Development of a Multifilament PIT V_3Ga Conductor for Fusion Applications

J. S. Distin, L. R. Motowidlo, P. J. Lee, D. C. Larbalestier, A. K. Ghosh, X. F. Lu, N. Cheggour, T. C. Stauffer, and L. F. Goodrich

***Abstract*—Previous studies on V_3Ga assert its suitability for use in proposed fusion reactors. V_3Ga may outperform Nb_3Sn in a fusion reactor environment based on its relatively flat critical-current profile in the 15 T–20 T range, resilience to applied strain, and reduced risk of induced radioactivity. A multifilament powder-in-tube V_3Ga conductor was designed, fabricated and tested with a focus on evaluating critical current versus applied field and applied strain performance, wire drawing difficulties, heat-treatment optimization, and overall feasibility of the concept.**

***Index Terms*—Fusion, ITER, PIT, V_3Ga.**

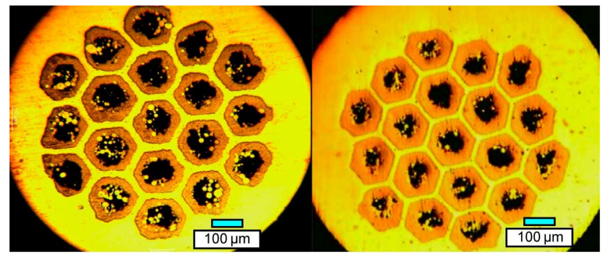

Fig. 1. Comparison of conductor designs before heat treatment. (a) is the preliminary design and (b) depicts the final, improved billet design with Nb barriers around each filament and a tighter s/D ratio.

I. INTRODUCTION

THE necessity of developing new types of energy generation and storage will intensify in the coming decades. The rapid increase in world population and the corresponding expanded reliance on fossil fuels will lead to a drastic global energy crisis within several generations if new energy sources are not established. The prospect of sustainable fusion technology has spurred projects like the International Thermonuclear Experimental Reactor (ITER), which may one day provide an environmentally friendly answer to growing energy problems.

Some of the most successful fusion experiments have used the "Tokamak Concept" for magnetic confinement of a hot ionized gas, or plasma [1]. In order to successfully confine the plasma, peak magnetic fields on the order of 12–13 T are required and can only be produced by magnets made of advanced superconductors such as Nb_3Sn [2]. Although Nb_3Sn is widely used in current research, V_3Ga exhibits properties that should prove indispensable as operational demands increase with advances in fusion technology [2], [3].

Recent studies have investigated the qualities of V_3Ga conductors [2]–[7]. The benefits of V_3Ga include a relatively flat profile of critical-current density (J_c) over the 12 T–20 T range as well as higher J_c values than those exhibited by Nb_3Sn from 15 T to 20 T. Also, V_3Ga has a better J_c to strain correlation. These characteristics may provide safer and more powerful fusion containment devices. Studies have also shown that Vanadium-based conductors should exhibit significantly less risk of induced radioactivity than Nb-based conductors when incorporated into fusion containment systems [2]. Developing a multifilament V_3Ga wire with the anticipated characteristics would greatly benefit the progress of experimental fusion reactor development.

In a previous study on mono-core V_3Ga powder-in-tube (PIT) conductors [3], Cu-Ga powders of 25 at.%, 30 at.%, and 40 at.% Ga content were used. The results of the investigation into high Ga content mono-core PIT conductors indicate that increasing the Ga content effectively improves the diffusion of Ga into the V sheath during heat treatments. However, with the highest Ga content powder, 40 at.%, an additional non-superconducting V_6Ga_5 layer was produced, greatly reducing the V_3Ga reaction area. It was apparent that optimized Ga content inside the PIT cores is between 30 at.% and 40 at.%. In this study, multifilament PIT conductors were fabricated using similar Cu-Ga powder variations: 25 wt.%, 30 wt.%, and 40 wt.%, each variation having slightly less Ga content than in the mono-core study. The wires were drawn to a diameter of 1 mm, heat treated, and submitted for microstructure and superconducting properties analysis.

II. WIRE DEVELOPMENT

In order to demonstrate the feasibility of a multifilament V_3Ga PIT conductor, a basic design was chosen to efficiently identify key manufacturing obstacles while verifying the anticipated benefits of the conductor. A basic 19-element hexagonal restack design was chosen for the preliminary billet design, pictured in Fig. 1(a).

The three different −635 mesh Cu-Ga powder mixtures were prepared via atomization by HJE Corporation via a proprietary

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L. R. Motowidlo and J. S. Distin are with SupraMagnetics, Inc., Plantsville, CT 06479 USA (e-mail: lmoto@cox.net; distin@ccsu.edu).

