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Development of the bronze processed Nb_3Sn multifilamentary wires using Cu-Sn-Zn ternary alloy matrix

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HIGHLIGHTS

- We fabricated new bronze processed Nb_3Sn wires using various Cu-Sn-Zn bronze alloy matrices.
- The additional Zn element remained homogeneously into the bronze matrix after the Nb_3Sn synthesis.
- Mechanical strength of Nb_3Sn wire was improved by the increase of the nominal Zn content of Cu-Sn-Zn ternary bronze alloy.
- The solid solution strengthening technique is simpler method, and it becomes one of the attractive high strengthening process on the bronze processed Nb_3Sn wire.

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ABSTRACT

The degradation of transport critical current density (J_c) property by the high mechanical strain on the practical Nb_3Sn wire is serious problem for applying the future fusion magnet system. We developed the various solid solution strengthened ternary Cu-Sn-Zn bronze alloys for the development of the high strength Nb_3Sn multifilamentary wires. The Zn element remained homogeneously into the bronze matrix after the Nb_3Sn synthesis heat treatment, and it contributed to strengthening the bronze matrix. Mechanical strength of Nb_3Sn wire was improved by the increase of the nominal Zn content of Cu-Sn-Zn ternary bronze alloy, and the tensile stress obtained to the maximum transport critical current (I_c) was enhanced from 80 MPa to 200 MPa. This value was comparable to the high-strengthened Nb_3Sn wire using the CuNb reinforcement technique. The solid solution strengthening technique on the bronze alloy was a simpler method compared with the reinforcement techniques and became one of the attractive high strengthening processes in the bronze processed Nb_3Sn wire.

1. Introduction

In the International Thermonuclear Experimental Reactor (ITER) project, the Cable-In Conduit (CIC) conductors for the superconducting magnets, such as Toroidal Field (TF) and Center Solenoid (CS) coils, are designed and mainly constructed by bronze processed Nb_3Sn superconducting wires. The CIC conductors for the TF and CS coils consist of more than 1000 Nb_3Sn strands and they were cabled by twisting in several stages. Nb_3Sn strand would experience higher magnetic field (above 12 Tesla) and large transport current (up to 68 kA). These experiences lead substantial transverse Lorentz forces [1], large mechanical strains and possibly Nb_3Sn filament breakage to reduce the transport properties [2]. Furthermore, it was also confirmed that the current sharing temperature (T_{cs}) performance was lowered with increasing the number of the repeated excitation tests in SULTAN [3,4]. This was also mainly caused by the Nb_3Sn filament breakage due to the repeated impression of the mechanical strain. For the progress of the prototype fusion reactor "DEMO", Nb_3Sn wire will meet more severe conditions, such as further critical current density (J_c) enhancement and higher Lorentz force environment. Therefore, Nb_3Sn wire which improves mechanical strength without lowering J_c performance is necessary for the fusion magnet system beyond ITER.

In the previous study, the various high mechanical strength Nb_3Sn wires were already fabricated. It is well known typically that the Ta and CuNb alloy reinforcements and the oxide dispersive strength (ODS) into stabilized Cu are effective methods for

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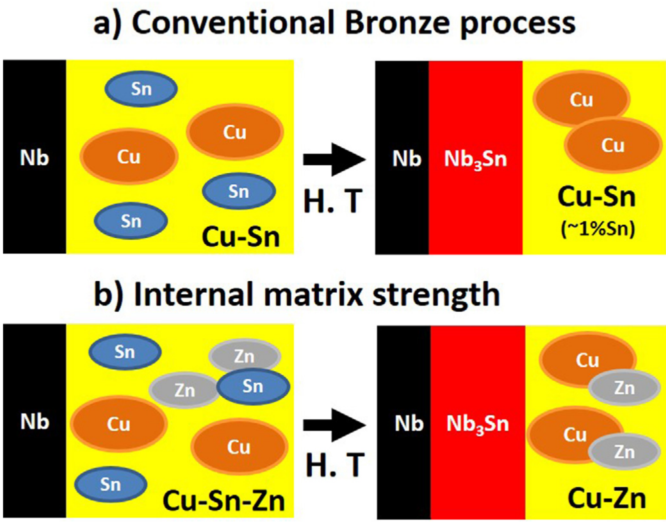

Fig. 1. The schematic views of the matrix strength mechanism due to the Zn solid solution strengthening.

improving the mechanical strength [5–7]. However, the overall J_c properties, the so-called engineering J_c (J_e), and thermal stability of these high strength Nb_3Sn wires were lowered by the increase of the non-superconducting area due to the reinforcement material. Thus, high strengthening related trade-off to the J_c and stability. We approached the high strength bronze matrix by the Zn solid solution strengthening based on the bronze process, because the internal matrix strength would be a simple method without reinforcement material, and be able to realize the high mechanical strength without both the lowering of overall J_c and non-superconducting area. For example, the matrix strength mechanism due to the Zn solid solution strengthening is shown in Fig. 1. In the case of the conventional bronze process shown in Fig. 1(a), the bronze alloy matrix was transformed to metal Cu matrix in order to form Nb_3Sn phase. In the case of the Cu-Sn-Zn ternary bronze matrix shown in Fig. 1(b), this ternary bronze alloy matrix will be transformed to Cu-Zn alloy after Nb_3Sn synthesis. We thought that the Cu-Zn alloy matrix after Nb_3Sn synthesis was contributed improving mechanical strength without both the lowering of the overall J_c property.

