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ENGINEERING DEPARTMENT

EN

# Extensive Characterisation of Copper-clad plates, bonded by the Explosive Technique;

## *for ITER Electrical Joints*


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# ITER Electrical Joint

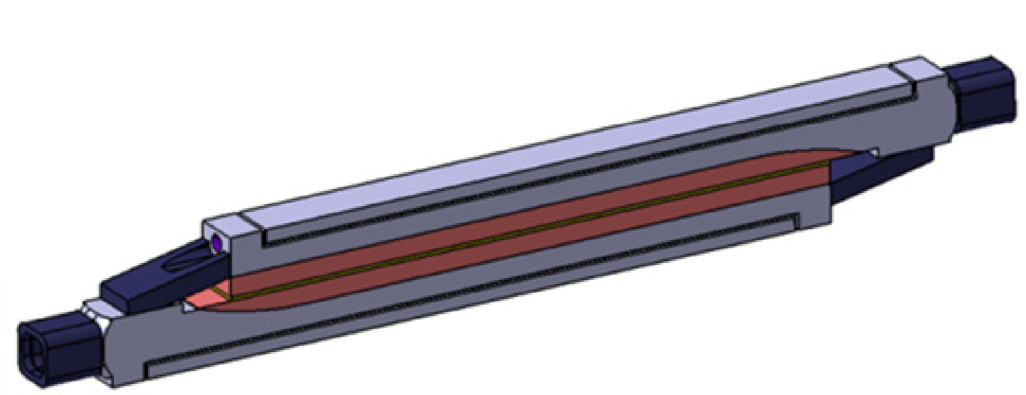

Figure 1: Twin-box shaking hands concept used for ITER electrical joints
G. Rolando et al., *Supercond. Sci. Technol.*, vol. 26, no. 8, p. 085004, Jun. 2013.

Design of the various ITER magnet systems imposes the use of highly performing electrical joints to connect unit lengths of superconducting coils.

Twin-box lap type joints are produced by compacting each cable end into a copper – stainless steel bimetallic box.

To validate technical joint solutions for the various magnet systems, an extensive characterisation is conducted to assess the performance of numerous copper-clad plates.

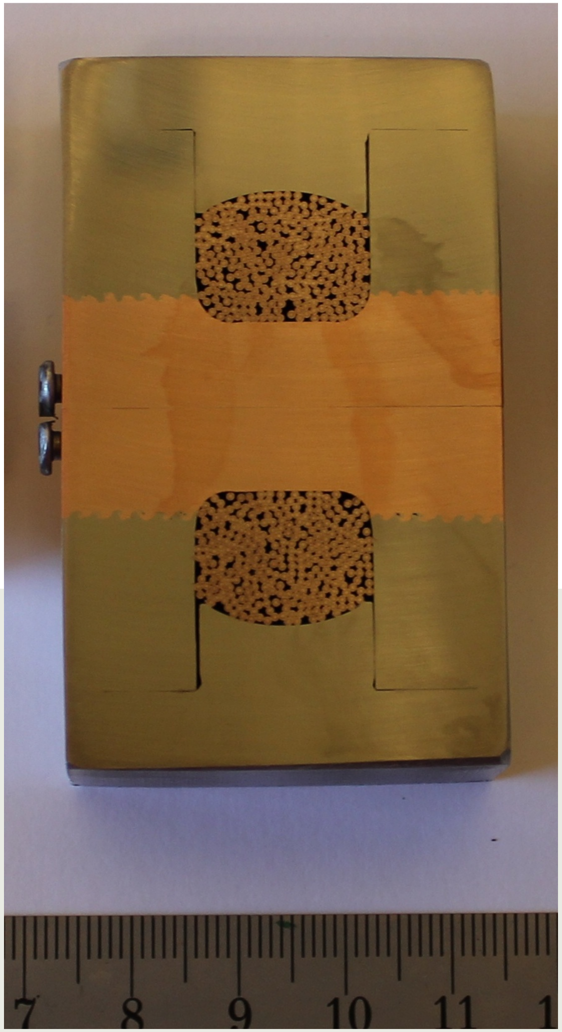

Figure 2: Cross-cut of a twin-box joint, demonstrating the employed bimetallic solution.