P. J. Lee and D. C. Larbalestier are with the Applied Superconductivity Center, NHFML, Tallahassee, FL 32310 USA.

A. K. Ghosh is with Brookhaven National Laboratory, Upton, NY 11973 USA.

X. F. Lu, N. Cheggour, T. C. Stauffer, and L. F. Goodrich are with the National Institute of Standards and Technology, Boulder, CO 80305 USA.

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TABLE I
ELEMENTAL ANALYSIS OF POWDER CORES

	60 wt.% Cu 40 wt.% Ga	**70 wt.% Cu 30 wt.% Ga**	**75 wt.% Cu 25 wt.% Ga**
Before heat treatment	61.6 wt.% Cu 38.4 wt.% Ga	71.75 wt.% Cu 28.24 wt.% Ga	77.35 wt.% Cu 22.64 wt.% Ga
650 C 100hrs	82.49 wt.% Cu 17.50 wt.% Ga	83.91 wt.% Cu 16.08 wt.% Ga	84.46 wt.% Cu 15.53 wt.% Ga
750 C 100 hrs	89.88 wt.% Cu 10.11 wt.% Ga	88.72 wt.% Cu 11.27 wt.% Ga	90.08 wt.% Cu 9.916 wt.% Ga

process. Analysis of the powders revealed particle sizes ranging from less than 5 μm to 20 μm in diameter, roughly spherical in shape.

As V tubing was not commercially available, it was fabricated by rolling high purity V foil into a cylindrical shape. The foil was inserted into Cu tubing and drawn through a series of dies to form Cu-clad V tubing. With this process, the V tube OD:ID (outer diameter/inner diameter) ratio could be carefully controlled. The S/d ratio (filament spacing divided by filament diameter) of the final restack assembly could also be affected by altering the thickness of the Cu tube used to fabricate the V tube assembly.

During the preliminary basic design study, 19-element hexagonal restacks of each of the Cu-Ga powder mixtures were assembled and drawn to a diameter of 1 mm. This was done to establish a baseline design from which key design elements could be improved and optimized. A second improved design was fabricated, focusing on optimizing the design using the results of the preliminary study as guidelines.

III. PRELIMINARY RESULTS

The three preliminary billets were fabricated using V tubes with 40% hole by area $(100 * (\text{V tube inner diameter})^2/(\text{V tube outer diameter})^2)$. This 40% hole was incorporated to maximize the amount of Cu-Ga powder introduced to the mono elements. The S/d ratio of the final multifilament billets was around 0.200. A depiction of the preliminary billet design is displayed in Fig. 1(a).

The preliminary design proved difficult to draw to 1 mm final wire size. The -635 mesh powders proved too coarse, and resulted in non-uniform filaments and wire breaks during the drawing process. Increasing the strength of the wire was a main requirement for further development. Short lengths at 1 mm were made, heat treated and sent for microstructure analysis.

Perhaps most important in this phase was determining the effect of the varying Ga contents on the extent and quality of the V_3Ga reaction layers. Samples were heat treated at 650 C and 750 C for 100 hours. An elemental analysis of the filament cores before and after heat treatments is recorded in Table I. Analysis of the reaction areas are listed in Table II. The reaction areas were sampled halfway between the inner and outer boundaries of the reaction layer.

As expected, higher Ga contents in the powder cores resulted in greater Ga diffusion into the V tubing (Table I). This is in agreement with previous studies [3]. Reaction depths ranged

TABLE II
ANALYSIS OF REACTION AREA (650 C, 100 HOURS)

	60 wt.% Cu 40 wt.% Ga	**70 wt.% Cu 30 wt.% Ga**	**75 wt.% Cu 25 wt.% Ga**
At. % V	72.409 %	73.859 %	73.389 %
At. % Ga	26.573 %	24.688 %	25.000 %
At. % Cu	1. 19 0 %	1.474 %	1.611 %

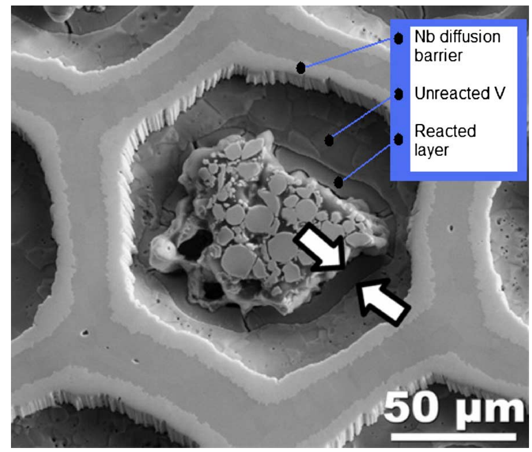

Fig. 2. Magnified cross section of the improved wire design. Filament degradation in the form of pitting and non-uniformity of the filament inner diameter is apparent due to the coarseness of the powders. Arrows indicate A15 reaction layer.

from 3–5 μm for the 25 wt.% Ga design to around 10–15 μm in the 40 wt.% Ga design for samples heat treated at 650 C, 100 hours. Analysis of the reaction layer indicates roughly a 3:1 V:Ga atomic ratio, confirming the presence of V_3Ga (Table II). In the 40 wt.% Ga design, there was no clear evidence of a V_6Ga_5 phase, which may be due to the slightly reduced Ga content as compared to the 40 at.% powder used in the previous mono-core study [3].

