Heat Treatment Sensitivity of ITER CS Nb_3Sn Wire

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Abstract

The characterization of the production Nb_3Sn strands used for ITER magnet coils is essential to the quality assurance of ITER magnets. In addition, due to the possible spatial temperature variations in the heat treatment of large central solenoid (CS) and toroidal field (TF) coils, it is necessary to study the strand's heat treatment sensitivity by characterizing the strands heat treated with slightly different temperature profiles. We present critical current (I_c), residual resistivity ratio (RRR) results of ITER CS strands which are heat treated with different temperatures and durations for the last heat treatment stage.

Introduction

For ITER magnets, heat treatment schedules are designed to achieve the best overall performance of the Nb_3Sn conductor. In the actual magnet coil heat treatment, deviation from the designed schedule may occur. For example, during heat treatment, the coil temperature may not be uniform for a period of time due to the small thermal diffusivity of the thermal mass. In order to ensure the performance of the magnet coil and understand the impact of minor aberrations during heat treatment, we performed the sensitivity study of heat treatment on Nb3Sn properties.

Heat Treatment

A bronze-process Nb_3Sn strand made by JASTEC and an internal-tin strand made by KAT are studied in this work. Micrographs of cross-sections for JASTEC and KAT samples prior to heat treatment are seen in Fig. 1 (a) and (b) respectively. The diameter of the wires are 0.82 mm and Cu/non Cu ratio of 1:1.

Samples are heat treated in argon atmosphere. The nominal heat treatment schedule for each wire is shown below. Ramp rate is 5 °C/h.

JASTEC:

570 °C for 250 h,	A = 640, 650, 660 °C.
A °C for X h	X = 0, 10, 20, 40, 80, 100, 150 h.

KAT:

210 °C for 50 h,	
340 °C for 25 h,	
450 °C for 25 h,	
570 °C for 100 h,	A = 640, 650, 660 °C.
A °C for X h	X = 100, 120, 150 h.

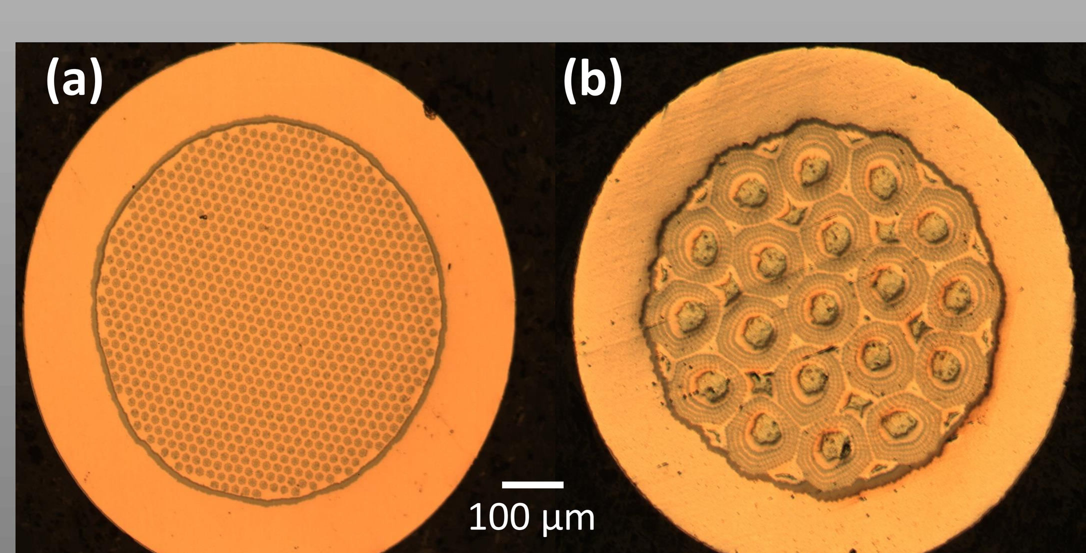

Fig. 1 JASTEC (a) and KAT (b) cross-sections before heat treatment.

Critical Current (I_c)

The effects of varying time and temperature on I_c can be seen in Fig. 2.
For JASTEC wires,

- I_c increases almost linearly with time at 650 °C. It saturates at only 20 hrs.
- I_c is not sensitive to the heat treatment temperature variation of ±10 °C.

Similarly, I_c of KAT wires seem to saturate before 100 hr.

