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著者	渡辺　和雄
journal or publication title	IEEE Transactions on Applied Superconductivity
volume	14
number	2
page range	1004-1007
year	2004
URL	http://hdl.handle.net/10097/47149

doi: 10.1109/TASC.2004.830367

Development of High-Strength Nb_3Sn Conductor

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***Abstract*—Nb_3Sn superconducting wires reinforced with Cu-Ni/Nb-Ti composite have been developed. Nb_3Sn wires reinforced with Cu-Ni/Nb-Ti showed good mechanical and electrical properties. In this study, 1.2 mm-diameter $(Nb, Ti)_3Sn$ superconducting wire of 13 km in length reinforced with Cu-Ni/Nb-Ti was successfully fabricated. Moreover, the effect of copper fraction to the strength of the wire was studied.**

***Index Terms*—Cu/Nb-Ti, high strength, intermetallic compound, Nb_3Sn, reinforcer.**

I. Introduction

RECENTLY, Nb_3Sn superconducting wires with reinforcer, such as CuNb composite [1], Al_2O_3-dispersed copper [2], and Tantalum [3] were developed to overcome huge electromagnetic stress. To obtain higher strength than these reinforced Nb_3Sn wires, the Nb_3Sn wire with intermetallic compound have been developed. Generally, intermetallic compound is very hard but brittle and have less workability than common metals. But if the components of the intermetallic compound can be worked together like Niobium and Tin of Nb_3Sn, intermetallic compound will successfully form at the final heat treatment for Nb_3Sn formation. In [4], we used the intermetallic compound formed between Nb-Ti and copper in a Cu/Nb-Ti composite as a reinforcer for the Nb_3Sn wire. The wire showed very high strength, but the strain limit of the wire was too low to practical use.

In this paper, we report on the properties of the $(Nb, Ti)_3Sn$ superconducting wire with Cu-Ni/Nb-Ti reinforcer $(CuNi - NbTi/Nb_3Sn)$ and the influence of copper fraction on the strength of the $(Nb, Ti)_3Sn$ superconducting wire with Cu/Nb-Ti reinforcer $(Cu - NbTi/Nb_3Sn)$ fabricated in laboratory scale (2 kg). Secondly, a fabrication of the $CuNi - NbTi/Nb_3Sn$ in the industrial scale is also reported.

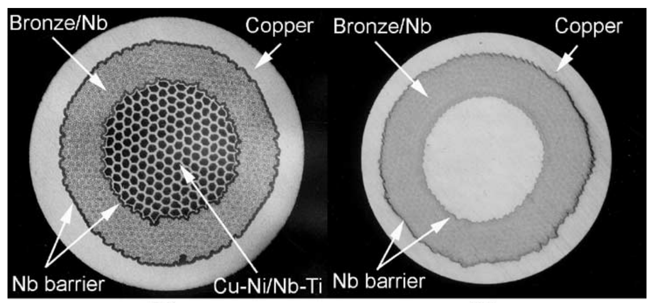
II. The Nb_3Sn Wire With Cu-Ni/Nb-Ti Reinforcer

A. Nb_3Sn *Wires With and Without Cu-Ni/Nb-Ti Reinforcer*

Table I shows major parameters of the $CuNi - NbTi/Nb_3Sn$ wire and the wire without reinforcer (Cu/Nb_3Sn). The wire and filaments are 1 mm and 3.5 μm in diameter respectively. The filaments were pure niobium. Composition of bronze matrix of both wire before final heat treatment is Cu-14.2wt%Sn-0.2wt%Ti and bronze to niobium ratio was 2.3. The volume fractions of the superconducting areas including the diffusion barriers are 0.471 and 0.476 for the $CuNi - NbTi/Nb_3Sn$ and Cu/Nb_3Sn respectively. The volume fraction of reinforcer is 0.265 for the $CuNi - NbTi/Nb_3Sn$ wire. In the Cu/Nb_3Sn wire, Cu-Ni/Nb-Ti reinforcer was replaced with copper stabilizer in order to comparison. Cross-sectional views of both wires are shown in Fig. 1.

