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Procedural steps for reliability evaluation of ultrasonically welded REBCO coated conductor lap-joints under low cycle fatigue test condition

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Abstract

This study presents a comprehensive procedure for the low cycle fatigue test of ultrasonically welded (UW) coated conductor (CC) lap-joints. The entire process is examined in detail, from the robust fabrication of the UW REBCO CC joints to the reliability testing under a low number of repeated cycle fatigue conditions. A continuous I_c measurement system enables real-time monitoring of I_c variations throughout the fatigue tests. The study aims to provide a step-by-step procedure that involves joint fabrication, electromechanical property (EMP) tests under uniaxial tension for stress level determination, and subsequent low-cycle fatigue tests. The joints are fabricated using a hybrid method that combines UW with adding In-Sn soldering, achieving a flux-free hybrid welding approach (UW-HW flux-free). The selected conditions for the low cycle fatigue tests include a stress ratio of R=0.1 and a frequency of 0.02 Hz. The results reveal some insights into the fatigue behavior, irreversible changes, and cumulative damage in the CC joints.

Keywords: REBCO CC tapes, ultrasonic welding, low cycle fatigue, electromechanical properties, hybrid welding, flux-free

1. INTRODUCTION

Superconductors, particularly those made from rare-earth $Ba_2Cu_3O_y$ (REBCO) tapes, have earned significant importance in pursuing high-performance materials driven by their ability to sustain high magnetic fields. In applications like demonstration magnets, single-tape coated conductors (CC) composed of REBCO are arranged into cable or coil forms to achieve elevated magnetic fields. Diverse cable configurations, such as twisted-stacked tape cable (TSTC), Roebel assembled coated conductor cable (RACC), and conductor on the round core (CORC), showcase the adaptability of these tapes [1–3]. The versatility of REBCO CC tapes extends to their applications in superconducting devices subjected to high magnetic fields. These second-generation high-temperature superconductor (HTS) tapes, with their exceptional critical current (I_c) properties, can be helpful in various fields, including the fabrication of 45 T superconducting magnets, 10 MW-class superconducting wind power generators, superconducting magnetic energy storage (SMES), and nuclear magnetic resonance (NMR) reactors [4–7].

The application of REBCO CC tapes in superconducting devices necessitates precise joining methods, and among these, ultrasonic welding (UW) emerges as a key technology [8–11]. The hybrid welding method, specifically the ultrasonic welding-hybrid welding flux-free (UW-HW flux-free) approach, plays a crucial role in enhancing the joints. This method combines UW with the addition of In-Sn solder, creating a flux-free hybrid welding approach [12]. The significance of this joining technique lies in its ability to provide robust and reliable joints, ensuring the structural integrity of the CC tapes in operational conditions without the worries of corrosion-related problems in the long run.

Conducting proof tests under both tensile and bending conditions is a crucial step in assessing the inherent properties of the CC tapes themselves and the performance of the CC joints [13]. On the other hand, the cyclic loading conditions applied in this study simulate the complex stresses experienced by the CC tapes in practical applications, allowing for a comprehensive understanding of the joints' performance over time. The evaluation under such conditions is crucial for verifying the durability and long-term stability of the ultrasonically welded joints. By subjecting the joints to electromechanical property tests, this study aims to provide insights into the fatigue behavior, irreversible changes, and cumulative damage in the joints, ultimately contributing to developing reliable and resilient superconducting materials for practical applications [14-16].

Therefore, this study focuses on low-cycle fatigue tests of UW jointed CC tapes. To facilitate the evaluation process, a continuous I_c measurement system during cyclic loading is employed [17]. This system proves invaluable for assessing the mechanical and electromechanical properties of the CC tapes under various loading conditions. The continuous I_c measurement system offers real-time monitoring of I_c changes throughout the fatigue cycles, enabling a comprehensive analysis of the jointed CC tapes. This study describes the step-by-step procedure, from enhancing REBCO CC joints using the UW-HW flux-free method to the final testing under low cycle fatigue conditions. The carefully designed procedure encompasses

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TABLE 1
SPECIFICATIONS OF THE CC TAPE SAMPLES.

