, titanium crystals having a c-axis parallel to the magnetic field direction increased under the imposition of only the magnetic field. The aligned result can be explained from the viewpoint of anisotropy of the Joule loss and the magnetization energy.

1. Introduction

The imposition of an electric current on electrically conductive materials such as metals and alloys induces electro-migration and thermal strain in the materials, leading to deterioration and loss of continuity in electric circuits. These phenomena have been investigated mainly from the viewpoint of the reliability of integrated circuits so far, because the electric current density in LSI (large-scale integrated circuit) and ULSI (ultra-large scale integrated circuit) has drastically increased. For example, simulations and computer models \cite{1}, temperature dependence of electro-migration \cite{2}, and transformation behavior of solder alloys \cite{3}, have been performed. In these studies, copper, aluminum, and solder alloys have been treated as the test materials usually used in integrated circuits.

Conversely, an electric current has the potential to control the structure of a material because the transport phenomena of atoms, ions, and holes in a material can be controlled through electro-migration. For example, electro-migration has been applied to refining of an electrically conductive material \cite{4,5}.

On the other hands, a magnetic field is well known as a powerful tool for controlling crystal alignment of crystallographically anisotropic materials \cite{6-8}. In addition, a strong magnetic field affects concentration of an additional element at grain boundary in a solid alloy through an annealing process \cite{9,10}. This suggests that a strong magnetic field might affect diffusion behavior and these phenomena might introduce anisotropic growth of a solid metal or alloy. However, the effect of the
imposition of an electric current and/or a magnetic field on crystal alignment had not been discussed until now.

In this study, an electric current and/or a static magnetic field were applied to a titanium sample simultaneously parallel to each other to investigate the effect of the electric current and the static magnetic field on crystal alignment in the sample.

2. Experimental Procedure and Result

Titanium is chosen as a sample because it shows anisotropic nature in electric conductivity and magnetic susceptibility caused by its hexagonal crystallographic structure. In this study, the electric current was applied to a solid titanium sheet under the imposition of the strong magnetic field generated by a super conducting magnet. The magnetic field direction was parallel to the electric current direction as shown in Fig.1. The obtained structure was analyzed by XRD for the evaluation of the crystal orientation. To reduce the temperature change during the experiment, the sample was cooled by ion-exchanged water. In this experiment, two titanium sheets were used. The sample1, 2 and 3 were cut out from one titanium sheet, and the sample1’ and 4 were cut out from another one.

In the Debye Rings of every sample, three peaks of (100), (002) and (101) planes are mainly observed as shown in Fig.2. Cross-sectional profile at $\phi = 0$ degree is called the horizontal profile, while that at $\phi = 90$ degrees is called the vertical profile in this paper. The magnetic field direction and electric current direction are same with the direction of vertical profile in the Debye Rings shown in Fig.2.

Because the intensity of each ring is not uniform in azimuthal direction, titanium crystals in each sample are aligned to the specific direction.

As an index of crystal alignment, we introduced the peak intensity ratio of (002) plane peak intensity in vertical profile to that in horizontal profile, and evaluated ratio is shown in Fig.3. The intensity was evaluated by integrating the (002) profile with respect to the azimuthal direction.

Because sample1 and 1’ were cut out from different titanium sheet each other, the peak intensity ratio of sample 1 and 1’ in Fig. 3 were not the same value each other though both the samples were bought from the same company (THE NILACO CORPORATION: Titanium Foil, TI-453098). This might be because the rolling conditions for formation of the titanium samples before we bought were different. The intensity ratio decreased in the case of the imposition of only the electric current. This means that titanium crystals having a c-axis parallel to the electric current relatively decreased in comparison with titanium crystals having a c-axis perpendicular to the electric current. In the case of the imposition of both the electric current and the magnetic field, the experimental result was similar.
to that of the imposition of only the electric current though decrease of the intensity ratio was small in comparison with the result under the imposition of only the electric current. On the other hand, we can recognize that the intensity ratio slightly increased after the imposition of only the magnetic field as the intensity ratio of sample 4 increased compared to that of the sample 1’. Therefore, the imposition of the magnetic field might have a function to slightly increase the intensity ratio while the imposition of the electric current decreased the intensity ratio in this experimental condition.

