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Effect of cycling transverse load on the performance of round strands made by twisted stacks of HTS tapes

Cyclic load effect on round strands made by twisted stacks of HTS tapes

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Abstract

Various DC tests performed recently with full–size 60 kA HTS cable prototypes in the EDIPO test facility demonstrated that proposed design of HTS strand at Swiss Plasma Center (SPC) - stack of HTS tapes twisted and soldered between two copper profiles - is applicable for high-current fusion cables, but additional mechanical reinforcement is still needed. Based on experimentally obtained correlation between the performances of cable prototypes at different operating conditions, further investigation of cyclic transverse load on the strand performance was performed at 77 K. Aiming to obtain a strand design able to withstand a continuous cyclic load operation of some thousand cycles, influence of the strand geometry and tape's manufacturer has been studied. Cyclic load has been applied up to 1000 cycles for straight and bent samples at the load amplitudes up to 40 MPa. Based on the obtained data, next design of HTS cable prototype will be discussed.

Keywords: HTS high current cables, cyclic load

1. Introduction

Two test campaigns have been performed recently with the 60 kA HTS cable prototypes at SPC. Initial measurements of the current-sharing temperature demonstrated an excellent agreement with the expected cable performance for the operating current from 20 kA to 70 kA and in the background magnetic field up to 12 T [1]. During the cycling test, where the field was set at 12 T and the current was applied in a cyclic manner from 0 kA to 50 kA, a gradual decrease of the performance with the number of cycles has been observed [2]. After 2000 cycles this fatigue behavior results in $\approx 10\,\%$ and $\approx 20\,\%$ performance drop for the SuperPower and SuperOx prototypes respectively. Further inspection of the SuperOx prototype demonstrated that the Lorentz force acting on the strands in the cable is the key factor of the degradation. Thus, the HTS cable layout is feasible for application in fusion magnets, but requires additional reinforcement against the transverse load.

In order to formulate a scope of the work, let first see results of the corresponding mechanical analysis. Mechanical stresses for a geometry of the cable prototypes have been calculated in a 2D 'plain strain' FEM model similar to the one in [3]. The model also includes steel jacket domain with the Young's modulus 207 GPa. Each stack of the cable carries $I = 3\,$kA at $B = 12\,$T background field directed along the wide side of the cable. The self-field produced by the cable is also taken into account. Considering the Lorentz body forces acting on the stack domain and assuming zero-displacement for the bottom side of the jacket, distributions of the von Mises stress in the cable space are shown in figure 1 for the different orientations of the stacks in the cable.
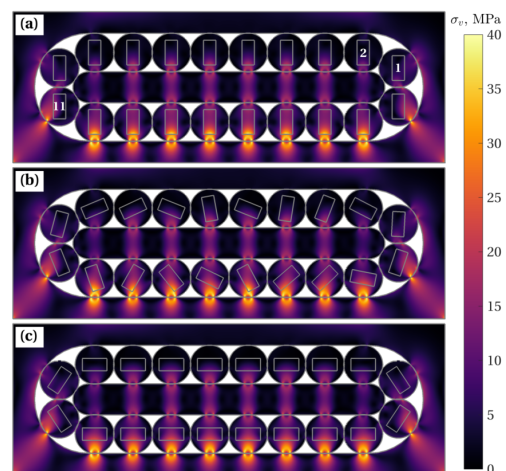

Fig. 1. Distribution of the von Mises stress in the cable operating at 60 kA in 12 T background field for the different stacks orientations.

Average von Mises stress in the stack domains is presented in figure 2. The labels of curves and strand numbers correspond to those in figure 1. A rough estimation of the transverse load as $2IB/D$ is close to the average stress obtained for the bottom layer of stacks (strand numbers from 11 to 20) of the (c) case, where $D = 6.2\,$mm is the strand diameter. Significantly higher stress is obtained for the (a) case, but the values stay below 20 MPa. Comparing the calculated stress with the performance of the single strands under the transverse load [3], significant degradation is not expected during the cable operation.

This leads to an assumption that the obtained performance degradation of the prototypes is not related to the stress magnitude, but could be linked with the fatigue properties of strands. Though a very stable performance at 77 K of the single ReBCO tapes was reported in the tensile [4–6] and transverse load fatigue tests [7, 8], the
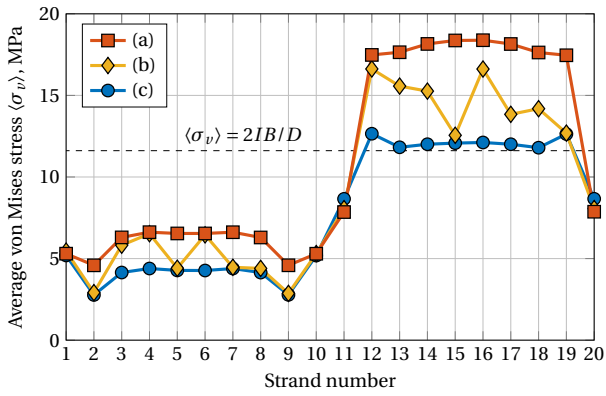
Fig. 2. Average von Mises stress in the stacks. See figure 1 for definition of the curve labels and strand numbers.

more sophisticated stress distribution in a multi-tape strand may result in a peel stress in the superconducting layer, what reduces drastically the fatigue properties of the strand.

