Operation and experience of a 2 km coated conductor REEL – to – REEL copper pulse plating facility

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Abstract. Bruker HTS manufactures YBCO based superconducting wires of the second generation on low-cost Stainless Steel substrate (100 µm thick). With 250 – 500 A/cm²@77 K, SF, 650 MPa tensile strength and 6 mm bending radius excellent electrical and mechanical properties are achieved. As complementation of the 2G fabrication technology an automated 2 km copper pulse plating facility has been installed in 2012. We report here the operation requirements and the experiences of the copper plating technique.

1. Introduction

Copper plating technique enables a fast and economic fabrication of a hard bonded copper layer on the superconductor surface. Thereby, as for LTS, metallic copper is the obvious metallic partner for the second generation 2G conductor. In addition, copper is one of inherent chemical constituents of all HTS. The copper shunt on the conductor gives a number of electric, thermal and mechanical advantages if power electric applications are considered. The developed physics and chemistry of pulse plating has been studied in the last years and transformed into the REEL – REEL technique for continuous deposition a 10 – 20 µm thick copper layer. The key issues of CuSO₄ plating and the governed electrochemical parameters following the Nernst equation for the Cu²⁺ dissociation are reported earlier [1-3].

For the purpose of the copper deposition on the surface of superconducting wires a fine-tuned electroplating technology using an aqueous CuSO₄ solution is found. Both acidic copper sulphate and alkaline solutions has been tested to optimize the plating process and deposition speed. An automated 12-chamber plating facility with up to 2000 m conductor length in REEL - to - REEL mode has been installed in 2012. We review and discuss here the wire plating concept, and the operation experiences with the REEL –to–REEL unit.

2. YBCO – Copper Hybrid wire

The basic wire architecture of the Bruker HTS wire is displayed in Fig. 1. It consists of the nonmagnetic 100 µm Nickel – Chromium Stainless Steel substrate, an YSZ/CeO₂ double buffer structure, and the pulsed laser deposited 1.2 µm thick Y-123 high-temperature superconductor on top. Finally, 0.5 µm thick Ag cap layer protects the wire in the initial processes. After this stages, the ready - processed tape is transferred into the copper plating facility, inserted into the REEL dynamics, and are subsequently covered with an appropriate metallic Cu layer. The advantage of the last process is the non-vacuum technology and the relatively low processing costs. From the plating process point of view the geometrical parameters of the conductor can be varied in a wide window. The electrochemical parameters follow the optimum current density per square centimeter of the electrode.

Further advantage of the Cu plating is the ability to deposit metallic copper both on Ni-W substrate directly as well as on Stainless Steel / Hastelloy surfaces (with a seeding layer between).

Figure 1. REBCO tape architecture of Bruker’s CC.
In Fig. 1 the quite sophisticated wire structure consists of altogether 5 layers of a total thickness of about 3 µm. The ABAD / IBAD template possess the advantage of a rather perfect texture transformation and avoid imperfect Y123 layer growth. In Fig. 1 electron microscopy demonstrates the perfection the REBCO layer. The high-resolution picture shows in addition the well oriented lattice structure in c-axis with the smooth surface. The copper layer of typically 20 µm thickness in one- side or double –sided geometry on top, that is was the wire user sees finally from the conductor.

3. Automated copper plating facility

3.1. Design and construction

The automated 6 m long modular plating facility is shown in Fig. 2, consisting of the central 12 chamber plating modules with Teflon slits for the moving tape cathode throughout. On both sides the coil bobbin reels are located capable to operate a REEL of a maximum diameter of 33” (838 mm). The electrical insulated REELS are connected with driving stepper motors on a shaft for a continuous tape speed through the plating chambers. The tape way is carefully aligned to avoid edgewise strains during the tape movement.

