The new route process of $V_3Ga$ mono-cored and multifilamentary wires using high Ga content Cu-Ga compound and V matrix precursor

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Abstract. $V_3Ga$ compound is one of the attractive low activation materials for high magnetic field superconducting magnet in the several V-based compounds because V-based superconducting materials have shorter decay time of induced radioactivity and high field property above 20 T. $V_3Ga$ compound has not only high upper critical magnetic fields ($H_{c2}$) above 20 T as well as Nb3Sn but also better mechanical property. However, the present critical current density ($J_c$) property of $V_3Ga$ compound wire is insufficiency to apply for large high field magnet such as fusion application. In the previous study, $V_3Ga$ compound wire was mainly investigated “Diffusion process” between Cu-Ga solid solution matrix within 20 at% Ga composition and V filament. Recently, we investigated the new route PIT process using high Ga content Cu-Ga compound to fabricate $V_3Ga$ mono-cored and multifilamentary wires in order to increase a volume fraction of synthesized A15 phase. It was confirmed that the thicker $V_3Ga$ layer formed along the boundary of Cu-Ga powder core and V matrix compared with previous diffusion processed samples in the case of the both mono-cored and multifilamentary wires. And $H_{c2}$ property of the samples using high Ga content Cu-Ga compounds was increased with increasing of Ga content into Cu-Ga compounds, and it showed about 23.0 T which value was 2.0 T higher than conventional processed samples.

1. Introduction

The nuclear fusion reactor is the equipment which extracts thermal energy from the high energy neutron during fusion reaction. In the case of typical fusion reaction such as the D-T reaction between deuterium (D) and tritium (T), 14 MeV high energy neutrons are sure to be formed during fusion reaction. In the scenario of future fusion power plants, kinetic energy of 14 MeV neutrons is exchanged to thermal energy via blanket system and it uses to generate electrical energy. Recently, the International Thermonuclear Experimental Reactor (ITER) has been started as the first step to realize burning D-T plasma and power generation, so that we think that the future fusion development must be discussed with acceptance on the D-T reaction. In the magnetic confinement fusion reactor such as ITER, the large high field superconducting magnet is one of the main components to confine and keep steady-state D-T plasma during long time. Furthermore, the fusion reactor will have also many large
ports to connect with plasma heating and control devices such as Electron Cyclotron Heating (ECH), Ion Cyclotron Heating (ICH) and Neutral Beam Injection (NBI) and diagnostic equipment. Fusion neutron will be streamed and penetrated to superconducting magnet through these large ports with damping of neutron energy, and these neutron streaming and penetration quantities are estimated to be order of $10^{11}$ n/m²/s (>0.1MeV) in the ITER design [1]. The superconducting magnet system for an advanced fusion reactor will assume to operate in the harder neutron irradiation environment compared with the ITER project. In the feature, it is necessary to consider carefully not only superconducting property but also neutron irradiation property in superconducting materials using fusion reactor. Recently, the simulation results on the decay time of Nb and V based superconducting wires at the position of TF coils in ITER design were reported (Figure.1) [2]. The decay time of induced radioactivity in Nb-based compound superconducting wires required a longer cooling time above ten thousands years until the remote handling recycle level at the first wall heat load condition of 10 MW/m². The long-lived nuclide of $^{94}$Nb is formed from nuclear transformation of $^{93}$Nb, and half-life of niobium is estimated to be $2.0 \times 10^4$ years. On the other hands, the decay times of non Nb-system superconductors such as MgB$_2$ and V$_3$Ga compound which had high critical magnetic field ($H_{c2}$) above 20 T showed within 10 years. Therefore, V$_3$Ga compound superconducting wire will be desirable as the candidate material to realize “low activation and high magnetic field superconducting magnet” for an advanced fusion reactor.

In the previous study, V$_3$Ga compound wire was mainly investigated “Diffusion process” between Cu-Ga solid solution matrix within 20 at% Ga composition and V filament [3-4]. However, critical current density ($J_c$) property of V$_3$Ga wire was lower than Nb-based superconductors, and it was necessary to improve $J_c$ property of V$_3$Ga wire to realize “low activation superconducting magnet” for an advanced fusion reactor. We reconsidered the wire fabrication of V$_3$Ga mono-cored wire in order to improve $J_c$ property due to increase the volume fraction of synthesized A15 phase [5] and investigated the new route PIT process using higher Ga content Cu-Ga compound to fabricate V$_3$Ga multifilamentary wires shown to figure.2 in this paper. The superconducting properties and microstructure of V$_3$Ga multifilamentary wires using new route process based on the concept of figure.2 were mainly reported.

