METALLOGRAPHIC INVESTIGATION OF FRACTURE BEHAVIOR IN ITER-STYLE NB$_3$SN SUPERCONDUCTING STRANDS

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Abstract

In this work we specify the extent to which fracture in two ITER-style Nb$_3$Sn composite strands occurs in a collective or individual manner, under mechanical tension and bending from the TARSIS apparatus at the University of Twente. A bronze-route strand from European Advanced Superconductors (EAS), which has very uniform, well-spaced filaments, has a widely distributed (200 μm) fracture field and exhibits a composite of individual and collective cracks. An internal tin strand from Oxford Instruments – Superconducting Technology (OST) demonstrates much more localized, collective fracture behavior. The filaments in this strand are about four times larger (in area) than the filaments in the EAS strand, and also agglomerate significantly during heat treatment upon conversion of the Nb to Nb$_3$Sn. These results demonstrate that the architecture of the strand can play a significant role in determining the mechanical toughness of the composite, and that strand design should incorporate mechanical considerations in addition to electromagnetic and fabricability considerations.

INTRODUCTION

Fracture of Nb$_3$Sn filaments is a primary cause of irreversible critical current degradation in cable-in-conduit magnet systems utilizing Nb$_3$Sn composite wire. Under large Lorentz forces, the accumulated magnetic pressure can cause individual filaments or collections of filaments to fracture, preventing them from carrying electrical current. In general, the brittle Nb$_3$Sn phase fractures intergranularly and leaves the ductile interfilamentary Cu and any unrected Nb intact.

However, there exists relatively little data in the extant literature to describe the mechanisms and microstructural features that lead to crack formation and propagation. In fact, direct observation of the number, size, and distribution of fracture events in Nb$_3$Sn composite wire has received surprisingly little attention by the superconducting community. Zhang, Ochiai, and Osamura [1] evaluated fracture using metallography in bronze-processed wires in 1989. Their uniaxial strain test (conducted at room temperature) concluded that lower Nb$_3$Sn fractions in the composite actually increased fracture due to the matrix more effectively transferring load to the filaments. Van Oort [2] also examined fracture behavior after cabling by metallography and noticed that fracture incidents seemed to be correlated with microstructural features such as Kirkendall voids. Lee [3] has detected fracture events in Nb$_3$Sn tape conductor using an acoustic emission (AE) technique. While AE is attractive because it is non-destructive, the spatial resolution of the technique is not sufficient to image cracks in the 3 – 5 μm filaments of modern Nb$_3$Sn strand.

There is also not a great deal of relevant literature available from the wider metal-matrix composite (MMC) community. In the vast majority of MMC systems, the filamentary component is designed to improve the mechanical properties (strength, stiffness, or toughness) of the composite. Most experimental characterization and modeling efforts focus on how the filamentary structure affects the fracture or fatigue properties of the matrix. There are few applications for which the continuous mechanical integrity of the filaments is important for its own sake. Nevertheless, there are a few tantalizing clues in the literature to suggest that filament architecture can play an important role in determining the fracture behavior of the composite. For example, the results of Brockenbrough [4] suggest that the filament stacking pattern (square, hexagonal, etc.) has a very significant effect on the constitutive response of aluminum-boron MMC material as measured in transverse tension and transverse shear.

In this study, we will compare the fracture morphology (as revealed by metallography) of two commercially useful Nb$_3$Sn ITER-style conductors that have been subjected to electromechanical testing in the TARSIS apparatus at the University of Twente.

EXPERIMENTAL PROCEDURE

The TARSIS strain rig is a unique device invented at the University of Twente (Netherlands) that allows for the simultaneous mechanical deformation and critical current testing of Nb$_3$Sn superconducting strands. A more complete description of the technique and some representative results may be found here [5]. TARSIS can be equipped a periodic bending probe that uses a series of protruding bulges, arranged in a periodic fashion around the circumference of a barrel, to apply a combination of tension and periodic bending to the superconducting sample. In the sample set investigated here, the bending probe had a wavelength of 5 mm.

Each sample was extracted from the probe after full electromagnetic characterization, and metallographically mounted in the plane perpendicular to the loading direction. This allows for purely tensile (at the full wavelength position) and purely compressive (at the half wavelength position) regions to be imaged for damage characterization. Metallographic polishing was performed using SiC paper for rough grinding and flattening, followed by fixed diamond abrasives at 15 μm and 8 μm and diamond paste on napless cloth at 3 μm and

1 µm. Final polishing was performed on a napless chemo-textile cloth using 0.05 µm colloidal silica.

Imaging was performed on a Zeiss 1540 XB Field Emission Scanning Electron Microscope (FESEM) using both secondary (SE) and backscatter electron (BSE) detectors.

