Mechanical Treatments at Room Temperature of Nb_3Sn Practical Wires: Pre-torsion for Wires with a Different Architecture

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***Abstract* - Room temperature mechanical treatment consisting of multiple torsion loadings (named pre-torsion) was applied to short samples of Nb_3Sn composite wires with different architecture to reduce thermal residual compressive strain experienced by the superconducting Nb_3Sn filaments. Due to this effect all investigated wires have shown enhancement of the critical current density, I_c up to 56% at 15T and 4.2K. Enhancement of I_c was larger for the reinforced wires than for the wires without reinforcement suggesting that reinforcement is useful in strain relaxation during pre-torsion. The best results were obtained when the position of the reinforcement was located in the outer region of the wire. Pre-torsion is similar or more efficient than cycles of bending loadings (named pre-bending). For pre-torsion, important parameter is the rotation angle per length of the wire and optimum conditions for short wires are valid for long wires. Nonuniformity of I_c along the length of a 0.99 m wire after pre-torsion was minimal, within uncertainty of I_c measurement.**

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I. INTRODUCTION

Practical Nb_3Sn wires are fabricated at temperatures higher than 600°C while they should operate at low temperatures. In such composite materials, the difference in thermal contraction of the components generates a residual compressive state of Nb_3Sn filaments, which deteriorates the superconducting characteristics. Mechanical treatments of the wires at room temperature were proposed to solve this issue. Ochiai et al. applied loading-unloading cycles of tensile type [1], Awaji et al applied cycles of bending [2] and recently Badica *et al.* demonstrated cycles of torsion and of complex mechanical treatments [3]. All these mechanical treatments are performed at room temperature and are aiming at obtaining strain/stress states as close as possible to the stress/strain free ones and, hence, at improving superconducting properties toward maximum theoretical limits. They are named “pre-loading” mechanical treatments since they are applied before coil winding and we shall use terms pre-tensile, pre-bending and pre-torsion. The idea of these treatments is to realize a controlled deformation of the plastic components of the wire so that strain of the Nb_3Sn filaments is relaxed and their breakage is avoided.

In this article we present our comparative results of critical current behaviour in wires with different architecture submitted to pre-torsion. Three types of wires were selected; with and without reinforcement. Pre-torsion was also applied to a longer wire to check I_c-uniformity along the length of the wire and the reliability of pre-torsion as a preliminary step for further industrial processing.

II. WIRE SAMPLES AND EXPERIMENTAL PROCEDURE

Six practical Nb_3Sn wires were used in our experiments. Cross sections and specifications of the wires are shown in Figure 1 and Table 1 respectively. Wires are of three architecture types, A, B, C. Wire of type A, denoted US-J (US-Japan standard wire) has no reinforcement and filaments are not twisted.

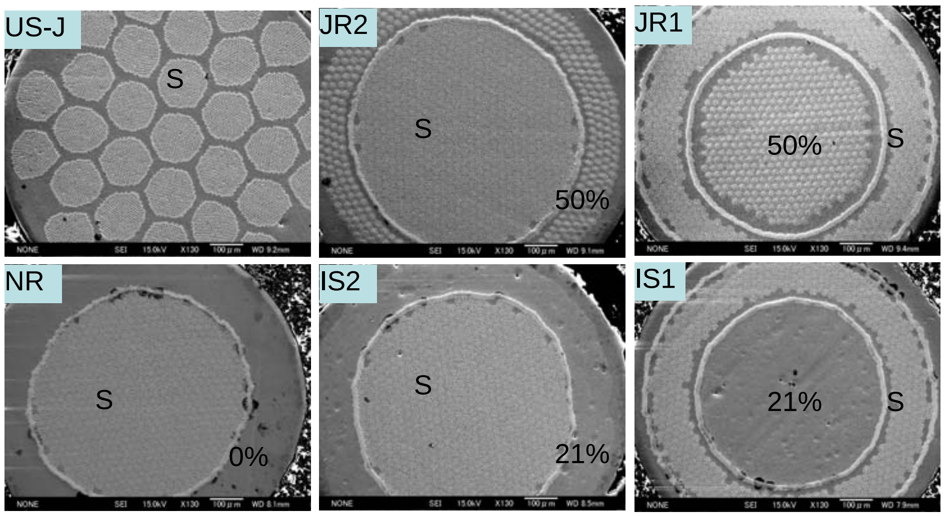

Fig: 1. SEM images of the cross section view of the Nb_3Sn wires (see notation in Table 1). S indicates the regions with Nb_3Sn superconducting filaments and % is the amount of Nb in the CuNb reinforced regions.