Study of the fatigue phenomena on the strands was performed on the experimental assembly that described in the following section. Obtained results on a set of SuperOx and SuperPower strands for different magnitudes and directions of the transverse load will be presented and discussed in section 3.

2. Experimental details

Original press assembly that was used in the preliminary transverse load tests of the strands [3] was upgraded for an automatic control, see figure 3. Signal from the piezo sensor is used as a feedback for control of the DC motor. Worm gear installed on the top plate of fiberglass support serves as a reduction drive (20:1) for the motor and also prevents release of the applied force at a system idle.

During the system operation the strand in the press is immersed in a liquid nitrogen bath. In order to reduce heat transfer from the cooling region of the system the steel shaft is composed of three pieces with a hollow part in the center. External force is applied in a cyclic manner from 0 to the maximum value F corresponding to the pressure $p_{max} = F/(lD)$, where $l = 15\,mm$ is the length of the anvil. Note that actual body force acting on strands in the cable is simulated by the contact force between the strand and anvil.

Two types of strands that have been selected for the cyclic load tests are presented in table 1. The SuperOx strands correspond to those used in the 60 kA cable prototype and aimed to reproduce the fatigue properties obtained during the cable measurements [2]. The SuperPower strands composed of 3 mm wide tapes have demonstrated promising results in the bending and transverse load tests [3] and were selected for the measurements to further validate as a possible candidate for the next cable prototype.

In total 6 strands have been manufactured: 3 SuperOx and 3 SuperPower. One of the SuperPower strands has non-annealed copper profiles, while the other samples
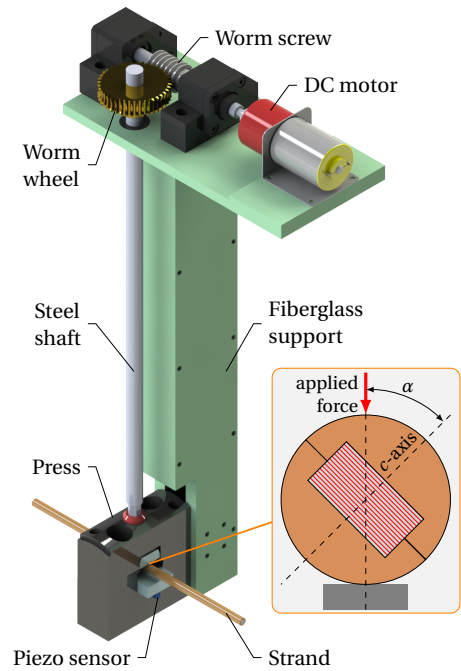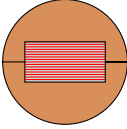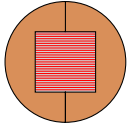

Fig. 3. Experimental setup for the cyclic transverse load test at 77 K.

Table 1. Parameters of strands used for the sample manufacturing.

Tape's manufacturer	SuperOx	SuperPower
Cross-section		
Width of tape w, mm	4	3
Thickness of tape d_t, μm	110	93
Number of tapes n	16	26
Diameter D, mm	6.2	6
Strand I_c at 77 K/sf, A	≈ 1600	≈ 1000

were manufactured with the ones preliminary annealed at 300 °C, what strongly reduces the yield strength of copper. Aiming to better reproduce the mechanical state in the cable, two samples were also bent before the cyclic loading at radius ≈ 360 mm, what corresponds to strand bending around the cable edge in the prototypes [9]. Each sample is about 30 cm long and contains 4 regions with the voltage taps at a distance 2 cm to be tested in the press, see figure 4. The transverse load was applied on the region from 0 to p_{max} up to 1000 cycles, with intermediate measurements of the strand I_c as a function of number of cycles n_c at zero and maximum load p_{max}.

