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ABSTRACT

The effect of transverse stress on critical current has been examined for Cable-In-Conduit Conductors (CICC's) containing three active superconducting composite strands in cables containing a total of 21 strands. In measurements of this type reported previously, only soft copper was used for the inactive strands, allowing the possibility that peaking of stresses at strand cross-over points were avoided by deformation of the copper strands during CICC fabrication and testing. In the present experiments, the degree of critical current degradation was measured as a function of applied load for various void fractions for cable patterns using stainless steel wires as the inactive strands. The reduction of critical current, expressed as a function of load divided by the projected area of the core of the superconducting composite strand, was found to be similar to that observed in cables containing copper inactive strands. All the CICC's tested show a higher sensitivity to transverse stress as compared to single wires. At compressive loads of 50 MPa or less, the region of interest to magnet designers, the critical current is, at worse, 79% of the critical current in unloaded samples. The sensitivity to transverse load is a function of CICC void fraction, lower void fractions having less susceptibility to degradation. The results of this investigation indicate that the performance of large magnets employing CICC designs need not be seriously degraded due to transmitted or self-induced Lorentz loads.

INTRODUCTION

The effect of axial strain on Nb_3Sn superconductors has been widely studied and documented (see for example Ref. 1 and 2). This previous work has led to the development of strain scaling laws for the prediction of H_{c2} and I_c as a function of residual or applied strain and the prediction of multifilamentary conductor stress states based on the volume fractions and thermal-mechanical properties of the conductor constituents. [3,4,5]

Recently the effect of transverse stress on single wires of Nb_3Sn has been studied.[6,7,8] Investigators have found that degradation of I_c with stress apparently occurs much faster under conditions of transverse stress than equivalent conditions of axial stress. Significantly degraded performance is observed at compressive stress levels as low as 50 MPa in multifilamentary superconductors.[6]

This has raised serious question about the suitability of CICC's in large applications where transverse stresses, either transmitted from adjacent conductors or generated within a single CICC, could potentially degrade performance below acceptable levels. Recent work shows that transmitted loads are not a concern in CICC's.[9] The conductor conduit is extremely stiff with respect to the internal cable and bears a major fraction of loads transmitted from adjacent conductors. The average stress transmitted to the cable is only 3% of the average applied load and the peak stress is about 7%.

Although the effect of transverse stress is reasonable well understood for monolithic conductors and single wires, analysis of the effects of self generated loads in a CICC is complicated. This complication arises from the variation in the size of the load "footprint". Conductors lying on the inner face of the conduit in the direction of the J X B forces have a contact footprint on the conduit side that may be conveniently described by some aspect of their geometry, such projected cross sectional area, projected area of superconducting core, etc. The opposite face of these conductors in the direction of the interior of the CICC, as well as other conductors within the cable space, have load footprints that are described by the contact points between wires in the cable. The size of these contact points are a function of the cable size, cable twist pitch, and the amount of compaction during CICC fabrication.

Previously we reported the results of an investigation to experimentally measure transverse stress effects in CICC's of various void fractions. [10] Critical current degradation under transverse loads was found to be significantly worse than in single wires, however at low compressive stress ($\sigma < -50$ MPa) performance was not sufficiently degraded to preclude the use of CICC's in large applications such as magnets for fusion energy. The CICC's used in this investigation were fabricated using 3^3 cables of which 3 strands were superconductor and the remaining 24 strands were inactive copper. This configuration was chosen to reduce the effect of self generated lorentz loads, allowing control of transverse loads by external means under the experimenter direct control.

However, these CICC samples had several deficiencies. First, the position active superconducting strands with the conduit and cable bundle is random due to cable transposition. At certain locations the superconductor may lie along the inner wall of the conduit, while at other locations it may be found near the center of the cable. The geometry of wires near the center of the cable is also variable as the number of nearest neighbor wires is random. Thus the number number and type of load contacts variy from specimen to specimen and along the length of individual specimens. This was suspected of causing the large scatter in previously reported data. A second disadvantage of the earlier specimen design is the use of copper strands as the inactive elements. It was suggested that at high applied loads the soft copper could deform and increase the size of the load footprint thus reducing the effect of transverse compression.

In this investigation we tested CICC specimens fabricated using cables with a $(6 \times 1)^3$ cable pattern wherein the central strand is superconductor and the outer six strands are stainless steel. The hard stainless steel will not easily deform under applied load and will tend to minimize the size of the load footprint. Secondly the 6 x 1 cable first element, with the superconductor in the center, will mitigate geometry effects as the superconductor will always have 6 wire nearest neighbors and no contact with the inner face of the conduit.

