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Enhancement of critical current density in superconducting wires NbTi

Abstract. *The research that was done has proven that it is possible to enhancement J_c in NbTi wires, by means of cold drawing of the wire (wire drawing machine). We believe that it is a vital piece of information particularly for those institutions that possess NbTi wires and superconducting NbTi magnets. Cold drawing of the wire does not decrease critical temperature and critical magnetic field of the wire.*

Streszczenie*. W artykule przedstawimy wyniki pomiarów J_c w drucie NbTi. Otrzymane rezultaty udowodniły iż za pomocą zimnego przeciągania można zwiększyć J_c w drutach NbTi. Przeprowadzone pomiary udowodniły także że zimne przeciąganie nie zmniejsza parametrów krytycznych drutu NbTi: temperatury krytycznej T_c i krytycznego pola magnetycznego B_{c2}.. Analiza siły pinningu, analiza Kramera i skalowanie siły pinningu pozwoliły określić źródło regeneracji i zwiększenia J_c i F_p.* ***(Zwiększenie krytycznej gęstości prądu w nadprzewodnikowym drucie NbTi)***

Keywords: NbTi, critical current
Słowa kluczowe: NbTi, prąd krytyczny.

Introduction

After a long-term use of the NbTi wires, they begin to lose their parameters, such as: J_c. As far as J_c of superconducting NbTi wires is concerned, it depends mainly on the following factors: grains size, grains boundary, the number, shape and thickness of αTi precipitations, grains elongation, the homogeneity of both the copper matrix and the superconducting material, the size of the filament, arrangement of filaments and the distance between them, the distance between the grains separation and α Ti precipitations, defects, dislocations, doping and also on the inter- grain connections and the volume of β NbTi phase [4,10].

In NbTi wires the magnitude of J_c depends on parameters of αTi precipitations. The α Ti precipitations appear as a result of annealing, yet, the very process of annealing makes α Ti precipitations very big and thick (200 nm and 800 nm wide) [6]. In order to obtain a good pinning centre, α Ti precipitations need to have the same magnitude as the thick of coherence i.e. 5 nm or less [9,10]. The rapid temperature change causes the following: material degradation, cracks and voids in the structure, shifts and dissipation of defects. By means of the cold drawing process it is possible to repair the aforementioned factors that had been lost or damaged. In numerous articles [3,5,6] authors have proven that the cold drawing of NbTi wires significantly influences the α Ti precipitations, namely, it decreases their thickness (1-5 nm), increases their length [8,9], alters their shape from ellipsoidal into a strip, changes their arrangement toward the flow of current, decreases the distance of α Ti separations (3-6mm), and it also enlarges the coiling and bending of the ribbons of αTi precipitations [4].

In the following articles [4,6] authors have described the influence of cold drawing on the change of grain size of NbTi. NbTi grains become elongated towards the drawing axis due to the cold drawing process. In the article [2] the influence of low angle cold drawing on the filament's parameters of a multifilament wire is presented. J_c of the current in a superconducting filament depends on several aspects, such as: filament diameter, number of filaments, length and direction of the twist, material homogenity in the filament, distance between filaments, filament transposition and distribution of filaments. The biggest influence on J_c in a wire has the very diameter of the filament. However, the diameter of the filament generates both the hysteresis loop and residual magnetization, which highly decrease J_c. In order to reduce their influence on J_c it is advisable to obtain filaments of the smallest possible diameter [1].

In the following articles [8,11] authors proved that the cold drawing made the dislocations. They deduced that dislocations increase J_c in high magnetic field.

The obtained samples

The measurements were performed for the multifilament NbTi wire type SKNT which possessed 8910 filaments, the filament's diameter equaled 6 μm and the wire's diameter was 0.9 mm. The NbTi wire was composed of Ti (66 wt % Ti) and Nb (34 wt % Nb), the samples were obtained via the cold drawing process with the use of a drawing machine. As a result of this drawing 6 samples have been obtained with the following diameters: 0.85 mm, 0.8 mm, 0.75 mm, 0.70 mm, 0.65 mm, 0.60 mm, 0.5 mm.

