Characteristics of Cu Stabilized Nb_3Al Strands with Low Cu Ratio

A. Kikuchi, R. Yamada, E. Barzi, M. Kobayashi, M. Lamm, K. Nakagawa, K. Sasaki, T. Takeuchi, D. Turrioni, and A. V. Zlobin

***Abstract*—Characteristics of recently developed F4-Nb_3Al strand with low Cu ratio are described. The overall J_c of the Nb_3Al strand could be easily increased by decreasing of the Cu ratio. Although the quench of a pulse-like voltage generation is usually observed in superconducting unstable conductor, the F4 strand with a low Cu ratio of 0.61 exhibited an ordinary critical transition of gradual voltage generation. The F4 strand does not have magnetic instabilities at 4.2 K because of the tantalum interfilament matrix. The overall J_c of the F4 strand achieved was 80-85 % of the RRP strand. In the large mechanical stress above 100 MPa, the overall J_c of the F4 strand might be comparable to that of high J_c RRP-Nb_3Sn strands. The Rutherford cable with a high packing factor of 86.5 % has been fabricated using F4 strands. The small racetrack magnet, SR07, was also fabricated by a 14 m F4 cable. The quench current, I_q, of SR07 were obtained 22.4 kA at 4.5 K and 25.2 kA at 2.2 K. The tantalum matrix Nb_3Al strands are promising for the application of super-cooled high-field magnets as well as 4.2 K operation magnets.**

***Index Terms*— Nb_3Al strand, copper stabilizer, magnetization, Rutherford cable, small racetrack magnet.**

I. Introduction

ONE kilometer-long copper stabilized RHQT (rapid heating/quenching and transformation) processed Nb_3Al strands can be fabricated with reel to reel ion-plating and electroplating at the National Institute for Materials Science, NIMS [1], [2]. Mechanical rolling test of the Nb_3Al strand does not show critical current degradation or separation of the copper stabilizer. There are no apparent merged filaments as a result of cabling, and the *RRR* value does not degrade like the internal-tin Nb_3Sn strands [3]. The Nb_3Al strand does not exhibit tin leakage. Using both a tantalum interfilament matrix and a strand twist pitch of about 45 mm apparently improved the magnetic stability at low fields at 4.2 K [3]. In addition, the RHQT-processed Nb_3Al strand exhibits a relatively small sensitivity to both axial and transverse stress [3], [4]. Therefore, these recent results with Nb_3Al strands are highly encouraging for the development of Rutherford cable for future accelerator magnet application. Feasibility studies for the high field Nb_3Al accelerator magnet are being done at Fermilab and KEK with a cooperation of NIMS [5]-[8]. However, it is desirable to improve its critical current density, J_c, which is somewhat lower than that of recent internal-tin Nb_3Sn strands.

So far, the usual Cu ratio has been 1.0 for the F1- and F3-Nb_3Al strands. The reduction of Cu ratio is an easy way to increase the overall J_c. In this paper, a tantalum matrix Nb_3Al strand F4 with the low Cu ratio of about 0.61 was demonstrated, and its critical current and magnetic stability were investigated. In addition, Rutherford cable and a small racetrack magnet (SR07) using the F4-Nb_3Al strand were fabricated and tested at Fermilab [9].

II. Characteristics of F4-Nb_3Al Strand

Fig. 1 shows the cross section of (a) the F1 strand with niobium matrix and (b) the F4 strand with tantalum matrix. Their Cu ratios are 1.0 and 0.61, respectively. The copper stabilizer for F4 strand was fabricated by the reel to reel electroplating with a high velocity of 7 m/h, which is 3.5 times faster than that for the F1 strand. The F4 strand shows good bonding with the electroplated copper because of the copper ion-plating in high vacuum. Table I shows the specifications of the F1 and F4 strands.

