Strongly enhanced critical current density in Nb 47 wt.% Ti having a highly aligned microstructure

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The transport critical current density increased from 2610 to 5200 A/mm² at 5 T, 4.2 K, when a round monofilament Nb 47 wt. % Ti composite was rolled to an aspect ratio of 9.7 and was tested with the broad face of the tape parallel to the field. This value exceeds the previous maximum of 3700 A/mm² by about 50%. Transmission electron micrographs show that more than 90% of the α -Ti precipitates in the optimum-rolled filament are aligned within 10° of the broad face of the tape, whereas the precipitates had a random azimuthal orientation prior to rolling. The strong alignment caused the elementary pinning force to be greatly enhanced in the parallel-field orientation; however, in the orthogonal orientation the J_c fell to low values characteristic of conventional wires having no α -Ti flux pinning centers.

Calculations of the elementary pinning force (f_p) produced by α -Ti precipitates in Nb-Ti composites indicate that the maximum pinning critical current density (J_c) should be about 18000 A/mm² at the benchmark field and temperature of 5 T, 4.2 K. This value is almost five times higher than the highest values yet measured, which are near 3700 A/mm².^{2,3} This relatively poor experimental performance could have several causes. For example, flux pinning calculations are seldom accurate to factors of 2 or 3. Also, the size, spacing, and volume fraction of α -Ti may not be optimum, and in round wires there is no preferential alignment of the α -Ti ribbons with the vortices. In this letter we address particularly the latter point by comparing a high J_c round wire with randomly oriented precipitates to a tape having highly aligned precipitates. Earlier, Meingast and Larbalestier⁴ had proposed that only 50% of the precipitates, namely, those whose orientation is more parallel to the field than perpendicular, were effective at pinning fluxons. This was demonstrated by the good agreement found between the specific pinning force,⁵ $Q_p = F_p/N_p\lambda$, and f_p over a wide range of precipitate density (N_p) and bulk pinning force (F_p), when the efficiency factor (λ) was taken to be 0.5. F_p can indeed be made stronger and the J_c increased by refining the α -Ti precipitate structure by cold work,⁶ where

$$F_p = N_p \lambda \cdot f_p \quad (1)$$

J_c has been found to increase in direct proportion to the volume fraction of precipitate⁷ in Nb 46.5 wt. % Ti, where λ is not changed. Record J_c values should be obtained for about 30 vol.% of precipitate. Unfortunately, this level of precipitation cannot be achieved in an alloy with overall composition Nb 46.5 wt. % Ti.

However, the efficiency factor should be strongly enhanced in aligned microstructures. Such alignments have been inferred from enhancements in J_c when the broad face of the tape was parallel to the field for rolled wires.^{8,9} Our own studies¹⁰ indicated that a 5–10% increase in the parallel field J_c occurred after slightly rolling final-size Nb-Ti monofilament composites. Encouraging as these results

were, the J_c never exceeded the best values obtained in round wires. In the present experiment, we modified our previous attempts by beginning the rolling process at a strain of about 1.5 less than that of the optimum round wire, so that a greater aspect ratio could be achieved. We were able to increase the J_c (5 T) from 2610 to 5200 A/mm², at an aspect ratio (filament width to thickness) of 9.73. This result is the first which exceeds 4000 A/mm² in a Nb-Ti composite.

A round Nb 47 wt. % Ti monofilament composite with a Nb diffusion barrier was given three heat treatments of 80 h at 420 °C beginning after a prestrain of 9. Strains of 1.15 were inserted between heat treatments. Very high J_c values had previously been achieved by using such a heat treatment schedule.² After the third heat treatment, a final strain (ϵ_f) of 4.17 was given before the composite was separated into two pieces. The first (control) piece was drawn further to an ϵ_f of 5.7, while the second piece was rolled to various aspect ratios up to 12.1. The rolled-filament data are presented in Table I.

The transport critical current (I_c) was measured for the samples in both groups by the standard technique¹¹ using a resistivity criterion of 10^{-14} Ω m. The transport J_c (J_{ct}) was then determined by $J_{ct} = I_c/A$, where A was the cross-sectional area of Nb-Ti. The round wire demonstrated an increase in J_{ct} (5 T) with increasing ϵ_f from 2610 to 3130 A/mm² for $\epsilon_f = 5.55$. A much stronger increase in J_{ct} (5 T) was observed in the tapes, up to 5200 A/mm² for an aspect ratio of 9.73; the tapes were tested with their broad faces parallel to the magnetic field. Figure 1 shows the J_{ct} values as a function of aspect ratio for the rolled samples, at fields of 2, 5, and 8 T. Additionally, the J_c in the orthogonal field orientation, J_{cl} , was measured, along with $J_{c||}$, using a vibrating sample magnetometer (VSM). The Bean model was used to calculate J_c from the width of the magnetization hysteresis. For the 10.9:1 tape, J_{cl} was approximately 286 A/mm², at 4.25 K, which is less than 1/13 of the measured $J_{c||}$ (3810 A/mm² at 4.28 K) for the same sample.