Table.1. Samples

Sample number	Diameter [mm]	Number of drawing pre sample	comments
1	0,85	0	The current I_c measurements were made when the wire was produced in 1999
2	0,85	0	The current I_c measurements were made in 2010
3	0,8	1	cold drawing
4	0,75	2	cold drawing
5	0,7	3	cold drawing
6	0,65	4	cold drawing
7	0,6	5	cold drawing
8	0,5	6	cold drawing

The wire cross section area reduction during the process of cold drawing equaled from 12 % to 18 % for all the samples. The drawing angle for all the samples was 18 degrees except for the sample of 0.65 mm where the angle equaled 12 degrees. The reduction of the wire diameter was 0.05 mm per pass.

Measurements

Critical current measurements were made for all the samples in the temperature of 4.2K. They were made with a constant current supply or in a constant magnetic field. The voltage drop was measured by means of a four-probe resistive method with the 1μV/cm criterion. For the two samples 0.85 mm and 0.5 mm the following measurements were made: the critical temperature was measured with the use of transport (physical property measurement system - PPMS) and magnetic method (VSM), hysteresis loop was measured by means of a vibratory magnetometer (vibrating sample magnetometer - VSM) and photos of cross section and longitudinal section were taken by SEM microscope.

Results and discussion

Even though we know that the process of cold drawing would increase J_c and F_p in high magnetic fields, we did not expect that the increase would be so considerable [11]. Eventually, J_c and F_p in high magnetic fields increased by 28 % (Figures 1 and 2) [3].

The obtained measurements have proven that cold drawing of the NbTi SKNT 8910 wire influences neither the critical temperature nor critical magnetic field. Measurements which were made via magnetic and transport methods have shown that critical temperature of 0,9mm sample and 0,5mm sample is nearly the same and equals respectively 9,2K for transport measurements and 9,1K for magnetic measurements (Figures 3 and 4).

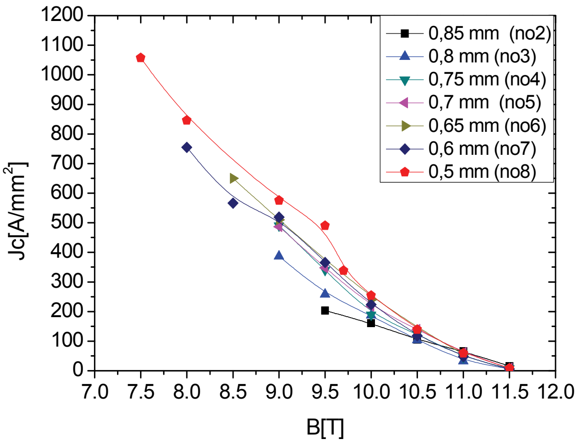

Fig. 1. Critical current density dependence on magnetic field

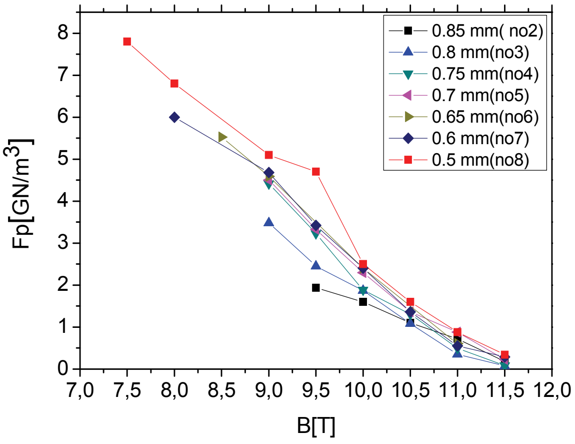

Fig. 2. Pinning force dependence on magnetic field

Yet, measurements that were made with the use of VSM in the temperatures 4.2K have shown that B_{c1} and B_{c2} in 0.85mm sample and in 0.5mm sample are the same and equal B_{c1} - 0,0015T and B_{c2} - 12T (Fig.5). Photos of wires cross section taken by SEM have shown the change of the filaments diameters. Namely, the diameters decreased by 30%-60% (fig.6 and fig.7). The decrease of filaments diameter not only enhances filaments cooling, but it also increases J_c.

