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Temperature dependence on tensile properties of Cu-40mass%Fe dual phase alloy

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Abstract. The binary system of iron and copper shows low mutual solubility and cast Cu-Fe forms an iron (bcc) and copper (fcc) dual phase structure at room temperature. In this study, tensile properties, deformation and fracture behaviour of a rolled Cu-40mass%Fe alloy have been evaluated in order to reveal the temperature dependence on tensile properties in dual phase structures. The material formed a layer structure with ultra-fine grains of 1 μm in diameter. In both iron and copper grains, furthermore, many precipitates of copper or iron were revealed. The strength of this material increased at low temperatures, though the elongation was hardly changed, which suggests that fcc + bcc dual phase structure is effective to improve the tensile property at low temperature. Strain was inhomogeneously distributed at low temperature regardless of Cu and Fe region, and voids and cracks tended to form inside Cu layer. These results imply that the temperature dependence on tensile properties and deformation behaviour of each phase in dual phase structure is different from that of each single phase structure, and dual phase structure materials have a potential for becoming superior cryogenic structural materials.

1. Introduction

Mechanical properties of metallic materials depend on temperature, and the temperature dependence is closely related to the crystal structure. Bcc materials exhibit strong dependence and then their strength increases at lower temperature while the elongation is dramatically decreased. On the other hand, fcc materials are not too sensitive to temperature and show good ductility even at cryogenic temperature [1]. Although there are a lot of studies on the temperature dependence of mechanical properties in single phase materials, few studies on a dual phase structure have been done.

As an example, ferrite (bcc) + austenite (fcc) dual phase stainless steel shows good strength - elongation balance at low temperature [2]. However, the effects of temperature on mechanical properties for dual phase structure are unclear because metastable austenite transforms to martensite during deformation of this alloy. This transformation results in the higher work-hardening rate and elongation which is called the transformation induced plasticity (TRIP) effect [3]. Here, the binary system of iron and copper shows low mutual solubility in both matrix phases and cast Cu-Fe forms the iron (bcc) and copper (fcc) dual phase structure at room temperature. The TRIP effect does not occur



in this alloy system. Tensile properties, deformation and fracture behavior of a cold rolled Cu-40mass%Fe alloy in each temperature had been evaluated in order to reveal the temperature dependence of tensile behavior in dual phase structure.

2. Experimental procedure

The test material was a commercial cold-rolled Cu-40mass%Fe alloy. The specimen was annealed at 1123 K for 1.8 ks followed by water cooling. Microstructure was observed by optical microscopy (OM) and scanning electron microscopy (SEM), and crystal orientation was analyzed by means of electron backscattered diffraction (EBSD). EBSD data were analyzed with the software program OIM™ analysis 7.0.1 for phase and crystal orientation. Strain distribution was analyzed by digital image correlation (DIC) calculating strain from the difference of the digital images between before and after deformation. DIC analysis was carried out for SEM images of before deformation and 5% tensile deformation at each temperature with the software program (VIC-2D) under 51 pixels in subset and 5 pixels in step. Tensile test specimens with 20 mm in gage length and 4mm in width were cut from plates along the rolling direction. Tensile testing was carried out at an initial strain rate of about $5.2 \times 10^{-4} \text{ sec}^{-1}$ at 293 K, 77 K and 8 K.

3. Results and discussion

3.1. Microstructure

Figure 1 shows OM (a) and SEM (b) images of the annealed material. There were many inclusions as shown in (a), which were determined to be iron oxide from the results of electron energy dispersive x-ray analysis. These inclusions formed during casting the specimen and were distributed regardless of phase. Cu and Fe phase have layer structure along rolling direction and many precipitates were observed inside Fe layer (b). Hardness of Cu and Fe layer were 84 HV and 134 HV, respectively. Fig.2 shows inverse pole figure along the rolling direction in Cu (a) and Fe (b) phase. Cu and Fe layers had fine grains which are smaller than $1 \mu\text{m}$ in diameter, and $\langle 111 \rangle_{\text{Cu}} // \text{RD}$ and $\langle 110 \rangle_{\text{Fe}} // \text{RD}$ texture. In addition, Fe and Cu precipitates as indicated by the white arrow in Fig. 2 were observed inside Cu and Fe layers. These precipitates might suppress grain growth during annealing and then fine grain structure was maintained. From above results, the material has Cu and Fe layer structure macroscopically and fine grains and many precipitates in each layer microscopically.

