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Improvement Mechanism and Bending Strain Tolerance for Reinforced Bi2223 Superconducting Tapes.

M.K. Al-Mosawi, B. Xu, C. Beduz, Y. Yang, and N.G. Stephen

Mechanical Engineering, School of Engineering Sciences, University of Southampton, Southampton SO17 1BJ, UK.

maitham1@soton.ac.uk

Abstract. Comprehensive mechanical characterisation of stainless steel reinforced Bi2223 superconducting tapes was conducted using purpose built rigs. This included the effect of axial (tensile and compressive) and bending strain on the critical current (I_c) of reinforced Bi2223 tape. In addition, the axial tensile and transverse compressive stress properties of the tape were measured and evaluated. It was found that the I_c–bending strain characteristic of the tape was improved as a result of sheath reinforcement, compared to an identical tape without reinforcement. A mechanism for this improvement based on the homogenising effect of the reinforcement on strain is proposed. To avoid I_c degradation, the maximum axial stress on the reinforced tape should not exceed 350 MPa, or the tensile strain should be less than 0.65%. Furthermore, no I_c degradation was observed for transverse compressive stresses up to 100 MPa, while an axial compressive strain of about 0.3% causes about 10% drop in the critical current.

1. Introduction

As a result of significant developments in high temperature superconducting (HTS) wires, or tapes, medium scale power machines have been constructed and demonstrated [1,2]. In these power applications of superconductors, the tapes experience significant stresses and strains during initial device fabrication and subsequent machine operation. These stresses and strains are known to degrade the critical current of the tape. Hence the I_c-stress and strain characterisation of the conductor is an important parameter to be taken into account before designing and building practical HTS devices.

This paper describes the experiments undertaken to determine the I_c-dependence on stress and strain of superconducting tapes at 77 K, as part of a project at the University of Southampton to design, build and test a high temperature superconducting generator [1]. The stainless steel reinforced Bi2223 tape, with a nominal I_c of >115 A at 77 K, were manufactured by American Superconductors. The present results were crucial for modelling and predicting performances during operation of the generator and also represent a means of quality control to ensure suitability of the tapes and coils for use in the machine.

2. Axial strain measurement

Tensile and compression characteristics of superconducting tapes were undertaken. A tensile test machine was used for the stress-strain (σ-ε) characteristics of tapes with loads up to 25 kN applied through a load cell. Sample extension was measured by strain gauges mounted on the tape using a half bridge circuit to compensate for temperature changes. Critical current values for various strains were normalized by using the I_c value at zero-strain, $I_c(0)$, and are denoted as $I_{c,n}$. For the tensile test, superconducting tapes with flexible current leads and voltage taps were carefully gripped using purpose built non-slip chucks, and immersed in liquid nitrogen. In contrast, for the axial compression tests, an unsupported HTS tape specimen (10 cm long) has a very large slenderness ratio resulting in a low buckling load. Hence two tapes were soldered to the outer surface of an annealed copper tube and were positioned diametrically opposite to provide structural symmetry. The pre-strain due to the differential thermal contraction of the soldered tape and the copper tube at 77 K were taken into account by measuring the linear thermal contraction of both which was used to correct the axial compression strain experienced by the tape.

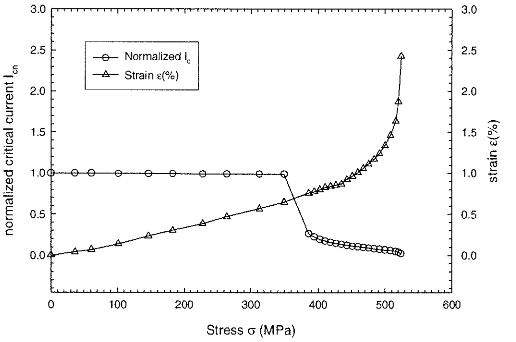

Figure 1 Axial tensile stress-strain-normalized critical current relationship for Bi-2223 reinforced tape.

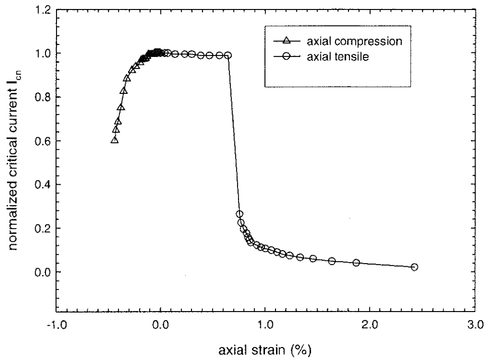

Figure 2 Effect of axial strain normalized critical current of Bi-2223 reinforced tape.