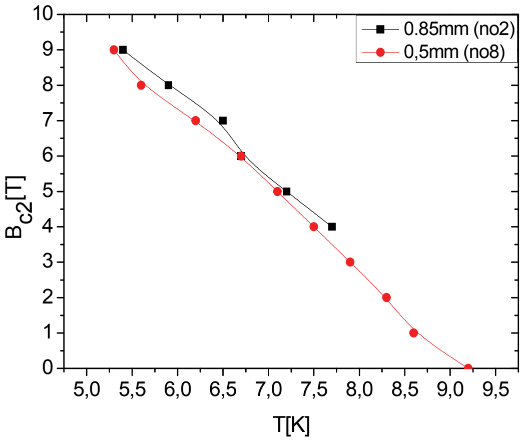

Fig. 3. Critical magnetic field dependence of temperature – transport method

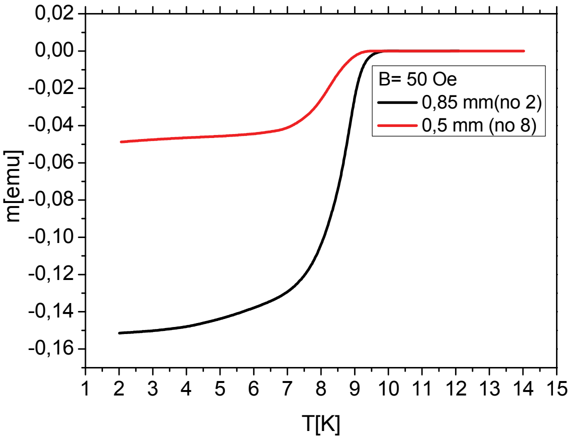

Fig. 4. Magnetic moment dependence on temperature – magnetic method

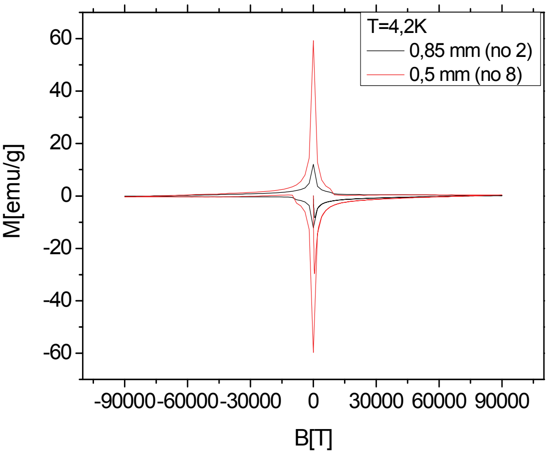

Fig. 5. Magnetization dependence on magnetic field

Figures 9 and 10 present (wires of diameter 0.5 mm) the comparison of J_c of the wire depending on the magnetic field with the measurements results that were made after the wire (wires of diameter 0.9 mm) had been produced. The J_c and F_p not changed in wire after 10 years.

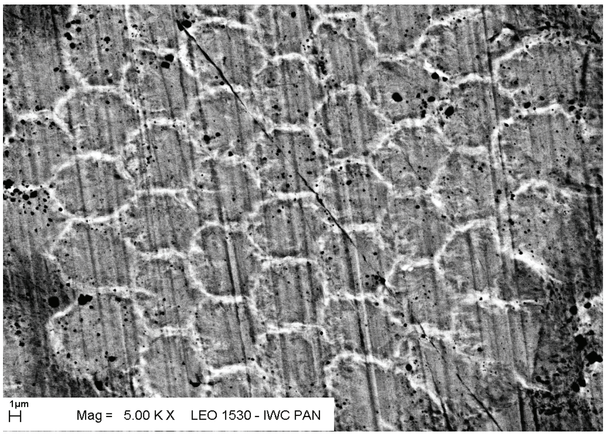

Fig. 6 The BSE view of the geometry of double stage construction of the filaments with the Cu grid stabilization - wire of diameter 0,85 mm

