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

for ITER Electrical Joints

S.A.E. Langeslag

S. Sgobba, P. Libeyre, C.-Y. Gung

8 July 2014
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.
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

The design is based on a twin-box lap type joint. By fabrication of twin terminals at both conductor ends, soldered together, the concept allows for the joints to be dismountable. Each terminal is manufactured by compacting the stripped cable end into a bimetallic box, machined from a copper-clad plate, bonded by the explosive technique (Ciazynski et al., 1996).

The terminal joint relies on both the structural as well as the conductive properties of the bimetallic box, for which it requires a tight mechanical link between the conductive copper-cladding and the structural stainless steel. Moreover, efficient current transfer through the copper side of the bimetallic box is essential. As a result of operating conditions involving transient magnetic fields during coil operation in certain magnet systems, eddy currents are induced in the copper sole of the bimetallic box, leading to Joule-heating, hence a reduced superconductor stability margin (Ciazynski and Martinez, 2002). The use of a low purity copper cladding, featuring a low Residual Resistivity Ratio (RRR) will be efficient to increase loop resistance and reduce the induced currents. However, the joint must also comply with a low DC resistance requirement to prevent excessive energy loss.

To validate technical joint solutions for the various magnet systems, non-destructive examinations, micro-optical and mechanical tests were conducted to assess the performance of numerous copper-clad plates. Additionally a discussion is presented concerning the suitability of certain copper purity grades, aiming at identifying the most suitable copper grades for the different types of joints.

### 2. Materials and Experimental Procedures

For the present study, bimetallic samples issued from various copper to stainless steel (Cu - SS) explosion bonded plates were made available for non-destructive examination and the assessment of microstructural, mechanical and thermo-electrical properties, in order to conclude on their suitability for future terminal joint productions. The list of the various blocks tested is presented in Table 1.

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

| Sample designation | Sample dimensions | Explosion welding Company | Producer Cu base plate | Material |
|--------------------|-------------------|---------------------------|------------------------|----------|
| Plate_1 p1         | 65 x 14           | Company B                 | Supplier A             | 316L C10100⁵ |
| Plate_2 p2         | 90 x 20           | Company B                 | Supplier A             | 316L C10100 |
| Plate_3 p3         | 33 x 12           | Company C                 | Supplier D             | 316L C10200⁶ |
| Plate_4 p4         | 40 x 12           | Company E                 | Supplier F             | 316L C12200⁷ |

---

⁵ OFE Cu; oxygen-free, electronic copper

⁶ OF Cu; oxygen-free copper

⁷ 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

8 July 2014
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

**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 | Material Cu |
|-------------------|---------------------------|---------|---------------------------|-----------------------|------------|-----------|
| Plate_1 p1        | 65                        | 14      | Company B                 | Supplier A            | 316L       | C10100a   |
| Plate_2 p2        | 90                        | 20      | Company B                 | Supplier A            | 316L       | C10100    |
| Plate_3 p3        | 33                        | 12      | Company C                 | Supplier D            | 316L       | C10200b   |
| Plate_4 p4        | 40                        | 12      | Company E                 | Supplier F            | 316L       | C12200c   |

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
Experimental techniques; specimens extracted

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

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

- 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

Figure 4: Tensile specimen extraction; extraction scheme (left), and machined specimens (right). Placement of the EB-weld in the 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).
Table 2: Summary of explosion weld test results including mechanical properties at ambient and cryogenic temperature

| Plate | Temp. [K] | $R_{p0.2}^a$ [MPa] | $R_m^b$ [MPa] | $\tau_{max,c} \Delta LD(TD)$ [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

---

3.2. Copper characteristics

Table 3 summarises the average results of the main copper cladding properties for the various copper-clad plates. The RRR results, obtained in two positions; in the vicinity of the bonded interface and towards the outer surface, obtained results.
Table 2: Summary of explosion weld test results including mechanical properties at ambient and cryogenic temperature

|       | Temp. [K] | $R_{p0.2}$<sup>a</sup> [MPa] | $R_m$<sup>b</sup> [MPa] | $\tau_{max}$<sup>c</sup> $LD(TD)$ [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                 |                                             |