# "As-received" Bimetallic samples





Table 1: Material characteristics of the "As-received" sample blocks

| | Sample designation | Sample dimensions SS [mm] | Cu [mm] | Explosion welding Company | Producer Cu base plate | Material SS | Cu |
|---|---|---|---|---|---|---|---|
| Plate_1 | p1 | 65 | 14 | Company B | Supplier A | 316L | C10100[a] |
| Plate_2 | p2 | 90 | 20 | Company B | Supplier A | 316L | C10100 |
| Plate_3 | p3 | 33 | 12 | Company C | Supplier D | 316L | C10200[b] |
| Plate_4 | p4 | 40 | 12 | Company E | Supplier F | 316L | C12200[c] |

[a] OFE Cu; oxygen-free, electronic copper
[b] OF Cu; oxygen-free copper
[c] DHP Cu; phosphorized, high residual phosphorus copper

Bimetallic samples issued from various copper to stainless-steel explosion bonded plates were made available for;

- Non-destructive examination
- Microstructural characterisation
- Mechanical properties
- Thermo-electrical properties

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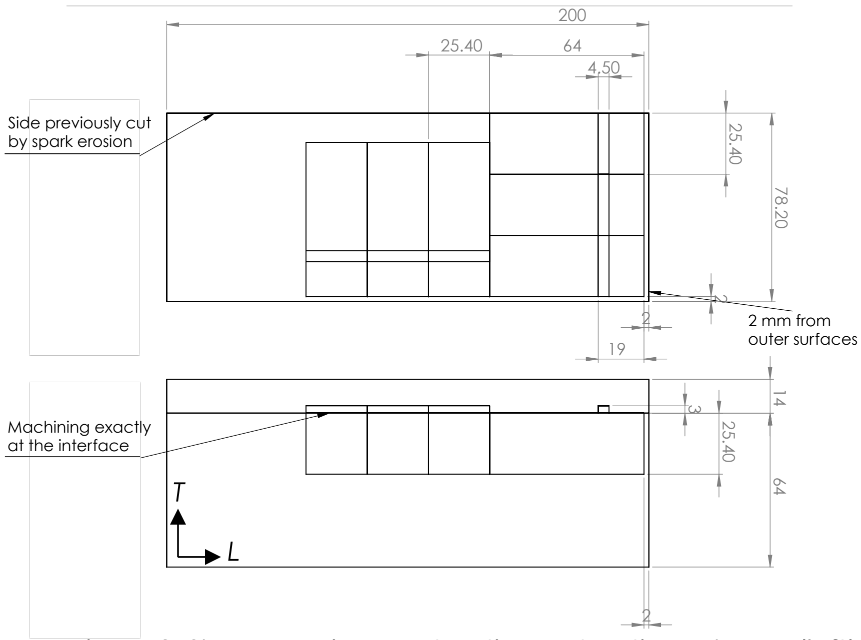
# Experimental techniques;
## specimens extracted



