Critical Current and Fracture Behavior of Nb₃Al Superconducting Strands under Cyclic Electromagnetic Force

Yoshihide Wadayama¹, Kyohei Natsume¹, Toshiyuki Mito^{1,2}, Shinji Hamaguchi², Nagato Yanagi^{1,2}, Kazuya Takahata^{1,2} and Shinsaku Imagawa^{1,2}

1. Department of Fusion Science, School of Physical Science, The Graduate University for Advanced Studies, Toki-city, Gifu 509-5292, Japan

2. National Institute for Fusion Science, Toki-city, Gifu 509-5292, Japan

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Abstract: To obtain basic information on fracture behavior and its critical current properties in superconducting strands with long-term periodic excitation, a unique experiment of cyclic strain loading was carried out. The strain was applied to a superconducting filament directly at 4.2 K using an electromagnetic (Lorenz) force instead of the usual mechanical load. The sample strands were Jelly-roll process Nb₃Al with a copper ratio of 2.1. A new magnet system to evaluate long-term cyclic strain loading was set up. It was able to generate external fields up to 14 T with 58 mm bore. Cyclic strain was applied by the sample current control: 500 A, 0.1 Hz. In the experiment, critical current measurements and applied cyclic strain were carried out in alternation and the variation of critical current was obtained during the cyclic test. In this paper, the experimental results of cyclic strain loading on the critical current of Nb₃Al strand and microstructural observation of fracture surface of the filaments is described. Our results show that degradation of critical current properties was not observed at cycle number $n = 1500$ under the applied axial strain of 0.17%. A noxious sample, from which the outside copper stabilizer was deliberately removed, broke after $n = 10$, and crack propagation was observed at the fracture surface of the Nb₃Al filaments. Under a microstructural observation of the break sample, the fracture points of the filaments were seen to be different in a longitudinal direction. A striped pattern like a beach mark due to crack propagation was also observed at the Nb₃Al fracture surface. It was found that the cross-sectional homogeneity of the strand is important to avoid the damage and breaking from cyclic loading.

Key words: Superconducting strand, mechanical strength, Nb₃Al, jelly-roll, cyclic strain, microstructure.

1. Introduction

A Nb₃Al multifilament superconductor is the most promising wire for high-field and large-scale magnet applications, such as a nuclear fusion and high-energy particle accelerators. In these applications, the superconducting wire requires high critical current properties and high tolerance to mechanical stress and strain [1]. In particular, the large-scale magnets have generally been fabricated by the react & wind process;

coil winding is carried out after reaction of the brittle superconducting phase. Nb₃Al strands have excellent strain tolerance and critical current properties in a practical metal superconductor [1]. So far, the effects of mechanical strain on their superconducting properties have been investigated for nuclear fusion magnets [2-6].

In the react a wind process, the mechanical strain of the superconducting wire is distinguished into two kinds: (a) Coil fabrication strain is caused by external mechanical deformation during coil winding; (b) Coil excitation strain is caused by electromagnetic force.

Corresponding author: Yoshihide Wadayama (1959-), male, research field: superconducting wire and magnet. E-mail: wadayama.yoshihide@hitachi-cable.co.jp.

Strain and stress act directly on superconducting filaments carrying an electric current. Previous investigation of strain effects considered coil fabrication only. In addition, cyclic strain loading on the superconducting wires was generally performed at room temperature using a mechanical testing machine [4, 5].

Going forward, it will be necessary for superconducting strands and cables used in high periodicity excitation magnets, such as pulse-magnets, to display long-term reliability as with cryogenic structural materials. In the case of large scale conductors, cyclic excitation (13 T, 46 kA) was performed at the ITER Nb₃Al insert coil test. Degradation of critical current was not observed after 10^3 cyclic excitations [7].

In this paper, the strain was applied directly to a superconducting filament at 4.2 K using an electromagnetic (Lorentz) force instead of the usual mechanical load. In the experiment, critical current measurements and applied cyclic strain were carried out in alternation and the variation of critical current was obtained during the cyclic test.

The main purposes of the present investigations are to set up a new magnet system to evaluate long-term cyclic strain loading and obtain basic information on the effects of cyclic strain on critical current properties of jelly-roll Nb₃Al strands with long term periodic excitation.

2. Experiment

2.1 Sample Strand

Samples for cyclic strain loading are multifilamentary Nb₃Al/Cu superconducting strands. Table 1 shows the main specifications of the strands. The strands were fabricated using a conventional Jelly-roll process [2]. In the process, alternate foils of Nb and Al are wound onto an Nb rod. After diffusion reaction the Nb/Al composite become an Nb₃Al superconducting filament. These filaments were stabilized by oxygen-free high-conductivity copper. The critical current of the

strand showed high uniformity in the longitudinal direction [8].

