ELSEVIER

Physica C 354 (2001) 406–409

PHYSICA C

www.elsevier.nl/locate/physc

Performance variation of KSTAR Nb_3Sn strand caused by heat treatment failure

M. Kim [a,*], K. Kim [a], Y. Chang [a], B. Lim [a], S. Kim [a], C.S. Yoon [b]

[a] *Energy Laboratory, Samsung Advanced Institute of Technology, Moonji-dong, Yusong-Gu, Taejon 305-380, South Korea*
[b] *Hannam University, Taejon 306-010, South Korea*

Abstract

The Korea Superconducting Tokamak Advanced Research (KSTAR) device is a tokamak with a fully superconducting magnet system which enables an advanced quasi-steady-state operation. The major radius of the tokamak is 1.8 m and the minor radius is 0.5 m with the elongation of 2. The superconducting magnet system consists of 16 TF coils and 14 PF coils. 16 TF coils and 10 PF coils use Nb_3Sn strands in a Incoloy 908 conduit. In order to investigate the effect of unexpected failure during the heat treatment procedure, six kinds of heat treatment scenarios were tested. Each of six samples was firstly heat treated using the given scenario and then heat treated again using the nominal heat treatment scenario. Critical current, AC loss, and residual resistance ratio were measured after the heat treatment. The required specification of the critical current density is above 750 A/mm^2 at 12 T and the hysteresis loss is below 250 mJ/cm^3 during +3 to −3 T operation. The normal heat treatment scenario is ramping up to 460°C in 6°C/h and treating for 100 h, then ramping up to 570°C in same rate and treating for 200 h, and finally ramping up to 660°C in 6°C/h and treating for 240 h.

Keywords: KSTAR; Critical current; Heat treatment; Hysteresis loss

1. Introduction

Korea Superconducting Tokamak Advanced Research (KSTAR) device is a tokamak with a fully superconducting magnet system which enables a long pulse operation at full parameters and is designed to operate a high-beta double-null and single-null plasma at full current. The TF coil system has 16 coils, a field of 3.5 T at a plasma major radius of 1.8 m, with a peak flux density of 7.5 T and the stored energy is 470 MJ. TF coils use Nb_3Sn strand in a 2.8 mm thick Incoloy 908 conduit. The cable pattern is $3 \times 3 \times 3 \times 3 \times 6$ of 486 strands. The nominal current of the TF coils is 35.2 kA with all coils in series. Each coil is continuously wound without joint. The PF system has 14 coils, eight in a central solenoid stack and six outer PF coils. These provide 13.6 V s and can sustain current-driven 2 MA plasmas indefinitely and inductively for 20 s. The CS and PF5 coils also use Nb_3Sn strand in an Incoloy 908 conduit, while the outer PF coils use NbTi strand in a 316LN conduit [1].

To satisfy the previously mentioned KSTAR operation scenarios, KSTAR adopts KSTAR

* Corresponding author. Fax: +82-42-865-4099.
E-mail addresses: mkkim@venus.sait.samsung.co.kr, mk-kim@saitgw.sait.samsung.co.kr (M. Kim).

0921-4534/01/$ - see front matter
PII: S0921-4534(01)00108-3

Table 1
Specifications of superconducting strands for KSTAR HP-III

Parameter	Unit	Value
Superconductor type		Nb_3Sn
Strand diameter	mm	0.78 ± 0.01
Non-Cu J_c (@12 T, 4.2 K)	A/mm^2	>750
n-value		>20
Non-Cu Q_h(per ± 3 T cycle)	mJ/cm^3	<250
RRR		>100
Cu/non-Cu ratio		1.5 ± 0.15
Plating material		Cr
Coating thickness	μm	1 ± 0.5
Twist pitch	mm	13 ± 1
Heat treatment scenario	Ramp rate:	6°C/h
	460°C:	100 h
	570°C:	200 h
	660°C:	240 h

HP-III specification for its superconducting strand. Table 1 shows the KSTAR HP-III specifications for Nb_3Sn strand in which the critical current density is greater than 750 A/mm^2 at 12 T, 4.2 K and the hysteresis loss is less than 250 mJ/cm^3 at field variation from +3 to −3 T at 4.2 K [2].