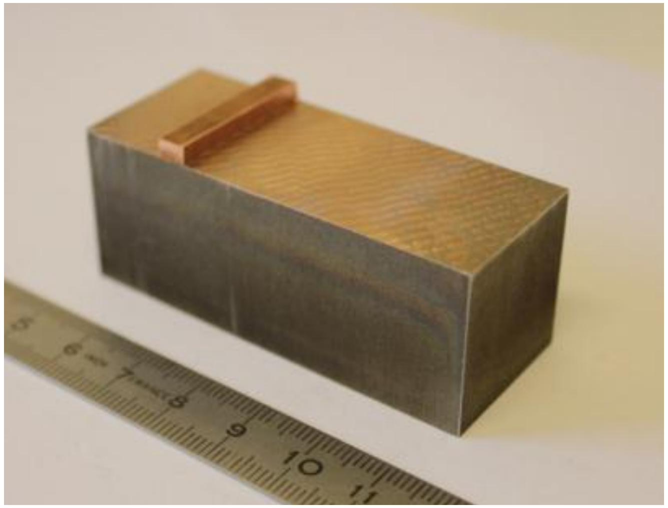
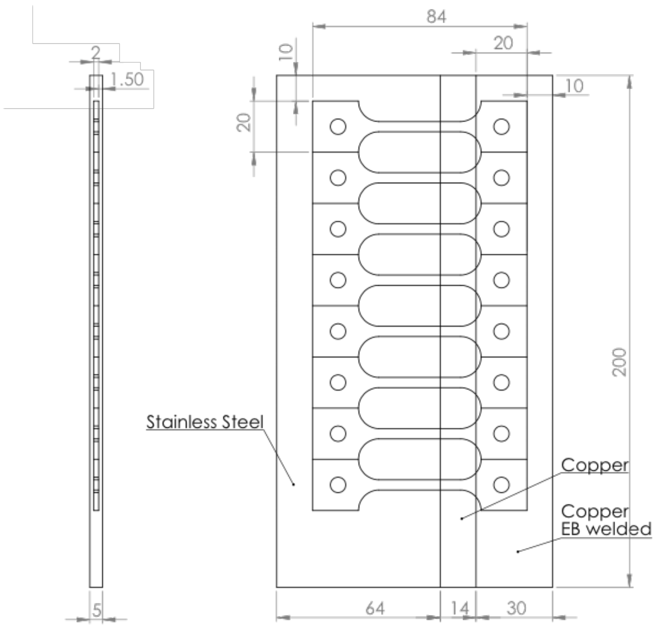



Figure 3: Shear specimen extraction; extraction scheme (left), and machined specimens (right). Machined carefully for shear measurement at the interface

- Shear specimens oriented in transverse as well as longitudinal direction
- carefully machined to ensure measurement of shear characteristics specifically at the interface.

# Experimental techniques;
## specimens extracted



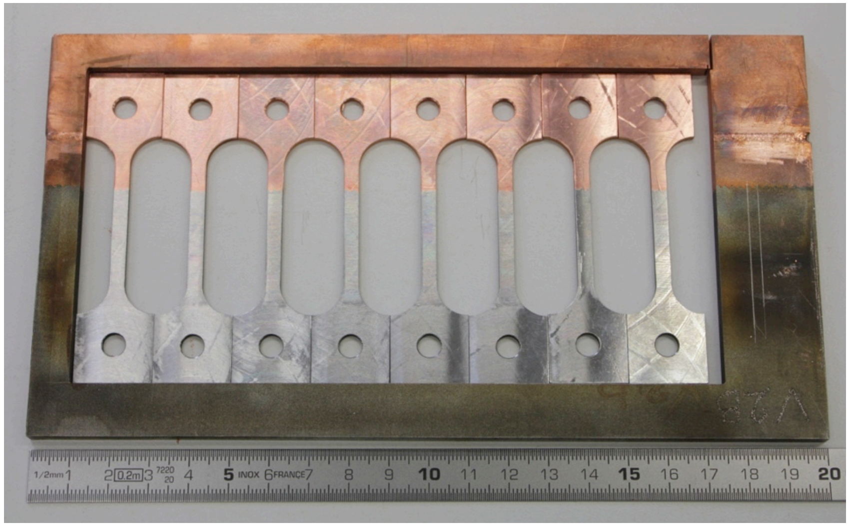



Figure 4: Tensile specimen extraction; extraction scheme (left), and machined specimens (right). Placement of the EB-weld in the larger portion of the head.

- Tensile specimens with longitudinal axis perpendicular to explosion bonded plane.
- Initial by spark-erosion machined slice Electron Beam (EB) welded to additional C10100 Cu strip.
  - To ensure positioning of the interface in the gauge length
  - Placement of EB-weld in larger portion of the head