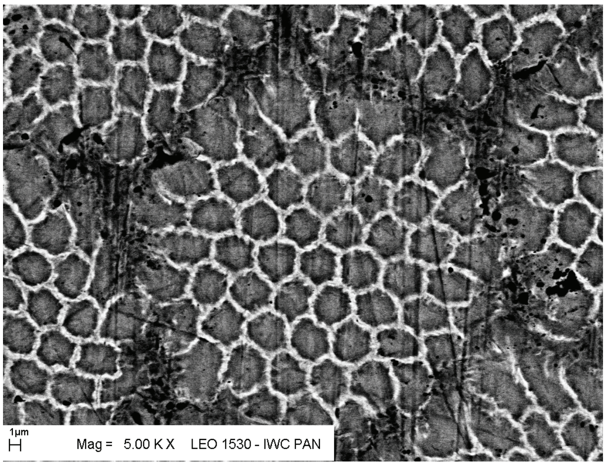

Fig. 7. The BSE view of the geometry of double stage construction of the filaments with the Cu grid stabilization - wire of diameter 0,5 mm

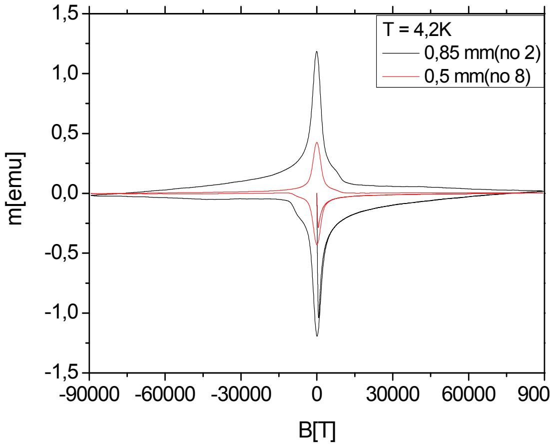

Fig. 8. Magnetic moment dependence on magnetic field

In article [7] we have shown SEM microstructural (wires 8910) analysis Moreover, it enables carrying away of heat, improve filaments mechanical bending strength, decreases hysteresis loop and residual magnetization. Basing on the magnetic moment measurements, it can be noticed that 0.5 mm sample has a smaller hysteresis loop and smaller residual magnetization than 0,85 mm sample (Fig. 8). On the basis of the photo of the wire cross section it can be stated that despite the wire diameter decrease by 41%, the ratio of matrix size to superconducting material does not undergo any changes. This factor is essential as it prevents the superconducting material from being destroyed. After comparing the current measurements with the ones that had been made six months ago no change in J_c of the wires has been observed (Fig. 12).

The cold drawing caused increase of J_c,. Photo 7 presents the influence of cold drawing on the filaments distribution in the wire and the filaments diameter. Due to the process of cold drawing the filaments diameter has decreased from 1 μm to 3 μm (Figures 6 and 7).

The biggest diameter reduction was observed among filaments that were placed in the very middle of the wire, and the smallest diameter reduction occurred in the filaments that were far from the wire's centre. After the cold drawing process J_c and the pinning force in a wire (0.5 mm) become 28 % higher than J_c (0.85 mm) in 4.2 K. On the basis of Bean model [12] J_{cm} and F_{pm} were calculated from the hysteresis loop and it turned out that in 4.2 K they are 60 % larger for the wire of 0,5 mm diameter than for the wire of 0,85 mm (Fig. 13).