The stress-strain characteristic and the normalized critical current I_c-axial tensile stress curve at 77 K are presented in Figure 1. It can be seen that there is no critical current degradation until the tensile stress reaches 350 MPa, at 0.65% strain, when an abrupt drop in the I_c occurs. This is followed by a gradual degradation until the sample fracture at a stress of about 524 MPa and a strain of 2.4%. It is of interest to note that this abrupt drop takes place while the stress-strain characteristic is still essentially proportional. The yield strength of the tape can be as large as 410 MPa (0.2% offset strength), which is more than six times the value for the conventional Ag sheathed tape [3]. This enhancement in performance can be attributed to the stainless steel reinforcement of the tape.

Figure 2 shows an asymmetric profile for a Bi-2223 reinforced tape under axial strain. The asymmetry is attributed to pre-compression of the ceramic filaments by the metal matrix during the cool-down from the annealing temperature to the 77 K test temperature according to the commonly accepted irreversible I_c reduction model proposed by ten Haken et al [4]. At low tensile strain levels, the plateau is partly due to relaxation of pre-compression. However, there is a small (0.06%) but noticeable plateau in the compressive regime, indicating an intrinsic I_c tolerance within the ceramic core. At large strain levels, the abrupt drop is thought to be due to the propagation of cracks. The compressive strain limit $\varepsilon_{c,0.9}$ (at 90% of the I_c at zero strain) is about −0.3%, which is smaller in magnitude than the tensile strain limit of 0.65%.

3. Transverse compression measurement

In the transverse compression test, Figure 3, a bar of 10 mm diameter was pressed onto a set of three tapes glued side by side with a 0.5 mm gap between; current leads and voltage taps were attached to the middle tape only, and were positioned to measure the voltage across the compressed section of the tape. The other two tapes helped to prevent tipping of the bar. The transverse compressive stress dependence of the normalized critical current $I_{c,n}$ of the reinforced tape at 77 K, self field is shown in

Figure 3. The stress limit $\sigma_{tc,0.9}$ is found to be about 100 MPa. This high compressive stress, compared to Ag and Ag alloy sheathed tapes, can be attributed to the high strength of the stainless steel reinforcement sheath.

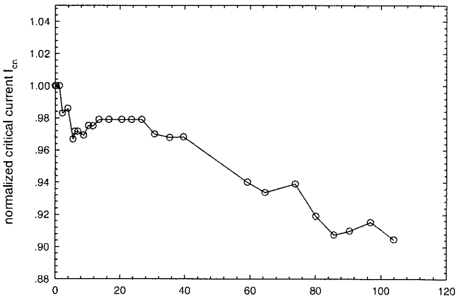

Figure 3 Effect of transverse compressive stress on I_c of Bi-2223 reinforced tape.

4. Bending strain measurement

The effects of bending strain on I_c at 77 K were also measured using a set of eight holders, of radii 54, 41, 30, 15, 12.5, 10, 7.5 and 5 mm. A specimen of the reinforced tape (RT), of length 95 mm, was instrumented, and successively mounted onto the holders to progressively decrease the bending radius to 5 mm. The experiments were then repeated with tape from which the stainless steel reinforcement had been removed (NRT).

Figure 4 shows the I_c-bending strain characteristic of the Bi-2223 tape with (RT), and without (NRT) reinforcement. For the RT, there is no drop in I_c up to a strain of 0.25% (bending radius of 48 mm), followed by a gradual decrease to 50% of I_c at a strain of 2.4% (bending radius of 5 mm). The degradation for the NRT seems to be always greater, although the difference is not significant for bending strains less than 0.4%, when the NRT performance declines rapidly. For strain above 0.8% the differences in I_c degradation between RT and NRT maintains a near constant value of 0.20 up to a bending strain of 2.4% at the smallest bending radius. The bending strain limits $\varepsilon_{b,0.9}$ for RT and NRT are 0.95% and 0.45%, respectively.

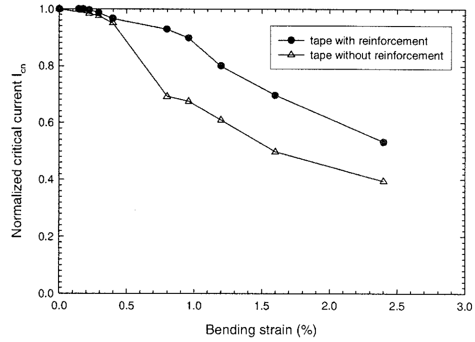

Figure 4 Effect of bending strain on normalized critical current of Bi-2223 tapes with and without reinforcement.