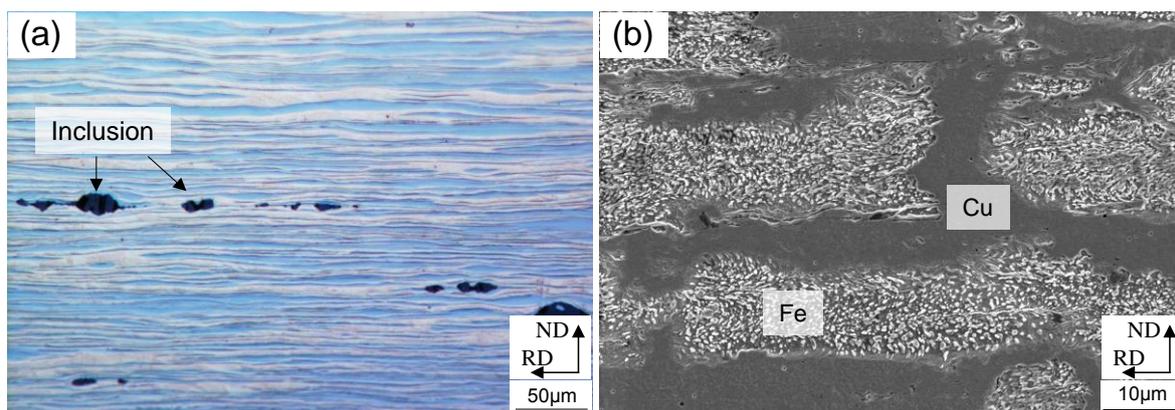


Fig. 1 OM (a) and SEM (b) image of annealed specimen.

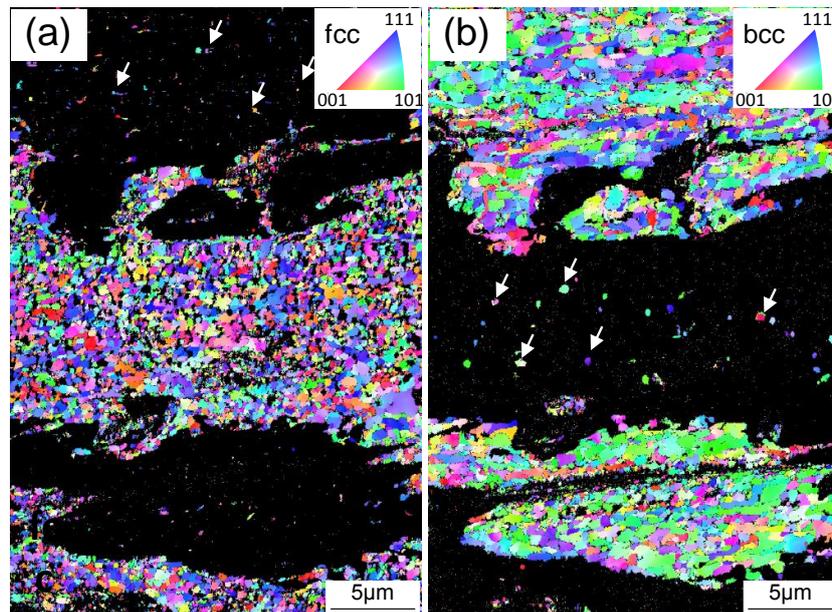


Fig. 2 Inverse pole figures of Cu (a) and Fe (b) phase in annealed specimen.

3.2. Tensile property

Figure 3 shows nominal stress - strain curves (a) and true stress or work hardening rate as a function of true strain (b) at 293 K, 77 K and 8 K. The work hardening rate had error at just after yield in tensile deformed at 293 K and 77 K because the flow stress was dramatically dropped after yield. Serration occurred by local rapid adiabatic deformation [4] appeared at 8 K, therefore, work-hardening rate at that temperature was calculated from the maximum stress at each serration neglecting other data. Serration may be formed by following mechanism: local rapid adiabatic deformation leads to rising the temperature within the local region and then applied stress dramatically decrease, after that, the stress continuously recovers with cooling the region and local rapid adiabatic deformation occurs again. Both yield and tensile stress continuously increased at lower temperature, and total elongation at 77 K is a little higher than the other test temperatures. The work - hardening rate also increased at lower temperature and uniform elongation is almost same among each temperature. From these results, it can be concluded that the strength - elongation balance in this alloy is improved at lower temperature. The Cu-Fe alloy has good temperature dependence on tensile properties than that of each phase single materials.