Wires of type B have filaments located at the center and reinforcement tube is present in the outer region of the wire, as for NR, JR2 and IS2. In type C, Nb_3Sn filaments are in the outer region (JR1 and IS1), while reinforcement is at the center (inner) of the wire. We should also note that reinforcement for IS-wires was obtained by in-situ process and for JR wires through the jelly-roll method.

Pre-torsion cycles were applied manually and at room temperature. Sample was fixed at one end in a conventional press (Riken Seiki Co. Ltd) at 2.4MPa shown in Figure 2. Before that, the free end was deformed in the press using the same pressure. For a wire with length of 30 mm, alternate rotations in one and opposite direction were performed with an angle φ of 12, 24, 48, 60, 75 and 90°. The total number of rotations was 15; this number was selected based on our previous results [3] showing that above this number strain relaxation and, hence, I_c saturates due to work hardening of the plastic components (mainly Cu).

After mechanical treatment, endings were cut and the current-voltage (I-V) curves in magnetic fields of 14 to18T (generated by a He-cooled 18T JASTEC magnet installed at HFLSM, Institute for Materials Research, Tohoku University) were measured at 4.2 K by the standard four-point method. The distance between voltage contacts was 5 mm and I_c was determined using the criterion of 1μV/10 mm.

Table 1. Wire Description

Wire	(A)-type US-J	(B)-type NR	IS2	JR2	(C)-type IS1	JR1
Bronze	Cu-13.2wt.%Sn-0.3wt.%Ti	Cu-14%wt.Sn-0.2wt.%Ti	Cu-14wt.%Sn-0.2wt.%Ti	Cu-14%wt.Sn-0.2wt.%Ti	Cu-14%wt.Sn-0.2wt.%Ti	Cu-14%wt.Sn-0.2wt.%Ti
Barrier	Nb	Nb	Nb	Nb	Nb	Nb
Reinforcement	-	Cu	Cu-21%vol.Nb	Cu-50vol%Nb	Cu-21vol%Nb	Cu-50vol%Nb
Reinforcement position	-	outer	outer	outer	inner	inner
Wire diameter (mm)	1.06	1	1	1	1	1
Filament diameter (μm)	3.8	3.3	3.3	3.3	3.3	3.3
No. of filaments	361x31= 11191	11457	10167	11457	9690	9690
Pitch of twisted Nb3Sn filam. (mm)	-	30±3	30±3	30±3	30±3	30±3
Cu / reinf. mater / supercond. (%)	46.2 / - / 53.7	52/-/48	20.7/34.5/44.8	20.2/31.8/48	17.3/31.2/51.5	15.8/33.3/50.9
Final heat treatment	645°C/200h	670°C/96h	670°C/96h	670°C/96h	670°C/96h	670°C/96h
Fabricated by	Hitachi Cable	Furukawa Electric Co. Ltd.	Furukawa Electric Co. Ltd.	Furukawa Electric Co. Ltd.	Furukawa Electric Co. Ltd.	Furukawa Electric Co. Ltd.

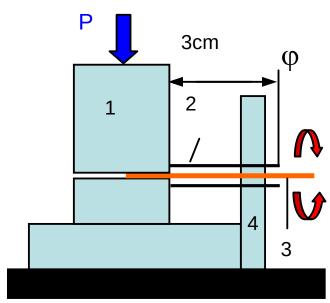

Fig 2. Experimental arrangement for pre-torsion: 1- press, 2- guiding quartz tube, 3- Nb3Sn wire, 4- holder-plate with indications of rotation angle φ; P = pressing pressure = 2.4MPa.

