Change in Critical Surface of Nb_3Sn Wire by Neutron Irradiation*)

Arata NISHIMURA, Yoshimitsu HISHINUMA, Hidetoshi OGURO[1)] and Satoshi AWAJI[2)]

National Institute for Fusion Science, Toki 509-5292, Japan
[1)]Tokai University, Hiratsuka 259-1292, Japan
[2)]Tohoku University, Sendai 980-8577, Japan

(Received 9 January 2023 / Accepted 12 June 2023)

Neutron irradiation on Nb_3Sn wire changes its superconducting properties. It is well known that the critical current increases by the irradiation once and then decreases by further irradiation. In this paper, the effective upper critical magnetic field and the critical temperature of the irradiated Nb_3Sn wire were investigated, and the mechanism that causes such changes were discussed qualitatively by focusing on the role of the irradiation defects together with the normal metallurgical flaws. In addition, a critical surface was taken up and the general tendency of the change in the surface was discussed.

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Keywords: critical surface, Nb_3Sn, neutron irradiation, irradiation defects, pinning site

DOI: 10.1585/pfr.18.2405063

1. Introduction

A fusion reactor will yield lots of neutrons with high kinetic energy, and fusion power generation succeeds when the kinetic energy is converted into the thermal energy and extracted as electrical energy. As designed in ITER project [1], the superconducting magnet will be irradiated by fusion neutrons, and its superconductivity will be changed. To study the neutron irradiation effect on the superconducting material, a novel test facility on the superconductivity measurement for post irradiation has been installed in a radiation control area at Oarai center in the Institute for Materials Research in Tohoku University in 2012 [2], and much valuable data has been presented and published, while many steady improvements have been made [3–8]. Also, studies on the irradiation effect on high temperature superconducting tapes are undergoing with this facility [9].

In order to achieve carbon neutrality, the fusion power generation is expected in the world as one of the strong candidates to reduce the green-house gases. And the neutron irradiation tests provide an important information for the design and construction of the fusion reactor and the superconducting physics. In this study, the effective upper critical field (B^*_{C2}) and the critical temperature (T_C) were evaluated experimentally, and the mechanism on the superconductivity change was studied qualitatively based on the consideration on a pinning model, Also, the change in the critical surface due to the neutron irradiation was visualized and discussed following the results obtained in the experiments.

author's e-mail: nishimura.arata@toki-fs.jp

*) This article is based on the presentation at the 31st International Toki Conference on Plasma and Fusion Research (ITC31).

2. Test Material and Test Procedure

The test sample shown in this paper is a Nb_3Sn wire used for the ITER toroidal field (TF) coil. Sample was provided by JASTEC and Hitachi and named as ITER #1 and #2. The cross-sectional view is shown in Fig. 1. The heat treatment was carried out with the standard condition for the ITER TF coil wire (240 hours at 650°C). The wire was produced by bronze-route process in around 2000. The improved wire was supplied to ITER project. The diameter is 0.8 mm, and many fine filaments were arranged at the core.

The neutron irradiation tests were carried out at Belgian Reactor #2 (BR2). The samples were set in an aluminum alloy capsule, and the inside of the capsule was gas-replaced with helium gas. The capsule was hold in the BR2 for a certain time without any special shielding. The cooling water flowed outside of the capsule, and water temperature was controlled at about 50°C.

The neutron fluence ranges from 8.23×10^{21} n/m^2, 4.90×10^{22} n/m^2 and 1.71×10^{23} n/m^2 (> 0.1 MeV). The latter two cases exceed the ITER design value (2.0×10^{22} n/m^2) and were expected in the range of a fusion

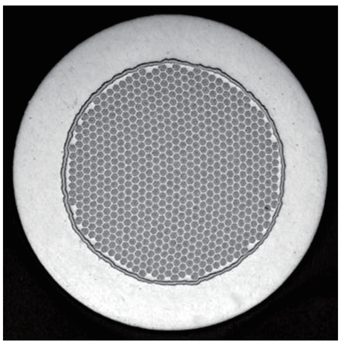

Fig. 1 Cross-sectional view of Nb_3Sn sample used.