TABLE I
Major Parameters of Fabricated Wires

Items	CuNi-NbTi/Nb_3Sn	Cu/Nb_3Sn
Wire diameter (mm)	1.001	1.002
Twist pitch (mm)	30	
Filament diameter (mm)	3.5	
Number of filament	10127	11229
Reinforcer	CuNi-NbTi	-
Diffusion barrier	Nb 11 μm	
Fraction		
Copper (stabilizer)	0.264	0.524
Superconducting area	0.471	0.476
Reinforcer	0.265	-



(a) (b)

Fig. 1. Cross-sectional views of the Nb_3Sn superconducting wire. (a) With Cu-Ni/Nb-Ti reinforcer $(CuNi - NbTi/Nb_3Sn)$. (b) Without reinforcer (Cu/Nb_3Sn). Cu-Ni/Nb-Ti reinforcer is placed center of the wire surrounded by the niobium diffusion barrier. Both wires were before heat treatment.

B. Properties

1) Critical Current: Critical current densities of both wires at the magnetic fields from 8 to 14 T are shown in Fig. 2. Critical current was measured with four probe method using 25 mm-diameter FRP mandrel. Criteria of the critical current is 10^{-5} V/m. Critical current density with copper stabilizer and reinforcer area $J_c(SC + barrier)$ was given as the critical current divided by the amount of the bronze/filament area and niobium barrier area. $J_c(SC + barrier)$ of the $CuNi - NbTi/Nb_3Sn$ wire at 12 and 14 T is 625 and 415 A/mm^2, while that of Cu/Nb_3Sn wire at 12 and 14 T is 655 and 455 A/mm^2, respectively. $CuNi - NbTi/Nb_3Sn$ wire shows 95% of critical current of Cu/Nb_3Sn wire at 12 T, while Nb_3Sn wire with

Manuscript received October 21, 2003.

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Digital Object Identifier 10.1109/TASC.2004.830367

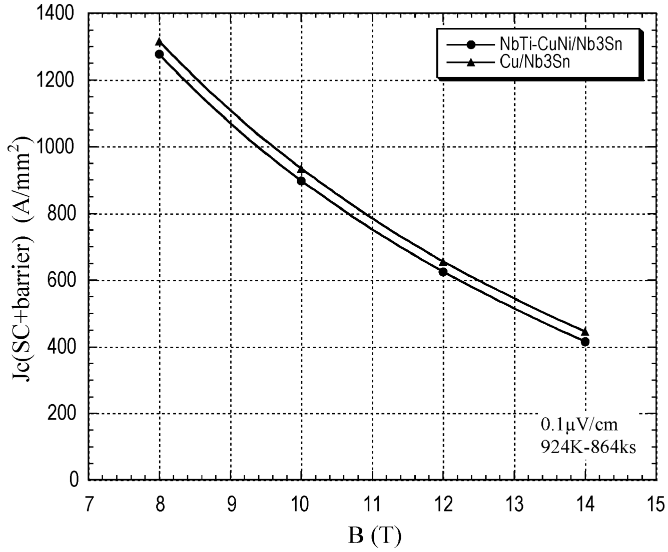

Fig. 2. Critical current density as a function of magnetic field for $CuNi - NbTi/Nb_3Sn$ wire and Cu/Nb_3Sn wire. Both wires were heat treated at 924 K for 864 ks. $J_c(SC + barrier)$ was given as the critical current divided by the amount of the bronze/filament area and niobium barrier area.