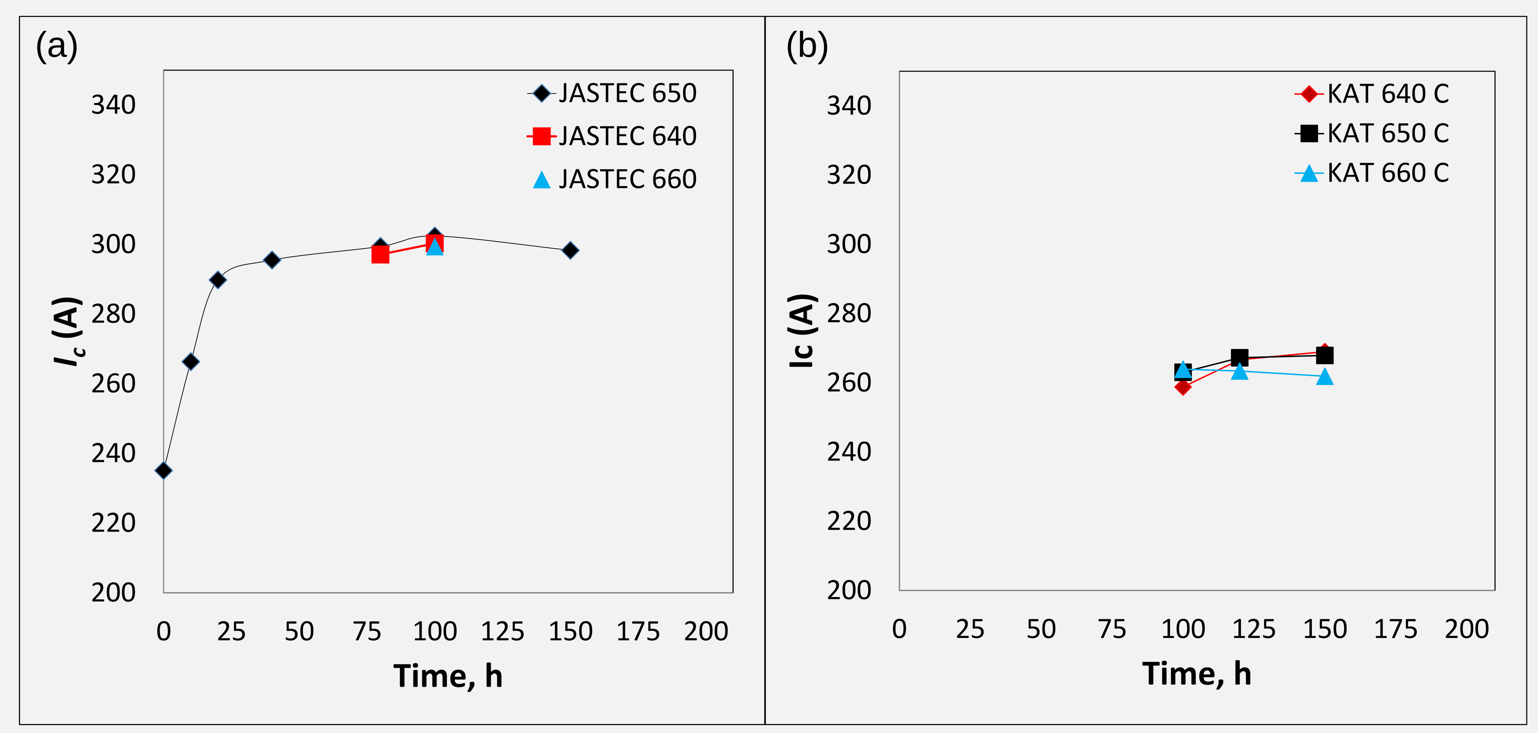

Fig 2. I_c vs heat treatment time at 12 T, 4.2 K for (a) JASTEC samples and (b) KAT samples.

Cross-sectional SEM of JASTEC samples in Fig. 3 reveals the diminishing unreacted Nb core with heat treatment time.