# Quality of Bonding;
## obtained results

Table 2: Summary of explosion weld test results including mechanical properties at ambient and cryogenic temperature

| | Temp. [K] | $R_{p0.2}{}^{a}$ [MPa] | $R_m{}^{b}$ [MPa] | $\tau_{max.}{}^{c}$ $LD(TD)$ [MPa] |
|---|---|---|---|---|
| Plate_1 | 293 | 259 ± 3 | 261 ± 2 | 269 ± 24 (317 ± 15) |
| | 4.2 | 311 ± 7 | 453 ± 6 | |
| Plate_2 | 293 | 239 ± 4 | 251 ± 1 | 378 ± 14 (294 ± 1) |
| | 4.2 | 278 ± 12 | 459 ± 9 | |

[a] 0.2% Yield strength
[b] Maximum tensile strength
[c] Maximum shear strength

- High average maximum shear values are obtained
- Results are largely subject to the interlocked state at the sheared boundary

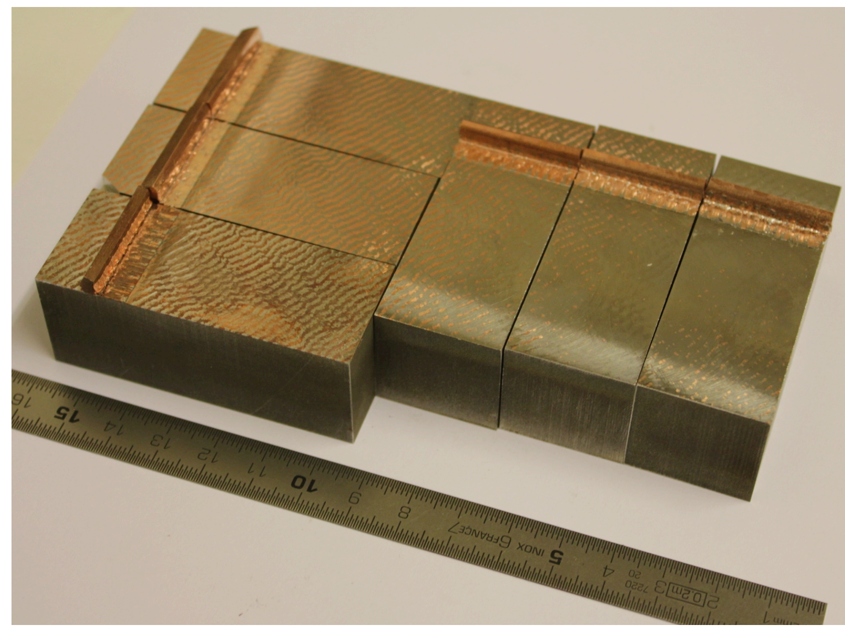


Figure 5: Specimens tested for plate_1, in shear, in longitudinal (left) and transverse direction (right).

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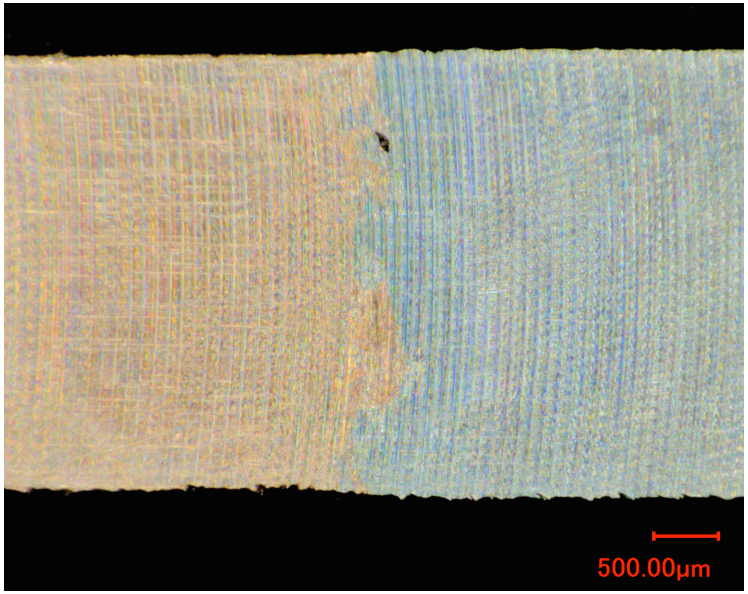


Figure 6: Bonded interface of tensile specimen 4.2 K_2 (plate_2) prior to measurement.