![Fig.1 The simulated results of the decay time of the various superconductor (Ref. 2).](image1)

![Fig.2 The concept of new wire fabrication process of V$_3$Ga using high Ga compound.](image2)
2. Sample procedure
The various high Ga content Cu-Ga compound ingots were made by the Tammann dissolution in Ar atmosphere using pure metal Cu foil (99.9%) and granular metal Ga (99.999%). The compositions of Cu-Ga compound ingots were 25, 30, 40, 50 and 64 at%Ga respectively. And then their ingots crushed and ground by hand-milling into coarse powders. The particle size of the high Ga content Cu-Ga compound powder was smaller with increasing of the Ga content into compound. The prepared Cu-Ga compounds were packed tightly into a high pure metal Vanadium (V) sheath tube having 10 mm outer diameter and 6 mm inner diameter. The precursor mono-cored wires were fabricated through the Powder-In-Tube (PIT) process. Wire drawings were carried out using grooved roller and cassette roller dies. The precursor mono-cored wires finally have 1.04 mm diameter. Moreover, we also fabricated to the V₃Ga multifilamentary wire. The part of mono-cored wire was cut into short pieces, and they were stacked into a V tube. The numbers of stacked mono-cored wires were 19, 55 and 121 pieces. These stacked composites were carried out wire drawing as well as mono-cored wire, and then multifilamentary wires also finally have 1.04 mm diameter. The intermediate annealing did not be required during these wire drawings. These mono-cored and multifilamentary wires were heat treated in a vacuum.

After the heat treatments, critical temperature ($T_c$) and the transport critical current ($I_c$) at 4.2 K were measured by using a DC four-probe method. $H_{c2}$ and $I_c(4.2K)$ measurements under high magnetic fields were carried out in Tsukuba Magnet Laboratory National Institute for Materials Science (NIMS). $J_c$ values were defined as the $I_c$ divided by the only cross-sectional area of diffusion layer and then they were so called “Layer $J_c$”. The microstructures of the samples were observed by using a scanning Electron microscope (SEM). Element mapping and quantitative composition analysis of V₃Ga phase were carried out using an energy dispersive x-ray (EDX) spectrometer.

3. Results and discussions

3.1. Microstructures of the V₃Ga mono-cored and multifilamentary wires

The V element distribution mapping and quantitative composition on the cross-sectional region of high Ga content Cu-Ga compound /V sheath mono-cored PIT wires sintered at 700°C for 100 h is

![Fig.3 The V element distribution mapping on the cross sectional area of several Ga content mono-cored wires.](image-url)
shown to figure 3. Figs 3 (a)-(c) are indicated 25, 30 and 40 at%Ga samples, respectively. The thickness of diffusion reaction layer was obtained to be about 20 μm, 40 μm and 50 μm, and then the increase of diffusion layer with increasing of Ga content was confirmed. This tendency was also observed in the multifilamentary wires, and we thought that the high Ga content into the precursor was suitable to increase easily the volume fraction of the V₃Ga phase. In the case of 25at%Ga and 30at%Ga, only V₃Ga single phase was formed along the boundary between Cu-Ga compound and V sheath. However, the formation of two phases was confirmed in the case of 40 at%Ga mono-cored sample. One was V₆Ga₅ phase which was formed about 30 μm along the Cu-Ga compound core side region, and the other was V₃Ga phase which was formed about 20 μm along the V₆Ga₅ phase. These suggested that the difference of phase formation was caused by the interposition of the liquid phase transformed from the Ga-rich CuGa₂ compound of above 40 at%Ga composition powder. However, no observation of secondary phase was clearly in the all composition multifilamentary wires because the Ga volume quantity per powder filament was decreased due to the size reduction by the multifilament. According to Cu-Ga binary phase diagram, the melting point of Cu-Ga compound is lowered with increasing of Ga content. In the heat treatment above 600°C, the all compositions of over 35 at%Ga have a coexistence region of liquid and solid phases. In the both 25at% and 30at%Ga mono-cored samples, forming of single V₃Ga phase might be caused by solid-solid phase reaction, and then Cu element into Cu-Ga compound and partial liquid phase promoted to the diffuse between Ga and V elements just like conventional “Bronze process”. In the 40at%Ga mono-cored sample, the V₆Ga₅ phase was probably formed preferentially due to supply excessive Ga component released from Ga-rich liquid phase, and then V₃Ga phase was formed by the diffusion reaction between V₆Ga₅ phase and V sheath. The other hands, the average Ga composition of V₆Ga₅ phase was obtained from 26.05 to 27.22 at%Ga, and these composition ratio were shifted to Ga-rich compared with the stoichometric composition (25 at%Ga). Especially, Ga composition of core side was higher than that of sheath side. This difference of Ga composition was originated from grain growth of V₃Ga phase due to supplying of excessive Ga content into V-Ga diffusion reaction and higher heat treatment temperature.

