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Superconductivity under uniaxial tensile strain on internal reinforced Nb_3Sn multifilamentary wire using Cu-Sn-Zn ternary alloy matrix

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Abstract. The degradations of superconducting properties by mechanical strain on actual Nb_3Sn wire are a serious problem for the future fusion magnets operated under high electromagnetic force. Recently, we succeeded to fabricate Cu-Sn-Zn ternary alloy matrix, which is high strength alloy by the Zn solid solution strengthening, based on the internal reinforced bronze process in order to investigate the mechanical strength improvement. In this study, the upper critical magnetic field (H_{c2}) under uniaxial tensile deformation on several bronze-processed Nb_3Sn multifilamentary wires were evaluated. We confirmed that the peak tensile strain values, which obtained maximum H_{c2} under uniaxial tensile deformation, were shifted to higher tensile strain region with increasing amount of Zn composition in the Cu-Sn-Zn ternary alloy matrix. The internal reinforced bronze matrix via solid solution strengthening would become attractive and simple method without reinforcement material.

1. Introductions

Nb_3Sn superconductor is the A15 phase intermetallic compound, essentially hard and brittle material. Mechanical and thermal strain sensitivity on superconducting properties of commercially available Nb_3Sn wire is a serious problem under the higher electromagnetic force environment in a Fusion reactor and/or high energy accelerator [1]. That is, the high mechanical strength of actual Nb_3Sn wire will become one of the important research subjects to contribute to progress of future "Big science" such as fusion reactors and high energy accelerators. In previous high strength research, composite arrangement techniques with metal Ta fiber, CuNb alloy and NbTiCu compound as the reinforcement material and alumina dispersion reinforcement to stabilized copper were investigated [2-4], and we found that these techniques could lead to high mechanical strength of the Nb_3Sn wire. However, these composite arrangement techniques promote not only the increased production cost but also the increase of non-superconducting components in the Nb_3Sn wire. Furthermore, it caused the lowering of the engineering critical current density (J_e), which value is equal to the over-all critical current density (J_c) and is mainly used and discussed on engineering design activity on large fusion magnets.

In addition, with the alumina dispersion reinforcement technique, the lowering of cooling and electrical stabilities will be caused by replacement of part of the stabilized copper by the alumina dispersion copper. In this way, we thought that a simple reinforcement process with new concept unlike the previous reinforcement technique was necessary to enhance the application region of the Nb_3Sn wire.

Recently, we explored the internal solid solution strengthening process, which corresponded to the high strength of the bronze matrix using solid solution strengthening after the Nb_3Sn formation. [5, 6] The concept of the internal solid solution strengthening process was to protect the Nb_3Sn phase from external stress and strain under the higher electromagnetic force environment using the solid solution strengthened bronze matrix. On the conventional bronze process, with most of the Sn element diffused with the Nb filament from the Cu-Sn-(Ti) matrix to form Nb_3Sn phase, a small amount of the Sn content remained in the matrix after Nb_3Sn formation heat treatment. Thus, the Cu-Sn-(Ti) matrix after heat treatment transformed to Cu alloy including a small amount of Sn content, and did not act as the reinforcement material and electrical stabilizer. We expected that the high mechanical strength of Nb_3Sn wire without lowering of superconducting properties and electrical stability could be realized if the transformed matrix after heat treatment could act as the reinforcement material.

On the internal solid solution strengthening process, on the other hand, the Cu-Sn-Zn-(Ti) ternary alloy was used as the alternative Cu-Sn-(Ti) matrix material. In this ternary alloy matrix case, non-reactive Zn element remained mainly in the matrix after heat treatment, and acted as the solute element of the solid solution strengthening. According to the Cu-Zn binary phase diagram, Zn element has a large solid solubility limit above 30 mass% compared with the Sn element. The Cu-Sn-Zn-(Ti) ternary alloy is of interest as the matrix material on the internal solid solution strengthening process, and several internal reinforced Nb_3Sn multifilamentary wires using Cu-Sn-Zn ternary alloy matrices having practical bronze compositions (Sn content: 10 ~ 13.5 mass%) were fabricated.

In this study, the upper critical magnetic field (H_{c2}) values which were estimated from the electrical resistivity (R)-magnetic field (B) curve under uniaxial tensile strain on the Nb_3Sn multifilamentary wires using Cu-Sn-Zn-(Ti) ternary alloys were evaluated, and the effect of the internal reinforcement via the Zn solid solution strengthening mechanism was investigated.