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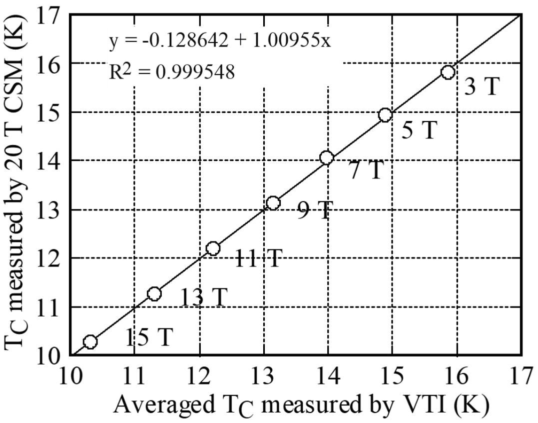

Fig. 2 Relation between T C measurement results at HFLSM with 20 T magnet and Oarai center with 15.5 T.

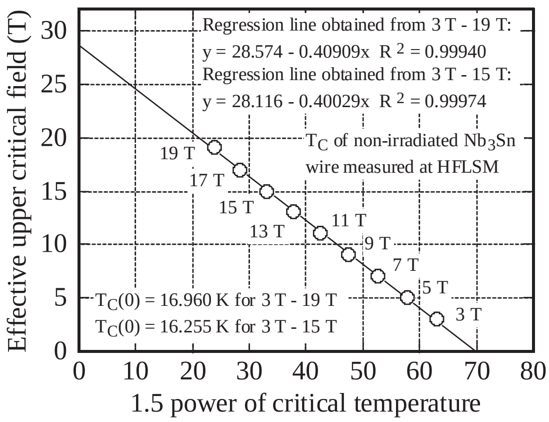

Fig. 3 Relation between effective upper critical field and 1.5 power of critical temperature of non-irradiated Nb_3Sn wire.

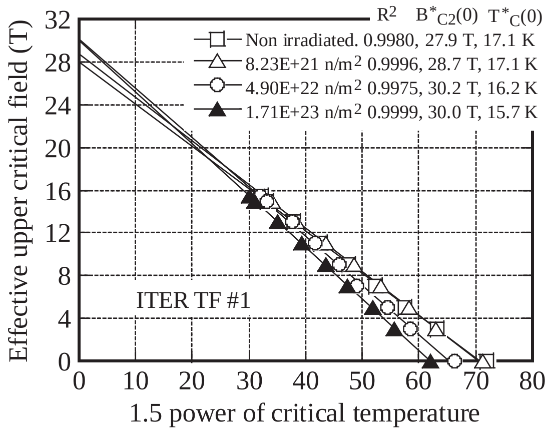

Fig. 4 Relation between effective upper critical field and 1.5 power of critical temperature of irradiated Nb_3Sn wire.

DEMO.

Post irradiation tests on the superconductivity were carried out at Oarai center using 15.5 T superconducting magnet and the valuable temperature insert (VTI). The VTI is cooled down by two sets of G-M refrigeration, and the sample holder is cooled by thermal conduction using super purified (over 4 nines) pure aluminum. Therefore, the temperatures of positive and negative electrodes are not the same. So, the average temperature was used as the sample temperature. The details of the test facility and the test procedure were described in reference 2 - 5.

3. Measurement of Critical Temperature

To compare the T_C data of the Nb_3Sn wire, the T_C test was carried out at High Field Laboratory for Superconducting Materials (HFLSM) in the Institute for Materials Research, Tohoku University, using 20 T superconducting magnet and T_C measurement facility. The sample was cooled down and kept a certain temperature by helium gas at HFLSM. The both results at HFLSM and Oarai center are shown in Fig. 2. The linear coefficient between T_C at HFLSM and that at Oarai is 1.00955 and the coefficient of determination (R^2 where R is multiple correlation coefficient) is 0.999548. From these results, it is recognized that the T_C measurement at Oarai center gives the same results as those at HFLSM.