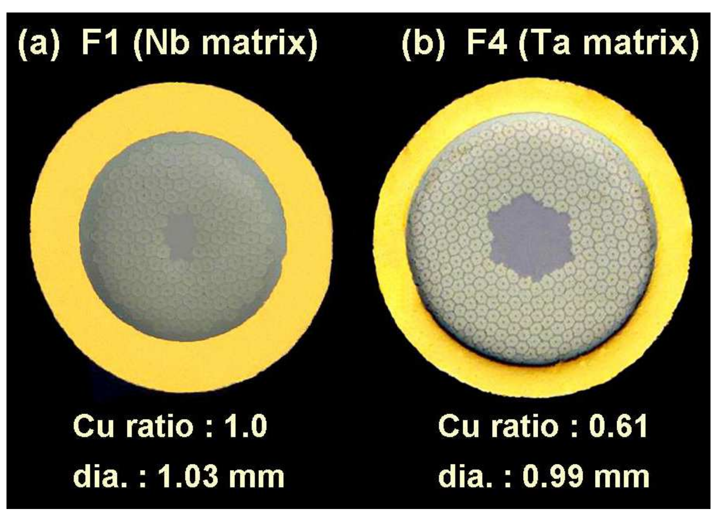

Fig. 1. A cross section of (a) F1- and (b) F4- Nb_3Al strands, which were used for SR04 and SR07 magnets, respectively.

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TABLE I
SPECIFICATIONS OF Nb_3Al ROUND STRANDS

Strand ID	F1	F4
Strand Dia. (with Cu)	1.03 mm	1.00 mm
Strand Dia. (w/o Cu)	0.72 mm	0.78 mm
Number of Jelly-Rolled (JR) Filament	144	276
Physical JR Filament Dia.	50 µm	35.8 µm
Cu/non-Cu ratio	1.0	0.61
Interfilament Matrix	Niobium	Tantalum
Central Core of JR Filament	Niobium	Tantalum
Central Dummy Filament	Niobium	Tantalum
Outermost Matrix	Niobium	Niobium
Area Reduction (AR)	71.6 %	65.3 %
Cu Ion Plating Velocity	120 m/h	120 m/h
Cu Electroplating Velocity	2 m/h	7 m/h

In Fig. 2 are shown the voltage versus transport current curves for F4 round strand as a function of external fields. The I_c measurements were performed in liquid helium (4.2 K) with applied transverse magnetic fields up to 15 T. Ti-6Al-4V barrels were used for the sample holder. The I_c were determined by a common resistivity criterion of 10^{-14} Ωm at the overall cross-sectional area for the 750 mm distance between the voltage taps. Although the quench of a pulse-like voltage generation is usually observed in unstable superconductor, the F4 strand with a low Cu ratio of 0.61 showed ordinary critical transitions through gradual voltage generation. Fig. 3 shows the comparison of I_c as a function of applied magnetic field for F1 and F4 strands. The I_c (4.2 K, 12 T) of F4 strand is approx. 10 % larger than that of F1 strand. However, the non Cu J_c of F4 strand is slightly lower, possibly caused by the different rapid heating/quenching conditions. Table II is the summary of major performances of F1 and F4 strands.

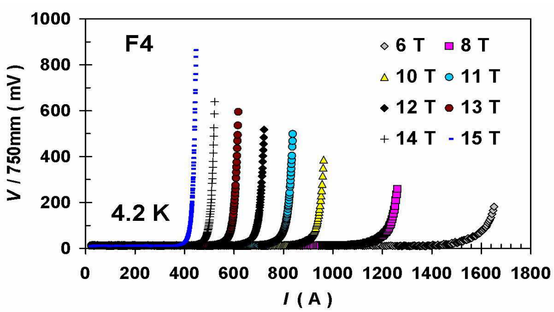

Fig. 2. The voltage versus current curves at 4.2 K as a function of external fields for the F4-Nb_3Al round strand with a low Cu ratio of 0.61.

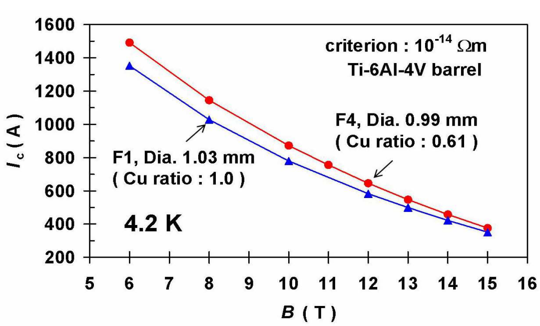

TABLE II
MAJOR PERFORMANCES OF Nb_3Al ROUND STRANDS

Strand ID	F1	F4
I_c (4.2 K, 12 T)	582.9 A	645.9 A
I_c (4.2 K, 15 T)	351.5 A	376.5 A
non-Cu J_c (4.2 K,12 T)	1,400 A/mm^2	1,352 A/mm^2
non-Cu J_c (4.2 K, 15 T)	844.2 A/mm^2	788.3 A/mm^2
n value (4.2 K, 12 T)	40.3	40.0
n value (4.2 K, 15 T)	35.5	34.3
RRR (300K/20K)	150-200	150-250

Fig. 3. Magnetic field dependence of I_c at 4.2 K of F1 and F4 strands.