Fabrication process	IBAD/RCE-DR
	Ag/GdBCO/$LaMnO_3$/ IBAD-MgO/ Y_2O_3/Al_2O_3/ Stainless steel
REBCO film thickness	~ 1.5 µm
Critical current, I_c	~250 A
Dimension, t x w	0.134 mm x 4.05 mm
Substrate/ thickness	~100 µm
Stabilizer/technique,	Cu electroplated, surround (~15 µm)

joint improvement, electromechanical property (EMP) tests for stress level determination under tensile conditions, and subsequent low-cycle fatigue tests. The goal is to provide a detailed understanding of the performance and reliability of ultrasonically welded jointed CC tapes, contributing to the advancement and optimization of superconducting materials in practical scenarios.

2. EXPERIMENTAL PROCEDURES

2.1. CC tape sample

Commercially available CC tape, with type II classification superconductor, was selected for testing, with specifications detailed in Table I. The sample, with gadolinium barium copper oxide (GdBCO), underwent ion beam-assisted deposition (IBAD) and was produced using the reactive co-evaporation by deposition and reaction (RCE-DR) process on a stainless steel substrate. It featured a protective layer of approximately 1 µm of Ag on the electroplated Cu stabilizer.

2.2. Ultrasonic welding setup and electrical property measurement

An ultrasonic welder (KORMAX, KM-2035) was employed in this study, as illustrated in Fig. 1. To ensure the stability and proper alignment of the overlapping samples during the UW process, a pair of toggle clamps were utilized. The horn and anvil configurations, differentiated by tip patterns, offered distinct contact area ratios. The UW-HW approach adopted the pre-solder insertion method, integrating a thin $In_{52}Sn_{48}$ solder strip between the overlapped CC tapes, as shown in Fig. 1. The solder strips, uniformly rolled to ~20 µm thickness, underwent ethanol cleaning before UW. The welding time was systematically adjusted to optimize the UW-HW CC joint with pre-solder insertion to explore potential reductions in joint electrical resistance (R_j). The four-probe method, incorporating voltage clipping, was employed to measure the R_j of CC joints formed through various methods at 77 K [18]. Voltage clips were positioned 5 mm from both ends of the joint part and ensured complete current transfer during the measurements with the voltage criterion for I_c measurements set at 1 µV/cm. Fig. 2 shows the I_c and R_j of the UW-HW CC joints. Consequently, the optimal parameters are 50% vibration amplitude (~31 µm

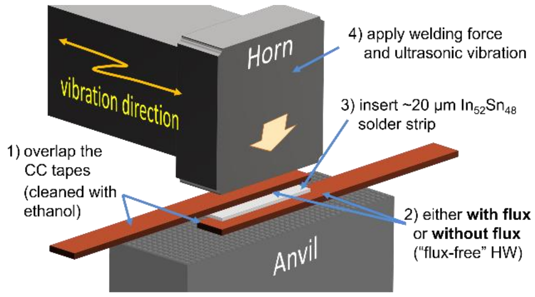

Fig. 1. Ultrasonic welding procedure for hybrid flux-free method of REBCO CC tapes. Figure adopted and reproduced from [12].

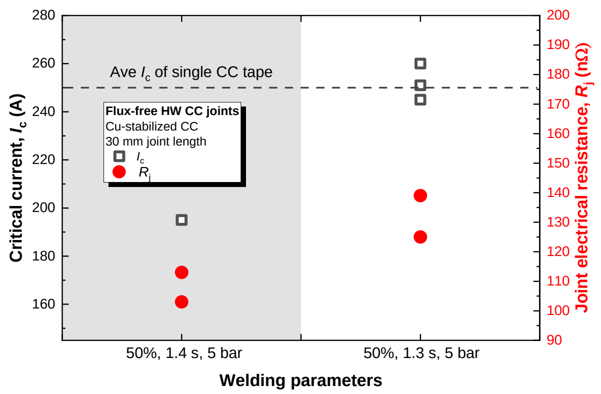

Fig. 2. Critical current (I_c) and joint electrical resistance (R_j) values for REBCO CC joints.