![Automated continuous copper plating machine with individual electrolytic cells.](image)

The REEL-to-REEL transport system of the equipment can handle tape length up to 4 km which has been tested for all speeds with NiCr Stainless Steel tape. The control of the speed torque and force reduces the handling and fits the plating process cycle time by virtue it’s closed –loop constant movement and constant tape tension control.

The plating cells are positioned in the centre of the facility, neighboured by the two bobbin REELS. The conductor is run through slits from one cell to the next driven by two plating propulsion motor units at a speed of up to 100 m/h. The complete machine is designed and constructed according to the technique of semiconductor processing machines. The modular character with the plating stations provides an ease of process modification, variation and line expansion. The electric plating parameters are delivered by individual current voltage power supplies with a maximum current per cell of 3 Amperes. The cell voltage is a sensitive function of the actual substrate and electrolytic solution conductivity. The tape conductivity in the process is a strong function of the growing thickness of the Cu layer. At a copper thickness of a few micrometers the cell voltage is a measure of the CuSO$_4$ concentration of the plating solution and provides a control of the copper yield per cell.

3.2. Mechanical tape properties

Coated conductors produced by Bruker HTS are optimized for application at 77 K, where most of the applications are performed. For low temperature and high- field applications the wires are usually tested at 4.2 K showing much higher I$_c$ values. A 4 mm PLD wire test sample with a length of about 6 m with 2 x 45 µm thick copper layers could carry at liquid Helium temperature (4.2 K) currents of almost 0.5 kA and 2.0 kA at a external field of 18 Tesla by field orientation B||c and B||a, b, respectively. In general, the wire manufacturers’effort is aimed to improve the electrical parameters I$_c$ (B) at 77 K.

![Critical current as a function of axial strain at 77 K.](image)
In Fig. 3 the critical current $J_c$ for the applied axial force of a 4 mm wire is plotted in absolute Ampere values and relative to the zero force data $I_{c0}$. It is demonstrated that the current increases slightly up to a critical stress of about 550 MPa. Above 600 MPa it drops down within 50 MPa to zero indicating the situation that the generated strain is fully transferred to the YBCO layer.

The design of the Cu reel-to-reel plating facility considers this strain sensitivity. Thereby, the transport and the plating operation implicate mechanical forces on the tape. The tape has to be kept in a defined and constant distance to the separate anodes to ensure an efficient electrolytic field. The 33 inch REELS are driven of variable speed and electronic control for the transport through the cells. Because of the high sensitivity of the fully processed and therefore valuable coated conductor a careful operating procedure during the plating process is ultimate.

To control and to limit the possible forces and torques on the processing tape a mechatronics part and sensors are adapted to the REEL system. Fig. 4 displays the principal control detectors of the dynamical force and torque. In addition, for large tape lengths on has to limit the pre-tension on the tape. Applying pre-tension to the already processed tape results often in too strong radial forces that keep the inner layers on the REELS under unwanted high compressive stress.

Figure 4 shows the winding and tension control parts on both REEL chambers. In a compromise between force and the necessary tape stiffness in the cells, the control system reduces the torque of the powered motor drive continuously with increasing diameter of the winded tape on the REEL. For a tape length of up to 2000 m the REEL control reduces the winding force in three steps from 12 N to 10 N, and finally to 8 N for the outermost layers.

Fig. 5 displays the measurement of the influence of the tape bending on the critical current density $J_c$. In extreme assembling situation of coil winding the pure tape shows a tolerance in $J_c$ up to bending radius of 10 mm. The copper layer on the wire improves further the $J_c$ tolerance level up to very narrow bend radius of 6 mm.