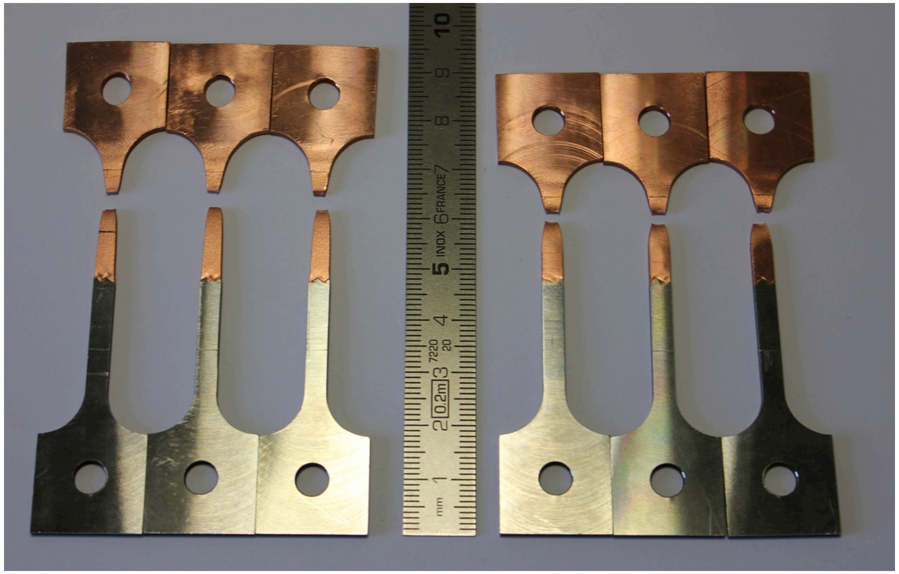

Figure 7: Specimens tested for plate_2, in tension, at 4.2 K (left) and 293 K (right). Failure consistently takes place in the copper cladding

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Room temperature results are consistent with C10100 values in the H02 temper (Hardesty, 1980).

Hardesty, F., 1980. ASM handbook. Volume 2, properties and selection: Nonferrous alloys and pure metals

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Table 3: Summary of resistivity vs. hardness results for plate_1 and plate_2

| | | Distance from interface | HV10 | HRF[a] | RRR |
|---|---|---|---|---|---|
| Plate_1 | Top | at 11 mm | 86 | 78 | 154 |
| | Bottom | at 5 mm | 96 | 84 | 116 |
| Plate_2 | Top | at 17 mm | 85 | 77 | 191 |
| | Middle | at 11 mm | 94 | 83 | 146 |
| | Bottom | at 5 mm | 99 | 86 | 126 |

Twarm [K] = 293.0
Tcold [K] = 4.5

[a] F-scale Rockwell Hardness (HRF) values are converted from the collected Vickers Hardness (HV) data following ASTM E-140

Macro-hardness measurements on the metallographic specimen, performed in the region of failure for the tensile tests, confirmed the H02 temper.

Hardesty, F., 1980. ASM handbook. Volume 2, properties and selection: Nonferrous alloys and pure metals

# Quality of Bonding;
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The Residual Resistivity Ratio (RRR) results, obtained in 2-3 positions show decreased values in the vicinity of the bonded interface where the plastic deformation during the explosion bonding process is largest.

This finding is consistent with the obtained results during hardness measurements, which are inversely linked.

Table 3: Summary of resistivity vs. hardness results for plate_1 and plate_2

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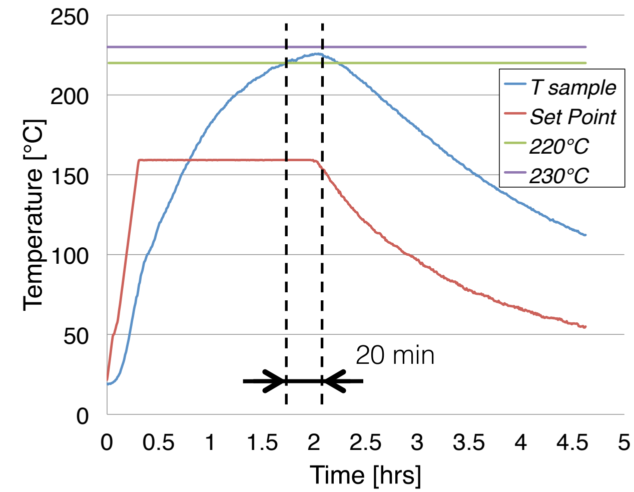
# Heat-treatments;
## simulating final joint formation