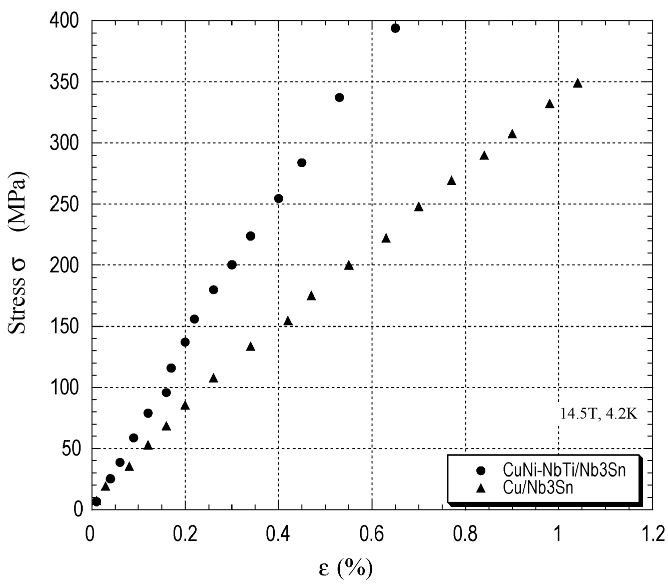

Fig. 3. Stress-strain curves of the $CuNi - NbTi/Nb_3Sn$ wire and the Cu/Nb_3Sn wire at 4.2 K and 14.5 T. Both wires were heat treated at 924 K for 864 ks.

CuNb reinforce stabilizer showed 87% of critical current of Cu/Nb_3Sn wire [5].

2) Tensile Properties and Strain Effect: The stress-strain curves of the $CuNi - NbTi/Nb_3Sn$ and the Cu/Nb_3Sn wire at 4.2 K, 14.5 T are shown in Fig. 3. The yield stress of the $CuNi - NbTi/Nb_3Sn$ and the Cu/Nb_3Sn wire at 4.2 K are 370 MPa and 150 MPa respectively. The stress effects on I_c at 14.5 T and 4.2 K for both wires are shown in Fig. 4. In this measurement, criteria of critical current is 1 $\mu V/cm$. The maximum $I_c(I_{cm})$ was 172 A at $\varepsilon = 0.18\%$ for the $CuNi - NbTi/Nb_3Sn$ wire and 179 A at $\varepsilon = 0.12\%$ for the Cu/Nb_3Sn wire. It indicates that the intrinsic superconducting properties for both wire are nearly the same and the difference in the strain state for both wire causes a different superconducting behavior for both wires.

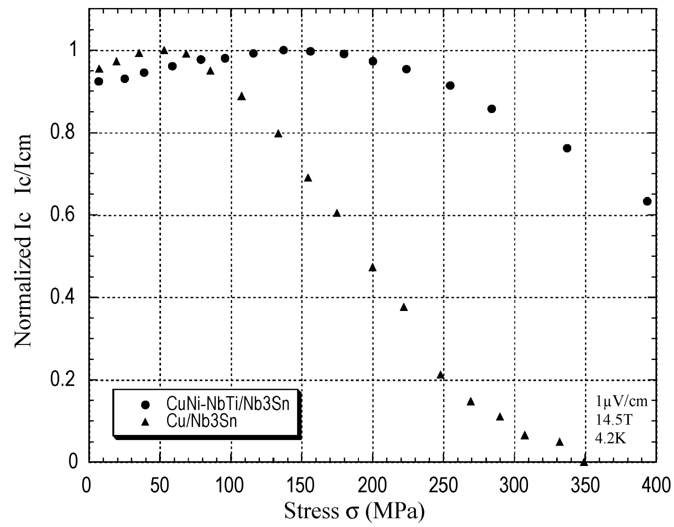

Fig. 4. Stress effects on I_c for the $CuNi - NbTi/Nb_3Sn$ wire and the Cu/Nb_3Sn wire at 4.2 K and 14.5 T. Both wires were heat treated at 924 K for 864 ks. I_c criteria was 1 $\mu V/cm$.

TABLE II
MAJOR PARAMETERS OF $Cu - NbTi/Nb_3SN$

Items	Sample A	Sample B	Sample C
Wire diameter (mm)	1.0	1.0	1.0
Filament diameter (μm)	3.5	3.5	3.5
Reinforcer	Cu/NbTi	Cu/NbTi	Cu/NbTi
Diffusion barrier	Ta	Ta	Ta
Fraction			
Copper(stabilizer)	0.326	0.383	0.435
Superconducting area	0.510	0.468	0.431
Reinforcer	0.164	0.149	0.134

It is clear in Fig. 4 that the $CuNi - NbTi/Nb_3Sn$ wire shows higher critical current than the Cu/Nb_3Sn wire at the stress over 100 MPa. These high stress tolerance of the $CuNi - NbTi/Nb_3Sn$ wire is very useful for the practical use.