The magnetization tests for the F4 strand were performed by using a balanced coil magnetometer [10]. The results are shown in Fig 4 (a) for the low field region from 0 T to 3 T, and (b) for the high field region from 10 T to 13 T. The F4 strand was right-hand twisted with a twist pitch of 45 mm. Due to an interfilament coupling through the niobium matrix, the F1 strand showed very large magnetic flux jumps at low fields around 1.5 T [3]. The F4 strand does not show an abnormal magnetization at 4.2 K because of the tantalum matrix. The effective filament diameter, D_{eff}, was calculated by the Bean model, and determined by the magnetization, ΔM, at 12 T as shown in Fig. 4 (b). A D_{eff} of 42.8 µm was obtained.

Fig. 5 (a) shows the magnetic field dependence of the overall residual resistivity, ρ, at 20 K and 300 K, for F4 strand with an electroplated copper and the typical NbTi strand with oxygen-free copper (OFC) matrix. Their *RRR* values (300 K/20 K) shown in Fig. 5 (b) were calculated from the data of Fig. 5 (a). The *RRR* of F4 strand in low fields are apparently higher than those of NbTi, which indicates that the electroplated copper has excellent high quality more than OFC. *RRR* values of both strands decrease gradually with increasing the external fields through the effect of the magnetoresistance.

The F4 strand showed good stability characteristics by avoiding interfilament coupling by the tantalum matrix, small D_{eff} of 42.8 µm and high quality of the electroplated copper stabilizer, even though it has a small Cu ratio of 0.61.

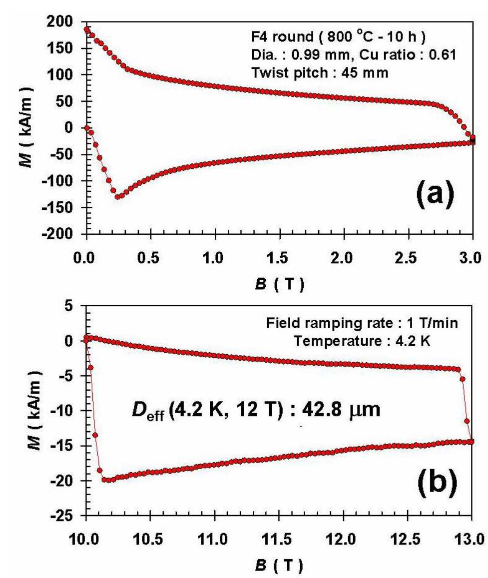

Fig. 4. The magnetization curves of F4 strand at 4.2 K between (a) 0 T and 3 T and (b) 10 T and 13 T.

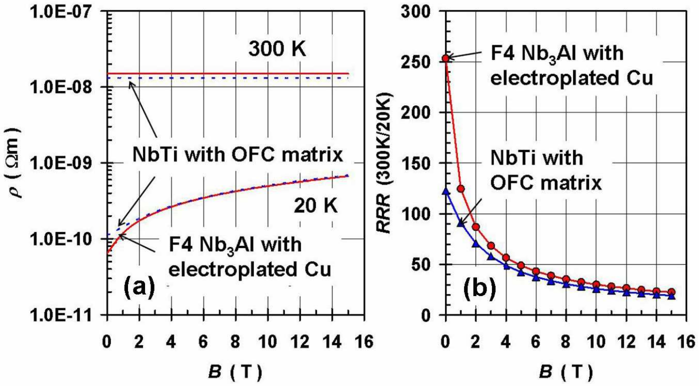

Fig. 5. Magnetoresistance of the F4 strand with an electroplated Cu and the typical NbTi strand with OFC matrix. (a) Overall residual resistivity and (b) RRR (300 K/20 K) as a function of applied magnetic fields.

III. Rutherford Cable and Small Racetrack Magnet

The Nb_3Al strand cabling studies are being done through a collaboration between NIMS and Fermilab. Using F1 strand, we have made a rectangular 27 strand Rutherford cable with a low packing factor of 82.5 %. The F1 cable is 14.17 mm wide, 1.99 mm thick, and has a 15 degree lay angle. The F1 strands at the edges of the cables show a small void occasionally, due to copper separation, as shown in Fig. 6 (a). (Notice the strand with a void at the lower right corner.) Recently, we have made a rectangular 28 strand Rutherford cable with a high packing factor of 86.5 % by using F4 strands. The F4 cable was 13.95 mm wide, 1.85 mm thick, and has a 15 degree lay angle. Because of the improvement of the ion-plating conditions, there was much less copper separation with recent F4 cable, as shown in Fig. 6 (b).