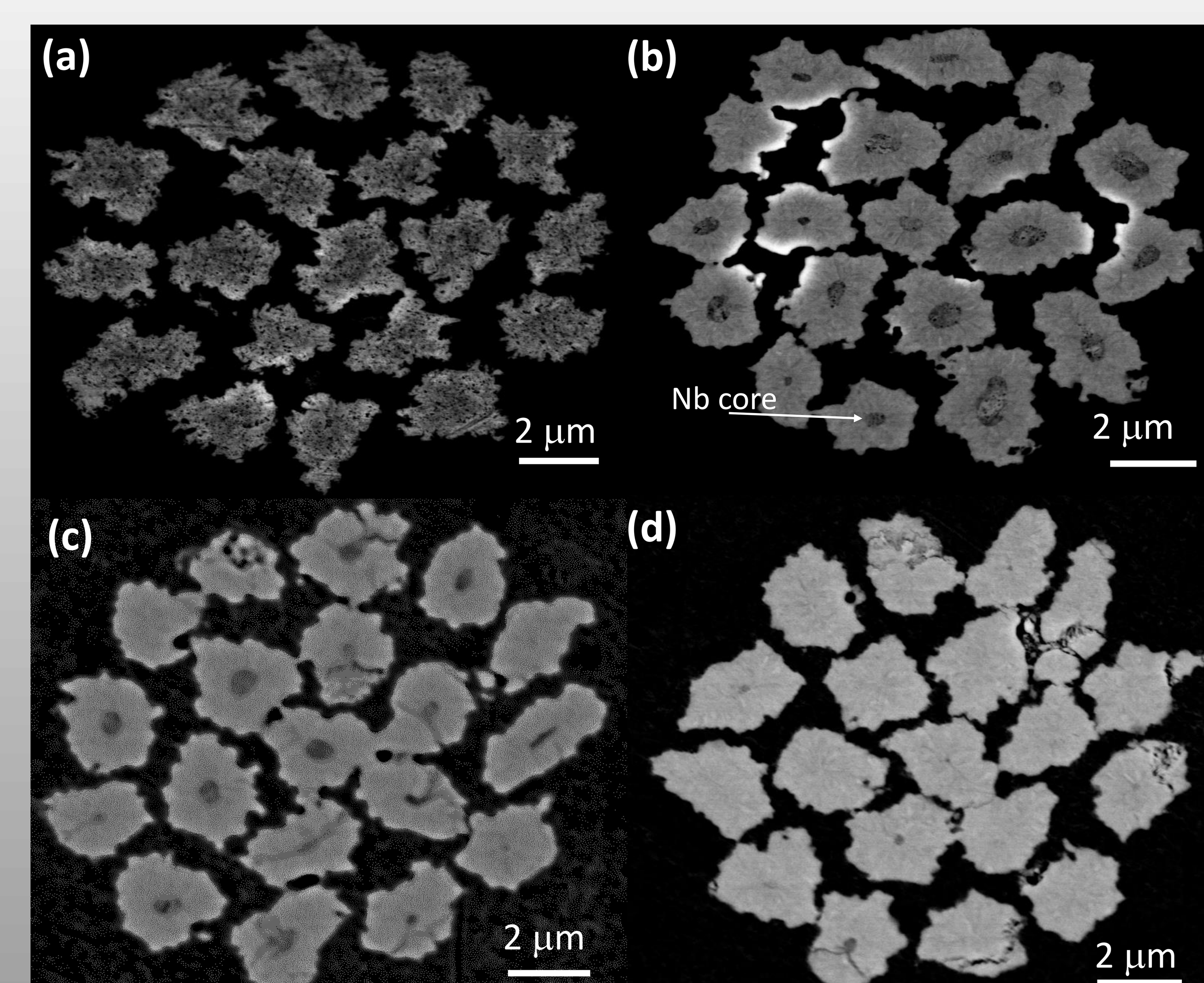

Fig. 3. SEM micrographs of JASTEC samples heat treated at 650 °C for different durations (a) 0 h, (b) 10 h, (c) 40 h, (d) 150 h.

RRR

It is widely accepted that diffusion of plated Cr layer into the copper stabilizer leads to the degradation of RRR [1]-[5]. A representation resistivity $\rho(x)$ due to Cr distribution across the copper shell [4,5] is

$$\rho(x) = \rho_0 + \delta\rho C(x) \quad (1)$$

$$C(x,t) = C_0\left[\mathrm{erfc}\left(\frac{x}{2(Dt)^{1/2}}\right)\right] \quad (2)$$

$$D = (D_0^*)e^{\frac{-E_a}{RT}} \quad (3)$$

Where ρ_0 is resistivity of the non-contaminated stabilizer, and $\delta\rho$ is the resistivity increase for 1 at % Cr. C_0 is the solubility of Cr in Cu at 650 °C, x is the distance from the Cr layer, and D, t are the diffusion coefficient and the heat treatment time, respectively. D_0^* is a diffusion constant, E_a is the activation energy, R is the universal gas constant. Fig. 4 below illustrates RRR of (a) JASTEC and (b) KAT samples with corresponding simulation curves calculated based on eqs. (1)-(3).
Our simulation gives E_a = 49.2 kcal/mol and D_0^* = 3.1 cm²/s. This can be used to predict the RRR of Nb3Sn with different heat treatment.

