Realization of a first series of Single Channel Prototypes for the SPIDER grids

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Abstract

The SPIDER and MITICA experiments, planned to be built at Consorzio RFX for the development and optimization of the ITER Heating and Current Drive Neutral Beam Injectors, feature a number of components interested by high heat fluxes, that must be cooled during operations by means of suitable high performance cooling systems. As the design for such cooling systems presents some technological and heat transfer issues, a specific R&D program have been carried out, particularly referred to the accelerator grids that are among the most critical components.

These components are foreseen to be manufactured by electrodeposition of pure copper onto a copper base plate to realize cooling channels and magnets slots, while the connection with the feeding manifolds is foreseen to be realized by friction welding or electron beam welding.

Suitable manufacturing parameters and production methodologies have been identified by constructing and testing a first series of prototypes. A set of thermocouples have been embedded in some prototypes, to allow the evaluation local heat transfer coefficients and identification of local spots where dry-out phenomena might occur. To this purpose, a dedicated electrodeposition process has been developed.

Keywords: friction welding, electrodeposition, SPIDER, grids, prototypes

Introduction

Active cooling of the SPIDER and MITICA experiments [1, 2] presents critical issues and, in order to validate and to develop the design methods, proper research activities are required to investigate heat transfer and technological aspects in electrodeposited cooling channels. In particular, a precise estimation of the cooling capability of the cooling channels of the accelerator grids is required for the thermo-mechanical design in order to avoid overheating, a bad flow distribution and, as a consequence, the risk of dry-out in hot spots with burning phenomena.

It is foreseen to manufacture the grids by copper electrodeposition on a copper base plate; in this way, it is possible to obtain small internal cooling channels and magnets slots. Friction Welding (FW) and Electron Beam Welding (EBW) have been both employed to realize copper (Cu) to stainless steel (SS) junctions in components for fusion experiments [3, 4].

FW is a method for making welds in the solid phase in which one component is moved relative to and in pressure contact with the mating component to produce heat at the faying surfaces, the weld being completed by the application of a force during or after the cessation of relative motion. Under normal conditions, the faying surfaces do not melt. Filler metal, flux, and shielding gas are not required with this process [5].

EBW is a fusion joining process that produces a weld by impinging a beam of high energy electrons to heat the weld joint. An EBW gun uses a high intensity electron beam to target a weld joint, in a vacuum chamber. The kinetic energy of the electrons in transformed into heat upon impact.

The electrodeposition technique permits to obtain a complex geometric shape (with very small cooling channels that run inside the grid and embedded magnets) and to have good mechanical properties, due to the high purity and to the very small grain size. A typical yield strength obtainable on electrodeposited copper is in the order of 180-200 MPa [6].

These manufacturing techniques are not widely used and their employment in the grids production needs customization. Moreover, there is few information in literature about friction welding of SS to Cu and Cu electrodeposition [7, 8, 9]. Hence, suitable manufacturing parameters and production methodologies have been identified by producing a first set of prototypes. In particular, some technological aspects imply an accurate testing, like the assessment of expertise in electrodeposition (featuring cooling channels and magnets grooves) and friction welding processes, the definition of a reliable manufacturing process for the grids, the accurate estimation of the grid manufacturing costs and methods for embedding of thermocouples.

For the prototypes, FW was preferred to EBW to obtain the heterogeneous SS-Cu junctions because it was found to be more versatile (with FW it is possible also to weld adjacent tubes with a small interaxis distance, as foreseen in the SPIDER grids design) and cheaper.

Moreover, the prototypes were designed to be employed to carry out heat transfer and fluid-dynamic analysis in the ICE (Insulation Cooling Experiment) test bed [10] for the following investigations: evaluation of the heat transfer coefficients, evaluation of pressure drops for flow rate variations, estimations on the grids temperature distribution, investigations on the criti-
1. Design of single channel prototypes

Three prototypes (with dimensions 200 mm x 30 mm x 10 mm) have been realized for each cooling channel geometry: plasma grid like (with a 3 mm x 2 mm channel), extraction grid like (with double 3 mm x 2.5 mm channel) and grounded grid like (with a 5 mm x 3 mm channel). The nine Single Channel Prototypes (SCPs) have been obtained from a single plate (200 mm x 300 mm x 10 mm), with a geometry as similar as possible to the grids of the SPIDER experiment. Doing so, it has been possible to face the problems related to the construction of a generic grid: welding of a narrow array of tubes on the side of the grid, machining, electrodepositing and thermocouples embedding on a grid. Fig. 1 shows a CAD drawing and a picture of the SCPs.