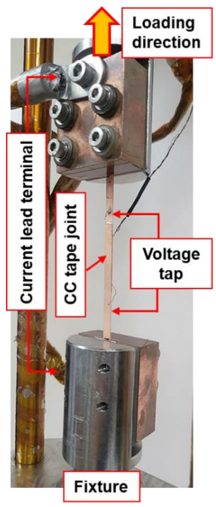

Fig. 3. Setup used for determining the electromechanical properties of REBCO CC tapes at 77 K and self-field under uniaxial tensile load.

displacement), 5 bar (~3.9 kN) welding pressure, and a 1.3 sec welding time.

3. EXPERIMENTAL RESULTS

3.1. Continuous I_c measurement results through tensile test for EMP evaluation of CC lap-joints

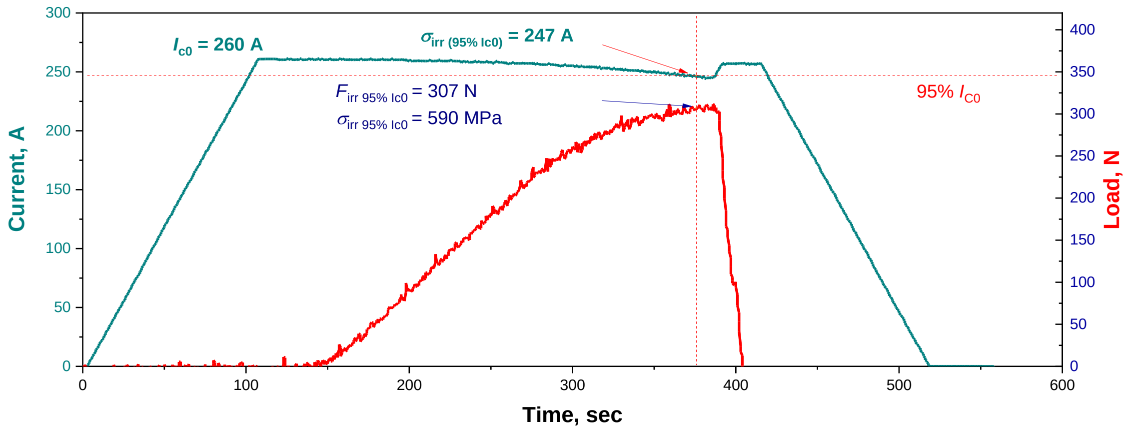

Fig. 4. Histories of I_c and tensile load obtained using the continuous I_c measurement system for electromechanical property evaluation at 77 K and self-field of the IBAD/RCE-DR CC joints.

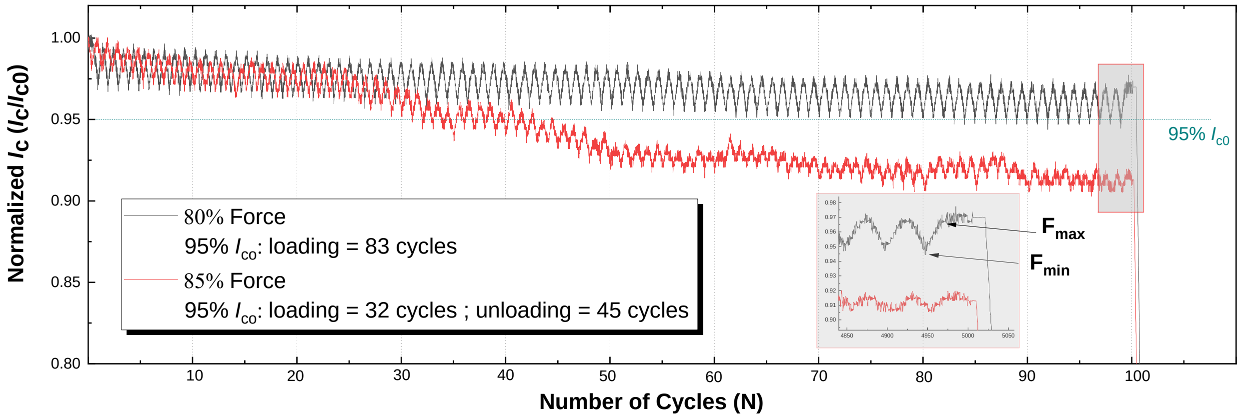

Fig. 5. Low cycle fatigue behaviors of IBAD/RCE-DR GdBCO CC joints under different applied stress levels.