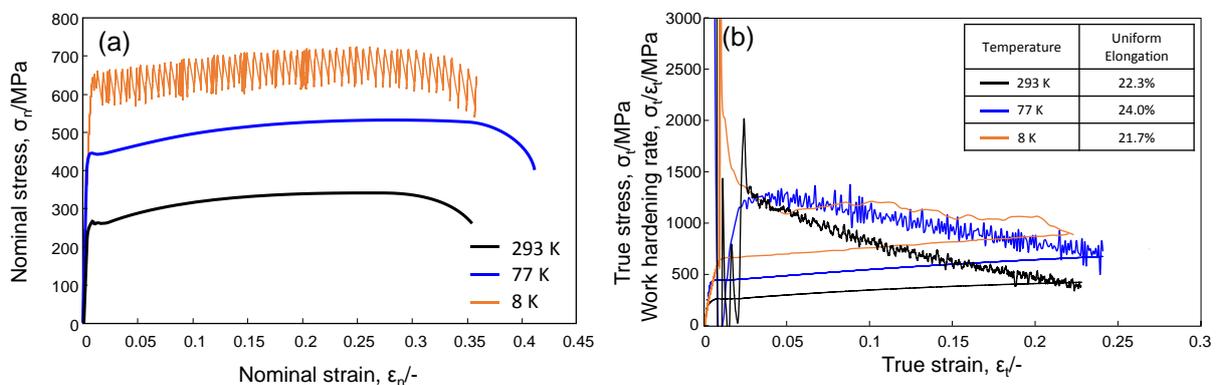


Fig. 3 Nominal stress - strain curve (a), and true stress or work hardening rate as a function of true strain (b) at 293 K, 77 K and 8 K.

3.3. Deformation and fracture behaviour

Figure 4 shows the ϵ_{xx} strain distribution in 5% tensile deformed material at 293 K (a), 77 K (b) and 8 K (c). Minimum and maximum strain in color bar are 0 and twice as much as average strain, respectively. The white dash line indicates Fe/Cu layer boundary. High strain tended to be distributed on Fe layer at 293 K as indicated by the black arrows in (a), implies that the Fe layer is more deformable than Cu layer at 293 K. Strain partitioning between Fe and Cu layer was low at 77 K (b) and 8 K (c); the average strain of Fe and Cu layer in tensile deformation at 8 K are 5.46% and 5.52%, respectively, means Fe and Cu layer were simultaneously deformed at these temperatures. On the other hand, strain distribution became inhomogeneous as lowering temperature, high strain region over twice as much as average strain and low strain region is approximately 0% at 8 K (c). In addition, strain was continuously distributed along 45 degrees which is the maximum shear stress direction regardless of Cu and Fe layers.

Figure 5 shows histograms of ϵ_{xx} strain obtained from the strain distribution (Fig. 4). Standard deviation corresponds to the width of the histogram and inhomogeneity of strain distribution in this analysis, it increases as lowering the temperature though the average strain is almost same among each temperature. This inhomogeneous strain distribution may be caused by local deformation of both phases; 48 slip systems in Fe phase: $\{110\}\langle 1-11\rangle$, $\{112\}\langle 11-1\rangle$, $\{123\}\langle 11-1\rangle$ are restricted to 12 slip systems: $\{110\}\langle 1-11\rangle$ at low temperature due to the temperature dependence of critical resolved shear stress in each slip system [5]; dislocation structure in Cu phase tends to be planar at low temperature due to the decrement of stacking fault energy as lowering the temperature. This inhomogeneous strain distribution may lead to high work-hardening rate and it is one of the reason for good strength - elongation balance at low temperature in this alloy.

Figure 6 shows SEM images at an uniform deformation (a) and a necking (b) regions in fractured specimen at 8 K. There were no voids or cracks in both phases at an uniform deformation region (a), while small voids or large crack as indicated by black arrows in (b) was observed within only Cu layer. Considering Fe and Cu layer were simultaneously deformed at 8 K, Fe layer has enough ductility even at 8 K which is under ductile to brittle transition temperature in polycrystalline Fe single phase material [6]. Fine grains or Cu precipitates may suppress the brittle fracture of Fe phase in this material, and the ductile deformation of Fe phase lead to good elongation at low temperature.