The microstructure of a round filament in transverse

TABLE I. Mean filament thickness, cross-sectional area, aspect ratio, and transport critical current density (at 5 T, 4.2 K) for the rolled monofilament samples. The aspect ratio of 1.0 corresponds to the round wire prior to rolling ($\epsilon_f = 4.17$).

Thickness (mm)	Area (mm ²)	Aspect ratio	J_{c_i} (A/mm ²)
0.153	0.0188	1.00	2610
0.129	0.0192	1.16	2760
0.102	0.0188	1.81	3090
0.083	0.0186	2.67	3230
0.062	0.0175	4.57	3880
0.046	0.0164	7.82	4880
0.040	0.0152	9.73	5200
0.037	0.0150	10.9	4390
0.035	0.0147	12.1	4080

cross section, immediately prior to rolling (at $\epsilon_f = 4.17$), is illustrated in Fig. 2(a). Folded α -Ti ribbons (the lighter features) represent roughly 20% of the cross-sectional area, a value which is similar to that of other Nb 47 wt. % Ti composites having had a similar heat treatment schedule.¹² At this relatively low final strain the α -Ti ribbons are somewhat thicker (1.5–12 nm) than for a fully optimized wire (0.6–4 nm).^{4,6,13} There are already clusters, in which the α -Ti ribbons are parallel and closely spaced, but the ribbon spacing in the clusters is typically 5–15 nm, as compared to less than 5 nm in a fully optimized microstructure.^{4,6,13}

In Fig. 2(b), a transmission electron microscopy (TEM) view of a transverse cross section of the highest J_{c_i} , 9.73:1 tape is shown. More than 90% of the α -Ti ribbons are aligned within $\pm 10^\circ$ of the broad face of the tape. In addition to the strong alignment, it should be noted that the average ribbon thickness (~ 1.5 nm) and spacing (~ 6 nm) is much closer to that of an optimized filament,^{4,6,13}

FIG. 1. Transport critical current density as a function of filament aspect ratio for the rolled monofilaments. The aspect ratio of 1.0 represents the round wire prior to rolling ($\epsilon_f = 4.17$).

FIG. 2. Bright field TEM images in transverse cross-section of (a) the composite prior to rolling, and (b) after rolling to an aspect ratio of 9.73. In these images the lighter phase (due to its relatively lower atomic number) is the "normal" α -Ti precipitate, the intermediate contrast regions are the β -NbTi superconducting matrix, and the very dark regions are strongly diffracting areas close to the β -110 pole.

although there is still a large variation in precipitate thickness (0.6–12 nm).

We believe that a major contribution to the marked increase in J_{c_i} as a function of filament aspect ratio is an increase in λ . From the TEM results λ should be about 0.9 for the rolled filament having the highest J_{c_i} . Using Eq. (1), the ratio of the best tape J_{c_i} (5200 A/mm²) to the best wire J_{c_i} (3130 A/mm²) indicates that λ increased from 0.5 to 0.84, assuming that the density of pins is the same in both cases. However, since the area reduction is increased at a faster rate by drawing than it is by rolling, it is likely that N_p is higher in the round samples, and λ would then be closer to the value indicated by the TEM results.

The calculated maximum pinning force mentioned in the opening paragraph was evaluated by estimating the maximum amount of nonsuperconducting metal which could be placed in a superconductor, such that the maximum pinning force is obtained with minimum depletion of

the order parameter within the superconductor by the proximity effect. This was estimated to be about 40 vol %.¹ In our experiment, however, only 20% of the filament is composed of α -Ti ribbons, which are spaced by 0.3–0.6 a_0 (the fluxon lattice constant) at 5 T. Thus, we should be able to realize only about 30% of the maximum J_c , ~ 5400 A/mm². This number is very close to the maximum J_{c_i} measured.

The VSM experiment verifies that the precipitate alignment does indeed occur throughout the entire rolled-filament cross section. Since J_{c1} is on the order of the J_c measured for nonheat-treated Nb 47 wt. % Ti composites,¹⁴ the pinning by the precipitates is ineffective in this orientation. This suggests that the maximum benefit obtainable by rolling has been achieved. Also, the observed anisotropy in J_c is greater than that observed in a Nb 50 wt. % Ti monofilament composite by Best *et al.*,⁸ but the general dependence of J_c on filament aspect ratio, in both orientations, is in agreement with their results.

In summary, J_{c_i} with the field parallel to the broad face of the tape increased from 2610 to 5200 A/mm² at 5 T, 4.2 K when a round monofilament Nb 47 wt. % Ti composite was rolled to an aspect ratio of 9.73. The high J_{c_i} values were achieved by aligning the α -Ti precipitates with the broad faces of the filament and the field. This alignment increases the efficiency with which the fluxons are pinned (in parallel field) from 0.5 to about 0.9, whereby F_p is increased. The enhancement in parallel field occurred at

the expense of pinning in perpendicular field, where J_{c1} fell to the level of a Nb-Ti composite without heat treatment, and J_{c1}/J_{c1} exceeded 13. These high J_c results are the first which exceed 4000 A/mm² at 5 T, 4.2 K.

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