EXPERIMENTAL PROCEDURE

We elected to evaluate transverse stress effects using sub-sized CICC conductors manufactured using 21 strand cables in a $(6 \times 1)^3$ cable pattern. Although we wanted to examine the effects of the internal, self generated load in a CICC, we also wanted to have external control of the transverse load, To accomplish that, we elected to test CICC's with a weakened jacket wall to allow direct transfer of an external load. Additionally, the cables inside were fabricated with only three active superconducting strands (the remaining 18 were stainless steel) so that the self-generated transverse load was minimal and the total transverse load on the strands was dominated by the externally applied load. The superconductor employed was a 0.9 mm diameter, modified jelly roll, binary Nb_3Sn with a non-copper volume fraction of 0.65.

The 27 strand cables were inserted into 304 stainless steel tubes and processed with a combination of swagging and Turk's head rolling to produce CICC's of square cross section. The rolling and swagging operations were terminated at reduction levels which produced conductors with helium void fractions of 0.40 and 0.30. Current contacts were attached to the specimens by swagging ETP copper fittings to the wire bundles protruding from the ends of the tubes. The CICC specifications are shown in Table 1.

The CICC were then given a reaction heat treatment at 700° C for 100 hours. After removal from the furnace opposite faces of the CICC were slotted with using an end mill. The slots were centered on the CICC face, were approximately 150 mm long, and sufficiently deep so as to leave only a thin foil

Table 1. Specifications of the CICC's used in this investigation.

Void Fraction %	Cable Pattern	External Dimension (Flat to Flat) mm	Wall Thickness mm
40	$(6 \times 1)^3$	6.33	0.71
30	$(6 \times 1)^3$	6.06	0.76

of the conduit at the bottom of the slot. The purpose of the slot was to remove supporting structural material so that the conduit was free to collapse on application of applied load. Virtually all of the applied transverse force is transmitted to the cable. This configuration and loading sequence efficiently mimics the internal J X B forces experienced by a much larger CICC.

The CICC's were tested in a 12 T split pair solenoid superconducting magnet equipped with a transverse load cage. The load cage is constructed of 304 stainless steel and consists of a movable ram that is actuated by a pressurized diaphragm. The diaphragm and cage assembly is immersed in LHe and is usable up to approximately 13.5 MPa, the solidification pressure of He at 4.2 K.

The loading forces are transmitted through the specimen and reacted against a fixed anvil attached to a tension tube and located at the opposite end of the load cage. The test specimen enters the assembly through a radial access port in the magnet and passes through a slot in the transverse load cage. The anvil and ram apply the load to a 38 mm length of the CICC. A diagram of the apparatus is shown in Figure 1.

The amount of force is measured indirectly using two temperature and field calibrated strain gages attached to the tension tube of the load cage and

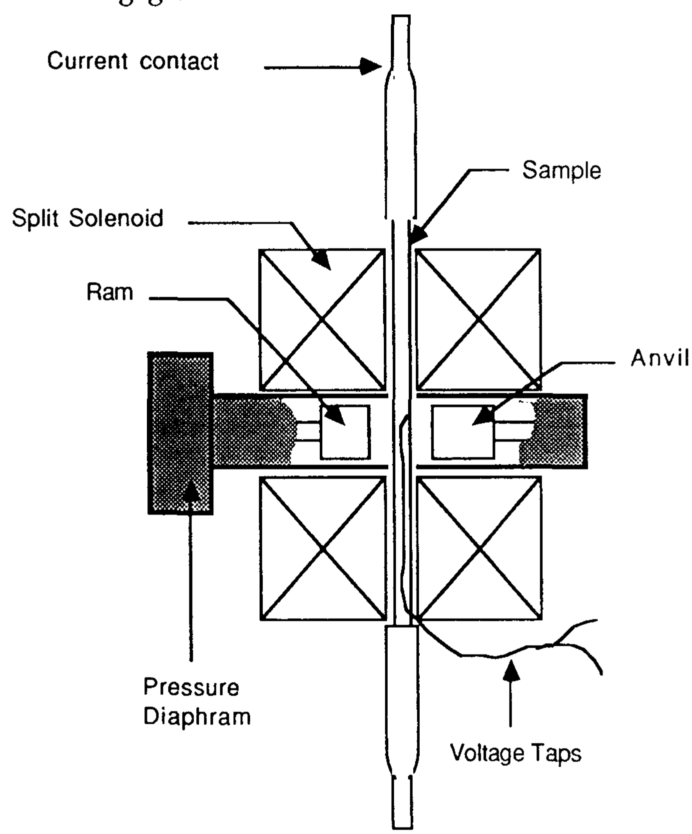

Figure 1. Sample arrangement within the test magnet and transverse load cage. (not to scale)

located 180° apart. Published values for the 4 K modulus of 304 stainless steel were used for purposes of calculation. The stress in the cable is calculate using the projected area of the non-Cu cores.