RESULTS AND DISCUSSION

Figures 1 and 2 show longitudinal cross section of EAS and Oxford ITER strands, respectively, near the peak bending position where fracture occurs. The inset in each image shows a transverse cross section of the strand being imaged, and also specifies the maximum peak bending strain on the sample, along with the fraction of initial critical current (I_c) remaining after testing.

The EAS strand is a bronze-process strand comprised of 8305 filaments segregated into 151 sub-bundles. The filaments are in general well-separated one from another, both before and after heat treatment. The filaments have an average post-heat treatment area of 9.0 µm^2, which corresponds to an effective circular diameter of 3.4 µm.

The Oxford strand is an internal tin strand comprised of 3097 filaments segregated into 19 sub-bundles. The filaments in this strand, while well-separated before heat treatment, tend to agglomerate after conversion from Nb to Nb_3Sn. These filaments are also much larger than the EAS filaments, with an area of 31.1 µm^2, which corresponds to an effective circular diameter of 6.3 µm.

The fracture morphology resultant from the TARSIS test is shown for EAS and Oxford strands in figures 1 and 2, respectively. The thick, horizontal layer on the top and bottom of each image is the Ta diffusion barrier of the wire. The EAS strand demonstrates a combination of individual and collective cracking events. The cracking is distributed over approximately 200 µm of wire length, and although some sub-bundles do fracture in a collective manner, there is no single dominant fracture event, despite this strand being deformed to 1.7% peak bending strain. At that strain value, the strand still retained 15% of its original I_c value.

The Oxford strand, by contrast, exhibits a completely collective cracking event. The entire damage region consists of a single crack that propagates through the peak bend strain position. The spatial extent of the fracture field is very narrow (less than 10 µm). Interestingly, the sub-bundle cores (the locations of the Sn reservoir prior to reaction in this internal Sn strand), which are now primarily filled with Cu, do not, in general, fracture. The interpretation here is that the soft, ductile Cu arrests crack growth, but since the brittle filaments form a partially agglomerated annulus around the core, the cracks can propagate circumferentially. Note that this relatively simple damage layer degrades I_c to just 3% of its original value, compared to 15% remaining for the EAS strand with the much wider fracture field.

There are at least two clear implications from this work. First, that the architecture of the stand – the size, spacing, and agglomeration of the filaments – can have a significant impact on the fracture properties of the material.