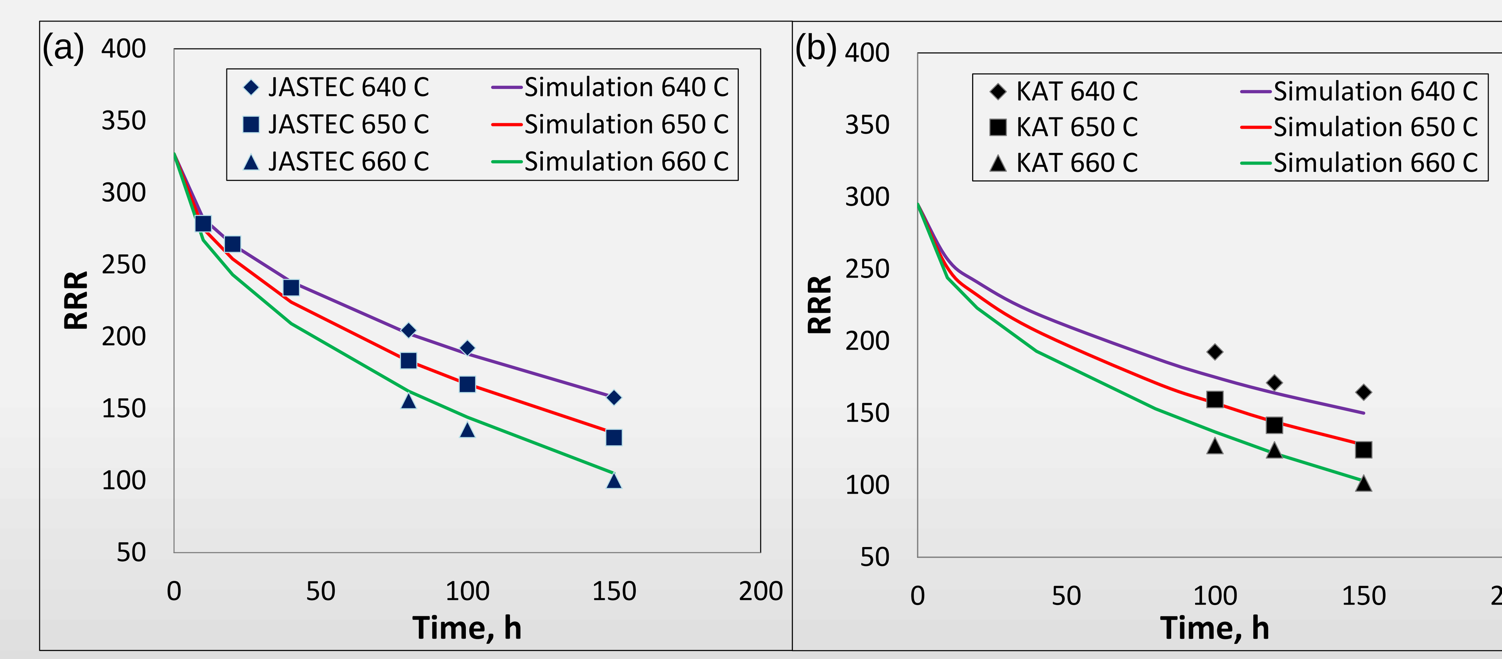

Fig. 4 RRR of JASTEC (a) and KAT (b) samples as a function of heat treatment time for a given temperature.

Conclusion

- Experimental data indicates that the properties of ITER Nb_3Sn wires are not sensitive to moderate variations in heat treatment time (80 – 150 hrs) and temperature (640 – 660 °C).
- It is suggested that the final heat treatment stage should not exceed 150 hours. I_c does not benefit from an extended time and RRR steadily decreases as Cr further diffuses into the copper stabilizer.
- Our RRR simulation may be used to predict RRR of Cr plated Nb_3Sn wire based on given HT schedule.

Acknowledgements

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References

[1] M. D. Sumption and E. W. Collings, *Proceedings of Workshop on the Effects of Chromium Coating on Nb3Sn Superconductor Strand*, Lawrence Livermore Natl. Lab., 1994.
[2] A. Vorobieva, et al., *IEEE Trans. Appl. Supercond.*, vol 10, no 1, p 1004–1007, 2000.
[3] J. Kim, et al., *IEEE Trans. Appl. Supercond.*, vol 18, no 2, p 1043–1047, 2008.
[4] D. S. Novosilova et al., *Physics of Metals and Metallography*, v 113, n 10, p 957-962, 2012.
[5] D. Butrymowicz et al., *Journal of Phys. and Chem. Ref. Data*, vol 4, no 1, p 196-198, 1975.