<sup>a</sup>0.2% Yield strength  
<sup>b</sup>Maximum tensile strength  
<sup>c</sup>Maximum shear strength

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
Quality of Bonding; obtained results

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

| Distance from interface | HV10 | HRF \(^a\) | RRR |
|-------------------------|------|----------|-----|
| Plate_1 Top at 11 mm    | 86   | 78       | 154 |
| Plate_1 Top at 11 mm    | 85   | 77       | 191 |
| Plate_1 Bottom at 5 mm  | 99   | 86       | 126 |
| Plate_2 Top at 11 mm    | 94   | 83       | 146 |
| Plate_2 Middle at 11 mm | 94   | 83       | 146 |
| Plate_2 Bottom at 5 mm  | 99   | 86       | 126 |

\(^a\) 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.

Room temperature results are consistent with C10100 values in the H02 temper (Hardesty, 1980).
In Table 2, one can observe the results of the shear measurements. High average maximum shear values were obtained for p1 (p2), both in longitudinal, 269 MPa (378 MPa), as well as transverse direction, 317 MPa (294 MPa), with respect to the main direction of explosion bonding. The difference in shear strength between the two measured directions is quite significant, with a large spread in the individual results. However, when observing the specimens post measurement (Fig. 3c), it can be seen that these results are largely subject to the interlocked state of the stainless steel and copper at the sheared boundary. As the boundary covers a thickness of \( \sim 1 \text{ mm} \) (Fig. 2a), the shear interface is located within this range. An interface machined slightly towards the stainless steel side (Fig. 3c, right) will be sheared mainly in the stainless steel and will therefore exhibit higher shear properties. In all cases, the shear plane during measurement cuts through both materials, indicating a shear strength of the interface beyond the ones of the individual materials.

### 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  |

^aF-scale Rockwell Hardness (HRF) values are converted from the collected Vickers Hardness (HV) data following ASTM E-140

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

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 8 July 2014
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).

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).

8 July 2014
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).

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).
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).

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).
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  |
|-------------------------|--------------|---------------------|------|-----|------|
| Top                     | C10100       | As-bonded           | 86   | 78  | 154  |
|                         |              | 20 min at 230°C     | 86   | 78  | 176  |
|                         |              | 6 h at 400°C        | 42   | 30  | 524  |
| Bottom                  | C10100       | As-bonded           | 96   | 84  | 116  |
|                         |              | 20 min at 230°C     | 98   | 85  | 134  |
|                         |              | 6 h at 400°C        | 43   | 32  | 474  |
| Middle                  | C10100       | As-bonded           | 94   | 83  | 146  |
|                         |              | 6 h at 400°C        | 43   | 32  | 474  |
| Bottom                  | C10100 Certified plate (coiled; 14 mm) | 45   | 35  | 345  |
| Top                     | C10100       | As-bonded           | 85   | 77  | 191  |
| Middle                  | C10100       | As-bonded           | 94   | 83  | 146  |
| Bottom                  | C10100       | As-bonded           | 99   | 86  | 126  |
|                         |              | C10100 Certified plate (coiled; 20 mm) | 40  | 29 | 365  |
| Top                     | C10200       | Annealed            | 46   | 36  | 95   |
| Top                     | 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                  | 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.

*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

| Distance from interface | Copper purity | State                  | HV10 | HRF | RRR |
|-------------------------|--------------|------------------------|------|-----|-----|
| Top                     | C10100       | As-bonded              | 86   | 78  | 154 |
| Top                     | C10100       | 20 min at 230°C        | 86   | 78  | 176 |
| Top                     | C10100       | 6 h at 400°C           | 42   | 30  | 524 |
| Bottom                  | C10100       | As-bonded              | 96   | 84  | 116 |
| Bottom                  | C10100       | 20 min at 230°C        | 98   | 85  | 134 |
| Bottom                  | C10100       | 6 h at 400°C           | 43   | 32  | 474 |
| Top                     | C10100       | certified plate        | 45   | 35  | 345 |

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

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

RRR as function of HRF for the examined copper claddings

- 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.

8 July 2014
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.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.
