Submitted, July 29, 2009; accepted September 8, 2009. Reference No. ST129; Category 5

HTS Coated Conductors Developed for the European Super3C Cable

Alexander Usoskin[1], Alexander Rutt[1], Herbert C. Freyhardt[1,3], Burkhard Prause[1], Klaus Schlenga[1], Jean-Maxime Saugrain[2], Arnaud Allais[2], Dag Willén[4]

[1] Bruker HTS GmbH, Siemensstrasse 88, 63755 Alzenau, Germany
[2] NEXANS, 16, rue de Monceau, 75008 Paris, France
[3] TcSUH, University of Houston, 202 UH Science Center, Houston TX 77204, USA and ZFW gem. GmbH, D-370079 Goettingen, Germany
[4] Dag Willén; NKT Cables, Brondby, Denmark

Abstract **– Within the European Super3C project, a 30m-long one-phase cable was manufactured by employing high-performance coated conductors which were processed by high-rate pulsed-laser deposition of YBCO on stainless-steel tapes coated with an Yttria-Stabilized-Zirconia bi-axially textured buffer layer. This paper briefly summarizes the advanced tape processing, which includes the plating with a copper shunt layer, as well as the lamination of the tapes. Tapes without patterned filaments could be manufactured with homogeneous I_c values along the full length, and rather low AC losses. Their electromechanical performance with satisfactory limits to irreversible degradation and good stability in aggressive environments offer a high degree of reliability in applications.**

Submitted , July 29, 2009; accepted September 8, 2009. Reference No. ST129; Category 5.

Keywords **- superconducting, YBCO, high temperature superconductor, coated conductors, HTS cable**

I. INTRODUCTION

Around the world, several High Temperature Superconducting (HTS) cable prototypes were manufactured with HTS bismuth-based multifilamentary wires as current carrying elements [1-3]. This technology is now moving towards the pre-commercial stage through multi-hectometer cable projects. However, such multifilamentary wires are expected to be soon replaced by a new generation of cheaper HTS wires, the Coated Conductor (CC) or 2G (2^{nd} Generation) HTS tapes [4-6]

The European Super3C project aims at establishing the feasibility of a low-loss HTS power cable using CC tapes. It comprises the development, manufacturing and testing of a functional model consisting of a one-phase, 30-meter-long, 10 kV, 1 kA cable with its terminations.

In the present paper we report on major development steps accomplished to provide the cable with a CC having critical current, mechanical stability, ac losses, *etc*., which meet the specifications of superconducting cables based on 2G HTS tapes.

II. COATED CONDUCTORS: BASIC ARCHITECTURE

Recent progress in the development of YBCO coated conductors with long length (up to 100m), favourable mechanical stability and improved homogeneity of the critical current, I_c, was reported elsewhere [5,6]. The description of processing steps was given there. The basic architecture of our CCA is as follows. Nonmagnetic CrNi stainless steel tape, 0.1mm thick, is employed as a substrate. Prior to the YBCO deposition, the stainless steel tapes are coated with an Yttria-Stabilized Zirconia (YSZ) bi-axially textured buffer layer and, finally, with a “cap” layer of ceria, CrO_2. YBCO films are deposited employing a high-rate pulsed laser deposition (HR-PLD) at a processing rate of 10m of CC per hour. At the last processing step, the coated tapes are provided with a 2 µm thick shunt layer of silver and a 25 µm thick copper shunt layer.

III. COPPER PLATED SHUNT

Copper plating by pulsed galvanic deposition is employed to provide a reliable shunt, which will ensure a protection against high current overloads. The Cu is plated onto the surface of the silver layer. This not only improves adhesion of the Cu, but also reduces the interfacial resistance to values below 0.2 µOhm·cm^2.

A water-solution-based galvanic deposition was used for plating, with a throughput speed of about 5 m/hour. At this speed, the thickness of Cu plating was 25µm.

Because of its porosity, the resistivity of the plated Cu was approximately twice as high as the resistivity of ideal copper. An example of a Cu-plated 42m long CC taped is depicted in Figure 1.

Fig. 1. Cu-plated CC on a drum holder, which is employed for end-to-end I_c measurements.

IV. PROPERTIES OF CC TAPES

A. Critical Transport Currents

The critical current, I_c, in each of the CC tape sections was determined as an end-to-end transport current. To perform position-dependent critical current measurements, the CC tape was mounted on an insulating drum with a diameter of 35 cm. The tape ends were soldered to the current leads made of flexible copper cables. Movable potential probes were mechanically driven by a 2D manipulator which allowed to measure voltage drop across the tape length with a spatial resolution of 55cm.