2. Sample and experimental procedure

2.1 Sample preparations

Table.1 indicates that the sample code and the nominal compositions of Cu-Sn-Zn-(Ti) ternary bronze alloy matrices on the internal reinforced Nb_3Sn multifilamentary wires in this study. The commercial bronze-processed Nb_3Sn multifiamentary wire using 16 mass%Sn-0.2 mass%Ti bronze alloy matrix (Sample-F) was also prepared as a reference wire for comparison. The quantitative composition shown in Table.1 was estimated by ICP-mass analysis. Prepared Nb_3Sn multifilamentary wires using Cu-Sn-Zn ternary alloy matrix (Sample-A, B, C and D) have 0.9 mm outer diameter, 7771 Nb filaments, Nb barrier and stabilized Cu (Cu ratio: 1.3). All of those wire samples were heat treated under Ar atmosphere to form the Nb_3Sn phase. Zn has a higher vapor pressure, and the Ar atmosphere is to

Table 1. Sample code and nominal compositions of Cu-Sn-Zn-(Ti) ternary bronze alloy matrices on the internal reinforced Nb_3Sn multifilamentary wires in this study

Sample code	Nominal composition, mass% (Cu-Sn-Zn-(Ti))	Quantitative composition, mass% (Cu:Sn:Zn:Ti)
Sample-A	Cu-10Sn-10Zn-0.3Ti	79.97 : 9.73 : 10.00 : 0.30
Sample-B	Cu-12Sn-6Zn	82.07 : 11.99 : 5.94 : 0.00
Sample-C	Cu-12Sn-6Zn-0.3Ti	82.04 : 11.75 : 5.94 : 0.27
Sample-D	Cu-13.5Sn-4Zn-0.3Ti	82.25 : 13.49 : 3.98 : 0.28
Sample-F (Ref.)	Cu-16Sn-0.2Ti	No data

prevent and control the Zn evaporation during heat treatment. In this study, two-stage heat treatment (1st. 550 ^{0}C for 100 hrs + 2nd. 650 ^{0}C for 100 hrs) was performed.

2.2 Experimental procedure

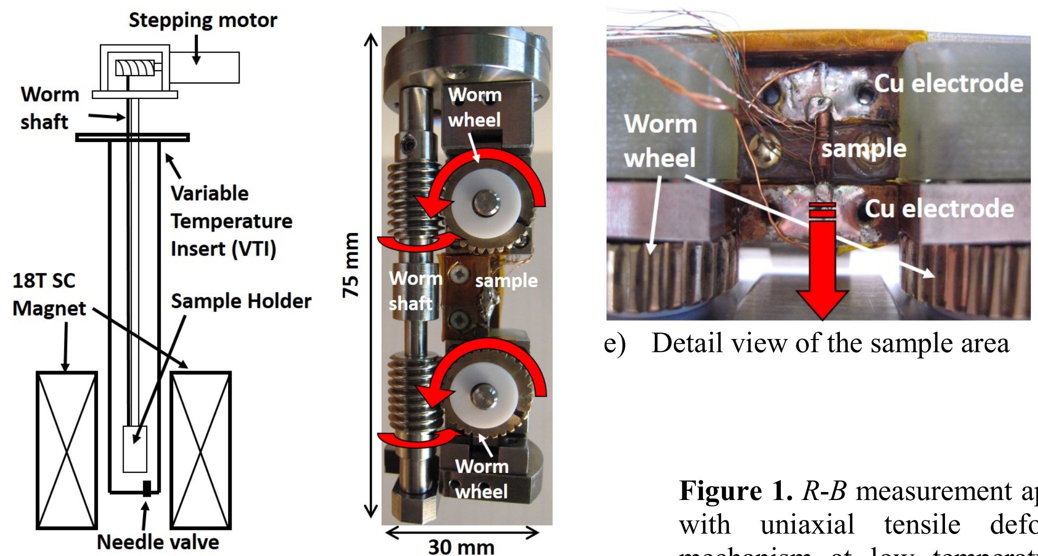
The H_{c2} values under uniaxial tensile strain on the Nb_3Sn multifilamentary wires using Cu-Sn-Zn-(Ti) ternary alloys were measured using *R-B* measurement apparatus with uniaxial tensile deformation mechanism at low temperature and high magnetic field shown in figure 1. This apparatus is installed at the Institute for Material Research, Tohoku University. The wire was cut to a length of 20 mm and was fixed on the Cu electrodes of the sample holder by soldering. Uniaxial tensile strain was applied by moving one Cu electrode shown in figures 1 (b) and (c). The electrode movement was adjusted by the worm gear controlled by the stepping motor. The uniaxial tensile strain was measured by strain gauge method. In order to eliminate the bend distortion component of the gauge and to obtain accurate measurements, a two-gauge method was adopted. The strain gauges were symmetrically glued onto both sides of the wire surface. The tensile strain was defined as the average value of two attached strain gages.

