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Overview of Nb_3Sn and V_3Ga conductor development in Japan

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ABSTRACT

In the early stage of high-field A15 conductor development in Japan, different type of V_3Ga conductors were fabricated. Then, Ti-doped Nb_3Sn conductors have been developed, and widely used for high-field generation. Increase of Sn concentration in the bronze produces an appreciable progress in the performance of bronze processed $(Nb,Ti)_3Sn$ conductors. New internal Sn processed $(Nb,Ti)_3Sn$ conductors with modified cross-sectional configurations have been produced, which exhibit large J_c in high fields as well as reduced AC loss. Both bronze processed and internal Sn processed $(Nb,Ti)_3Sn$ conductors satisfy recent ITER magnet specifications. As for new type Nb_3Sn conductors, powder core and Jelly Roll processed $(Nb,Ta)_3Sn$ wires with improved high-field performance have been fabricated.

1. Introduction

A15 crystal-type compound wires, e.g. Nb_3Sn, Nb_3Al and V_3Ga, are indispensable for generating fields over 10 T at 4.2 K. The generation of higher magnetic field is required in NMR facilities, fusion devices, refrigerator-cooled superconducting magnets, etc. Japan has been quite active in the research and development of A15 compound superconductors. A unique achievement in this area is the discovery of the effect of Cu for the promotion of V_3Ga synthesis, which has become the starting point of the commercialization of A15 superconductors [1]. The first multifilamentary A15 wire was fabricated using a composite of V cores and a Cu–Ga alloy matrix. As for Nb_3Sn, the internal Sn(IT) process was initiated in Japan [2]. Subsequently, the effect of a small amount of Ti addition to the bronze matrix of Nb_3Sn strands, which enhances the upper critical field B_{c2} (4.2 K) from 20 T to 25 T, was discovered [3]. Ti-doped bronze processed and IT processed Nb_3Sn wires have been widely used for the generation of high magnetic fields. Recently, new fabrication processes for high-field Nb_3Sn wires are also being developed. Present article provides the overview and the present status of Nb_3Sn and V_3Ga conductor development in Japan.

2. V_3Ga conductors

In the diffusion reaction between V and molten Ga at temperatures below 800 °C, two compounds richer in gallium than V_3Ga are predominantly formed. Only a very small amount of V_3Ga is formed between the Ga-rich compound and V through the grain boundary diffusion. The addition of a small amount of Cu which is soluble to the Ga-rich compound enables the formation of a thick V_3Ga layer at temperatures below 700 °C, changing the diffusion mode from a grain boundary one to a bulk one [1]. The Cu does not dissolve into the V_3Ga, and hence does not deteriorate the intrinsic superconducting properties of the V_3Ga. The V_3Ga tape fabricated by this procedure was used for the construction of a 17.5 T superconducting magnet which established the highest field record at that time [4]. As a fundamental study, the microstructure of the V_3Ga tape was investigated by a transmission electron microscope. This pioneer work clearly indicated that the major flux pinning centers in A15 phase were grain boundaries [5].

The multifilamentary V_3Ga wires stable under time varying fields were commercially fabricated from a composite of Cu–Ga alloy matrix containing 15–20 at.%Ga and V cores [6]. The composite was fabricated into a thin wire, and then heat treated at a temperature between 600–650 °C. In the heat treatment, Ga in the Cu–Ga alloy matrix selectively diffused into V, and only V_3Ga layers were formed around the V cores. Subsequently a systematic study on the *in situ* processed V_3Ga wire was performed [7]. Cu–V binary alloys with different composition where fabricated into thin wires and continuously coated with Ga, and finally heat treated at ~500 °C to form V_3Ga filaments. The *in situ* V_3Ga wire shows large critical current density (J_c) in the field range of 15–18 T, the non-Cu J_c at 17 T and 4.2 K being ~1000 A/mm^2 which is a several times larger than that of the bronze processed V_3Ga wire. No apparent research has been performed on V_3Ga after that, however, recently it is reconsidered for fusion application due to its much shorter decay time of induced radioactivity than Nb-based A15 compounds [8]. The fabrication of V_3Ga wires through a new powder-in-tube (PIT) process using high Ga content Cu–Ga compound powders has been initiated [9].

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3. Nb_3Sn conductors

3.1. Bronze processed conductors

The Cu addition to Sn is effective for the promotion of Nb_3Sn layer synthesis as in the case of V_3Ga. Then multifilamentary Nb_3Sn wires were fabricated from the composite of Nb and Cu–Sn bronze matrix. The addition of a small amount of Ti to the bronze matrix was found to enhance significantly both the B_{c2} and the formation rate of Nb_3Sn layer [3]. This procedure does not introduce complexity or additional cost in the conductor fabrication. Table 1 indicates the relation between amount of Ti addition to the bronze and the amount of Ti in the Nb_3Sn layer and other properties of the Nb_3Sn [10]. Ti added to the bronze is quite easily incorporated into the Nb_3Sn layer. Critical temperature T_c shows a small peak at 0.2 at.%Ti addition, and then decreases. B_{c2} increases rapidly up to 0.35 at.%Ti addition and then gradually decreases. Normal state resistivity ρ_n value also increases sensitively with increasing amount of Ti in the Nb_3Sn layer. B_{c2} may be enhanced by the increase of ρ_n, and then decreases by the reduction in T_c.