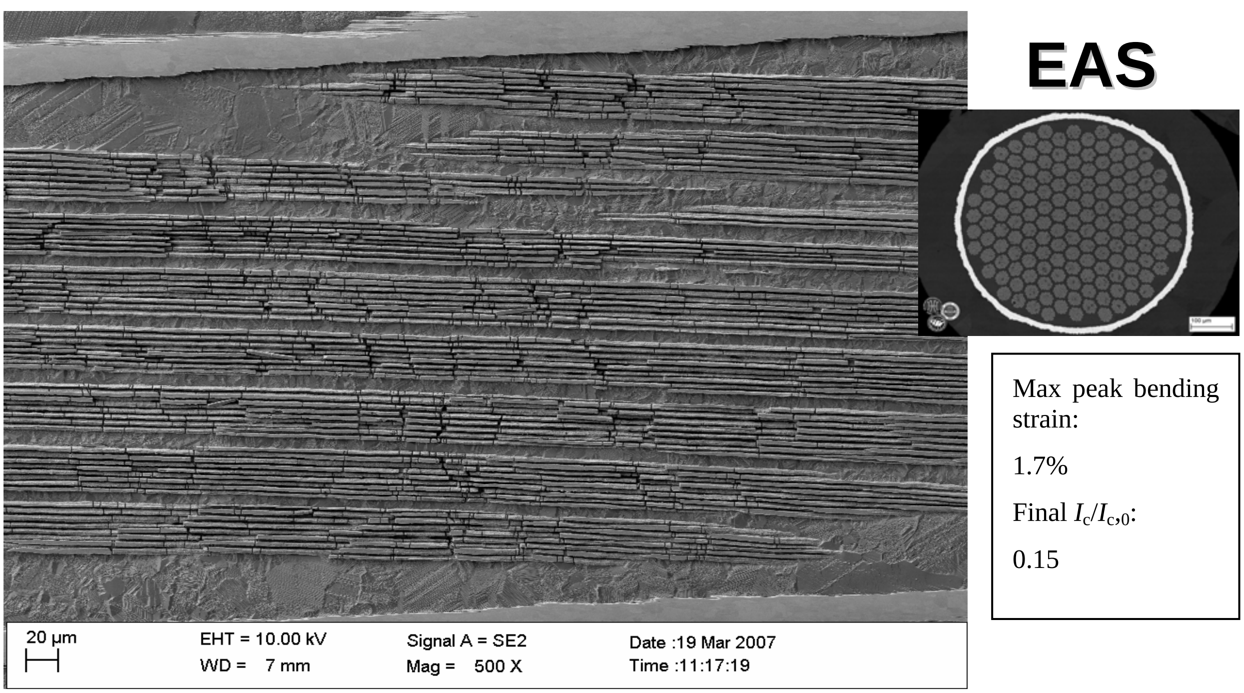
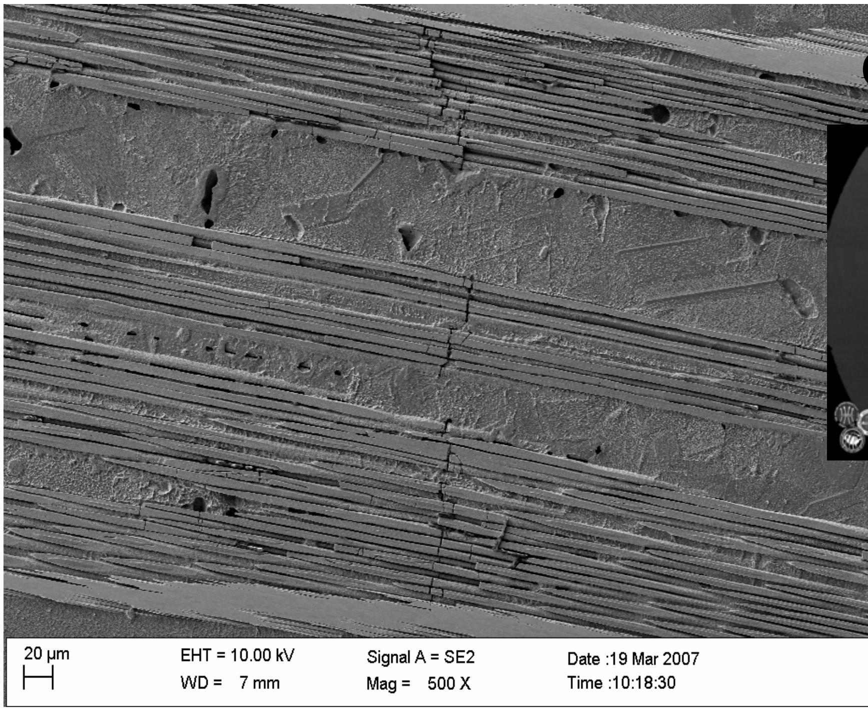
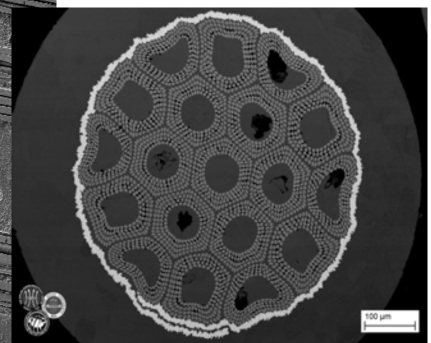


Figure 1. EAS 5 mm bend fracture field after TARSIS testing. The spatial extent of the fracture field is ~200 µm, with a balanced mixture of correlated and non-correlated fracture events.



Oxford ITER



Max peak bending strain:

1.5%

Final $I_c/I_{c,0}$:

0.03

Figure 2. Oxford ITER 5mm bend fracture field after TARSIS testing. Here, the fracture is clearly centered around a central crack, with almost no ancillary damage whatsoever.

In particular the larger, more highly agglomerated Oxford filaments provide a much more conducive environment for the propagation of cracks than the smaller, well-distributed filaments of the EAS design. In the EAS strand, the interfilamentary Cu arrests crack growth more effectively since the cracks can not find a mechanically connected path to jump from filament to filament.

The second implication of this work is that the extent to which fracture is individual or collective plays a key role in determining the I_c degradation experienced by the strand. The EAS strand has, numerically, over an order of magnitude more cracks than the Oxford strand, yet resists I_c degradation much better since the cracks are more individual and less collective in nature.

CONCLUSIONS

Two ITER candidate strands were evaluated metallographically for fracture propensity after electromechanical testing in the TARSIS apparatus at the University of Twente. The bronze-process EAS strand has small (3.4 µm diameter), well-separated filaments, and the resulting fracture field is distributed over 200 µm, with a mixture of individual and collective fracture events. The internal tin Oxford strand, by contrast, has larger (6.3 µm dimater) filaments that are partially agglomerated. Here, the fracture pattern is highly collective.

The more collective cracking clearly has a more significant impact on the I_c, with the Oxford strand falling to just 3% of its original value, compared with 15% in the EAS strand. Thus, there is a clear role for strand manufacturers to help provide mechanical toughness to Nb_3Sn strands through the design process.

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