The reaction heat treatment condition recommended by the strand manufacture has to be optimized in order to meet various requirements for the large coil reactions and to prevent stress accelerated grain boundary oxidation (SAGBO) of Incoloy 908 [3]. The reaction heat treatment scenario for KSTAR magnet is also specified in the Table 1. The temperature ramp rate during the reaction heat treatment procedure is 6°C/h and there are three plateaus: 460°C, 100 h to remove lubricants and contaminants from the cable, 570°C, 200 h to enhance the diffusion of Sn to Nb filament and 660°C, 240 h for the A15 reaction of Nb_3Sn. The reaction heat treatment is an important factor which determines performance of Nb_3Sn strands. If any failure occurred during heat treatment, the strand could show a degradation of the performance and it could affect the performance of the superconducting magnet system. In this paper, the performance of six superconducting strand samples under the different heat treatment failure conditions is discussed using parameters such as critical current, hysteresis loss and residual resistance ratio (RRR).

2. Experimental setup

In this experiment the Nb_3Sn strand manufactured by Mitsubishi Electric Co. has been used. The strand consists of 19 sub-assemblies and each sub-assembly is coated with Sn. Also each sub-assembly have a Sn core which is surrounded by above 400 of Nb filaments. Fig. 1 shows the cross-section of Nb_3Sn strand.

In order to investigate the effect of the heat treatment failure, six samples are prepared. Each sample is baked until the failure position of the given scenario and the heater has been turned off. After the sample is cooled down to the room temperature, the sample is heat treated again using the nominal heat treatment scenario. Failure positions are located at 300°C (sample #1), the start of the 460°C plateau (sample #2), the end of 460°C plateau (sample #3), the start of the 570°C plateau (sample #4), the end of 570°C plateau (sample #5), 100 h after the 660°C plateau (sample #6). Fig. 2 shows these failure positions and the nominal heat treatment procedure.

Critical currents are measured using 32 mm diameter Ti–6Al–4V alloy barrel holders with copper terminators. The voltage-tap separation is 0.5 m at 4.2 K with the criterion of 10 μV/m. The n-value of the V–I curve is evaluated in the voltage range of 10 and 100 μV/m. The hysteresis loss is

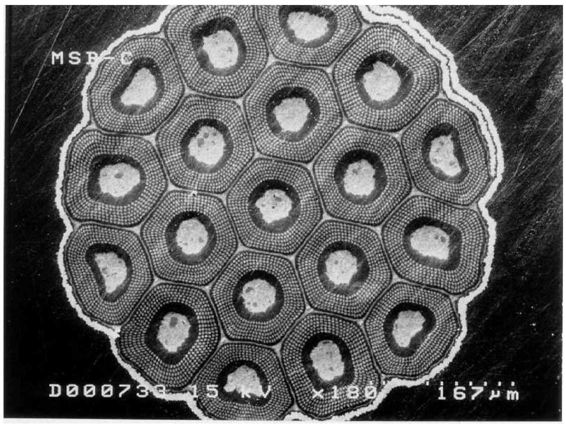

Fig. 1. Cross-section of Mitsubishi strand with Sn coated 19 sub-assembly and Ta barrier. And Sn cored sub-assembly and Ta barrier are surrounded by Cu stabilizer.