The H_{c2} measurement probe was inserted into the 18 T superconducting magnet using the variable temperature insert (VTI). Sample temperature was adjusted by the heater output and liquid helium flow rate, and these were controlled by the cernox sensor and Lakeshore Cryotronics Co Ltd temperature controller Model 340. The resistivity of the Nb_3Sn wire under uniaxial tensile strain at 10 K was measured by a four-probe method using a 100 mA sample current with ramping magnetic field from 10 T to 18 T. H_{c2} value was defined as the offset magnetic field on the *R-B* curve.

In part of the wire samples, micro focused XRD analysis was performed to investigate the phase transformation of ternary alloy after the Nb_3Sn synthesis. X-ray was focused to 100 μm diameter by the collimater.

3. Results and discussions

H_{c2} values at 10 K as a function of uniaxial tensile strain on Nb_3Sn multifilamentary wires using various Cu-Sn-Zn-(Ti) ternary alloy matrices are shown in figure 2. H_{c2} values before tensile deformation increased with increasing nominal Sn content of Cu-Sn-Zn-(Ti) ternary alloy matrices. In addition, the H_{c2} value of the Nb_3Sn wire with Ti addition (sample-C) was markedly higher than that of the wire sample without Ti addition (Sample-B). As well as conventional bronze processed Nb_3Sn



a) Schematic view of apparatus
c) Worm gear mechanism of sample holder
e) Detail view of the sample area

Figure 1. *R-B* measurement apparatus with uniaxial tensile deformation mechanism at low temperature and high magnetic field

wire, both the nominal Sn content of ternary alloy matrix and Ti addition were important issues to improving superconducting properties under high magnetic field of the internal reinforced Nb_3Sn multifilamentary wire using Cu-Sn-Zn ternary alloy matrix. All of the H_{c2} values in this study were improved by uniaxial tensile deformation. This was caused by release of internal compressive and/or residual stresses. Here, H_{c2}max is defined as the maximum peak H_{c2} value applying uniaxial tensile strain, and H_{c2}max values of 15.444, 15.917 and 16.193 T were obtained on Sample-A, C and D. The peak tensile strain H_{c2}max also increased with increasing nominal Zn content of the ternary alloy matrix. Especially with nominal Zn content above 6 mass%, this effect was clearly confirmed.

The normalized H_{c2} (H_{c2}/H_{c2}max) corresponds to the H_{c2} value applying tensile strain divided by the H_{c2}max, and we thought that the normalized value means the rate of H_{c2} degradation was caused by tensile deformation. The normalized H_{c2} value at 10 K between several Nb_3Sn multifilamentary

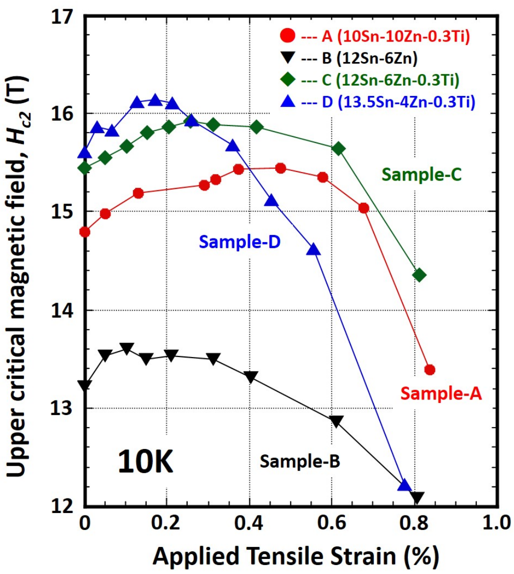


Figure 2. H_{c2} values at 10 K as a functions of the uniaxial tensile strain on Nb_3Sn multifilamentary wires using various Cu-Sn-Zn-(Ti) ternary alloy matrices

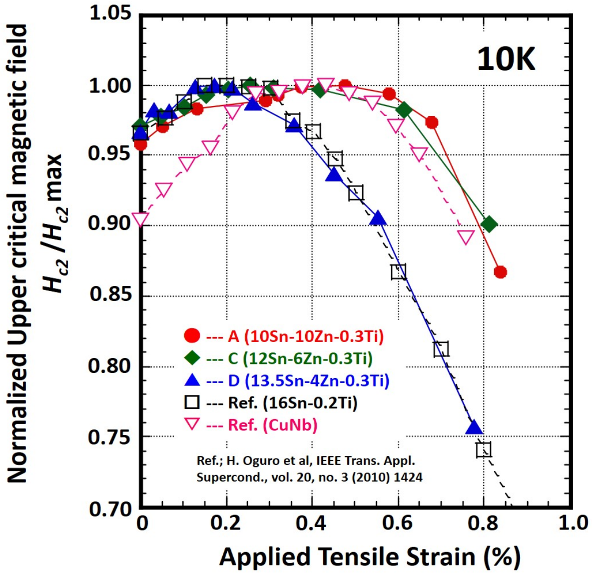


Figure 3. Comparisons of normalized H_{c2} value (H_{c2}/H_{c2}max) at 10 K between several Nb_3Sn multifilamentary wires using various Cu-Sn-Zn-(Ti) ternary alloy matrices