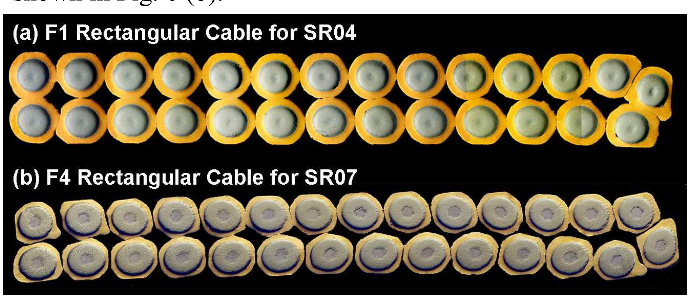

Fig. 6. Cross-sections of (a) a 27 F1 strand rectangular Rutherford cable with a low packing factor 82.5 % and (b) a 28 F4 strand rectangular Rutherford cable with a high packing factor 86.5 %.

The small racetrack magnets, SR04 and SR07, were fabricated from 14 m long pieces of F1 and F4 cables, respectively. The cables were insulated with ceramic tape, and wound into a double-layer racetrack in the same direction. Pictures of SR04 and SR07 are shown in Fig. 7 (a) and (b). Both magnets were heat-treated in Ar gas flow in a two-step cycle (500^{o}C/5 h, 800 ^{o}C/15 h) recorded by type K thermocouples. The extracted strands taken from F1 and F4 cables were also heat-treated as witness samples. The magnets after the heat treatment were impregnated with CTD101K epoxy.

Fig. 8 shows the overall J_c for the F1 and F4 extracted strands. The results of the RRP internal-tin extracted strands taken from SR03 cable is also shown for a comparison [11]. The overall J_c of both F1 and F4 extracted strands are lower

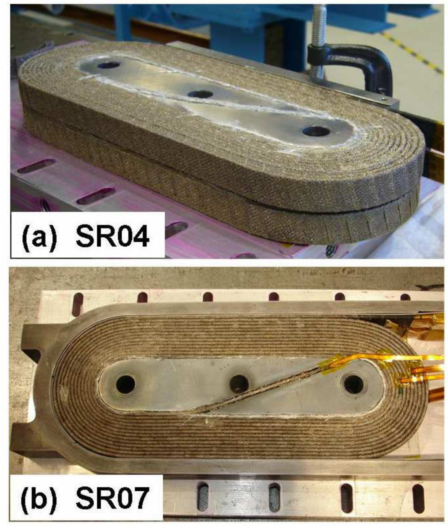

Fig. 7. Pictures of (a) SR04 and (b) SR07 before epoxy impregnations. Both magnets are the double-layer racetrack designed

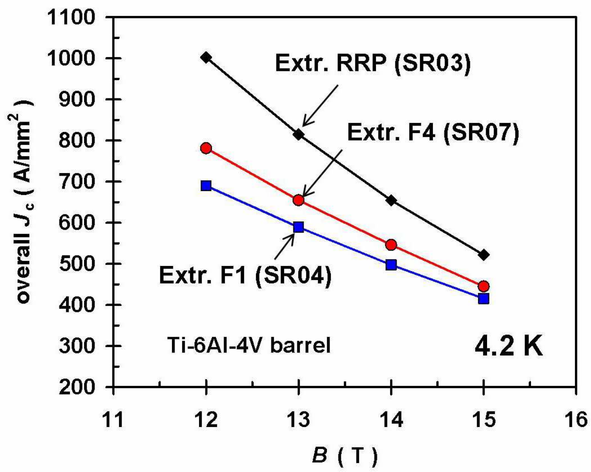

Fig. 8. The overall J_c for the extracted strands taken from F1- and F4-Nb_3Al, and RRP-Nb_3Sn cables [11]. Those cables were used for small racetrack magnets of SR04, SR07 and SR03, respectively.

than that of the RRP extracted strand. However, due to the reduction of Cu ratio, the overall J_c of the F4-Nb_3Al strand have achieved to 80-85 % of the RRP-Nb_3Sn strand. The RRP strands are showing more than 20% J_c degradations under 100 MPa of transverse pressure [12], and the Nb_3Al strands are not showing apparently [3]. For the overall J_c as well as the engineering J_c under the large mechanical stress, the Nb_3Al strands might be comparable to the high J_c RRP-Nb_3Sn strands. Furthermore, both F1 and F4 strands, the J_c degradations by the cabling were less than 5 %. The Nb_3Al strand shows no apparent merged filaments, because the filaments are a quite hard Nb-Al supersaturated solid solution alloy. The internal-tin strands, in particular located at the edge of the cables usually have merged filaments, and show tin leakage sometime. For the future application in magnets, there will be very serious problems. Therefore the Nb_3Al strand has another big advantage for the high field accelerator magnet applications in addition to its excellent strain tolerance.