IV. IMPROVED DESIGN RESULTS

The results of the preliminary wire design indicated that improving the strength and uniformity of the filaments at final wire size was crucial for demonstrating a successful conductor. The key problem in wire drawability was the coarseness of the Cu-Ga powder. As finer powder was not immediately available, the improved wire design included mono elements with thicker V walls. The V tubes were drawn through dies to reduce the hole area to about 20% before packing with Cu-Ga powder. Although this measure did not allow for optimum powder content in the filaments, it was necessary for increasing the strength and drawability of the wire. Also, a Nb diffusion barrier was incorporated around the V tubes (this layer was included in the hole percentage calculation). The S/d ratio of the new restack billet was trimmed to about 0.110 to improve filament uniformity. The improved wire design is depicted in Fig. 1(b).

Although the best reaction area observed in the preliminary wire designs was obtained using the 40 wt.% Ga powder, there was still concern over the possibility of an unwanted V_6Ga_5 phase developing in the improved wire design. The 30 wt.% Ga powder was selected for the improved wire design in an effort to

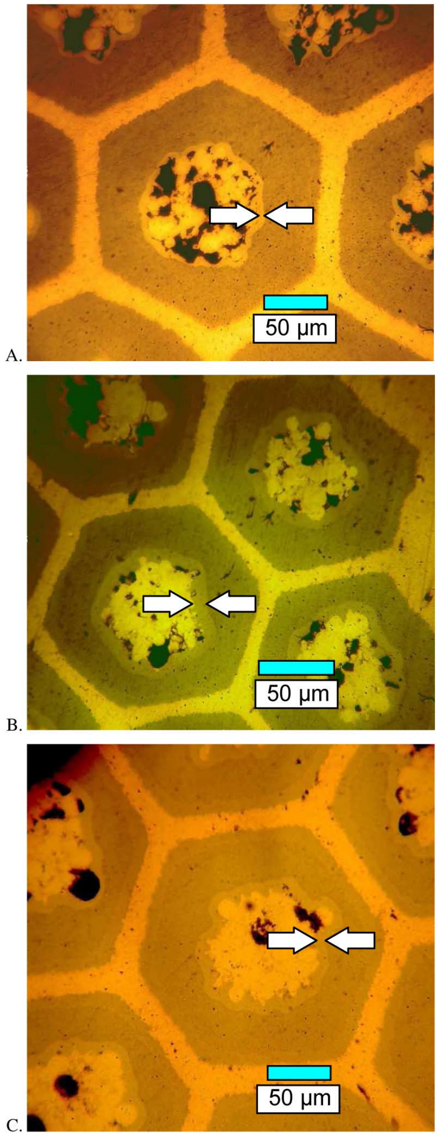

Fig. 3. Results of various heat treatments on the improved wire design V_3Ga reaction layer. (a and b) show samples treated at 610 C for 120 hours and 700 C for 100 hours respectively. (c) depicts a sample treated at 610 C for 330 hours, with an expanded reaction area as compared to Fig. 3(a). Arrows indicate relative A15 reaction layer thicknesses.

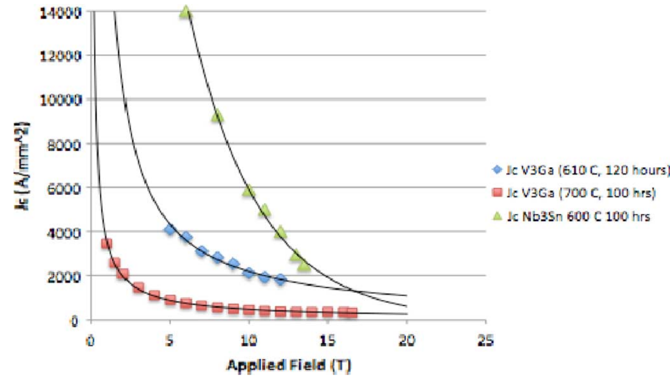

Fig. 4. Intrinsic Jc vs. applied field for two samples of the improved wire design with different heat treatments and a Nb3Sn 120 octagonal restack by SupraMagnetics (measurements taken at 4.2 K) [9]. Jc values were determined by transport measurements.

