Crystallographic orientation on raft-like structure developed by tensile deformation in Cu-Fe dual phase alloy sheet

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Abstract. The crystallographic orientation of a raft-like structure developed by tensile deformation in Cu-40 mass%Fe dual phase alloy sheet was investigated. The sheet exhibited Cu and Fe layer structure aligned along the rolling direction (RD). The tensile tests were carried out parallel to the RD. The rearrangement of the layer structure was observed in a necked region, where the layers were distorted and aligned along the normal direction (ND). The layered structure perpendicular to the tensile direction is similar to the raft structure developed by creep deformation in a nickel-based super alloy. The bending of layers in the raft-like structure and shear fracture were detected in the cross-section of the samples. The raft-like structure in Cu-Fe dual phase alloy displayed a specific crystal orientation such as <111>_{Cu}//ND, <101>_{Cu}//RD, <101>_{Fe}//ND, and <111>_{Fe}//RD. The orientations are matched to those rotated 90 degrees around the transverse direction of the layer structure. Therefore, the bending of the layer structure in a necked part and/or local shear deformation may be responsible for the raft-like structure development in Cu-Fe dual phase alloy.

1. Introduction

The crystallographic orientation in a metal continuously rotates during tensile deformation because an active slip direction moves in the direction parallel to the tensile axis [1]. The crystallographic orientation rotation develops the deformation texture of the metal, depending on its crystal structure. Generally, bcc and fcc metals develop <110> and <111> textures along the tensile direction, respectively, owing to those slip systems [2]. In addition, a local deformation, i.e. necking, also occurs during a tensile test. Within a necking region, the stress state becomes triaxial; however, the texture within necking regions has not been investigated thoroughly.

The binary system of copper and iron exhibits low mutual solubility in both matrix phases and, therefore, Cu-Fe alloy forms a copper (fcc) and iron (bcc) dual phase structure at room temperature. Cu-Fe alloy has been reported to exhibit excellent tensile properties at cryogenic temperatures, compared to those of single-phase materials [3-4]. In this study, we discovered the characteristic deformation structure within the tensile necking region of a Cu-Fe binary alloy, and the formation mechanism of the characteristic deformation structure was discussed through analysis of the crystallographic orientation.
2. Experimental procedure
The material used in this study was a commercial cold-rolled Cu-40 mass%Fe alloy. The specimen was heat-treated at 1123 K for 1.8 ks and subsequently followed by water cooling. The microstructure was observed by an optical microscope (OM) and scanning electron microscope (SEM), while the crystal orientation was analyzed with the electron backscattered diffraction (EBSD) method. Tensile test specimens of 20 mm in gage length and 4 mm in width were cut from the plates along the RD. The tensile test was carried out at initial strain rate of approximately $5.2 \times 10^{-4}$ s$^{-1}$ at 293 K. After tensile test, EBSD analysis was conducted on normal direction (ND) planes within the necking region in the fractured specimen. Crystallographic orientation in the rolling direction (RD) and transverse direction (TD) planes were evaluated from the obtained data by using OIM$^\text{TM}$ analysis 7.0.1. Additionally, the Cu-50 mass%Fe alloy was tensile tested in liquid nitrogen (77 K), and the microstructure within the necking region in the fractured specimen was observed by using SEM.

3. Results and discussion

3.1. Initial microstructure
Figure 1 shows OM images of the RD, TD, and ND planes after heat-treatment in the Cu-40 mass%Fe alloy. Fe and Cu layers were linearly aligned along the RD. The layer structure included some defects, i.e., there were many interruptions and bends of the layer. Individual layer thickness was approximately 10 μm. Figure 2 presents the inverse pole figure (IPF) maps depicting the crystal orientation of the ND, RD, and TD in the Cu and Fe phases in the Cu-40 mass%Fe alloy. The intensity distribution of crystal orientation plotted on the standard stereographic triangle is also displayed in Figure 2. The crystal orientation rotation within a grain was gradually developed in both the Cu and Fe phases from line profile analysis, indicating that strain introduced during cold rolling remained even after annealing. The Fe phase exhibited a general rolling texture [5] such as $<111>_{\text{Fe}}//\text{ND}$ or $<001>_{\text{Fe}}//\text{ND}$, while the crystal orientation in the Cu phase was $<111>_{\text{Cu}}//\text{ND}$, which did not match with the general rolling texture [6] such as $<110>_{\text{Cu}}//\text{ND}$, $<211>_{\text{Cu}}//\text{ND}$, and $<123>_{\text{Cu}}//\text{ND}$. As the part of Cu phase was finely recrystallized grain and twinned. These features may affect the texture of the Cu phase after annealing.

![OM images on RD, TD and ND after hear-treatment in the Cu-40 mass%Fe alloy.](Figure 1 OM images on RD, TD and ND after hear-treatment in the Cu-40 mass%Fe alloy.)
3.2 Deformation structure within necking
Figure 3 (a) shows an SEM image of the fractured specimen in the Cu-40 mass%Fe alloy. Since both the Cu and Fe phases exhibit high ductility at room temperature, the necking region appeared clearly in the Cu-Fe alloy. Figures 3 (b) and (c) are enlarged SEM images within the white squares in (a) and (b). Within the necking region, part of the layer structure was rearranged perpendicular to the tensile direction as shown in Figure 3 (c). This characteristic deformation structure is similar to the layer structure developed by creep deformation in a nickel-based super alloy [7]. The nickel-based super

Figure 2 Inverse pole figure maps of ND, RD and TD in Cu and Fe phases after heat-treatment in the Cu-40 mass%Fe alloy. The intensity distribution of crystal orientation is plotted on the standard stereographic triangle.