Vacuum furnace heat-treatment at low T to simulate the soldering cycle of the terminals for joint formation.

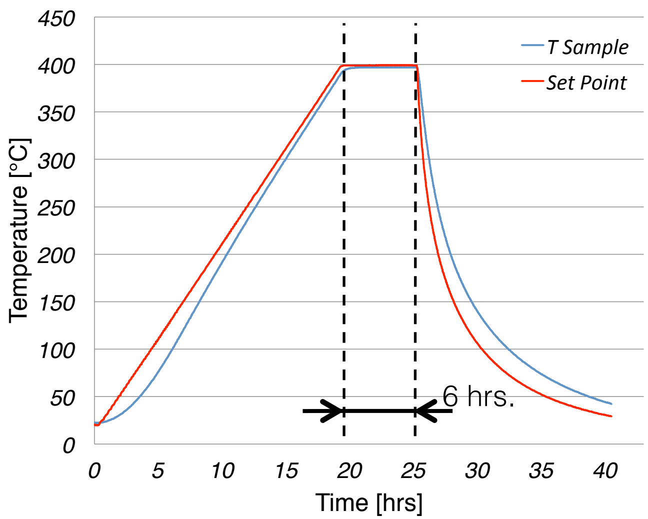
Ramp-up to 230°C over 1.5 hours to simulate heating in 8 steps during the soldering procedure where heating power is maintained at every step until joint temperature is stabilized.

Temperature hold at 230±10°C for 20 min (threshold T = 220°C).

*Thermal treatment 20 min @ 230°C*




*Thermal treatment 6 hrs. @ 400°C*




Additional vacuum furnace heat-treatment at high T to simulate optional end heat-treatment of terminal box prior to cable insertion (for copper softening).

Ramp-up rate: 20°C/hr.

Temperature hold at 400°C for 6 hrs. (samples in tube to avoid exposure to direct radiation).

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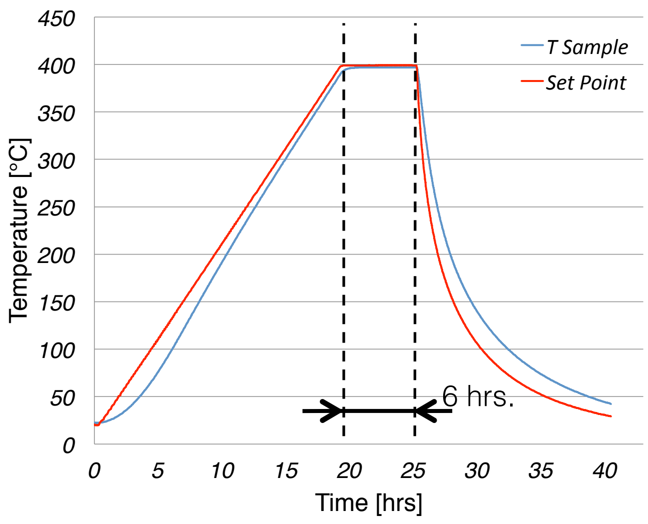


Figure 8: RRR and hardness specimens positioned for initial heat treatment at 230°C for 20 min.