Measurements with higher resolution along the length were performed employing a reel-to-reel tape transport. In the characterization setup used for this aim, the transport current was delivered to the analyzed section of CC tape through 2 sliding contacts which were pressed onto the tape during each particular cycle of local measurements. With such a technique, a linear resolution on the scale of 10 mm could be achieved. Both methods described above were used for the CC tape characterization after Cu-plating.

Previously, we reported on critical current measurements performed on 5-m-long sections, which demonstrated the very high I_c homogeneity of the CC tapes with a standard deviation of approximately 2.5% only [6].

In the case of the SUPER3C CC tapes, a noticeable I_c decrease was sometimes observed within very short tape sections. Sometimes we were even not able to determine how short the defective sections were; often definitely less than 20 mm.

A typical illustration of the distribution of defects along a CC tape is depicted in Figure 2, where local current drops are marked with arrows and extended defect areas are plotted as dashed lines. These areas were more often observed at the beginning than at the end of a batch length. Frequently, such defects appeared after the galvanic plating. It could be proven that the presence of the extended areas with reduced I_c originates from the path of the current transport into the tape during the initial step of Cu plating. Optimizing the current "injection" into the CC tapes resulted in a considerable suppression of extended defects.

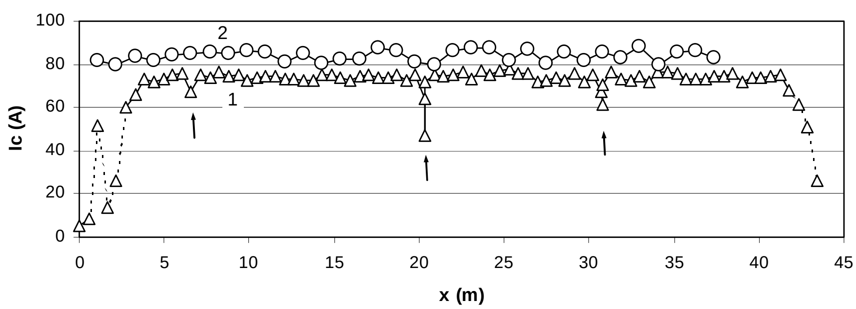

Fig. 2. Critical current, I_c, versus length coordinate x. 1 – CC tape with local defects marked with arrows and extended defect areas plotted as dashed lines; 2 –CC tape without apparent defects.

B. Electromechanical Properties of Coated Conductors

HTS conductors employed in cables are subjected to magnetic fields lower than 0.2 T and to mechanical strains during handling and cooldown reaching 0.2 to 0.3 %. Consequently, electromechanical tests have been performed in order to determine the robustness and sensitivity to mechanical stresses of our high-performance CC, the main conductor for the cable prototype.

For measurements of the critical current density, J_c, versus axial and compressive strains we use the setups of the University of Houston and of the National Institute of Standards and Technology at Boulder (two different measurements setups were used which are described in ref. [7] and [8]). We tested both Cu/Au- and Cu/Ag-shunted, well characterized CC samples. We found very early that in tension an irreversible degradation starts only when the strain, ε, reaches about 0.8%. This was a remarkable result. The maximum in the I_c *versus* ε curve appears at about 0.35 to 0.40) %, which clearly indicates that the YBCO layers of these CC are pre-strained after the processing. An example of $I_c(\varepsilon)$ plots for two CC tapes, with a 2.7 µm YBCO layer and a 20 µm Cu shunt, is depicted in Figure 3. This natural pre-straining can favourably be used to optimize the behaviour of the conductor in the cable put under tension. When normalized to zero pre-strain, the I_c (ε) dependence becomes rather symmetrical in tension and in compression. Furthermore, the coated conductor samples proved to be only moderately sensitive to hard bending, *i.e.*, in-plane bending, of the tape. This could clearly be demonstrated for a CC sample with 1.25 µm YBCO, covered with Ag (2.5 µm) and Cu (~25 µm) protective/conductive layers where bending radii well below 4 mm did not irreversibly deteriorate the current carrying capabilities.