Critical current was measured by voltage taps attached to the specimen conduit in the loaded section. The distance between voltage taps was 20 mm and I_c was determined using a voltage criteria of 1 $\mu V\ cm^{-1}$.

RESULTS

The data obtained from tests of 40% and 30% void fraction CICC's is shown in Figure 2. For reference a plot of Ekin's data for single round wires shown. His 10 T data was converted to 12 T using a procedure described previously.[10] The shaded region bounds the results of previous tests of 27 strand CICC's containing Cu inactive strands.

A cross section of a region in a 40% void specimen that was not loaded in compression is shown in Figure 3a. The three active strands of superconductor can be seen at the center of each 6 x 1 first element. Note the severe deformation of the superconductor that occurred during fabrication. A cross section of the same specimen in a region actively loaded during testing is shown

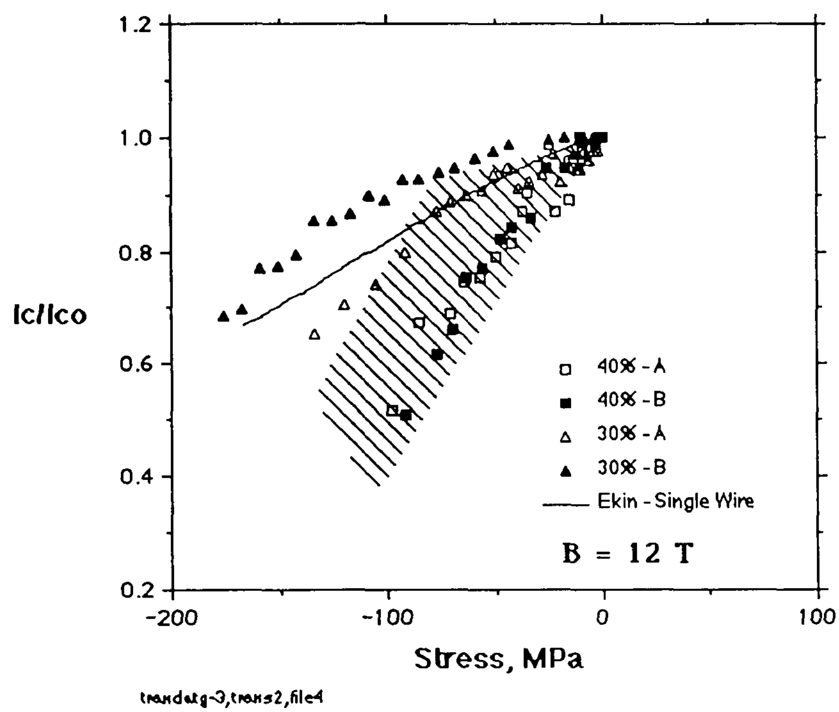

Figure 2. Normalized critical currents in $(6 \times 1)^3$ cables as a function of transverse stress and the void fractions shown. Data points A and B at each void fraction are for multiple specimens. The shaded area bounds a region in which data for 27 strand 3^3 cables using Cu inactive elements lies. Ekin's data for single strand wire is shown for reference.

in Figure 3b. Note the slits in the conduit wall that allow almost all the applied load to be transmitted to the cable. Deformation of the superconductor that occurs during testing is not discernable because of the deformation occurring during fabrication.