Figure 2. Debye rings of each sample and definition of angle $\phi$

Figure 3. Peak intensity ratio of (002) in vertical profile / (002) in horizontal profile
3. Discussion
Because the magnetic susceptibility of titanium in the c-axis was larger than that in the a-axis when \( T = 300K \) (Table 1), the adsorption of migrating titanium ions or atoms on a titanium crystal with a c-axis parallel to the magnetic field might occur from the viewpoint of magnetization energy. Then, magnetization energy difference per unit volume \( U_M \) can therefore be calculated by the following equation:

\[
U_M = -\frac{\mu_0 \Delta \chi}{2} |H|^2
\]  

(1)

where \( \mu_0 \) is magnetic susceptibility in a vacuum, \( \Delta \chi \) is the magnetic susceptibility difference between magnetically easy axis and magnetically hard axis, and \( H \) is the intensity of the external magnetic field.

The calculated magnetization energy difference was 300 J/m\(^3\) for titanium at the experimental temperature of 300K. On the other hand, thermal fluctuation (\( k_BT \), \( k_B \): Boltzmann constant, \( T \): absolute temperature) was approximately \( 10^{-21} \) J when \( T = 300K \). Therefore, the minimum crystal size in which the magnetization energy difference was larger than the thermal fluctuation was calculated as \( 3.1 \times 10^{-8} \) m under these experimental conditions if the interfacial energy was neglected. The increase in the intensity ratio by imposing only the magnetic field can be explained from the viewpoint of the magnetization energy. However, mechanism why the magnetically stable crystals increased and/or grew in the solid metal under the magnetic field is future work while a strong magnetic field might affect diffusion behavior as mentioned in the introduction.

On the other hand, crystal growth whose c-axis is perpendicular to the electric current direction might occur to reduce the Joule loss in the sample, because the specific resistance in the c-axis was larger than that in the a-axis as shown in Table 2. In other words, c-axis of the titanium crystals aligned themselves to become perpendicular to the electric current direction. The Joule loss difference per unit volume, \( U_E \) was then calculated using the following equation:

\[
U_E = \Delta \rho |J|^2
\]  

(2)

where \( \Delta \rho \) is the specific resistance difference between electrically-easy axis and electrically-hard axis, and \( J \) is electric current density.

The calculated Joule loss difference was \( 3.5 \times 10^8 \) J/m\(^3\) for titanium at the experimental temperature of 300K. This value was about \( 10^6 \) times as large as the calculated magnetization energy difference per unit volume. That is, crystals whose a-axis were parallel to the electric current direction increased even though the magnetic field were simultaneously imposed on the sample from the energy viewpoint.

This agrees with the experimental results obtained under the imposition of only the electric current and the simultaneous imposition of the electric current and the magnetic field. Therefore, this might be the reason why the titanium crystals in the sample aligned to reduce the Joule loss even though the

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**Table 1. Magnetic susceptibility of titanium**

| T(K) | //c-axis ([-]) | ⊥c-axis ([-]) |
|------|---------------|---------------|
| 273  | 1.99E-04      | 1.70E-04      |
| 300  | 1.99E-04      | 1.71E-04      |
| 400  | 2.03E-04      | 1.77E-04      |

**Table 2. Specific resistance of titanium**

| T(K) | //c-axis ([10^-8Ωm]) | ⊥c-axis ([10^-8Ωm]) |
|------|----------------------|---------------------|
| 273  | 47.6                 | 45.35               |
| 300  | 53.8                 | 50.34               |
| 400  | 78.1                 | 71.65               |
magnetization energy difference was larger than the thermal fluctuation. In these conditions, migration caused by the imposition of the electric current might enhance the growth of the electrically stable crystals. However, further investigation is needed to confirm the mechanism.

4. Conclusion
To investigate the effect of the electric current and the static magnetic field on crystal alignment, an electric current and/or a static magnetic field was applied to titanium samples which have crystallographic anisotropy in electric and magnetic properties. The titanium crystals aligned to reduce the magnetization energy under the imposition of only the magnetic field. On the other hand, the titanium crystals aligned to reduce the Joule loss because the Joule loss was larger than the magnetization energy.

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