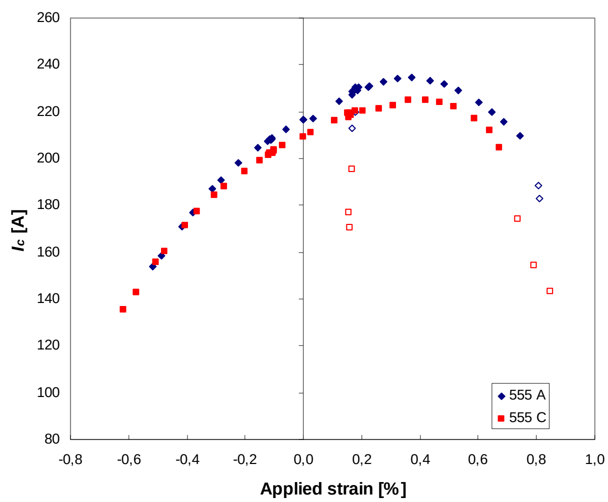

Fig. 3. Critical current I_c versus stress applied to a 4mm wide CC (2.7µm YBCO, 20 µm Cu shunt) by tape bending. Two different samples of similar quality were measured.

Deterioration of I_c in CC tape successively bent around mandrels of decreasing radius R is depicted in Figure 4. All these experiments clearly demonstrated that Cu-plated CC tape exhibited practically no I_c deterioration for bending radii larger than 6 mm. Without Cu plating, the irreversible deterioration threshold radii were almost twice as large [5].

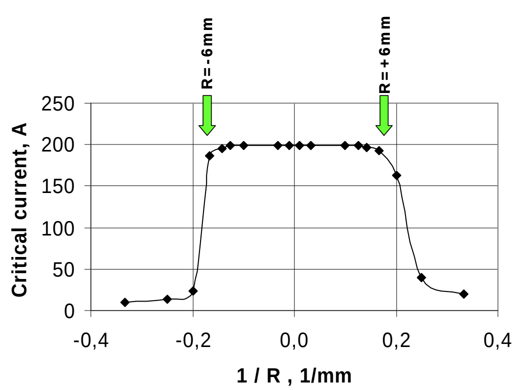

Fig. 4. The I_c in CC tapes during “positive” (HTS layer outside) and “negative” (HTS layer inside) bending

Due to the favourable mechanical properties, a critical angle of tape torsion is found to be sufficiently high. The critical angle was defined by a 5% drop of the critical current in a CC tape being under torsion combined with axial load. The torsion and the axial loads were applied to the cooled tape. In the case of 4-mm-wide Cu-plated coated conductors this angle exceeds 30° per cm-length at applied tensile forces of 40 N.

C. Behaviour in Magnetic Fields

Dependences of I_c *versus* field $\mu_0 H$ in moderate magnetic fields (typical in transformer and cable applications) are shown in Figure 5 for three different field orientations: parallel to the deposit texture *c* axis (orthogonal to the tape plane), parallel to the *ab* plane, and at 45^0 between the c axis and the *ab* plane. The most pronounce decrease of I_c is observed at the 45° field orientation. Nevertheless, we note that in tapical cable configuration the field is mainly oriented parallel to the tape surface. Thus only a moderate decrease of critical current (compared to values measured in the self-field) can be expected here.

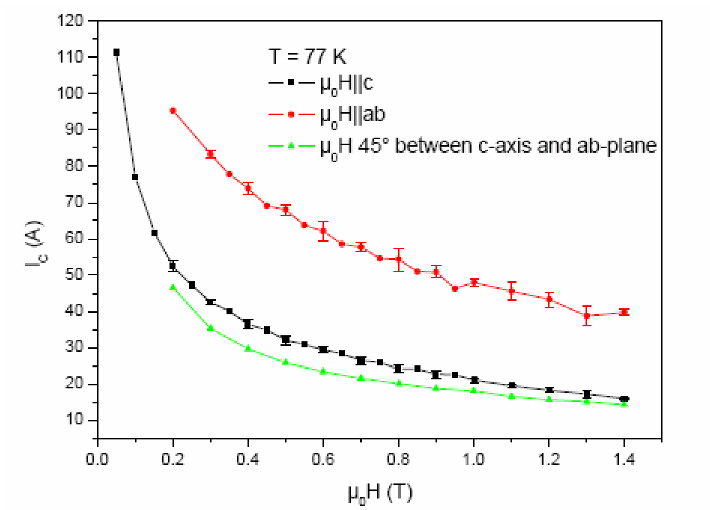

Fig. 5. Critical currents in moderate magnetic fields for two main field orientations and for an angle of 45°. Measurements of Bruker-HTS tapes were performed by Harald Weber at the Atominstitut, TU Vienna.