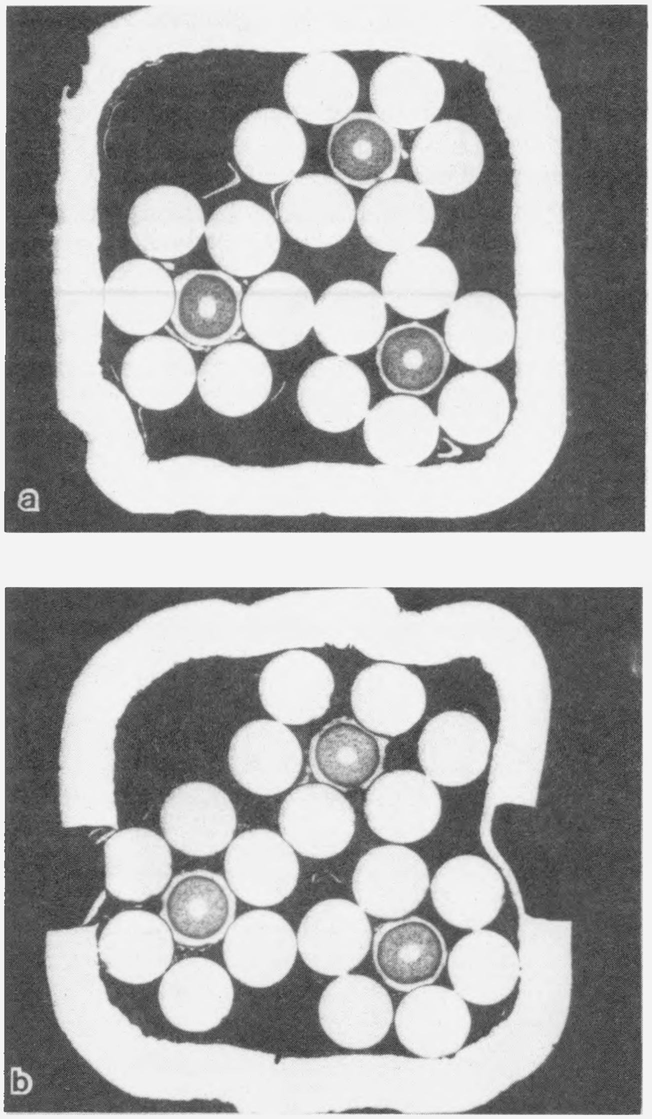

Figure 3. Cross section of a 40% void CICC specimen. A region of the specimen that was not loaded in compression is shown in 3a. An area of the same specimen that was loaded in transverse compression is shown in 3b.

DISCUSSION

While there is good agreement between the data for the two 40% void specimens, there is considerable scatter between the two 30% specimens. As with previous tests, the stress state of the Nb_3Sn wires may vary as a function of position within the CICC. This is particularly noticeable in the 30% void specimen B which has less sensitivity to transverse stress than single wires. Obviously one or more of the superconducting wires in this specimen is shielded from the applied load. Attempts to control the scatter by using 6 x 1 cable patterns have not been wholly successful.

Regardless of the scatter in data the effect of void fraction is clearly evident. The 40% void fraction specimens receive less compaction than the 30% void specimens during fabrication. Therefore, the cross over points between wires in the higher void samples do not deform as much as in the low void specimens. The load foot print is smaller in high void samples and the higher contact loading results in increased susceptibility to applied transverse loads.

Use of stainless steel wires in the cable may not have had the desired effect on transverse load sensitivity. One would assume that the inactive steel wires cannot be as easily deformed as the dead soft copper used in earlier studies. Ideally this would limit deformation at wire cross over points at high loads and result in more severe critical current degradation. As seen in Figure 2, however, all the data falls in or above the trend band for the cables made using copper wires.

A possible explanation for this is the high deformation that takes place during CICC compaction. The steel, although annealed, is harder to deform than the superconductor. When the CICC is swagged and rolled square allot of the deformation is taken up by the superconductor alone. Therefore the cross over points between the steel and Nb_3Sn are highly deformed prior to application of the transverse load. Point contact is not as severe and the samples show less susceptibility to transverse stress. Further testing using 25% and 35% void fraction specimens is being pursued and those results may confirm this hypothesis.

The impact of transverse stress effects on CICC's used in large applications is limited. As an example a 36 kA, 11 T superconductor proposed for ITER Toroidal Field (TF) coils will produce only a 30 MPa lorentz force due to self loading. The resulting degradation of critical current in this large conductor would be less than 20% according to this and previous data. In addition, a magnet designer also has the option to change the conductor height in the direction of the lorentz force thus reducing self loading.

CONCLUSIONS

Transverse stress effects scale with CICC void fraction. This is likely due to increasing point contact with increasing void fraction.

There is significant scatter in the data of some specimens tested. This indicates that geometric effects have not been fully mitigated by use of $(6 \times 1)^3$ cable patterns.

Use of inactive steel strands result in less sensitivity to transverse stress. this may result from high deformation at steel/Nb_3Sn cross over points during fabrication. This deformation masks the effect of the reduction of deformation anticipated during application of an external load.

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