Tolerance for the applied load p_{max} has been set conservatively to ±1 MPa in order to increase the frequency
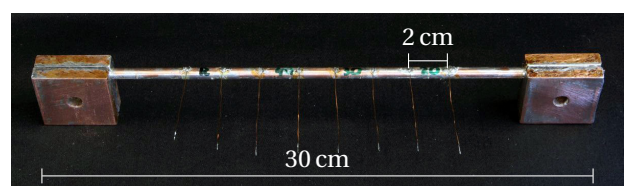

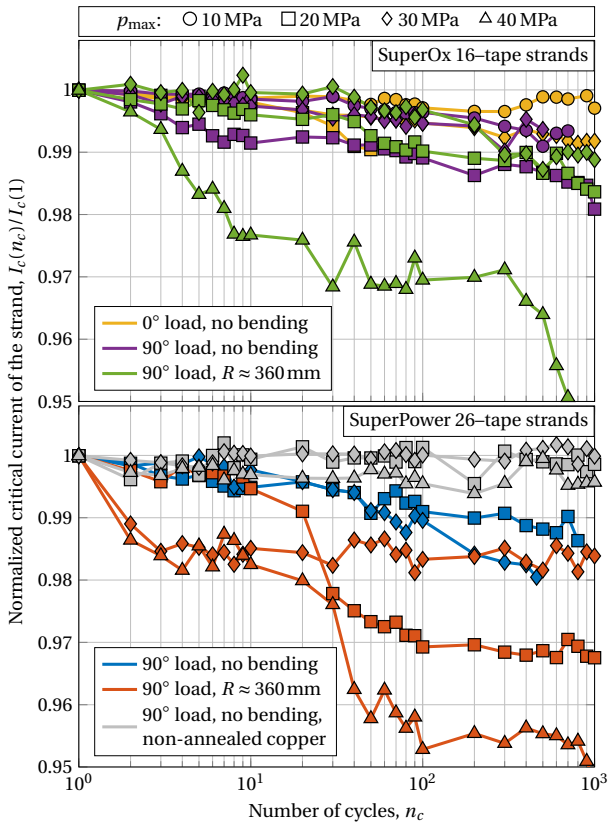Fig. 4. Photo of one strand used in the measurements.

Fig. 5. Evolution of I_c (at 77 K/sf) against the number of cycles n_c for SuperOx (top plot) and SuperPower strands (bottom plot) for different amplitudes of cyclic load p_{max}. Each individual color corresponds to one sample tested at selected bending and direction of the transverse load.

of operation. After the tuning of PID control, the system can operate up to 6 cycles per minute, what allows to perform a full cycling test on the strand region within one day. The maximum force that can be transmitted in the assembly is ≈ 10 kN, what corresponds to $p_{max} \approx 110$ MPa.

3. Results and discussion

Obtained test results are summarized in figure 5. The data are normalized to the critical current of the strand measured after the first load cycle $I_c(1)$ (see typical values in table 1).

Degradation of the strand performance during the cyclic loading has been observed. Considering the different load directions studied on the straight SuperOx strands, the cyclic load applied perpendicular to the c-axis of the stack (i.e. 90° load) leads to a higher degradation. Applied bending at 360 mm radius on the SuperOx strand does not cause weakening of the fatigue properties for the cyclic load at 20 MPa and 30 MPa, but at 40 MPa the strand performance degraded by 5 % already at 800 cycles. Nevertheless the I_c evolution of the SuperOx cable prototype during the cycling test [2] was not reproduced in the performed measurements of the SuperOx strands. On top of that, there is no data correlation for the different pressure amplitudes: the loading at 20 MPa results typically in the higher degradation than at 30 MPa.
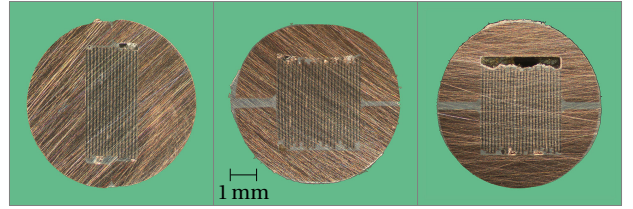

Fig. 6. Cross-section of the straight strands after 1000 load cycles (90° load, $p_{max} = 20$ MPa): left – SuperOx, center – SuperPower, right – SuperPower (non-annealed copper).

Possible reasons of these issues will be addressed below in this section.

The SuperPower strands with the annealed copper profiles performs weaker in the measurements than the SuperOx ones. Higher degradation has been obtained on both the straight and bent samples, with a higher impact of the bending on the fatigue properties. Similar misleading data correlation for the different values of p_{max} has been observed. On the other hand, the sample with the non-annealed copper profiles has demonstrated a very stable performance for the load amplitudes up to 40 MPa: strand I_c was almost not affected after 1000 load cycles. As a preliminary conclusion, annealing of the copper profiles could be responsible for the strand performance degradation in the cyclic load measurements.

Comparing $I_c(1)$ to the value measured before the loading, a noticeable irreversible degradation for some of the tested regions has been obtained (up to 5 %). This may indicate a presence of voids in the cross-section of the strand. In order to validate this assumption the strands were cut after the measurements at the locations of the test regions. The corresponding cross-sections that were subjected to 90° load at $p_{max} = 20$ MPa of the straight SuperOx and SuperPower (with annealed and non-annealed copper profiles) strands are presented in figure 6.