Recently performance of $(Nb,Ti)_3Sn$ strands has been appreciably improved by the increase of Sn concentration in the bronze as indicated in Fig. 1 [11]. The Sn concentration in the bronze was increased from 13 wt% to 16 wt% over the past decade, the solubility of Sn in bronze being 15.8 wt%. Fig. 2 illustrates an example of the cross-section and the specification of recent Ti-bronze multifilamentary Nb_3Sn conductor [12]. The bronze contains 15.5 wt%Sn and 0.3 wt%Ti. The diameter and the number of Nb–1 wt%Ta filaments are 3.0 μm and 11,077, respectively. Both the J_c and the hysteresis loss Q_h of the conductor satisfy the new ITER conductor specification.

Nb_3Sn wires for AC use were also developed through the bronze process. The simultaneous addition of a small amount of Ta to Nb filaments and Ge to the matrix is effective in reducing the hysteresis loss in the bronze processed Nb_3Sn wires. Fig. 3 shows the reduction in the diameter of Nb_3Sn filaments and the enhancement of AC performance in the bronze processed Nb_3Sn wire. The Q_h of the wire is reduced to $\sim$1 kJ/m^3 at ±2 T. A 50 mm bore 2 T magnet wound by the Nb_3Sn wire via the react and wind process has been successfully operated at 53 Hz and 4.2 K [13]. The mechanical tol-

Table 1
Ti concentration in Nb_3Sn, B_{c2} (4.2 K), and ρ_n value for quoted Nb/Cu–Sn–Ti composite wires reacted at 750 °C for 100 h

Wire (at.%)	T_c(K)	Ti content in Nb_3Sn (at.%)	Bc2 (4.2 K) (T)	ρ_n (μΩm)
Nb/Cu–7Sn	17.2	0	19.5	0.08
Nb/Cu–7Sn–0.2Ti	17.7	1.05	25.1	0.21
Nb/Cu–7Sn–0.35Ti	17.5	1.6	26.4	0.33
Nb/Cu–7Sn–0.5Ti	16.2	2.71	26.1	0.41
Nb/Cu–7Sn–1.0Ti	15.6	3.65	24.8	0.55
Nb/Cu–7Sn–1.5Ti	15.2	3.92	24.2	0.58

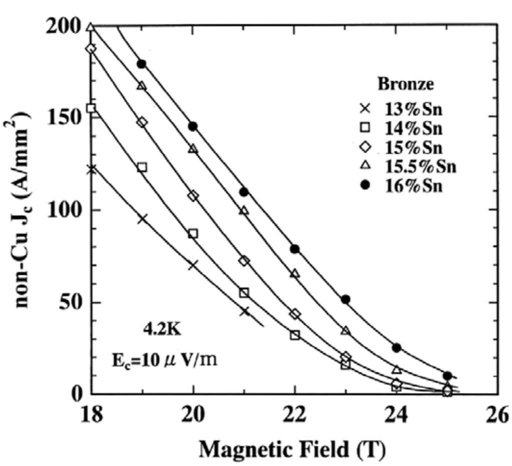


Fig. 1. *Non-Cu* J_c versus magnetic field curves of bronze processed $(Nb,Ti)_3Sn$ wires with quoted amount of Sn in the bronze. Ti concentration in the bronze is 0.3 wt% [11].

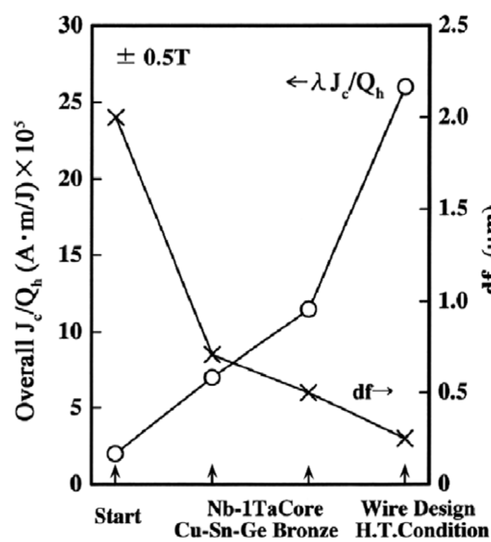
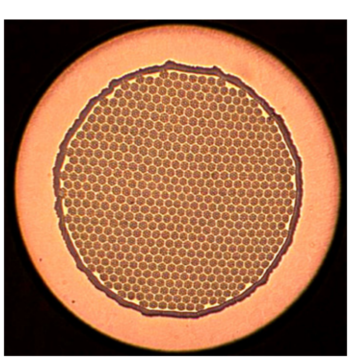


Fig. 3. Reduction in filament diameter d_f and enhancement in overall J_c/hysteresis loss Q_h value of bronze processed Nb_3Sn wire for AC use.



Wire diam. (with Cr plating)	0.826 mm
Twist pitch	15.0 mm
Bronze composition (wt%)	Cu-15.5 Sn-0.3Ti
Filament composition (wt%)	Nb-1.0 Ta
Filament diameter	3.0 μm
No. Filament	19×583=11,077
Cu/non Cu ratio	1.0
Barrier material	Nb
non Cu J_c @ 12 T, 4.2 K	820 A/mm^2
n-value @ 12 T, 4.2 K	30.0
Hysteresis loss @ ± 3 T, 4.2	620kJ/m^3

Fig. 2. Cross-section and specification of the bronze processed $(Nb,Ti)_3Sn$ conductor [12].