III. STRENGTH OF THE WIRE WITH DIFFERENT Cu FRACTION

A. Nb_3Sn *Wire With Cu/Nb-Ti Reinforcer*

For the electrical stability, amount of the copper stabilizer is very important. But the copper stabilizer is fully annealed during the final heat treatment for Nb_3Sn formation and shows very low yield strength. From the viewpoint of the strength, it seems very difficult to increase the total amount of copper stabilizer without degradation of strength. Consequently, we studied strength of the Nb_3Sn wire with Cu/Nb-Ti reinforcer $(Cu - NbTi/Nb_3Sn)$ provided with various copper fraction. The area ratio of the reinforcer to superconducting area is 0.3:1. Major parameters of $Cu - NbTi/Nb_3Sn$ wires are shown in Table II. Copper fraction of Sample A, B, and C is 32.6%, 38.3%, and 43.5% respectively. Of all three wires, tantalum was used for the diffusion barrier. Cross sectional view of Sample C is shown in Fig. 5.

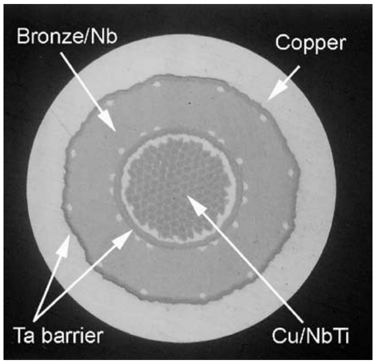

Fig. 5. Cross-sectional view of sample C. Cu-NbTi reinforcer is placed center of the wire surrounded by the tantalum diffusion barrier.

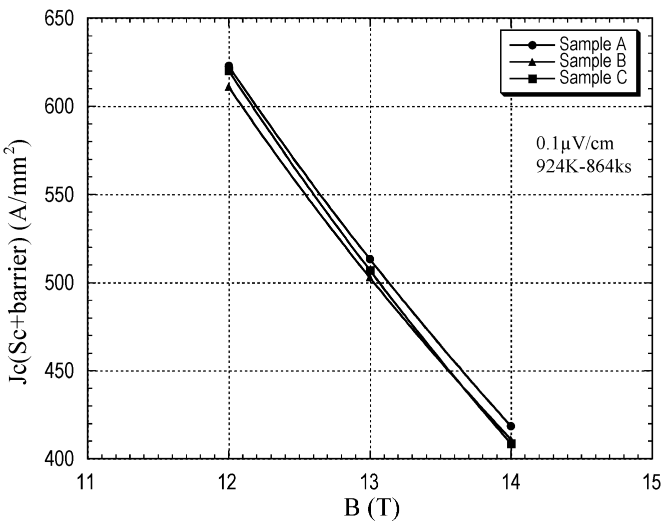

Fig. 6. Critical current density as a function of magnetic field for $Cu - NbTi/Nb_3Sn$ wires. Wires were heat treated at 924 K for 864 ks. $J_c(SC + barrier)$ was given as the critical current divided by the amount of the bronze/filament area and tantalum barrier area.

B. Properties

Critical current densities of three wires, Sample A, B, and C at the magnetic fields from 12 to 14 T are shown in Fig. 6. Critical current densities of these wires are 610–620 A/mm^2 at 12 T and 410–420 A/mm^2 at 14 T. There are no significant effects on critical current density caused by the difference in copper fraction of the wire.

The tensile strength and yield strength of sample A, B, and C are shown as a function of copper fraction in Fig. 7. It is clear that the strength of the wire is inversely proportional to the copper fraction of the wire.