All the pictures show an issue with the strand manufacturing: the slot space is not completely filled with solder. This leads to a higher stress concentration at the location of voids during the transverse loading. Comparing the cross-sections of the SuperPower strands, one can see effect of the annealing: the annealed profiles, being a 'softer' material, have a highly deformed shape, while the non-annealed ones are not damaged. It agrees with a distinction in the test results between the two SuperPower samples (see figure 5). Nevertheless by improving the strand manufacturing process, effect of the copper annealing on the fatigue properties could be significantly reduced if voids will not be presented in the strand volume.

Since the performance evolution of the SuperOx cable prototype was not reproduced in the cyclic load measurements, further study of the cyclic transverse load for the annealed and non-annealed copper profiles can be performed with new HTS cable prototypes. Preliminary details over the possible cable designs will be discussed in the next section.
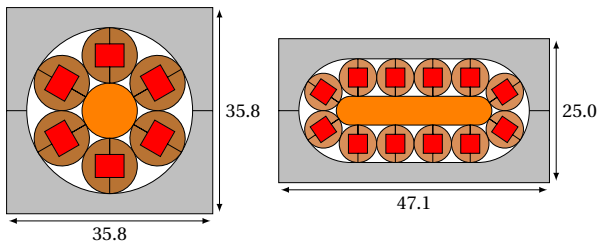
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Fig. 7. Cross-section of the HTS cables for CS coil: left ('round') – 5 mm width tapes, non-annealed copper profiles; right ('flat') – 3.3 mm width tapes, annealed copper profiles.

Table 2. Geometry parameters of the cable designs presented in figure 7.

Cable	Round	Flat
width of tape, mm	5	3.3
strand diameter, mm	9.6	6.5
annealing of copper profiles	No	Yes
number of strands	6	12
thickness of core, mm	9.6	5
cable space, mm^2	651	651

4. HTS cable prototypes

Next HTS cable prototypes at SPC are meant to demonstrate their applicability for the central solenoid (CS) coils of fusion magnets. In a layer winding design of the CS module with a superconductor grading (HTS is envisaged in high field section, Nb$_3$Sn – intermediate fields, NbTi – lowest fields), use of HTS conductors in the innermost layers at 1.9 m radius allows to reduce external radius of the CS module to 2.8 m [10]. For the conductors operating at 53.6 kA the estimated peak magnetic field in the CS midplane is ≈ 18 T. Hence, for the cable test in SULTAN at 10.8 T (peak field of the facility) the cables should be designed for the critical current ≈ 88 kA, assuming 13 % current margin and 1.43 scaling factor from 18 T to 10.8 T.

Preliminary design study of the cable prototypes composed of the annealed and non-annealed copper profiles was carried out for the HTS tapes produced by Shanghai Superconductor Technology (SST) company (width of the tapes: 3.3 mm or 5 mm, thickness: 60–100 μm, current density at 4.2 K/12 T: 55–90 A/mm). Obtained parameters for the two cable designs are summarized in table 2; also see corresponding illustrations in figure 7.

Several cable aspects have been addressed in the presented designs:

- The cable space has been set identical.
- While a flat geometry provides better bending properties for the cable, applying the same twist-pitches for the cables leads to a round geometry for the cable with non-annealed profiles in order to increase bending radius of the strand in the cable.
- In order to obtain similar current capacity for the two cables total width of HTS tapes in the cross-section should be adjusted. Depending on the SST tape current density required tapes' width for a 88 kA cable is from 0.9 m to 1.5 m. In the 'round' cable with 5 mm width tapes it can be achieved by using from 33 to 49 tapes per strand, in the 'flat' cable with 3.3 mm width tapes – from 25 to 37 tapes per strand.

As a result, the two cable designs have a similar geometry and represent a different arrangement of the superconductor. Thus, effect of the copper annealing on the cable performance can be revealed directly from the measurements in SULTAN. Six additional copper rods of 3.4 mm diameter might be used in the 'round' cable between the strands and steel jacket to increase the copper cross-section in the cable and to better redistribute the mechanical stresses (i.e. lower the stress in the stacks).

5. Summary

Influence of the cyclic transverse load on the round HTS strands has been studied at 77 K. While the I_c degradation during the cycling has been observed, performance evolution of the SuperOx cable prototype was not reproduced in the measurements. Cross-section analysis of the samples after the mechanical tests revealed the issue with the manufacturing process, which should be improved especially for the strands composed of copper profiles with a spit-line along the c-axis of the stack. Performance of the strand with non-annealed copper profiles was not affected during the cyclic loading.

Effect of the profile annealing on the cable properties will be further investigated during the test of HTS cable prototypes in the SULTAN test facility at SPC.

Acknowledgments

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