4. Relation between Effective Upper Critical Field and Critical Temperature

Regarding the relationship between B^*_{C2} and T_C, the following equation is well known [10].

$$B^*_{C2}(T_C) = B^*_{C2}(0) \times (1 - (T_C/T^*_C(0))^{\nu}), \quad (1)$$

where ν is a universal parameter of 1.5 and $B^*_{C2}(0)$ is B^*_{C2} at 0 K and $T^*_C(0)$ is T_C at 0 T.

The linearity of $B^*_{C2}(T_C)$ and $T^*_C(0)^{1.5}$ was investigated using non-irradiated Nb_3Sn wire. The results are shown in Fig. 3. A good linearity was observed and the data set from 3 T to 19 T and that from 3 T to 15 T give almost same results. $T^*_C(0)$ is 16.960 K for 3 T to 19 T and 17.024 K for 3 T to 15 T, respectively. $B^*_{C2}(0)$ is 28.574 T and 28.116 T, respectively. From these results, it is recognized that even if the both intercepts are extrapolated with data up to 15 T, they can be extrapolated with considerable accuracy, and the T_C test with 15.5 T magnet at Oarai center would give the proper T_C data.

The results of neutron irradiated Nb_3Sn wires are shown in Fig. 4. $T^*_C(0)$ changes 17.1 K (non-irradiated), 17.1 K (8.23×10^{21} n/m^2), 16.2 K (4.90×10^{22} n/m^2) and 15.7 K (1.71×10^{23} n/m^2). On the other hand, $B^*_{C2}(0)$ changes 27.9 T (non-irradiated), 28.7 T (8.23×10^{21} n/m^2), 30.2 T (4.90×10^{22} n/m^2) and 30.0 T (1.71×10^{23} n/m^2).

From these results, it is clear that $T^*_C(0)$ decreases monotonically and that $B^*_{C2}(0)$ is improved once, then slightly decreases as the neutron fluence increases.

The results obtained with ITER TF #2 which is also bronze route processed Nb_3Sn wire are shown in Fig. 5.

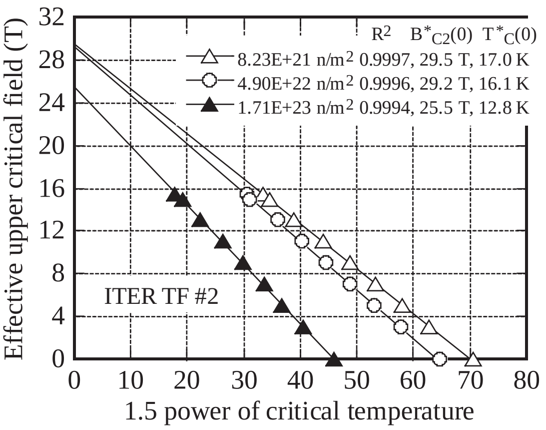

Fig. 5 Relation between effective upper critical field and 1.5 power of critical temperature of irradiated ITER TF #2 Nb_3Sn wire.

Although non-irradiated wire has not been tested yet, the irradiated wires show the degradation of $T^*_C(0)$ and $B^*_{C2}(0)$ as the fluence increases. When the degradation degree is focused, it is clear there is a big difference among the irradiated wires. At present, it is not easy to implement a quantitative discussion. It might be necessary to perform more precise irradiation using a D-T neutron facility and highly accurate post irradiation tests. But it is clear that the further investigation must be performed.

5. Change in Critical Current by Irradiation

The results of the critical current (I_C) against neutron fluence were presented already as shown in Fig. 6 [4–7]. It shows the relation between I_C/I_{C0} and neutron fluence of over 0.1 MeV. I_{C0} means the I_C on non-irradiation wire. Some other data in the published papers are also plotted [5–7]. There is a general trend that the I_C increases when the wire is exposed to the neutrons, and then deteriorates on the further heavy irradiation.