Figure 7 shows fracture surface at 293 K (a), 77 K (b) and 8 K (c). There were a lot of coarse voids generated from inclusions and micro voids formed regardless layers in every temperature. These coarse voids easily connected to each other through secondary voids which corresponds to micro voids in fracture surface, and then the specimen was broken. Therefore, this alloy has a possibility of improvement of elongation, especially local elongation, by removing these inclusions.

Temperature dependence on both tensile properties and deformation behaviour of each phase in dual phase structure materials disagree with that of each phase single materials. Fe (bcc) phase showed enough elongation even at low temperatures (Fig. 6). Cu (fcc) phase was simultaneously deformed with Fe phase (Fig. 4), which implies that Cu phase harden at lower temperatures. Although the reason for these unique properties of each phase at lower temperatures in dual phase structural material is unclear, dual phase structure materials have a potential to show superior mechanical property at cryogenic temperature than single phase materials.

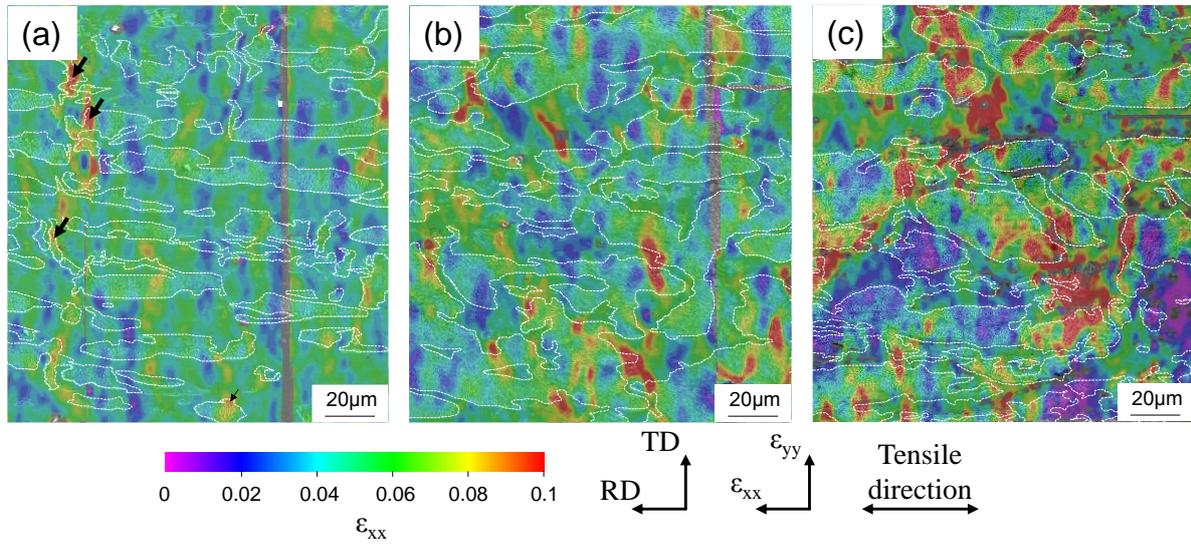


Fig. 4 ϵ_{xx} strain distribution in 5% tensile deformed at 293 K (a), 77 K (b) and 8 K (c).

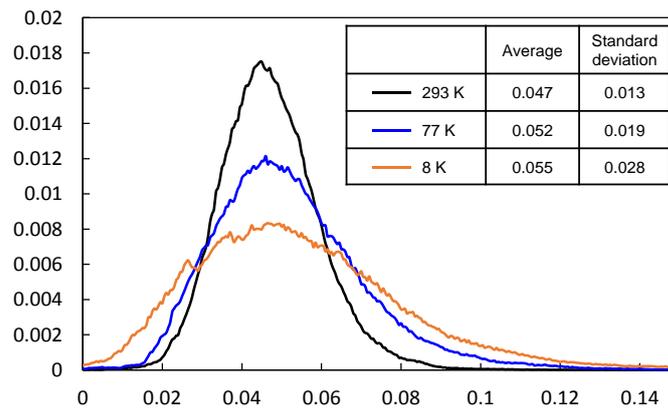


Fig. 5 Histograms of ϵ_{xx} strain in 5% tensile deformed at 293 K (a), 77 K (b) and 8 K (c).