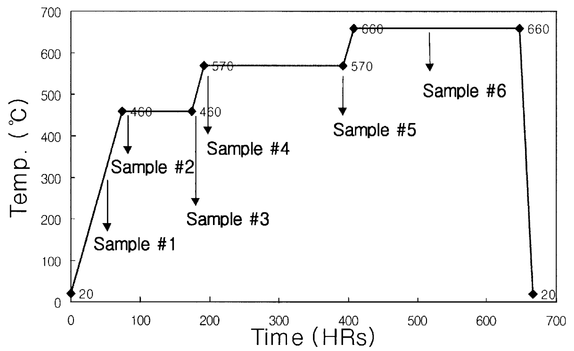

Fig. 2. Failure position and the nominal heat treatment procedure.

measured for the full cycle of $+3 \rightarrow -3 \rightarrow +3$ T with the DC extraction method. RRR is measured using the resistivity at 273.14 K and just above the critical temperature of Nb_3Sn (18.5 K).

3. Results and discussion

Table 2 shows the critical current density (J_c), the hysteresis loss(Q_h) and RRR of six different samples. In order to simplify the comparison of result, the critical current density at 12 T is shown in the table.

As expected, the RRR value does not depend on the heat treatment scenario.

If the nominal heat treatment scenario is used, 800 A/mm^2 of critical current density and 150 mJ/cm^3 of hysteresis loss are measured. However, in the experiment, samples #2, #4, and #5 show a degradation of critical current density and the measurement of hysteresis loss show the expected behavior of the reduction. Other samples show nearly the same performance compared to those of normal samples. Fig. 3 shows the critical current density as a function of the external magnetic field. The fitting curves are obtained by Kramer plot and the fitting equations are [4]:

Sample #1: $J_c = (103.44 - 4.20B)^2 B^{-0.5}$ (A),
Sample #2: $J_c = (101.37 - 4.25B)^2 B^{-0.5}$ (A),
Sample #3: $J_c = (103.93 - 4.25B)^2 B^{-0.5}$ (A),
Sample #4: $J_c = (99.52 - 4.31B)^2 B^{-0.5}$ (A),
Sample #5: $J_c = (96.55 - 3.92B)^2 B^{-0.5}$ (A),
Sample #6: $J_c = (103.52 - 4.23B)^2 B^{-0.5}$ (A).

Scanning electron microscopy (SEM) is used for the investigation of the filament structure and Fig. 4 shows photos from SEM with the magnification of 20,000. In sample #4 ($J_c = 660$ A/mm^2) the grain of the filament is less fine and less uniform compared to other sample. But in case of samples #2 and #5, it is difficult to detect different feature in filament grain structure. The sample #1 shows a relatively low hysteresis loss and the grain of the filament is more uniform and finer than the other samples.

Table 2
Test results of six samples

Samples	Non-Cu J_c		Non-Cu Q_h (mJ/cm^3)	RRR
	J_c (A/mm^2) at 12 T	n-value		
Sample				
#1	808	36	106	338
#2	730	33	112	314
#3	804	39	146	378
#4	660	33	115	315
#5	704	15	131	334
#6	798	36	152	364

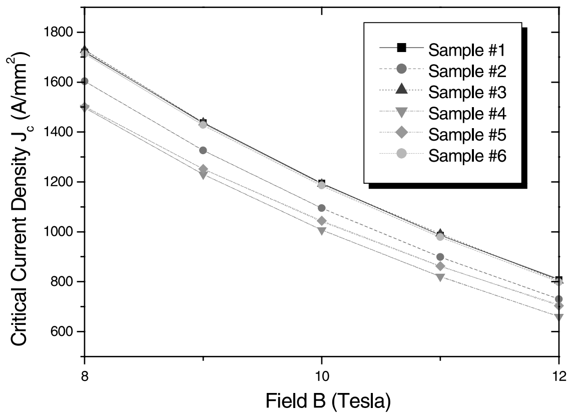

Fig. 3. Critical currents of six samples with fitting curves using Kramer plots.