As mentioned in section 3 related to Fig. 2, the temperatures of the positive and the negative electrode are different because of the very small difference of the contact resistance between the super pure aluminum rod and the copper electrode. Under the cryogenic temperature, the temperature difference becomes large because the thermal conductivity and the specific heat are very small. When the sample current runs though electrodes, the joule heating occurs and the temperatures on both electrodes rise very rapidly. So, the measured I_C must be temperature corrected. However, since the correction process is not clear, the uncorrected I_C and I_{C0} are used when Fig. 6 was made. The temperature correction will be performed near future based on the fundamental consideration on the temperature difference between the electrodes, and the I_C and I_{C0} at the same temperature, such as 4.5 K, will be evaluated. Then I_C/I_{C0} will be corrected. At present, the plotted data

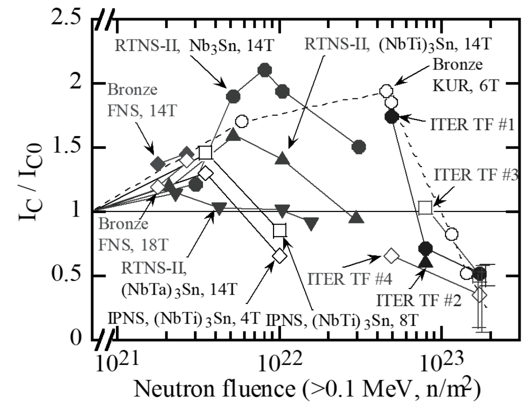

Fig. 6 Change in I_C/I_{C0} against neutron fluence of over 0.1 MeV [4]. Published data were plotted [5–7].

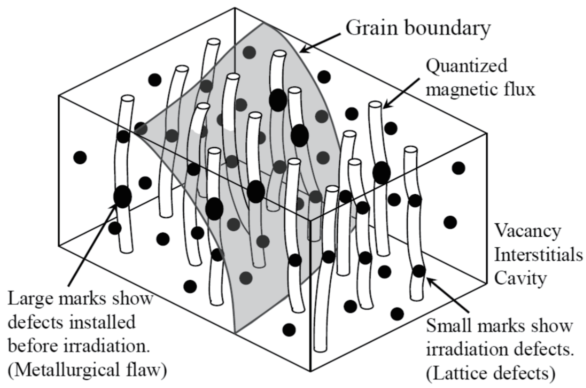

Fig. 7 Model of irradiation effect on magnetic flux pinning. Irradiation defects strengthen pinning force but break crystalline structure of Nb_3Sn at the same time.

contain a certain uncertainty, but several data sets suggest the common trend that was described above, and the I_C increases once and deteriorates drastically after the heavy irradiation.

6. Model of Irradiation Effect on Pinning Site

The model to explain the change in superconductivity by the neutron irradiation was considered as shown in Fig. 7. The inclusions and very fine precipitations will become a pinning site of the quantized magnetic flux. Therefore, the process of the installation and the generation of such metallurgical defects is very important to demonstrate the excellent superconductivity. On the other hand, the fast neutron will kick away the atoms that make up the superconducting phase of the Nb_3Sn wire, and the knocked-out atoms cause cascading and form a cluster. The defects are in lattice level, and these irradiation defects will become the pinning site.