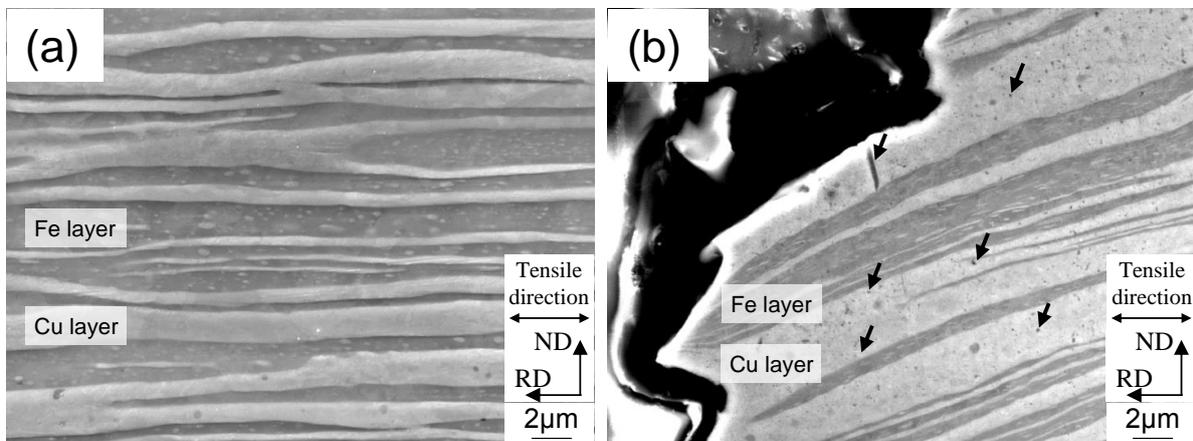


Fig. 6 SEM images at uniform deformation (a) and necking (b) region in fractured specimen at 8 K.

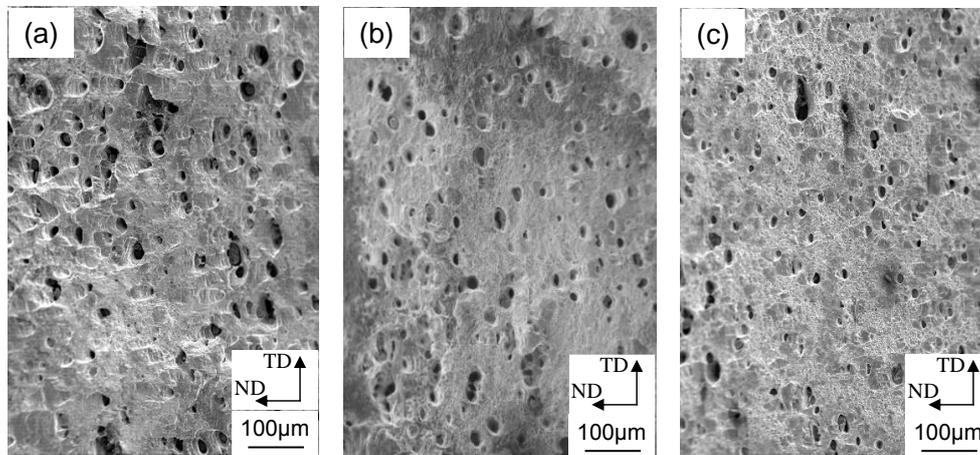


Fig. 7 SEM images of fracture surface at 293 K (a), 77 K (b) and 8 K (c).

4. Conclusions

Tensile properties, deformation and fracture behaviour of the rolled Cu-40mass%Fe alloy from 293 K to 8 K has been evaluated in order to reveal the temperature dependence on tensile properties in a dual phase structure material. Major results are summarized as follows:

The cold-rolled Cu-40%Fe alloy after annealing formed layer structure macroscopically and each layer had fine grains and precipitates. Yield stress, tensile stress and work-hardening rate continuously increased as lowering temperature though the elongation was hardly changed, which suggests that Cu-Fe alloy has the temperature dependence of strength in bcc structure and elongation in fcc structure. Strain was inhomogeneously distributed at low temperature regardless of Cu and Fe region. Voids and crack tended to generate inside Cu layer in fractured specimen at 8 K, implied that Fe layer has enough ductility even at 8 K. There were a lot of coarse voids generated from inclusions and micro voids formed regardless layers in every temperature on fracture surface. These results suggest that temperature dependence on tensile properties of dual phase structural materials is superior to that of each single phase materials and the materials have a potential to become good cryogenic structural materials.

5. References

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