III. RESULTS AND DISCUSSION

Plots of critical current *versus* magnetic field are shown in Figure 3. To easily visualize the differences between the wires, in Figure 4 are presented the curves of I_c and reduced critical current $I_c/I_c(\varphi=0°)$ as a function of pre-torsion angle φ at 15T. In all wires tested pre-torsion resulted in some I_c enhancement .

Both wires without reinforcement, US-J and NR are showing the lowest enhancement of I_c by pre-torsion (Fig. 4b), although they have different architecture, A and B respectively.

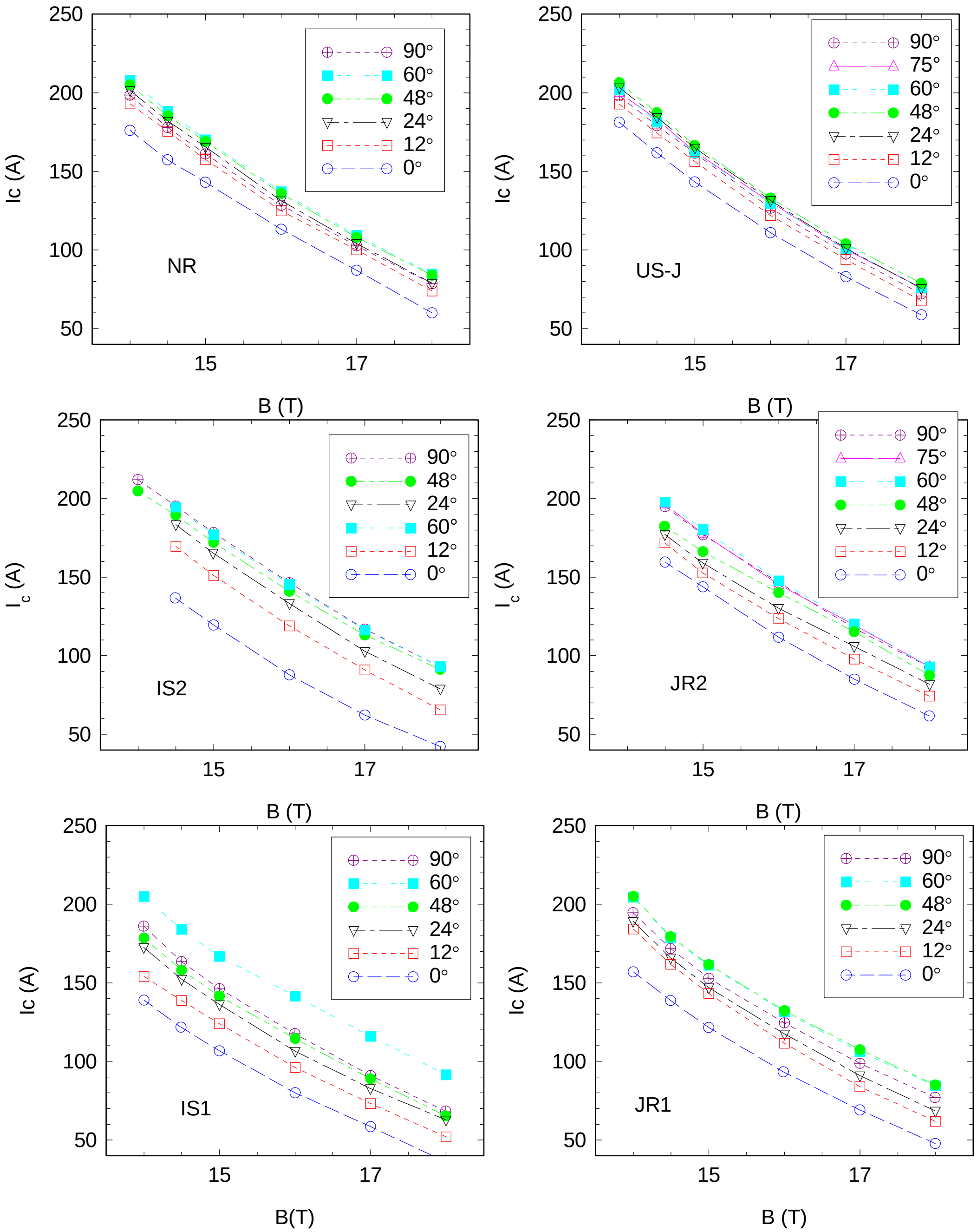

Fig 3. Critical current I_c *versus* magnetic field for different wires after pre-torsion.