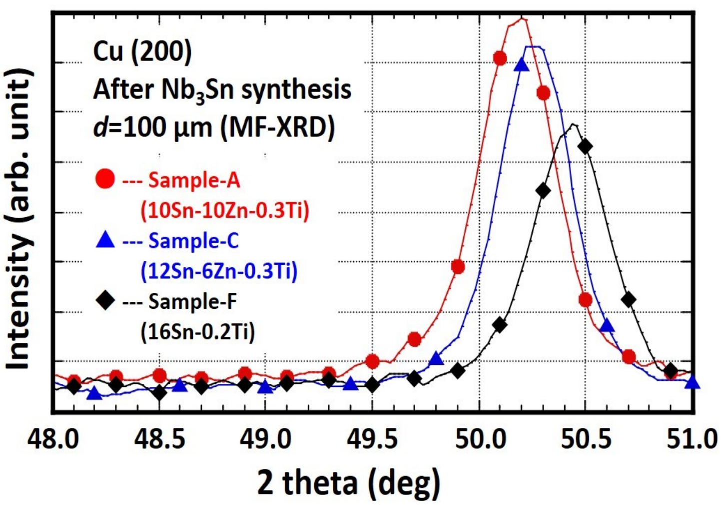


Figure 4. XRD patterns of the various ternary alloy matrices after Nb_3Sn synthesis heat treatment

wires using various Cu-Sn-Zn-(Ti) ternary alloy matrices is shown in figure 3. Typical normalized H_{c2} values of the CuNb reinforced Nb_3Sn wire are also plotted for comparisons [7]. The normalized H_{c2} behaviour of the sample having 4 mass%Zn content (Sample-D) was similar to the conventional bronze processed wire (Sample-F). On the sample having above 6 mass%Zn content, the peak tensile strain obtained with the normalized H_{c2} was shifted from 0.172 % to 0.2561 % and 0.4528 % with increasing nominal Zn content of the ternary alloy matrix. Especially, normalized H_{c2} behaviour of the sample having 10 mass%Zn content showed closely similar behaviour to the CuNb reinforced high strength Nb_3Sn wire. We found that the Zn content of Cu-Sn-Zn ternary matrix became the important factor to enhance internal reinforcement using the ternary alloy matrix; more than 6 mass%Zn was effective Zn content on the internal reinforcement using the ternary alloy matrix.

Figure 4 shows X-ray diffraction patterns of the various ternary alloy matrices after Nb_3Sn formation heat treatment. In the cases of Cu-Sn-Zn matrix samples, the main diffraction peaks of Cu (200) plane were clearly shifted to the lower angle side compared with the reference sample, and they were identified to the (Cu, Zn) solid solution phase. Furthermore, the shifted angle of the diffraction peak in the (Cu, Zn) solid solution was increased, depending on the Zn content in the Cu-Sn-Zn ternary matrix. The Zn element acted as the solute element to the (Cu, Zn) solid solution strength and the Zn content of the Cu-Sn-Zn ternary alloy matrix corresponded to the amount of Zn in the (Cu, Zn) solid solution. We found that the Cu-Sn-Zn ternary matrix after Nb_3Sn synthesis was transformed to (Cu. Zn) solid solution by interstitial Zn, and the (Cu, Zn) solid solution contributed to internal reinforcement.

4. Conclusions

The internal solid solution strengthening process using Cu-Sn-Zn ternary alloy matrix was a simpler reinforcement method compared with other techniques, and this process achieved similar mechanical property compared with CuNb reinforced Nb_3Sn wire. In the case of the Cu-Sn-Zn ternary alloy matrix, the ternary matrix was transformed to (Cu, Zn) solid solution after Nb_3Sn synthesis, and it contributed to the internal reinforcement material of the bronze processed Nb_3Sn wire. In future, the optimum adjustment between Sn and Zn contents in Cu-Sn-Zn ternary alloy is necessary to progress the solid solution strengthening due to the Cu-Sn-Zn ternary bronze matrix

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