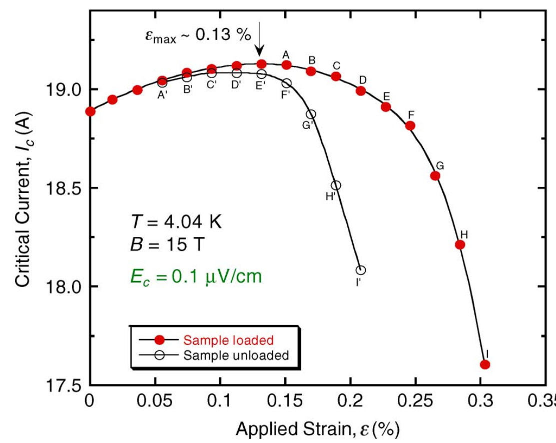

Fig. 5. Critical current vs. applied strain of the final wire design treated at 700 C for 100 hours. The sample's poor strain resilience is possibly due to the coarseness of the Cu-Ga core powder.

avoid this unwanted phase. A small amount of aluminum nanopowder (about 4 at.%) was also incorporated into the powder core of the improved wire design. A previous study has indicated that a 2 to 5 at.% Al content in the Cu-Ga powder can benefit the Ga diffusion during heat treatment [8].

The improved wire design drew to a diameter of 1 mm with more uniform filaments. The wire also suffered less breakage during the drawing process. Although far from perfected, the design had been greatly improved and can be further improved by reducing the Cu-Ga powder particle size (Fig. 2).

The improved wire design was heat treated for 120 hours at 610 C and 100 hours at 700 C. These samples are pictured in Fig. 3 (Figs. 3(a) and 3(b) respectively). Critical current measurements at various fields were made for both heat-treated samples. A plot of intrinsic J_c vs. applied field for both wire samples as well as a Nb_3Sn PIT sample by SupraMagnetics [9] is displayed in Fig. 4. The intrinsic J_c is the critical current divided by the average cross sectional area of the A15 reaction layer. Reaction areas were measured using high resolution digital microscope images and area analysis software. The data set for the 610 C sample has a more limited range of applied fields. The curve fit has been applied conservatively.

Although the reacted area resulting from the 610 C, 120 hour heat treatment is dramatically smaller than the reaction area in the 700 C sample, the intrinsic J_c is significantly higher in the 610 C sample. Both improved design data sets in Fig. 4 suggest a relatively flat J_c profile in the 10 T–18 T range; verifying one of the key anticipated benefits of a V_3Ga conductor over Nb_3Sn.

Fig. 5 indicates the critical current dependence on applied axial tensile strain of the final wire design heat treated at 700 C for 100 hours. Strain measurements were made by use of a CuBe Walters' spring apparatus [10]. The plots show that an irreversible behavior of J_c vs. strain starts soon after the peak is reached, indicating that the irreversible strain limit is very small. Although this is in contrast to the anticipated benefit of high resilience to applied strain in V_3Ga conductors, the failure of the sample in this capacity may be due to the coarseness of the powders used as well as the poor quality of the reaction area as indicated in Fig. 3. Samples treated at lower temperatures for longer periods may prove to exhibit greater resilience to applied strain.

Fig. 3(c). displays an image (bottom) of the improved design version of the wire treated at 610 C for 330 hours. This final heat treatment was performed in an attempt to improve the extent of the reaction area while maintaining the intrinsic J_c of the sample when treated at 610 C for 120 hours. The visibly larger reaction area suggests that by adjusting the heat treatment parameters, the conductor could be improved even with imperfect powder and filament quality. Measurements on this sample are underway.

In Fig. 4 the intrinsic J_c vs. applied field of the two $\mathrm{V_3Ga}$ heat treated samples (610 C, 700 C) are compared with the intrinsic J_c of a SupraMagnetics PIT $\mathrm{Nb_3Sn}$ sample [9]. The curve fits suggest that the 610 C sample may exhibit a higher intrinsic J_c than $\mathrm{Nb_3Sn}$ in the 18 T–20 T range. This comparison is further evidence that with improvements in Cu-Ga powder quality, mono element design (increasing the hole size to allow for increased Ga content), and heat treatment procedure, a superior multifilament PIT $\mathrm{V_3Ga}$ may be possible.

V. Conclusion

Studies have shown that $\mathrm{V_3Ga}$ has the potential to support future fusion technology [2], [3]. Providing a high performance multifilament PIT $\mathrm{V_3Ga}$ conductor may help foster the development of these future technologies. This investigation into the feasibility of such an endeavor has offered a glimpse into the effectiveness of $\mathrm{V_3Ga}$. More importantly, we have determined critical design modifications that may lead to conductor improvement.

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