In this study, we casted several commercial Cu-Sn-Zn-(Ti) ternary bronze alloys with high Sn content, and also fabricated bronze processed Nb_3Sn wires using their ternary bronze alloys to investigate the possibility of solid solution strengthening and to evaluate the Zn addition effect on the microstructure, J_c and mechanical properties.

2. Sample procedures

2.1. The casting of Cu-Sn-Zn-(Ti) ternary bronze alloys

The several Cu-Sn-Zn-(Ti) ternary bronze alloys were made from metal Cu (>99.96%), Sn (>99.9%), Zn (>99.95%), and Ti (>99.43%). These raw materials were put in the carbon crucible and were dissolved by the high-frequency induction heating [8]. The bronze alloy ingots were casted using the Unidirectional Solidification process [8]. This process is usually used for the high quality bronze production for the commercial bronze processed Nb_3Sn wire. These ingots were annealed at 600 °C for 100 h for homogenizing. The nominal compositions and the results of the Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) quantitative analysis on the Cu-Sn-Zn-(Ti) ingots are indicated in Table 1. No remarkable change of the compositions of all prepared ternary bronze alloy ingots after the casting was confirmed.

Table 1
The nominal compositions and the results of ICP-AES quantitative analysis on the several Cu-Sn-Zn-(Ti) ingots.

Sample code	Nominal composition (Cu-Sn-Zn-Ti) mass %	Quantitative composition (Cu:Sn:Zn:Ti) mass %
A	79.7Cu-10Sn-10Zn-0.3Ti	79.97:9.73:10.00:0.3
B	82Cu-12Sn-6Zn	82.07:11.99:5.94:0.0
C	81.7Cu-12Sn-6Zn-0.3Ti	82.04:11.75:5.94:0.27
D	82.2Cu-13.5Sn-4Zn-0.3Ti	82.25:13.49:3.98:0.28
Ref.	83.7Cu-16Sn-0.3Ti	–

2.2. Fabrication of the Nb_3Sn multifilamentary wire using Cu-Sn-Zn-(Ti) ternary bronze alloy matrix with stabilized Cu

At first, the various Nb/Cu-Sn-Zn composites having 19 Nb filaments were fabricated as the first billet material. These composites were hot-extruded and die-drawn to 1.6 mm in a diameter. These the first billets were deformed in the hexagonal shape using the hexagonal shaped drawing die. The 409 pieces of the hexagonal-shape billets as the second multi-billet were stacked into the Oxygen Free Cu (OFC) tube. And the Cu-10Sn-10Zn-0.3Ti alloy rod and the pure Nb sheet were also stacked as the spacer and barrier materials. The spacer and barrier material are to prevent the irregular wire deformation of Nb filaments and Sn diffusion to the stabilized Cu, respectively.

The second multi-billets were also hot-extruded and die-drawn with intermediate annealing at around 500 °C. We could fabricate various Nb/Cu-Sn-Zn multifilamentary wires having 7771 Nb-filament (19 × 409) and 0.9 mm diameter without wire-breaking. In this study, the commercial Nb_3Sn multifilamentary wire using bronze without Zn addition (Cu-16Sn-0.3Ti) was also prepared as the reference for the comparisons. Finally, these precursor wires were heat treated under Ar atmosphere to form the Nb_3Sn phase. Zn has a higher vapor pressure, and the Ar atmosphere is to prevent and control the Zn evaporation during heat treatment.

3. Result and discussion

3.1. Microstructure of the Nb_3Sn wire using the ternary bronze alloy matrix

Typical Scanning Electron Microscope (SEM) images of cross-sectional area on the Nb/Cu-Sn-Zn multifilamentary wires having 7771 Nb-filament and stabilized Cu are shown in Fig. 2. In all of the multifilamentary wire samples using these ternary bronze alloy matrices, no irregular wire deformation of Nb filaments, Nb barrier breakage and mechanical cracks were observed. These ternary bronze alloys showed excellent workability at room temperature. The intermediate annealing at around 500 °C is clearly an effective process to maintain excellent wire workability. This was caused by the absence of the coarse-sized Cu-Sn-Ti (δ phase) and the Zn-Ti precipitates in all of the ternary bronze matrices. Furthermore, we also confirmed that Zn was dissolved uniformly in Cu-Sn solid solution phase (α phase) of the ternary bronze alloys from results of the Field Emission Electron Probe Micro-Analyzer (FE-EPMA; JEOL JXA-8500F).

Fig. 3 shows the detailed element distributions of the cross-sectional area in the Nb_3Sn multifilamentary wires using these A and D ternary bronze matrices after the heat treatment. And the changes of the bronze matrix compositions before and after Nb_3Sn synthesis heat treatment are summarized to Table 2. On the diffusion layers between Nb filament and these ternary bronze matrices, homogeneous distributions of both Nb and Sn elements were confirmed. In addition, Sn contents of each matrix was drastically decreased by the heat treatment, and then the released Sn element

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