IV. Wire Fabrication in the Industrial Scale

A. Wire Fabrication

Due to the possibility of the formation of the intermetallic compound during the wire fabrication, it is important to ensure the fabricability of the $CuNi - NbTi/Nb_3Sn$ wire in industrial scale. We fabricated about 13 km(140 kg) of 1.2 mm-diameter $CuNi - NbTi/Nb_3Sn$ wire. Major parameters and cross section of the fabricated wire are shown in Table III and Fig. 8, respectively.

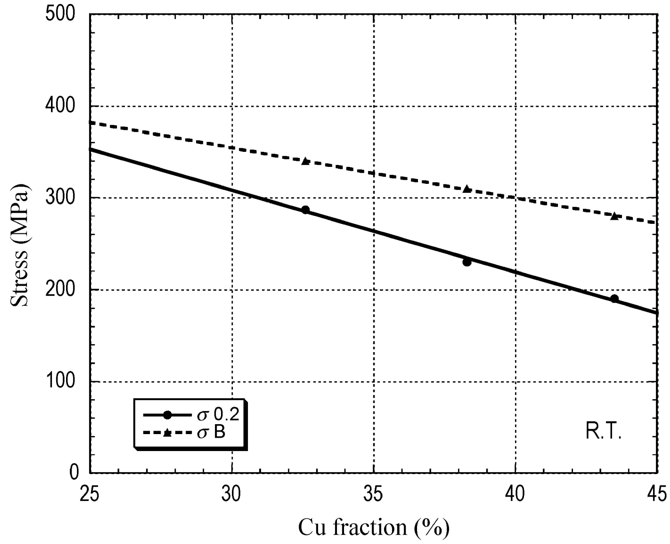

Fig. 7. Strength of the samples A, B, and C at R.T. as a function of the copper fraction. Wires were heat treated at 924 K for 864 ks.

TABLE III
Major Parameters of $CuNi - NbTi/Nb_3Sn$

Items	CuNi-NbTi/Nb_3Sn
Wire diameter (mm)	1.202
Twist pitch (mm)	50
Filament diameter (μm)	3.5
Number of filament	13034
Reinforcer	Cu-Ni/Nb-Ti
Diffusion barrier	Nb 15 μm
Fraction	
Copper(stabilizer)	0.310
Superconducting area	0.433
Reinforcer	0.257

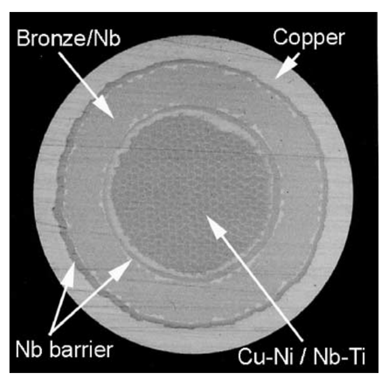

Fig. 8. Cross-sectional view of the Nb_3Sn superconducting wire with Cu-Ni/Nb-Ti reinforcer fabricated in industrial scale.

The fabricating procedure was ordinary bronze process and any special treatment was not required for the $CuNi - NbTi/Nb_3Sn$ wire. The $CuNi - NbTi/Nb_3Sn$ wire has good fabricability and we could fabricate a 13 km (140 kg) of $CuNi - NbTi/Nb_3Sn$ wire successfully.

B. Properties

Critical density of the $CuNi - NbTi/Nb_3Sn$ wire in industrial scale is shown in Fig. 9. Critical density of the wire