When a small amount of neutron hits the Nb_3Sn wire, the strain in the superconducting crystal will be released and B_{C2} will be improved. At the same time, as the num-

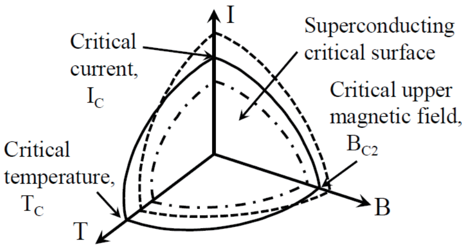

Fig. 8 Illustration of critical surface of Nb_3Sn wire. Solid line shows non-irradiated. Dotted line shows the irradiated a little, and dashed line shows the irradiated heavily.

ber of the pinning site increases, the I_C increases. However, when the sample temperature increases, the irradiation defects (clusters) become unstable, and some defects would start to move at higher temperature than 4 or 5 K. If the defects move, the magnetic flux will move, and the superconductivity will be broken. This is a T_C point. Therefore, although the B_{C2} and I_C will be improved by a small amount of the neutron irradiation, the T_C degrades monotonically. When the neutron fluence becomes larger, the superconducting phase would be destroyed by the fast neutrons and the I_C decreases. The B_{C2} will deteriorates due to much neutron irradiation, but the degree of the degradation is not as great as that of the I_C.

The image of the critical surface is shown in Fig. 8. The solid line, the dotted line and the dashed line show the non-irradiated, the irradiated a little and the irradiated heavily, respectively. This dynamic image was proposed for the first time in the world. To express the critical surface, A. Godeke et. al proposed the following equation [11].

$$I_C(B,T,e) = (C/B_{C2}(T_C)) \times S(e) \times (1\text{-}t^{1.5}) \times (1\text{-}t^2) \times h^{0.5} \times (1\text{-}h)^2, \quad (2)$$

where C is constant, S(e) is strain effect factor, t is $T_C/T_C(0)$, h is $B_{C2}(T_C)/B_{C2}(0)$. $T_C(0)$ is critical temperature at 0 field. $B_{C2}(T_C)$ is critical upper magnetic field at T_C K. $B_{C2}(0)$ is critical upper magnetic field at 0 K.

As discussed in Section 4, the $T_C(0)$ decreases faster than the $B_{C2}(0)$. Therefore, when a certain T_C is assumed, the $B_{C2}(T_C)$ becomes smaller as the fluence increases. So, t in equation (2) becomes larger and the value of $(1\text{-}t^{1.5}) \times (1\text{-}t^2)$ becomes smaller. At the same time, h becomes smaller and the value of $h^{0.5} \times (1\text{-}h)^2$ becomes smaller. S(e) is a parameter showing the strain condition. When the internal strain is released by the irradiation, S(e) becomes large. It is expected that the I_C of the irradiated wire would be evaluated with the experimental results.

From above consideration, it should be noted that the critical surface will shrink as the irradiation increases. To make a quantitative discussion on the critical surface, the further precise data sets are desirable.

7. Summary

The critical surface of Nb_3Sn wire varies due to neutron irradiation. The mechanisms of the critical surface change would be explained as follows:

1. I_C: By the neutron irradiation, a lot of irradiation defects are induced in the matrix and the number of the pinning sites increases. So, the critical currents increase once, but degrades with further irradiation.

2. B_{C2}: The neutron irradiation improves the crystal quality of the Nb_3Sn. For example, the residual strain in the matrix will be released. Therefore, the critical magnetic field increases. But it deteriorates since the crystal becomes amorphous by much irradiation.

3. T_C: The critical temperature decreases monotonically. The irradiation defects are mainly lattice defects. The lattice is oscillated by the heat and sensitive to the temperature rise. The instability of irradiation defects due to temperature rise would reduce the pinning force even in the presence of metallurgical defects such as inclusions.

Acknowledgement

The authors would like to express their sincere thanks to Prof. Tatsuo Shikama at Hachinohe Institute of Technology, Mr. Masanori Yamazaki at Tohoku University for their encouragement and contributions.

Part of this work was supported by the NIFS Collaboration Research Program (NIFS19KERF048 and NIFS 22KIEF011) and Grant-in-Aid for Scientific Research (19K03804).

This work was performed at the International Research Centre for Nuclear Materials Science and High Field Laboratory for Superconducting Materials in the Institute for Materials Research, Tohoku University.

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