2. Manufacturing phases

The materials used for the prototype construction are the AISI 316 L stainless steel for the tubes and the OFHC copper for the base plate. The main phases for the development of the prototypes have been:

1. FW process setup by FW samples manufacturing;
2. Testing of the FW samples (helium leak tests and tensile tests);
3. Special setup of the FW machine with a dedicated support and positioning system to weld SS rods onto a Cu base plate;
4. Welding of the SS rods onto both sides of the Cu base plate;
5. Machining of the cooling channels on the base plate and drilling through the SS rods and Cu base plate;
6. First electrodeposition to close the cooling channels;
7. Machining of the TCs housing grooves;
8. Second electrodeposition to embed the TCs;

The setup of the FW parameters is a very critical aspect. Furthermore, the geometries foreseen in prototype and grids production are unconventional for FW companies, because they feature several weldings on the same plate, small dimensions, diameter of tube to be welded with a similar size of the plate thickness, and welding of dissimilar materials (Cu and SS). The FW machine has been setup to weld cylindrical to plane pieces, as shown in Fig. 3.

2.1. Manufacturing of friction welding samples

As a preliminary phase, in order to develop the welding procedure, several FW samples have been manufactured with different welding parameters: rotational speed, friction pressure, burn-off length and forging pressure. The samples realization comprises friction welding of the SS rod to the Cu part and the blind hole axial drilling (from the SS side into the copper side). The FW process was monitored by recording the parameter set and the welding diagram for each sample, while the Cu-SS junctions were visually inspected on a first group of samples (see Fig. 2a).
Helium leak tests in high pressure and vacuum conditions (see Fig. 2b) have been carried out to detect leakages through the weldings. For the leak test at high pressure, the samples have been filled with helium at 25 bars; for the leak test in vacuum, the samples have been directly connected to the leak detector and helium was sprayed on the welding area from the outside. For both the tests, the measured leak rates were not significantly higher than the background noise levels, which were $4 \times 10^{-8}$ mbar l/s for the high pressure test and $3 \times 10^{-9}$ mbar l/s for the vacuum test. Hence, the leak tests can be considered passed.

Then, some samples have been subjected to tensile tests, in order to evaluate the mechanical resistance of the joint (see Fig. 2c). The tensile strength resulted to be always higher than 300 MPa. Fracture occurred on the copper side of the welding, where the material was torn after a large plastic deformation (see Fig. 2d).

From the friction welding samples, the welding parameters to manufacture the SCPs plate have been identified and are reported in Tab. 1.

### 2.2. Manufacturing of single channel prototypes

Once the friction welding procedure has been validated and the weldings have shown the required characteristics in terms of strength and leak tightness, the SCPs manufacturing started up. The SS rods have been welded to the sides of the copper plate (see Fig. 3a). A problem was experienced during the friction welding phase. Due to plate overheating, the welding of a rod did not succeed. This underlined the need for maximum temperature control during welding. After the welding of the rods, the cooling channels have been obtained on the plate by milling and the rods have been drilled to obtain a tube with 10 mm and 7 mm outer and inner diameter, respectively (see Fig. 3b).

Then, the cooling channels have been filled with conductive wax, so that the electrodeposition has been executed also over the channels. The plate was then mounted on a frame and inserted into a sulfuric acid based copper bath. Galvanic electrodeposition on the grid surface was obtained applying a voltage gap between the plate and a copper anode (both inside the bath). A first layer of copper (about 0.5 mm) was electrodeposited to close the channels. After removing the wax, a flow test and a helium leak test of the channels were carried out. Moreover, in order to relax the residual stresses, four thermal cycles in vacuum from 70 °C to 180 °C were performed maintaining the temperature for one hour.

<table>
<thead>
<tr>
<th>Friction phase</th>
<th>Rotational speed [RPM]</th>
<th>Contact pressure [MPa]</th>
<th>Shortening [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3000</td>
<td>56</td>
<td>2</td>
</tr>
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<table>
<thead>
<tr>
<th>Forging phase</th>
<th>Rotational speed [RPM]</th>
<th>Contact pressure [MPa]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>80</td>
<td>10</td>
</tr>
</tbody>
</table>

3. Insertion of embedded thermocouples

In order to measure the temperature at the cooling channel walls, a set of TCs was embedded in the prototypes during the electrodeposition. This has been carried out after the cooling channels had been created with a first electrodeposition. The insertion of TCs during electrodeposition was a new manufacturing process and so, different methodologies have been tested. Two different types of housing for the TCs have been designed to investigate which could guarantee the best performance for removal of wax and for TC positioning, aiming at measuring temperature as close as possible at the channel wall. TCs of two different diameters (0.25 and 0.5 mm) have been also tested to investigate the positioning easiness and the robustness. The thermocouple grooves have been realized as close as possible to the cooling channels, which had been already closed by an electrodeposited copper layer of about 1.5 mm. Two different types of grooves to embed the TCs have been realized. The first configuration foresees each thermocouple having its own site perpendicular to cooling channel. Parallel fingers were machined at different depth in the copper (see Fig. 4a). In the second configuration, TCs are housed in a common groove, which branches to route each thermocouple to its position (see Fig. 4b).