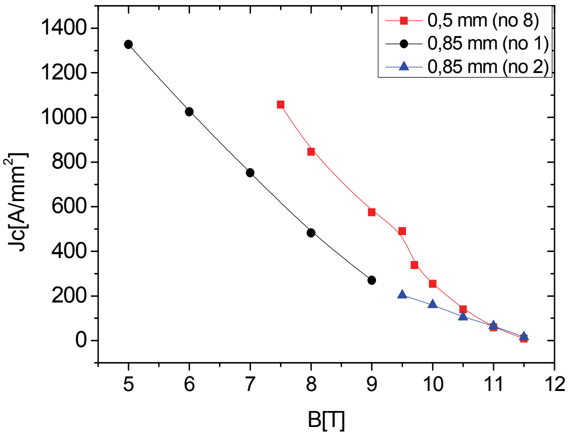

Fig. 9. Critical current density dependence on magnetic field

Comparing J_c that was obtained by means of transport measurements and J_{cm} that was obtained by means of the Bean's model it can be stated that J_c is 80% larger that the aforementioned J_{cm}. Similar dependence is noticed in the case of the pinning force, namely F_p obtained by means of transport measurements is 80% larger than the pinning force obtained via Bean model. The transport measurements (Fig. 9) for wires no 1 and no 9 showed changes of J_c with magnetic field. Kramer analysis we used to determine J_c at low magnetic fields (Fig. 13). We used scaling formulas no 1 and no 2 [8,13,14]. We determine on the basis of formula no 3 how the pinning mechanism is in influenced by cold drawing. The green line divides the Fig. 15 on two areas. The left area (Fig. 15) is dominated by the grain boundary mechanism. This mechanism has parameters p = 0,5 and q = 2. The right area (Fig. 18) is dominated by the point mechanism. This mechanism has parameters p = 1 and q = 2. We see it at Fig. 15 that cold drawing does not cause change of the pinning mechanism, because the curve samples no 1 and no 9 are similar in range of parameter b from 0 to 1. The increase of pinning centers density caused the increase of J_c and F_p. The elongation α Ti precipitations, the decrease of thickness α Ti precipitations and the increase of dislocation density caused the increase of pinning centers density.

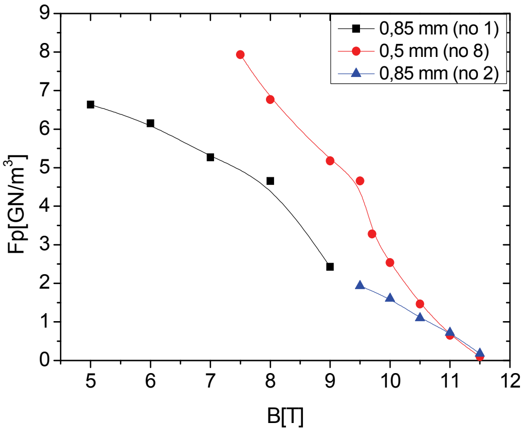

Fig.10. Pinning force dependence on magnetic field

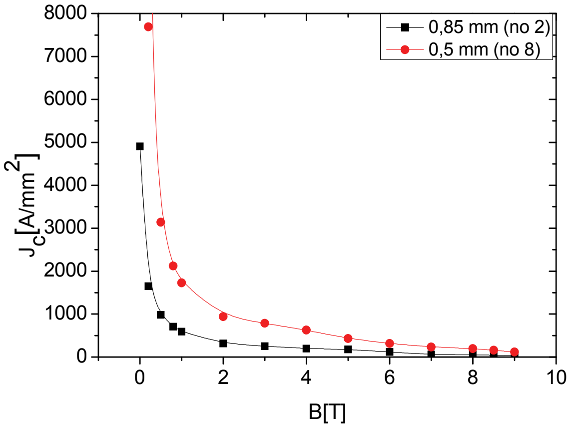

Fig. 11. Critical current density dependence on magnetic field – Bean model

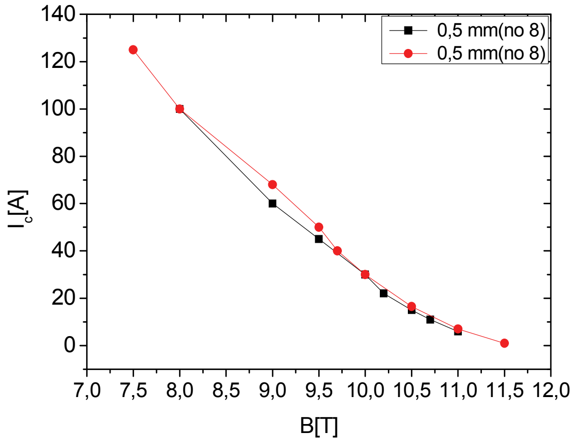

Fig.12. Critical current dependence on magnetic field

The maximum volume pinning force F_{pmax} of sample no 9 did not change significantly, compared with no 2 sample. This result suggested that the pinning mechanism was not changed during the cold treatment. We have supposed that the decrease of thickness α Ti precipitations and the increase dislocation density caused the shift of F_{pmax}.