Figure 3 (a) Whole SEM image of fractured specimen in the Cu-40mass%Fe alloy. SEM images (b) (c) are enlarged within white squares in (a) and (b), respectively.
alloy consists of a Ni matrix and cubic Ni$_3$(Al+Ti) ($\gamma'$). After creep test, the $\gamma'$ elongates along a direction perpendicular to the loading direction, which is defined as the raft structure. This raft structure is formed through a diffusion process by using the lattice misfit between the Ni matrix and $\gamma'$ precipitations as a driving force. Therefore, the raft structure in the nickel-based super alloy does not form under deformation at room temperature, where Ni and Al atom diffusions are negligible. Both Cu and Fe atoms also hardly diffuse at room temperature, and the formation mechanism of the characteristic deformation structure in Cu-Fe alloy differs somewhat from that in the nickel-based super alloy. Thus, we called the characteristic deformation structure a raft-like structure. The raft-like structure was intermittently developed within the necking region as shown in Figure 3 (b).

Figure 4 shows SEM images of the fractured specimen seen in Figure 3 with tilted at 70 degrees. The fracture surface lies approximately 45 degrees from Figure 4(a), indicating that the shear fracture occurred after necking in the Cu-Fe alloy. The layer structure within the raft-like structure bent to the ND as indicated by arrows in Figures 4 (b) and (c). Moreover, the SEM images observed from the RD plane in the fracture specimen (Figure 5) revealed that part of the layer widens along the ND. However, the bending of the layer structure to the ND was not observed from the RD plane (Figure 5). According to these observation results, it can be concluded that the raft-like structure forms by the bending of the layer to the ND around the TD axis.

Figure 4 (a) Whole SEM image of the fractured specimen seen in Figure3 with tilted at 70 degrees. SEM images (b) and (c) are enlarged within black squares in (a).

Figure 5 SEM image observed from RD plan in (a) as annealed and (b) fractured specimens in the Cu-40 mass%Fe alloy.

3.3 Crystallographic orientation in raft-like structure.

Figure 6 shows IPF maps of the Cu and Fe phases in the ND, RD, and TD in the same region as Figure 3 (c). The intensity distributions of crystal orientation within the layer structure (A) and raft-like structure (B) are displayed below the IPF maps. Within the layer structure (A), typical deformation textures of Cu and Fe were developed by tensile deformation, i.e. $<101>_{Cu}/\text{ND}$, $<111>_{Cu}/\text{RD}$, $<111>_{Fe}/\text{ND}$, and $<101>_{Fe}/\text{RD}$. In contrast, within the raft-like structure (B), specific crystal orientations such as $<111>_{Cu}/\text{ND}$, $<101>_{Cu}/\text{RD}$, $<101>_{Fe}/\text{ND}$, and $<111>_{Fe}/\text{RD}$ were developed.
Figure 6 Inverse pole figure maps of Cu and Fe phases on ND, RD and TD in the same region as Figure 3 (c). The intensity distributions of crystal orientation within the layer structure (A) and raft-like structure (B) were plotted on the standard stereographic triangle.

Therefore, the deformation texture and three-dimensional morphologies within the raft-like structure are possibly explained from the following formation mechanism, as depicted in Figure 7. Initially, the typical tensile deformation texture is uniformly developed in the specimen until necking. The layer structures then bend by necking as shown in Figure 7, and the crystal orientation within the necking region rotates from the typical tensile texture around the TD axis. Moreover, shear deformation occurs near the fracture region and also bends the layer structures to the ND, as seen in Figure 7. In the region where the layer completely rotates to the ND, the specific crystal orientation of the raft-like structure is developed. The raft-like structure intermittently observed in Figure 3 (b) may be due to defects of
layer structure and local shear deformation. In the Cu-50mass%Fe alloy which was tensile-deformed at 77 K (Figure 8), the raft-like structure appeared. The covered by the raft-like structure in this specimen was much larger than that in the Cu-40mass%Fe alloy, as the raft-like structure appeared in the entire necking region in Cu-50mass%Fe. Thus, the development of the raft-like structure should depend on tensile test conditions, volume fractions and distribution of each phase, although its formation factor is still unclear. Nevertheless, it appears that the raft-like structure in Cu-Fe alloy is developed through a deformation process, which completely differs from the raft structure developed in the creep deformation of nickel-based super alloy. Therefore, further study about the raft-like structure in Cu-Fe alloy, such as determining the formation factors of raft-like structure and its contribution to the mechanical properties, is necessary.

Figure 8 SEM image within necking region after tensile test at 77 K in the Cu-50 mass%Fe alloy.

4. Conclusions
The characteristic deformation structure within the necking region of tensile deformed Cu-Fe binary alloy was investigated, and the formation mechanism of the deformation structure was discussed through the analysis of crystallographic orientation. The major results are summarized as follows:

The layer structure of the alloy consisting of copper and iron phases, was partly rearranged perpendicular to the tensile direction within the necking region after tensile test. The resulting structure was similar to a raft structure developed during creep test of a nickel-based super alloy. Hence, the characteristic deformation structure in Cu-Fe alloy was labeled a raft-like structure.

Layer bending to the normal direction in the raft-like structure was observed in the cross-section of the samples. Moreover, shear fracture occurred, and the layers bent in the normal direction near the fracture surface.

The raft-like structure displayed specific crystal orientations such as \(<111>_{\text{Cu}}//\text{ND}, <101>_{\text{Cu}}//\text{RD}, <101>_{\text{Fe}}//\text{ND}, \text{and } <111>_{\text{Fe}}//\text{RD.} \) The orientations were matched to those rotated 90 degrees around the transverse direction of the layer structure. Therefore, the bending of the layer structure in a necked region and/or local shear deformation may be responsible for the raft-like structure development in the Cu-Fe dual phase alloy.

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