In the experiments, two samples with different copper ratios were evaluated. The Cu ratio of samples A and B were 2.1 and 1.2, respectively. Sample B had defects deliberately injected at the strand surface by dissolving the outer Cu stabilization using nitric acid.

The heat treatment condition was 1050 K, 44 ks in vacuum. Fig. 1 shows a cross sectional view of the sample strands. The sample configuration was a coil 43 mm in diameter and 50 mm in height. The strand length was about 600 mm and there were 5 turns.

2.2 Experimental Setup and Procedure

Fig. 2 shows the new magnet system which was prepared for the long-term cyclic experiment. External magnetic fields up to 14 T were generated by a superconducting magnet with a 50 mm bore. To apply the electro-magnetic force, sample strands are set in the superconducting magnet bore and electrified under a vertical external field.

Table 1 Main parameters of Nb₃Al sample strands.

Items	Sample A	Sample B
Process	Jelly-rolled, diffusion reaction	
Diameter	0.805 mm	0.690 mm
Soundness	normal	noxious
Cu ratio	2.1	1.2
Filaments	50 μ m $\times$ 90	
Twist pitch	31 mm	
RRR	260	
Heat treatment	1050 K-144 ks	
Critical current density	600 A/mm ² at 12 T, 4.2 K, non-Cu area

Fig. 1 Cross sectional view of the Nb₃Al sample strands.

Fig. 2 Experimental setup of cyclic strain loading. Cryostat: inner diam. 650 mm, depth: 1600 mm.

A cyclic sample current was controlled externally and typical current conditions were max. 500 A and 0.1-0.25 Hz triangle wave. The direction of sample stress and strain was tension. The sweep rate of the sample current was 100-250 A/s. The criterion of the critical current definition was 0.1 $\mu\text{V}/\text{cm}$. Quench detection and shut off of the current applying were carried out to protect the sample from meltdown. The threshold voltage of sample protection was 100 μV with an electric field of 4 $\mu\text{V}/\text{cm}$.

2.3 Condition of Lorentz Force at Cyclic Loading

Fig. 3 shows an electromagnetic scheme of the present experiment. In this method, a uniform axial body force is applied to the filament directly. External electromagnetic conditions were fixed in consideration of the sample critical current and current source capacity. In the experiment, the following steps are repeated: (a) Critical current measurement under from 9 T to 6 T; (b) Applying cyclic strain under 5 T. Variation of critical current properties can be evaluated continuously from the same sample.

In the experiment, the overall axial hoop stress of the cross sectional area of samples A and B are 124 MPa and 168 MPa respectively, as they have different Cu ratios.

In the experiments, the maximum number of cyclic strain loading events was $n = 1500$ considered the condition which cyclically excitation test of ITER conductor $n = 1000$ [7, 9].

3. Experimental Results

3.1 Cyclic Strain Loading Apparatus

Fig. 4 shows the results of heat load measurements of the new magnet system. Heat flux into the cryogenic area was evaluated by decreasing the liquid helium level. The heat load was about 2.5 W while the coil current was 245 A and the sample current was 500 A, 0.1 Hz. It was estimated that the cyclic test could be continued for a day, applying the strain over 5×10^3 cycles without liquid helium refilling. The sample is easily exchanged manually by evulsion of the sample holder.

3.2 Critical Current Properties

Fig. 5 shows the critical current of samples A and B. The critical currents were obtained before applying the cyclic strain. The critical current density of the samples was 600 A/mm² at 12 T. Sample B which had the outside copper stabilizer deliberately removed had a comparable critical current. The external field applied to the sample at the cyclic strain loading was determined

Fig. 3 Scheme of Lorentz force (hoop stress) loading.

Fig. 4 Heat load of the cyclic strain loading apparatus.

Fig. 5 Critical current of sample A and B before cyclic strain loading.

as 5 T, considering the obtained critical currents of the samples and current source capacity, 500 A max. During cyclic strain loading, the samples were not quenched at the conditions of 500 A, 5 T.

3.3 Effect of Cyclic Strain Loading on Critical Current

Fig. 6 shows the effect of cyclic strain on the critical current properties of sample A: $n = 1, 1500$. Figs 6(a) and 6(b) indicated linear and double logarithmic relation between sample current and voltage, respectively. At the relationship between sample current and voltage, no difference was observed after cyclic strain loading of $n = 1500$. The n -values of sample A also did not show a clear difference. The critical currents of the samples were determined under

the definition of $0.1 \mu\text{V}/\text{cm}$.