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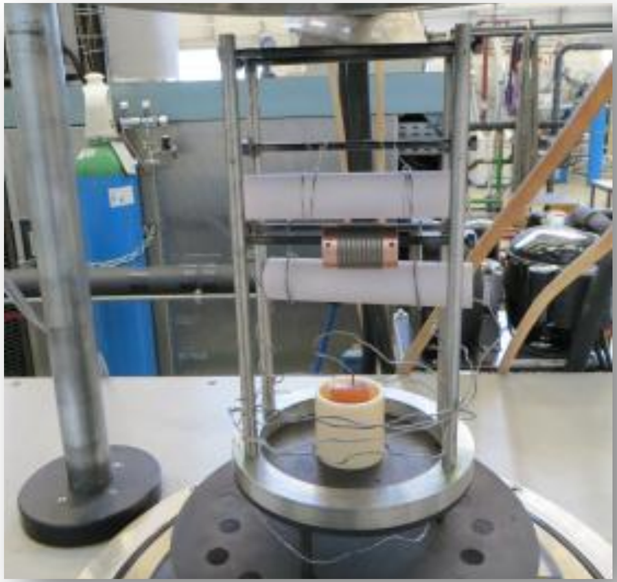

Figure 9: RRR and hardness specimens positioned for additional heat treatment at 400°C for 6 hrs.

# Copper sole;
## suitability of copper grades

Table 3: Summary of resistivity vs. hardness results for the examined plates prior and subsequent to heat-treatments, simulating final joint formation

| | Distance from interface | | Copper purity | State | HV10 | HRF | RRR |
|---|---|---|---|---|---|---|---|
| Plate_1 | Top | at 11 mm | C10100 | As-bonded | 86 | 78 | 154 |
| | | | | 20 min at 230°C | 86 | 78 | 176 |
| | | | | 6 h at 400°C | 42 | 30 | 524 |
| | Bottom | at 5 mm | C10100 | As-bonded | 96 | 84 | 116 |
| | | | | 20 min at 230 °C | 98 | 85 | 134 |
| | | | | 6 h at 400 °C | 43 | 32 | 474 |
| | | | C10100 Certified plate (coiled[a]; 14 mm) | | 45 | 35 | 345 |
| Plate_2 | Top | at 17 mm | C10100 | As-bonded | 85 | 77 | 191 |
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| | | | C10100 Certified plate (coiled; 20 mm) | | 40 | 29 | 365 |
| Plate_3 | Top | at 10 mm | C10200 | Annealed | 46 | 36 | 95 |
| Plate_4 | Top | at 9 mm | C12200 | As-bonded | 113 | 92 | 4.8 |
| | | | | 20 min at 230 °C | 112 | 92 | 4.8 |
| | | | | 6 h at 400 °C | 55 | 48 | 5.3 |
| | Bottom | at 5 mm | C12200 | As-bonded | 123 | 96 | 4.7 |
| | | | | 20 min at 230 °C | 117 | 94 | 4.8 |
| | | | | 6 h at 400 °C | 53 | 46 | 5.3 |

C10100, OFE copper explosion bonded to 316L stainless steel;

- Heat-treatment simulating soldering showed no significant effect on the hardness, while a small effect on the RRR is observed.
- In contrary; the subsequent softening cycle fully annealed the copper cladding beyond the initial state, prior to explosion bonding.

[a] Subsequent to production, the material is stored on a spool. The deformation results in additional hardening of the material.

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| | | | | 20 min at 230 °C | 117 | 94 | 4.8 |
| | | | | 6 h at 400 °C | 53 | 46 | 5.3 |