This result suggests that reinforcement is useful in relaxing thermal residual strain through the pre-torsion processing. A similar conclusion was obtained when pre-bending was applied [4]. The two wires without reinforcement, NR and US-J reach the maximum I_c for φ = 48° and this angle is smaller than for all the other wires (I_{cmax} for φ=60°). This effect is analogous to that observed for pre-bending [4], where the maximum I_c is obtained at an applied pre-bending strain of ε_{pb} of 0.5% for US-J, 0.8% for NR and 0.8% or 1% for all the other wires.

Another similarity with the results for the pre-bent wires is that the largest enhancement of I_c calculated using the formula $[(I_{c\ max} - I_{c\ as\text{-}reacted})/I_{c\ as\text{-}reacted}]$ is for the IS1 wire. However, there is one difference: the enhancement at 15T is larger for pre-torsion (56%) than for pre-bending (43.5%). We emphasize that for all the wires investigated in this work, pre-torsion leads to similar or better results than pre-bending. The reason for such behaviour is that depending on how the mechanical treatments are applied, it is 1D for pre-tensile, 2D for pre-bending and 3D for pre-torsion one can expect different relaxation patterns of the residual strain (and hence of the critical current) in terms of distribution and absolute value [3]. The implication is that mechanical treatments should develop a strain-free state, ideally with zero-strain for all the Nb_3Sn filaments in the composite wire and in all 3 directions.

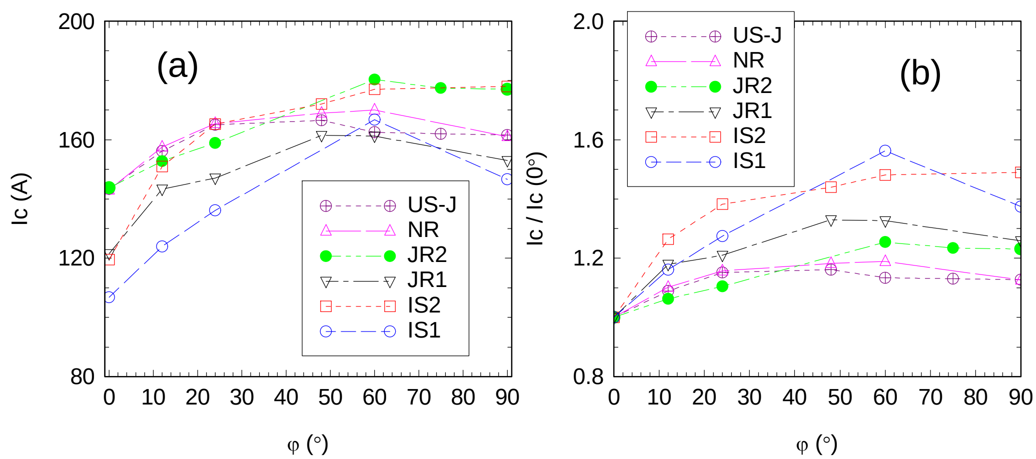

Fig 4. (a) Critical current I_c and (b) reduced critical current $Ic/Ic(0°)$ *versus* pre-torsion angle φ.

The maximum values of I_c for the reinforced wires depend on the architecture of the wires: wires JR2 and IS2 are showing almost the same values for $I_{c\ max}$ (Fig. 4a) and these values are the highest among the investigated reinforced wires. Such comparison is possible considering that for the reinforced wires superconducting region accounts for roughly 50% and wires of (B) type are sort of anti-symmetrical wires of (C) type (see Fig. 1 and Table 1). A similar result was obtained for pre-bending. We thus conclude that mechanically treated wires with reinforcement located in the outer region of the wires (JR2 and IS2) are new and promising candidates for fabrication of react-and-wind magnet coils.