3.3. Acidic versus alkaline Cu solution

The CuSO$_4$ plating process is most effective and non-poisonous for copper plating. The power supplies for the individual galvanic cells are designed and manufactured for low HTS wire conductivity (Hastelloy). It allows the current to flow constant, reverse or in a wide ratio of pulse plating. The typical electrolytic current distribution is shown in Fig. 2, where the starting current density is small, and few mA per square centimeter wire area. A copper seed is the primary target here followed by higher currents in the next cells. All plating parameters are determined and governed by the Nernst equation. The cell potential $E$ of a CuSO$_4$ solution relative to the standard potential $E_{0}$ is given by,

$$E = E_0 - \frac{RT}{nF} \ln \frac{C_1}{C_2}$$

R and F are the common Gas constant and the Faraday constant, respectively. $C_1$ and $C_2$ ($C_1 > C_2$) denote the electrolytic concentrations in the concentric and dilute status for n electron oxidation or reduction process, respectively. The standard potential for the reduction process at the cathode Cu$^{2+}$ (aqua) + 2 e$^{-}$ → Cu (s) is $E_0 = 0.337$ V. For the two electron process Cu (s) → Cu$^{2+}$ + 2 e$^{-}$ at the anode, the above equation at room
temperature becomes \( \Delta E = 0.0295 \text{ V} \times \log_{10} \left[ C_1 \left( \text{Cu}^{2+} \text{conc.} \right) / C_2 \left( \text{Cu}^{2+} \text{dilute} \right) \right] \), whereby \( \log_{10} \) is the common logarithm to the bases 10. The copper mass plated via CuSO\(_4\) can be calculated then by,

\[
m_{\text{Cu}} = \frac{I \times t}{(n \times F)}
\]

At an electrolytic current of 1.5 A applied for 2 minutes the theoretical galvanic deposited mass is 59 mg copper. This plated mass gives a thickness of 33 \( \mu \text{m} \) on 10 cm long and 0.4 cm width HTS 2G wire.

The \( \text{Cu}^{2+} \) concentration profile must adjust to match the mass transfer and reaction rate within the cell geometry.

An alternative way of plating is the use of a non-aqueous alkaline solution instead of acidic CuSO\(_4\) aqueous electrolyte. The alkaline electrolytic solution is a mixed copper complex salt and non-poisonous in contrast to the Cu(CN)\(_2\) route. We utilized again pulse plating technology to protect the tape. The applied chemical current density in the alkaline complex salt solution is by a factor of 2-3 smaller compared to CuSO\(_4\). The Cu layers become fine grained and are mechanically stable on the surface. A comparison of the two electrolytes is given in table 1. While the aqueous Cu sulfate electrolyte shows a 100% electrolytic current transformation the alkaline non-aqueous solution is less effective. On the other hand, the alkaline plating way displays a dense fine grained layer on the coated conductor wire.

### 3.4. Operation experience

Dependent on the wire substrate, non- textured Ni-Cr Stainless Steel or textured Ni-W5% tape, the plating tape speed with the 12 electrolytic cells is varied between 5 and 30 m/h. Within a program the current density is increased from 1-3 mA/cm\(^2\) up to maximum values of 30 – 50 mA/cm\(^2\) getting copper layer thicknesses of 20 – 30 \( \mu \text{m} \). The total current of each cell should limited to less than 3 Amperes preventing the summarized current on the tape of less than 30 A.

In principle, the plating facility is capable to operate tape length up to 4000 m. The tests of a SS substrate showed a safe and controlled REEL dynamics with speeds up to 100 m/h. The pulse plating technique can be programmed and selected in a wide variety of pulse durations and a fine tuned electrolytic load on the different tape positions.

### 4. Summary

After more than one year operation the experiences of automated REEL-to-REEL copper galvanic deposition equipment for 4 mm 2G PLD conductors is reported here. The plating unit is tested with speeds up to 100 m/h, and long- length SS substrate of 4 km was operated safe and controlled. The maximum axial stress of the tape is 600 MPa and the narrowest bend radius was 6 mm without degradation of \( J_c \). Both the standard aqueous Cu sulfate electrolyte and an alkaline non- aqueous solution has been used for continuous and pulse plating. The properties and the behavior of the different solutions are compared and evaluated.

### References

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[3] European Patent No. 131385, US Patent 7,048,840