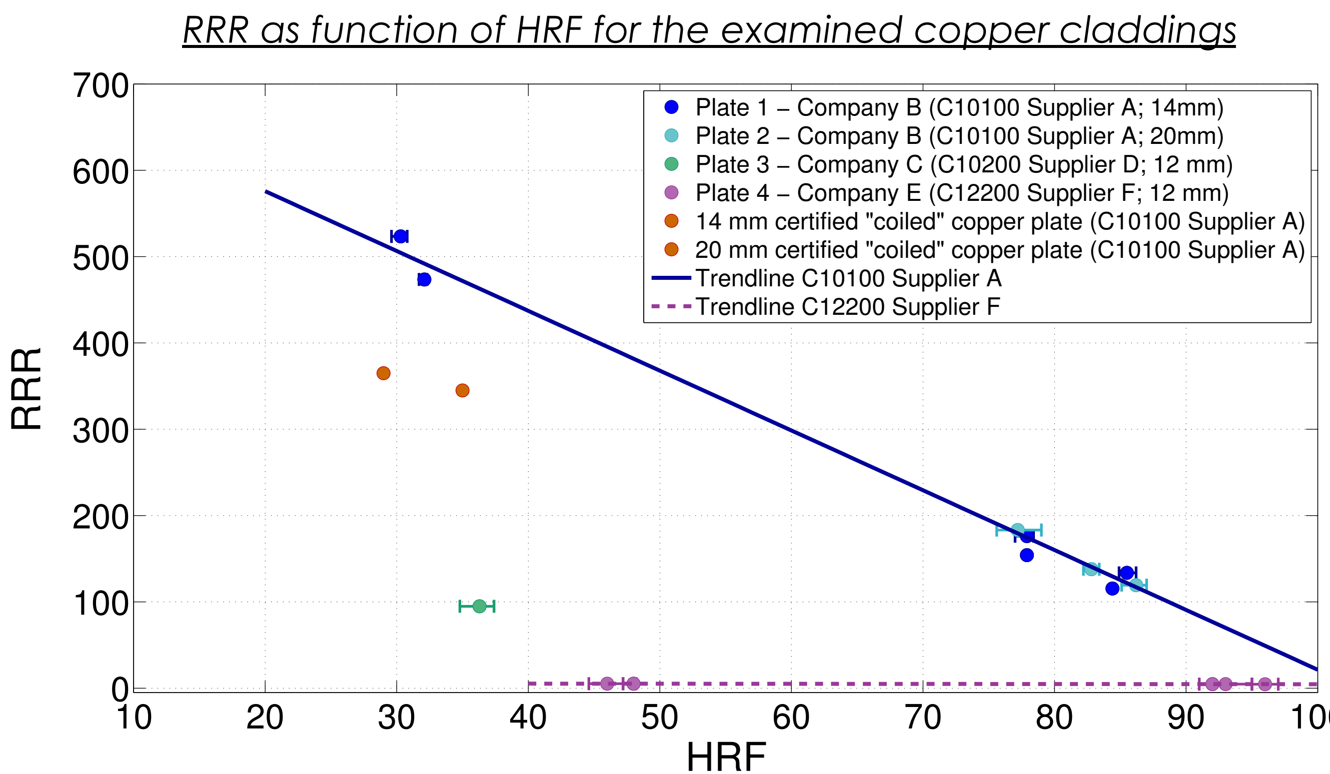
C12200, DHP copper explosion bonded to 316L stainless steel;

- Heat-treatment simulating soldering showed no significant effect on both hardness as well as RRR.
- In contrary; the subsequent softening cycle annealed the C12200 Cu cladding.
- For this low purity grade Cu, RRR is mainly driven by impurity content. No significant increase of RRR is noticed with material annealing by a severe thermal cycle, while a large decrease in hardness is observed.

[a] Subsequent to production, the material is stored on a spool. The deformation results in additional hardening of the material.

# Copper sole;

## suitability of copper grades




- Consistent trend-line for the highly pure C10100 copper, as used in p1 and p2.
- Indication of a slightly less pure C10200 copper in clad plate p3.
- As expected, the purity of the copper as used in p4, C12200, lies beneath the previously mentioned, and shows no noticeable dependence of RRR on hardness.

# Summary of findings

- An extensive characterisation is carried out on a diverse set of copper-clad plates for the electrical joints of the ITER magnet system
- The properties of the examined clad plates are dominated by the individual materials
- Increased hardening, beyond H02, towards the bonded interface
- Little effect of the terminal soldering process on the RRR and mechanical characteristics of both high purity, C10100, as well as low purity, C12200, copper grade claddings
- High purity C10100; A high RRR, low hardness, fully annealed state, beyond the initial state of the coiled copper plate, with final softening treatment
- Low purity C12200; RRR values are driven mainly by impurity content. No significant increase in RRR with material annealing, solely a large decrease in hardness
- For an electrical joint, connecting unit lengths of coils working in a pulsed regime, the use of a lower purity copper cladding could be a compromise

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