Fig. 7 shows the effect of cyclic strain on the critical current properties of sample B which had a deliberately introduced defect: $n = 1, 10$. Critical currents were measured at cycle numbers $n = 1, 10$. At the Critical current measurements at 7 T and $n = 10$, sample B broke suddenly. The strand could have been broken by the cyclic strain in sample B which had some defects and did not have outside copper stabilizer. Before the sample broke, special degradation and predictive phenomena were not observed.

Fig. 8 shows the effect of cycle number on the critical current of the samples. The critical currents of sample A decreased slightly after cyclic loading $n = 1500$, and the degradation ratio of currents tends to increase with higher field. In the case of sample B, which had cycle number $n = 10$, the critical current was depleted with every subsequent measurement: $B = 9 \text{ T}(n = 10)$, $B = 8 \text{ T}(n = 10)$ and $B = 7 \text{ T}(n = 10)$. It appears that Nb₃Al filaments are cumulatively damaged during cyclic loading and critical current measurements.

4. Discussion

4.1 Microstructural Observation

Fig. 9 shows a microstructural observation of the

Fig. 6 Effect of cyclic strain on critical current properties of Sample A: $n = 1$ and $n = 1500$.

Fig. 7 Results of critical current measurements of sample B; cycle numbers are 1, 10.

Fig. 8 Degradation of critical current of sample A, $n = 1500$ and sample B, $n = 10$.

fracture morphology on sample B. The fracture planes of the filaments were distributed in a longitudinal direction. Most of the fracture surface obtained by the usual mechanical test was a single plane [10]. A brittle fracture surface was observed on Nb₃Al filaments even though they were quenched during current application. The morphologies of the meltdowns caused by excessive Joule heating occurred in the copper stabilizer. It was considered that current was shunted from the Nb₃Al filaments to the copper during filament breaking. Among the fracture surfaces, a Nb core of the jelly-roll component was observed sticking out from the Nb₃Al

Fig. 9 Fracture surface of sample B which broke after cyclic loading ($n = 10$).

surface. A striped pattern like a beach mark was also observed at the Nb₃Al fracture surface. It may be fatigue crack propagation.

4.2 Estimation of Cyclic Strain by Lorentz Force

Fig. 10 shows estimated stress-strain curves of samples A and B obtained by low of mixture. Generically, low of mixture is expressed in the following form [11].

$$\sigma_{\text{strand}} = V_{\text{Nb}_3\text{Al}} \cdot \sigma_{\text{Nb}_3\text{Al}}(\varepsilon) + V_{\text{Cu}} \cdot \sigma_{\text{Cu}}(\varepsilon) \quad (1)$$

Fig. 10 Estimated stress-strain curves of Nb₃Al strand at 4.2 K.

where σ is the stress, V is the volume fraction of strand component.

The tensile properties of annealed copper at 4.2 K are expressed in the following equation [4, 12].

$$\sigma = Y + K(\epsilon_p)^n \quad Y = 70 \text{ MPa}, K = 397 \text{ MPa}, n = 0.489 \quad (2)$$

From the estimation, the strains which were applied samples A and B were about 0.17% and 0.22%, respectively. Even though there is no significant difference in the amount of strain between A and B, sample B broke after a number of cycles due to the removal of the outside copper stabilizer and partial exposure of the filament. It could be a factor of inhomogeneity of the cross-section configuration in the longitudinal direction caused by Cu dissolution in nitric acid. It was considered that the cross-sectional homogeneity of a strand is important to avoid the damage and breaking from cyclic loading.

Fig. 11 shows the effect of axial strain on the critical current of a Nb₃Al strand which had a similar cross-sectional structure [13]. The typical strain dependence of critical current for a (Nb,Ti)₃Sn strand is also presented. The Nb₃Al strand has excellent strain tolerance on critical current properties. Therefore, no difference was observed in the condition of present study: $\epsilon = 0.17\%$.

From the results of unique experiments, it was initially clarified that the critical current of a Nb₃Al

Fig. 11 Effect of axial strain on critical current of Nb₃Al and (Nb,Ti)₃Sn strands [13].

strand was not depleted under axial strain 0.17%, $n = 1500$, induced by an electromagnetic force. Also, it was found that the cross-sectional homogeneity of the strand is important to avoid damage and breaking from cyclic loading. After this, a systematic evaluation of the cyclic strain effect on the critical current of Nb₃Al and Nb₃Sn will be performed to accumulate information for superconducting magnet design.

5. Conclusions

The effect of cyclic strain by electromagnetic force on the critical current properties of Nb₃Al strands was investigated. In the experiment, critical current measurements and applied cyclic strain are carried out alternately and the variation of critical current was obtained consecutively.