3.2. Tₖ properties and Jₛ-B performances of the V₃Ga multifilamentary wires

The Tₖ values of the samples using high Ga content Cu-Ga compounds were almost obtained to be 15 K, and these values were about 1 K higher than those of conventional processed samples. And then, Tₖ property was improved by the increase of Ga content of Cu-Ga compound. Figure 4 shows the
typical Layer $J_c$-B performances of the V$_3$Ga multifilamentary wires using various high Ga content Cu-Ga compounds. Layer $J_c$ properties were improved with increasing of Ga content of Cu-Ga compound, and optimum Ga content into Cu-Ga compound on the $J_c$ property was the 50 at%Ga composition. We found that Layer $J_c$ property was depended on the Ga content into Cu-Ga compound and improved easily by the high Ga content of the precursor wire, and typical Layer $J_c$ value was obtained to be over 300 A/mm$^2$ under the magnetic field of 20 T. These suggested that the V$_3$Ga wire was desirable as the candidate material to realize “low activation superconducting magnet” for advanced fusion reactor and PIT process using high Ga content Cu-Ga compound was promising as alternative method of conventional process.

3.3. $H_{c2}$ property of V$_3$Ga multifilamentary wires

The typical R (Resistance)- B (Magnetic Field) curves of samples using high Ga content Cu-Ga compound are shown to figure 5. This measurement was carried out with ramping of magnetic field. In this study, the normal transition from superconductivity was defined as decrease of 90% in the normal state resistance. The normal transition magnetic field was improved with increase of high Ga content of filament compound and its property was similar to the $J_c$-B performances shown to fig.4. In the case of fig.5, the maximum transition field was estimated to be above 22 T when used the 50 at%Ga composition powder. The $H_{c2}$ properties of the samples using high Ga content Cu-Ga compound based on the Kramer formula are shown to figure 6. The broken lines into the fig 6 were fitting lines calculated by the $J_c$ value in estimating the $I_c$ value with 200 mA and the normal transition magnetic field from the figure 5. Generally, it is well known that $H_{c2}$ value is defined to magnetic field which converges zero on the Kramer formula. The $H_{c2}$ value which was estimated by the Kramer formula and R-B property was also improved with increasing of the Ga content of the filament powder as well as Layer $J_c$-B properties shown to fig.4. We confirmed that $H_{c2}$ property was improved about 23 T by the high Ga content of the precursor and its value was about 2.0 T higher than that of conventional processed samples when used the 50 at%Ga composition powder. These suggested that optimum Ga content was 50 at%Ga in the viewpoints of the $J_c$-B and $H_{c2}$ properties. The other hands, it was reported that $T_c$ value was depended on Ga composition into V$_3$Ga phase and the optimum Ga composition was estimated to about 26 at% in the case of V$_3$Ga thin film [6]. It was suggested that $H_{c2}$ property of V$_3$Ga phase depended on Ga composition into the V$_3$Ga phase. From the results of EDX analysis, the average Ga compositions of V$_3$Ga phase in the 30, 40, 50 and 64 at%Ga multifilamentary
precursor wires were obtained to be about 26-27 at%Ga, and their values were shifted to the Ga-rich composition compared with the stoichometric composition (25at%Ga). We thought that the $H_{c2}$ improvement by the high Ga content Cu-Ga compound was mainly caused by the Ga-rich composition into the V$_3$Ga phase.

4. Conclusions
The PIT process using Cu-Ga compound was easier wire deformation than conventional process. The superconducting properties were improved by the using of high Ga content Cu-Ga compound, especially $H_{c2}$ property was improved about 23 T by the high Ga content of precursor and its value was about 2 T higher than that of conventional processed samples. We concluded that V$_3$Ga wire was desirable as the candidate material to realize “low activation superconducting magnet” for an advanced fusion reactor and PIT process using high Ga content Cu-Ga compound was promising as alternative method of conventional process.

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