One of the limitations to applying mechanical treatments is the formation of cracks and their evolution. This is closely related with critical current decay [5]. For our samples submitted to pre-torsion at high angles φ>60°, I_c decay occurs, but it is not as large as for the pre-bending at high ε_{pb}>1% [4, 5]. If so, pre-torsion causes lesser irreversible cracks formation during mechanical treatment of the wire. This hypothesis needs further experimental confirmation. The difficulty is that I_c decay at φ > 60°cannot be determined precisely, because at the wire's fixed end the pressing load acts as a stress concentrator. Therefore, wires can break easily at this point rather than relax uniformly the residual strain, as for smaller angles of pre-torsion.

Uniformity of strain relaxation along the length of the wire during pre-torsion is important for future industrial application of this treatment. Therefore, a US-J wire of length L = 990 mm was submitted to alternate rotations. For a short US-J -wire sample of length l = 30 mm we have already determined that the optimum φ is 48° (Figs. 3 and 4). For the long wire we applied alternate rotation with an angle φ_{long}=($\varphi_{optimum}$ for 30 mm x L / l)=1584°. After pre-torsion, the wire was cut into short samples of 30 mm and *I-V* curves of selected samples were measured as described in Section II. The running length coordinates of these samples were 0-30, 210-240, 480-510, 710-740 and 960-990 mm from the fixed end. Figure 5 shows that I_c scattering along the length of the wire is about ±2.1A that is approximately the same as the measurement uncertainty. Hence, it can be considered that I_c is constant with running L of the wire after pre-torsion. This also indicates that pre-torsion can be successfully applied for long wires: the I_c for the long wire after pre-torsion is higher than for the as-reacted sample and it is at the same level as in analogous short samples (see Table 2). The key parameter is the pre-torsion angle per unit length φ/L. The results of I_c optimisation by pre-torsion of short wires can be easily extrapolated to long wires.

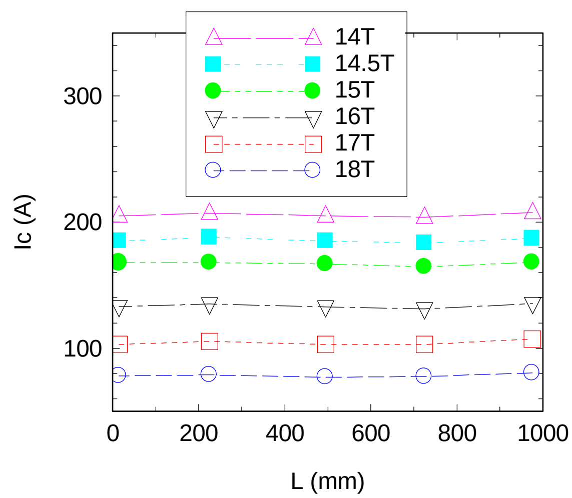

Fig 5. Critical current I_c along the length, L, of the US-J wire after pre-torsion processing.

Table 2 Values of I_c, for US-J wire: as-reacted sample, and short and long samples after pre-torsion.

Magnetic field (T)	As-reacted wire, I_c (A)	Short sample after pre-torsion ($\varphi_{optimum}$=48°), I_c (A)	Long sample after pre-torsion measured on piece" 0-30"mm, I_c (A)
14	181,2	206.5	205
14,5	161,8	187.2	185
15	143,3	166.5	168
16	111	133	133
17	83	104	103
18	58,7	78.8	78

IV. SUMMARY

In summary, pre-torsion treatment was applied to wires with a different architecture. Reinforcement of the wire can play a positive role in strain relaxation during pre-torsion treatment. For all the wires, the enhancement of I_c is at the same level or higher than for the case when pre-bending is applied. Pre-torsion is shown to produce the same positive results for long samples as for short ones if the rotation angle per unit length is maintained constant. Along the length of the 990 mm long wire, I_c scattering was low. The best results were obtained for the wires with outer reinforcement.

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