(1) A new magnet system to evaluate long-term cyclic strain loading was set up. The heat load of the magnet system was 2.5 W and over 5×10^3 cycles could be applied without liquid helium refilling.

(2) Clear degradation was not observed in the soundness sample after 1500 cycles. Whereas, the sample with deliberately injected defects was broken by electro-magnetic force after 10 cycles.

(3) Under a microstructural observation of the break sample, the fracture points of the filaments were seen to be different in a longitudinal direction. A striped pattern like a beach mark due to crack propagation was

also observed at the Nb₃Al fracture surface.

From the results of unique experiments, it was initially clarified that the critical current of the Nb₃Al strand was not depleted by the electromagnetic force under an axial strain of 0.17%, $n = 1500$. Also, it was found that the cross-sectional homogeneity of the strand is important to avoid the damage and breaking from cyclic loading.

References

- [1] T. Takeuchi, Nb₃Al conductors for high-field applications, *Supercond. Sci. Technol.* 13 (2000) 101-119.
- [2] F. Hosono, G. Iwaki, K. Kikuchi, S. Ishida, T. Ando, K. Kizu, Y. Miura, A. Sakasai, Production of a 11km long jelly roll processed Nb₃Al strands with high copper ratio of 4 for fusion magnets, *IEEE Transactions on Applied Superconductivity* 12 (2002) 1037-1040.
- [3] T. Hemmi, N. Koizumi, Y. Nunoya, Y. Okui, K. Matsui, Y. Nabara, T. Isono, Y. Takahashi, K. Okuno, N. Banno, A. Kikuchi, Y. Iijima, T. Takeuchi, Characterization of Nb₃Al strands subjected to an axial-strain for a fusion DEMO reactor, *IEEE Transactions on Applied Superconductivity* 19 (2009) 1540-1543.
- [4] S. Ochiai, K. Osamura, Influence of cyclic loading at room temperature on the critical current at 4.2 K of Nb₃Sn superconducting composite wire, *Cryogenics* 32 (1992) 584-590.
- [5] S. Ochiai, T. Sawada, S. Nishino, M. Hojo, K. Takahashi, Y. Yamada, Relation of strength distribution of Nb₃Al filaments to strength of multifilamentary superconducting composite wire, *Cryogenics* 36 (1996) 249-253.
- [6] T. Sawada, S. Ochiai, M. Hojo, Y. Yamada, K. Takahashi, N. Ayai, K. Watanabe, Fatigue behavior at room temperature and its influence on superconducting properties of Nb₃Al composite wire, *J. Japan Inst. Metals* 61 (1987) 822-828.
- [7] N. Koizumi, K. Okuno, H. Nakajima, T. Ando, H. Tsuji, Development of a Nb₃Al conductor to be applied to a fusion reactor and its application to a large superconducting coil, *J. of the Cryogenic Society of Japan* 38 (2003) 391-398.
- [8] Y. Wadayama, N. Hara, K. Azuma, Y. Suzuki, K. Aihara, Development of conduction cooled 10T-Nb₃Al superconducting magnet, *Abstracts of Cryogenic Society of Japan Conference*, 1999, p. 179.
- [9] Y. Nabara, Y. Nunoya, T. Isono, N. Koizumi, K. Hamada, K. Matsui, T. Henmi, M. Oshikiri, Y. Uno, S. Seki, S. Ito, M. Yoshikawa, Y. Takahashi, H. Nakajima, Quality control of Nb₃Sn superconducting strand for ITER TF coil, *Abstracts of Cryogenic Society of Japan Conference*, 2010, p. 188.
- [10] K. Katagiri, M. Fukumoto, K. Koyanagi, S. Nishijima, K. Saito, T. Okada, Fractography and mechanical properties of Paractical superconducting wires at cryogenic temperature, *J. of the Society of Materials Science, Japan* 36 (1987) 448-454.
- [11] T. Miyazaki, T.Z. Miyatake, N. Matsukura, H. Kurahashi, T. Kiyoshi, H. Wada, Development of (Nb,Ti)₃Sn superconductors for 1GHz class magnet, *R & D Kobe Steel Engineering Reports* 48 (1988) 55-60.
- [12] F. Schwartzberg, S. Osgood, R. Keys, T. Kiefer, *Cryogenic Materials Data Handbook*, Technical Documentary Report, No. ML_TDR_64_280, 1964, pp. 7-64.
- [13] Y. Wadayama, H. Nakajima, T. Ando, Y. Takahashi, T. Talkahashi, H. Tsukamoto, T. Isono, T. Tsuji, Effect of tensile strain on critical current of superconducting strands for ITER model coil, *Abstracts of Cryogenic Society of Japan Conference*, 1992, p. 197.