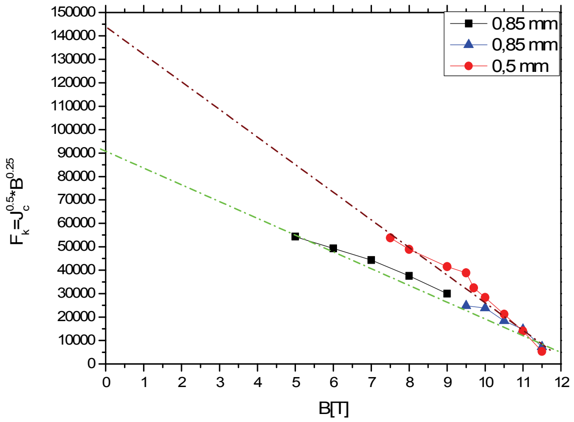

Fig. 13. Kramer plot dependent on magnetic field

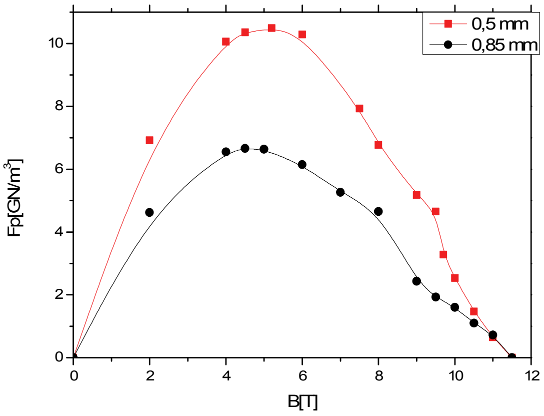

Fig. 14. Pinning force dependence of magnetic field

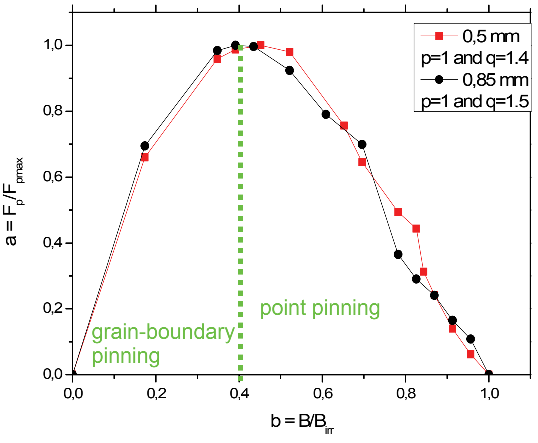

Fig. 15 Reduced pinning force *a* as a function on reduced field *b*

Conclusions

As far as the cold drawing of NbTi is concerned, it not only improves J_c regeneration but it also increases critical current density in NbTi superconducting wires (from 9 T to 10 T by 28 %). During the process of cold drawing two forces influence the wire. The first - stretching force is responsible for the elongation of NbTi grains, filaments, wire, α Ti precipitations; the second – pressing force decreases diameters of filaments, wires and Ti precipitations and also alters the shape and location of Ti precipitations. Such a distribution of forces increases both material homogeneity and grains boundaries, improves connection between filament, and also boosts and reinforces pinning centers (α Ti precipitations) and increasequantity line pinning centers and point pinning centers. One of the advantages of cold drawing under low angle is that the ratio of the matrix size to the superconductive material is constant. It is a very important coefficient for each superconducting wire as it saves it from being destroyed

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