Fig. 9 shows the maximum quench current, I_q of SR04 and SR07. The magnets were tested in liquid helium at 4.5 K and 2.2 K. The I_q of SR07 achieved 22.4 kA and 25.2 kA at 4.5 K and 2.2 K, respectively. The current was limited due to heating in the test Dewar power leads. If there were no heating of the copper power lead, we estimate the ultimate maximum quench values of the SR07 were at 24.5 kA and 27.0 kA at 4.5 K and 2.2 K, respectively, i.e. almost the short sample limit, determined from extracted witness sample. The detailed descriptions of the test results of SR07 are reported in [9]. The I_q of SR04 decreased by decreasing cooling temperature. Those were 21.4 kA and 16.3 kA at 4.5 K and 2.2 K, respectively. The D_{eff} of F1 strand for SR04 is much larger than that of F4 strand for SR07 [3]. In addition, F1 strand has been made with niobium matrix, which shows much strong superconductivity in low temperature of 2.2 K. The niobium matrix enhances interfilament couplings, which introduces a strong magnetic instability for F1 strand. On the other hand, the I_q of SR07 was remarkably increased by decreasing cooling temperature. This result indicates that the tantalum matrix F4 strand seems to keep a good magnetic stability at 2.2 K. Therefore, the tantalum matrix Nb_3Al strand is promising for the application of the super-cooled high-field magnets as well as 4.2 K operation magnets.

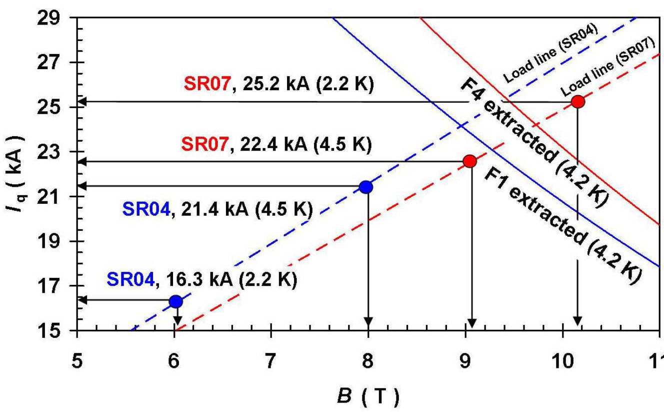

Fig. 9. Short sample limits at 4.2 K for SR04 and SR07. The achieved quench current, I_q, at 4.5 K and 2.2 K were plotted, respectively.

IV. Conclusions

The main results of this study are summarized as follows.

(1) The overall J_c of the Nb_3Al strand could be easily increased by decreasing the Cu ratio. Although the quench of a pulse-like voltage generation is usually observed with a unstable superconductor, the F4 strand with a low Cu ratio of 0.61 exhibited the ordinary critical transition of gradual voltage generation.

(2) The F4 strand does not show the magnetic instability at 4.2 K and at lower temperature, because of the tantalum interfilament matrix. The effective filament diameter, D_{eff}, was 42.8 μm.

(3) The overall J_c of the F4-Nb_3Al strand was 80-85 % of the RRP strand. For the overall J_c as well as the engineering J_c under the large mechanical stress of above 100 MPa, the Nb_3Al strands might be comparable to the high J_c RRP-Nb_3Sn strands.

(4) A rectangular 28 strand Rutherford cable with high packing factor of 86.5 % has been fabricated using F4 strands. The small racetrack magnet, SR07, was also fabricated by a 14 m long F4 cable. The J_c degradation of F4 strand by the cabling was less than 5 %.

(5) The achieved I_q of SR07 is 22.5 kA and 25.2 kA at 4.5 K and 2.1 K, respectively. The tantalum matrix Nb_3Al strand is promising for the application of the super-cooled high-field magnets as well as 4.2 K operation magnets.

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