5. Improvement mechanism in bending strain tolerance for reinforced tapes

The significant improvement in the I_c-bending strain characteristic of the reinforced tape is attributed to the homogenising effect on axial strain provided by the reinforcement; the argument is most easily developed in the context of tension, but readily extends to bending, which consists of tension and compression above and below the neutral axis. Close investigation of the tape cross section shows that the individual filaments within the tape are not of uniform cross-sectional area – if one were to prepare a second photomicrograph from some other location along the tape, one would expect the total cross-sectional area of all the ceramic fibres to be largely unchanged, while the cross-sectional area of individual fibres occupying the same nominal location within the cross-section would be different. Consider an idealisation of one such fibre whose cross-sectional area is assumed to reduce linearly from a maximum value A, to a minimum area a, over some gauge length L (Figure 5), representing sausaging of the filaments; the generic cross-sectional area may be expressed as

$A(x) = A(1 - x/L) + ax/L$.

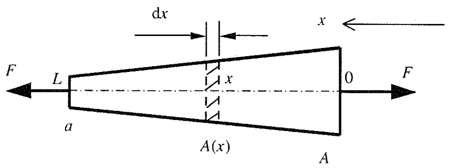

Figure 5 Schematic representation of an individual filament.

The critical current of this fibre will be determined by the maximum axial strain, which will occur at the smallest cross-section and may be expressed as

$\varepsilon_{\max} = F/(Ea)$,

where F is the axial force carried by the fibre, and E is the Young's modulus. For a typical element of length $\mathrm{d}\,x$, the change in length δL due to the applied force F is

$\delta L = \varepsilon_x \times \mathrm{d}\,x$

where ε_x is the local strain, calculated as

$\varepsilon_x = F/(E \times A(x))$.

On the other hand, the apparent axial strain over the gauge length L may be calculated as

$$\varepsilon_{apparent} = \frac{1}{L}\int_0^L \delta L = \frac{1}{L}\int_0^L \frac{F}{EA(x)}\mathrm{d}\,x .$$

Substitute $A(x)$ into the above equation, and $\varepsilon_{apparent}$ can be rewritten as

$\varepsilon_{apparent} = F\ln\left(A/a\right)/\left(E\left(A-a\right)\right)$;

this is what is measured on the surface of the tape. For an area ratio $A/a = 2$, the maximum strain is 44% greater than the apparent strain. It is concluded that the effect of tape reinforcement is to level out the "peaks and troughs" in the axial strain, and so reduce the maximum axial strain closer to the apparent value and, in turn, increase the critical current.

6. Summary

Mechanical tests on Bi2223 tapes at 77 K indicate that in order to avoid I_c degradation, the maximum tensile (hoop) stress on the reinforced tape should be no more than 350 MPa, or the tensile strain should be less than 0.65%. To maintain the $I_{c,n}$ above 0.9, the axial compressive strain should not exceed –0.3%. The transverse compressive stress should not exceed 100 MPa to avoid an abrupt drop in performance. The bending radius of the coil should not be less than 13mm (corresponding to 0.9% bending strain) due to the effect of bending strain on the tape during the winding operation.

The results show that the specifications and properties of the tape fulfilled the requirements for the design and construction of the superconducting generator, and confirm that the reinforced tape has much better handling characteristics. A mechanism for this improvement, based on the homogenising effect of the reinforcement on strain, is proposed.

References

[1] Al-Mosawi M.K., Beduz C. and Yang Y., "The Construction of 100KVA High Temperature Superconducting Synchronous Generator", *IEEE Transaction on Applied Superconductivity*, 15(2), 2005, pp. 2182-2185.

[2] Kalsi S. , "Advances in Synchronous Machines Employing High Temperature Superconductors", *Electric Machines and Drives Conference 2003, IEMDC '03, IEEE International*, **1**, June 2003, pp.24-28.

[3] Ullmann B., Gabler A., Guilitz M. and Goldacker W., "Transport critical currents of Bi(2223) tapes at 77K under mechanical stress", *IEEE Transaction on Applied Superconductivity*, 7(2), 1997, pp. 2042-2045.

[4] ten Haken B., Godeke A., Schuver H. and ten Kate H.J., "Descriptive model for the critical current as a function of axial strain in Bi-2212/Ag wires", *IEEE Transaction on Magnetics*, 32(4), 1996, pp. 2720-2723.