4. Conclusion

In this experiment, we measured performance variations caused by heat treatment failure. The summary of performance variation in six samples is given as follows:

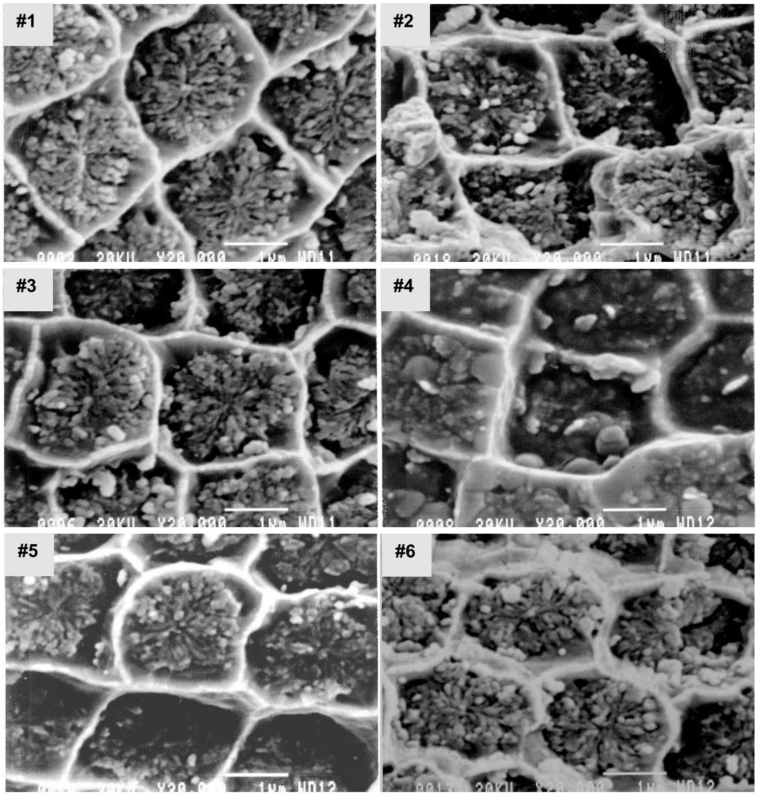

Fig. 4. SEM micro-photographs of the six samples with magnification of 20,000.

1. Sample #1 (stopped at 300°C): 808 A/mm^2, 104 mJ/cm^3 $\rightarrow$ no degradation in performance, rather good in hysteresis loss.
2. Sample #2 (stopped at 460°C, 0 h): 730 A/mm^2, 112 mJ/cm^3 $\rightarrow$ 9% of degradation compared to normal results.
3. Sample #3 (stopped at 460°C, 100 h): 804 A/mm^2, 146 mJ/cm^3 $\rightarrow$ no degradation in performance.
4. Sample #4 (stopped at 570°C, 0 h): 660 A/mm^2, 115 mJ/cm^3 $\rightarrow$ 18% of degradation compared to normal results.
5. Sample #5 (stopped at 570°C, 200 h): 704 A/mm^2, 131 mJ/cm^3 $\rightarrow$ 12% of degradation compared to normal results.
6. Sample #6 (Stopped at 660°C, 100 h): 798 A/mm^2, 152 mJ/cm^3 $\rightarrow$ no degradation in performance.

In samples #2, #4 and #5, the degradation of the performance occurred. The heat treatment in 460°C plateau is adopted to remove oil and contamination in magnet. The failure of sample #2 occurred at the start of 460°C plateau, it results the degradation of the performance. The heat treatment in 570°C plateau is used to enhance the Sn diffusion and increase the critical current density. Heat treatment failure in the 570°C plateau is expected to affect the performance; In fact, samples #4 and #5 show performance degradation and special precautions are required to prevention it.

References

[1] KSTAR team, KSTAR Tokamak Systems Engineering Review Documents, KSTAR Tokamak System Review, 1997.
[2] J.H. Schultz, KSTAR Design description Document, KSTAR Magnet. Syst. Rev. T13/14, 1999.
[3] M. Takayasu, et al., IEEE Trans. Appl. Supercond. 9 (1999) 64.
[4] E.J. Kramer, J. Appl. Phys. 44 (1973) 1360.