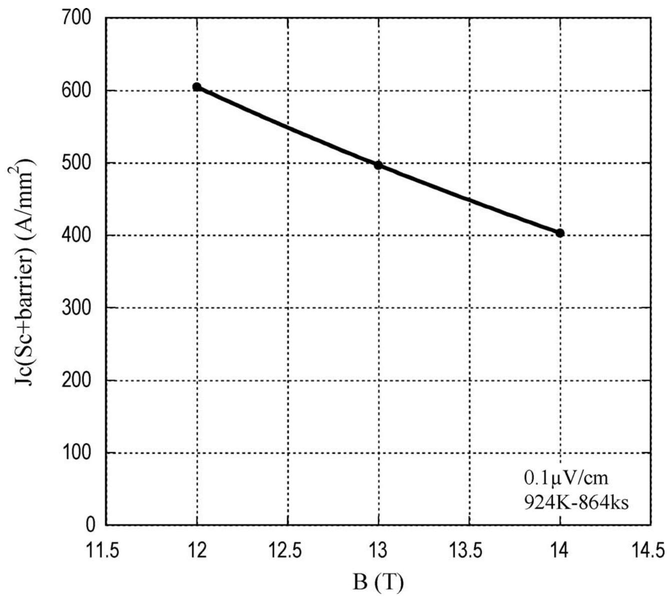

Fig. 9. Critical current density as a function of magnetic field for $CuNi - NbTi/Nb_3Sn$ wire fabricated in industrial scale. Wire was heat treated at 924 K for 864 ks. $J_c(SC + barrier)$ was given as the critical current divided by the amount of the bronze/filament area and niobium barrier area.

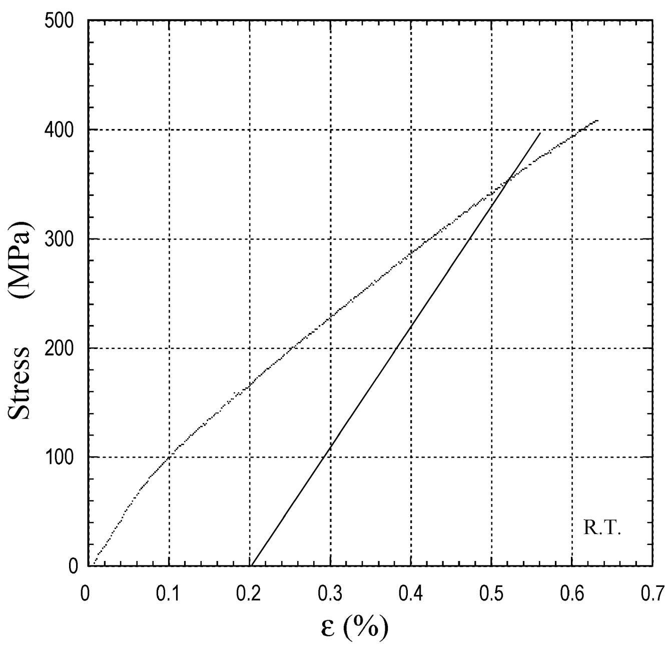

Fig. 10. Stress-strain curve of the $CuNi - NbTi/Nb_3Sn$ wire fabricated in industrial scale at R.T. Wire was heat treated at 924 K for 864 ks.

is 604 A/mm^2 at 12 T and 403 A/mm^2 at 14 T. They are very close to the results of lab.-scale wires. It indicates that no harmful damage occurred in the longer fabricating process than lab.-scale one.

Stress-strain curve of the wire is shown in Fig. 10. Yield strength (0.2% proof stress) of the wire is 350 MPa.

V. Conclusions

The $(Nb, Ti)_3Sn$ superconducting wire with Cu-Ni/Nb-Ti reinforcer $(CuNi - NbTi/Nb_3Sn)$ was successfully fabricated. Critical current density of $CuNi - NbTi/Nb_3Sn$ was almost the same as that of the $(Nb, Ti)_3Sn$ superconducting wire without reinforcer (Cu/Nb_3Sn). 0.2% proof stress of $CuNi - NbTi/Nb_3Sn$ was more than two times of that of Cu/Nb_3Sn.

Strength of the wire is inverse proportion to the copper fraction, while critical current density is not sensitive to the copper fraction.

In the industrial scale production, $CuNi-NbTi/Nb_3Sn$ wire of 13 km in length was successfully fabricated. The wire showed a good fabricability through out the production. Critical current density at 12 T is 603 A/mm^2. The 0.2% proof stress at R.T. of the $CuNi - NbTi/Nb_3Sn$ wire is 350 MPa.

Acknowledgment

The authors thank Prof. Katagiri, Iwate University, for the evaluation of the mechanical properties at 4.2 K and the strain effect of J_c.

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