A survey on TCs types and dimensions has been carried out to select the sensors to be inserted in the prototype plate. Insulation tests on TC prototypes supplied by different companies have been carried out, both in dry and wet condition. The TCs technical specifications are listed in Tab. 2.

The embedding procedure steps are the following:
Table 2: Thermocouples technical specifications.

<table>
<thead>
<tr>
<th></th>
<th>Mineral insulated cable</th>
<th>Transition</th>
<th>Cable transition</th>
<th>Resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulant</td>
<td>High purity magnesium oxide 99.4%</td>
<td></td>
<td>Special resin</td>
<td></td>
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<tr>
<td>Sheath material</td>
<td>INCONEL 600</td>
<td></td>
<td>- Duralco 4460</td>
<td></td>
</tr>
<tr>
<td>Sheath diameter [mm]</td>
<td>0.25 and 0.5</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Length [mm]</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductors material</td>
<td>Type K standard alloys</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>ANSI MC 96.1 Class 1 as per IEC 60584-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. operating temp. [°C]</td>
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<td></td>
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<tr>
<td>Junction</td>
<td>Insulated</td>
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<tr>
<td>Diameter [mm]</td>
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<td></td>
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<tr>
<td>Length [mm]</td>
<td>30</td>
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<td></td>
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<tr>
<td>Material</td>
<td>Stainless steel</td>
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<td></td>
</tr>
<tr>
<td>Max. operating temp. [°C]</td>
<td>250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>Two insulated wires with outer insulation</td>
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<td></td>
</tr>
<tr>
<td>Insulant</td>
<td>Kapton</td>
<td></td>
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</tr>
<tr>
<td>Conductors material</td>
<td>Type K standard alloys</td>
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<tr>
<td>Calibration</td>
<td>ANSI MC 96.1 Class 1 as per IEC 60584-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length [mm]</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. operating temp. [°C]</td>
<td>250</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resin</td>
<td>Special resin for vacuum - Duralco 4460</td>
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<td></td>
</tr>
</tbody>
</table>

1. Pre-coppering of TCs to have a good bonding during copper electrodeposition;
2. Milling of channels for TCs;
3. Milling of copper plate to a thickness of 0.7 mm over the cooling channel;
4. Fixing of the TCs by caulking with a piece of weak copper wire to hold them in position;
5. Filling of the channels with wax (except TCs tips);
6. Embedding of the TCs tips by copper electrodeposition;
7. Cleaning of the plate surface and grinding the copper to the base plate level;
8. Final electrodeposition to obtain the required layer thickness (1.5 mm over the cooling channel, 0.7 mm over the TCs channel);

The outcomes from the embedding of TCs are the following. Concerning the dimensions, being the 0.5 mm TCs less fragile than the 0.25 mm ones, the pre-coppering and electrodeposition processes were easier, but the 0.25 mm ones were easier to set in their site. Regarding the housings, the advantages in using a common groove for all the TCs (parallel to the cooling channel) are the easier handling during the manufacturing and the possibility of inserting the TCs from both sides of the plate. On the other hand, the employment of a single groove for each TC permits an easier fixing and waxing, but can be applied only at the edges of the grids.

Conclusion

Suitable production methodologies for the manufacturing of high heat flux components for fusion experiments have been investigated at Consorzio RFX by prototypes construction and testing. Nine single channel prototypes of the SPIDER accelerator grids were manufactured using the FW and electrodeposition techniques. A set of tests has been carried out to qualify the usage of FW for joining the SS tubes to the Cu grid sides and of electrodeposition for the realisation of embedded cooling channels. Moreover, a method for the embedding of TCs in copper components by electrodeposition has been successfully developed.

A test campaign is planned for these prototypes in the ICE test bed, aiming at investigating the thermo-hydraulic behavior of grid-like cooling channels in conditions similar to the ones foreseen in the SPIDER and MITICA experiments.

Acknowledgements

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References