D. AC Losses in the Coated Conductors

The dependence of power losses upon the applied current in CC tape at a frequency of 50 Hz are depicted in Figure 6. A straightforward simple estimation based on this measured data shows that the absolute value of the AC loss in a single, 4mm wide CC tape corresponds to 4 mW/m at a current I_{rms} = 50 A. From this loss per tape, the entire AC loss of a 1kA-cable can be extrapolated. It should amount to only 80 mW/m. Such a value of AC losses in the conductor is rather low when compared to the cooling losses caused by the heat exchange with environment which already exceed 1 W/m. These low AC losses are achieved without CC “filamentization” [9].

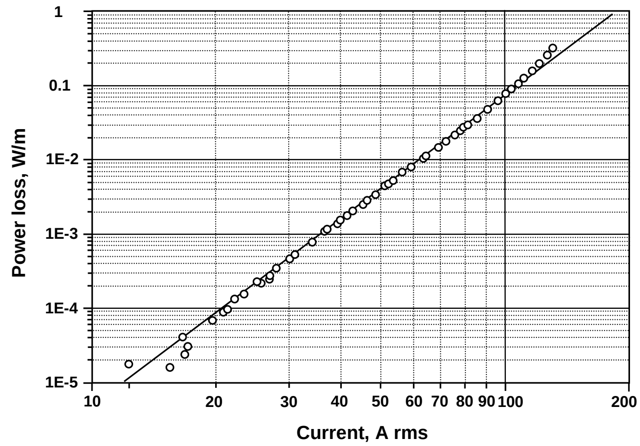

Fig. 6. AC losses *versus AC* current in a 4mm wide Cu plated CC. Open circles correspond to measured values.

E. Stability in Aggressive Environment

The stability of critical currents in Cu-plated coated conductors in environments of the vapour of a NaCl water solution was investigated. Two types of coated conductors (i) with YSZ/CeO_2 and (ii) with $Y_2O_3/MgO/YSZ/CeO_2$ buffer systems have been compared. Both samples were under the influence of vapour of a 2% NaCl water solution, at 25°C. Small "punctures" (with diameters of 0.1 mm) were provided in the Cu coating to speed up diffusion processes.

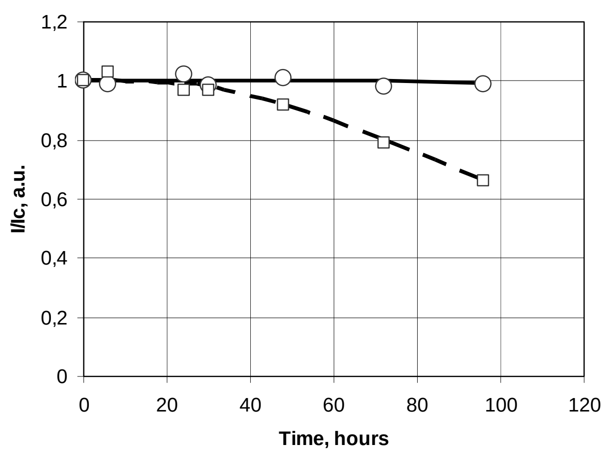

Fig. 7. Stability of critical currents in Cu-plated coated conductors with YSZ/CeO_2 (solid line) and $Y_2O_2/MgO/YSZ/CeO_2$ (dashed line) buffer systems. Samples subjected to the influence of vapour of a 5% NaCl water solution, at 25°C. Small "punctures" (with diameter of 0.1 mm) were provided in the Cu coating to speed up the diffusion processes.

Results of this observation are shown in Figure 7. Both types of CC are stable against this environment within the first 2 days. Afterwards a deterioration of critical currents in the CC architecture that includes a MgO layer is commencing. Obviously this effect is caused by the penetration of water into the multilayer of the (ii)-type.

YSZ/CeO_2 buffer layers assure higher stability of the coated conductor, at least within the first 100 hours of exposing to salted water vapour. Long-term investigations of in "aggressive" environment will be continued.

V. LAMINATED CC TAPES

In order to increase the critical current in CC tapes, where the critical current variations along the length occur, two "compensation" methods were employed where (i) two CC tapes with complementary I_c distributions are soldered one to the other or (ii) one CC tape is soldered to 0.1 mm thick copper tape. These methods became possible after we confirmed that Cu-plated CC tapes withstand the soldering procedure performed at a temperature of 300°C in the solder-flux environment.