A comprehensive description of the continuous I_c measurement system is available in [17]. The arrangement for the uniaxial tensile test at 77 K and self-field is illustrated in Fig. 3. Initially, the specimen's initial I_c (I_{c0}) was determined without any applied load. Throughout continuous I_c monitoring, the voltage was fixed to a constant level. The application of tensile stress can induce damage in the superconducting layer of the joints, altering the I_c due to increased R_j at the interface. These variations are tracked by monitoring the I_c history, as depicted in Fig. 4 to illustrate the I_c changes with applied load. The test can be halted automatically or manually upon reaching a specified I_c degradation target (*e.g.*, 95% I_{c0} in this study or up to joint failure), facilitating a straightforward and efficient assessment of both electrical and mechanical behaviors of the CC tape joints.

The I_c of the RCE-DR CC tape joint exhibited gradual degradation at a load application rate of 0.1 mm per min, and with the joint' I_c values rated at ~260 A, the criteria for the irreversible stress limit (σ_{irr}) is when the I_c reached 95% of the I_{c0} (equal to 247 A) (Fig. 4). At the 247 A mark, the corresponding σ_{irr} and F_{irr} were determined, as equal to 307 N or 590 MPa. The corresponding load at the 95% I_{c0} mark serves as the σ_{irr}. This σ_{irr} value is employed as criteria for subsequent low-cycle fatigue tests. The unique advantage of this novel system lies in its ability to concurrently assess mechanical, electromechanical, and electrical properties within a relatively shorter test duration compared to the traditional repeated loading-unloading test scheme.

3.2. Low-cycle fatigue test results at different stress levels

After achieving the target joint properties, low-cycle fatigue tests were conducted on the CC tape joints. Using a stress ratio (R) of 0.1 and frequency of 0.02 Hz, the maximum force (F_{max}) and the minimum force (F_{min}) were obtained using the formula $R = F_{min}/F_{max}$.

Gradual degradation in I_c was observed at a stress level of 80% σ_{irr}, with F_{max} set at 246 N, and F_{min} was calculated as 24.6 N. The I_c experienced a gradual degradation after 100 cycles. The I_c was reduced to 249 A at the unloaded state (F_{min}) after 100 cycles, indicating the occurrence of irreversible damage within the joint. The I_c degradation reached 95% of I_{c0} after 83 cycles in the loaded state (F_{max}), suggesting the existence of a critical point in the fatigue behavior. This observation aligns with the expected fatigue behavior, suggesting that cumulative damage occurred, surpassing a critical stress threshold.

At 85% of σ_{irr}, F_{max} and F_{min} were determined as 261 N and 26.1 N, respectively. At this stress level, I_c exhibited a sharp degradation after 100 cycles, reaching 240 A. Notably, within 32 cycles during F_{max} and 45 cycles during F_{min}, I_c dropped to 95% of I_{c0}. The accelerated degradation observed at this higher stress level implies a more rapid accumulation of damage, surpassing the joint's fatigue behavior more quickly than the 80% stress level. These findings provide valuable insights into the fatigue behavior of RCE-DR CC tapes, emphasizing the importance of considering operational stress levels in specific applications for a comprehensive understanding of their performance and durability. This parameter serves as a valuable metric to assess the endurance and reliability of the joint under repeated loading conditions.

Considering the expected operational stress, these findings have implications for the practical application of REBCO joints. It is crucial to note that these results represent preliminary findings, with only two stress levels applied to CC tape joints. The study primarily focuses on establishing the procedural reliability of the joints. In the next iteration of this research, a comprehensive set of stress levels will be explored to fully understand the fatigue behavior of the joints under various conditions. This iterative approach is essential for obtaining a more comprehensive understanding of the reliability of the joints in diverse operational scenarios.

4. SUMMARY

This study has provided valuable insights into the low-cycle fatigue behavior of ultrasonic weld REBCO CC lap-joints. The effectiveness of the procedural steps employed in this study for the reliability evaluation of the joints is evident. The systematic approach allowed for a detailed examination of the joints' fatigue behavior, providing crucial data for understanding their performance under specific stress levels. These findings are preliminary and represent an initial step in the ongoing study of CC joint reliability. Future iterative tests encompassing a broader spectrum of stress levels and different CC tapes will further enhance the understanding and establish a robust foundation for joint reliability assessment under diverse operational conditions.

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