Using this technique, a length of about 800 m of CC tape was assembled into a double- tape configuration (see Figure 8).

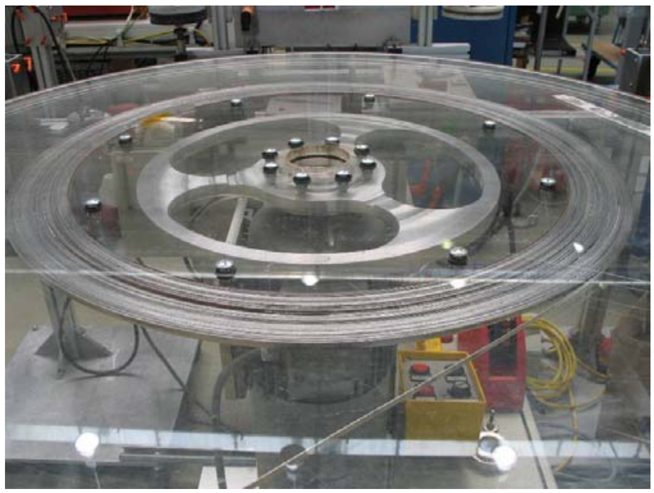

Fig. 8. The 800 m length of HTS coated conductors (Bruker-HTS) assembled into a double tape.

In the method (i), I_c values in the double CC tapes typically exceeded the sum of particular critical currents measured in the separate CC tapes. Moreover, the I_c in the double tape was usually close to the sum of I_c values in the homogeneous parts of CC tapes. Thus, the influence of weak areas was to a large extent suppressed.

Measurements performed before and after tape stranding resulted in the average critical current of 125 to 135A in the laminated CC tape (of 4 mm width) measured at 75K. This sufficiently high current is practically not influenced by mechanical loads that are to be applied in the course of cable fabrication. Moreover, it is important to note that in the current double-tape laminated design the "sensitive" surface of the CC becomes well-protected, while the influence of local zones with reduced critical current is significantly suppressed due to lamination.

VI. SUMMARY

Laminated coated conductors with critical currents of 125 to 135 A were successfully manufactured for the 30 m European Super3C cable. The double-tape configuration is best suited for tape handling and protection of the HTS layers. Possible local current deterioration in either of the partner tapes is smoothed, while both tapes generally exhibit a very high I_c homogeneity with a standard deviation of only 2.5%. Copper plating by pulsed galvanic deposition provided a reliable shunt to ensure a protection against high current overloads. The measured low AC losses of only 4 mW/m (at I_{rms} = 50 A) translates into an AC loss of 80 mW/m for a 1 kA cable. This value is much lower than the cooling losses caused by the heat exchange with environment (which exceed 1 W/m). The electromechanical performance of the CC tapes exhibited an attractive limit of about 0.8% tensile strain before any irreversible degradation of the critical current would occur. Together with the pronounced stability of the coated conductors in aggressive environments this offers a high degree of reliability for their applications.

ACKNOWLEDGEMENTS

The authors acknowledge the support of this work: in-part provided by EC within the Sixth Framework Programme/Sustainable Energy Systems, Project No. 502615, and in-part by the German Ministry of Economy and Technology (BMWi), Project no. 0327456A.

REFERENCES

[1] R. Weinstein *et al., Physica* C, **341-348**, Part 3, 1415-1418 (2000).
[2] Y. Bugoslavsky, G. Perkins, P. Buscemi, *et al.*, *IEEE Trans. Appl. Supercond.*, **11**, No. 1, 2788 – 2791 (2001).
[3] R. Inada, Y. Fukumoto; T. Yasunami, *et al.*, *IEEE Trans. Appl. Supercond.* **18**, No 2, 1163-1166 (2008).
[4] Y. Yamada, T. Watanabe, T. Muroga, *et al*, *IEEE Trans. Appl. Supercond.* **15**, No. 2, 2600- 2603 (2005).
[5] Usoskin, A.; Rutt, A.; Knoke, *et al.*, *IEEE Trans. Appl. Supercond.* **15**, No. 2, 2604–2607 (2005).
[6] A. Usoskin, *ESNF,* No. 2, ST8, (2007).
[7] J. W. Ekin, *Cryogenics* **20**, 611 (1980).
[8] D. C. van der Laan, J. W. Ekin, *Appl. Phys. Lett.* **90**, 052506 (2007).
[9] R. Duckworth, Y. Zhang, F. List, *ESNF,* No. 7, ST111 (2009).