Investigation of the Thermo-mechanical Properties of Electro-deposited Copper for ITER

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Abstract

The optimal behaviour of copper as heat sink material makes it suitable for many components of nuclear fusion devices subjected to cyclic heat loads with high power densities. In particular, this material is considered for several water cooled components for the ITER Neutral Beam Injector, like the ion source and the acceleration grids. The electrodeposition technique permits to obtain complex geometric shapes (with small cooling channels and embedded magnets) and to have good mechanical properties at the same time, due to the high purity and to the very small grain size. Consequently, the thermo-mechanical properties of electro-deposited pure copper are considered as a crucial aspect for the design of the new generation fusion experimental devices. This paper presents an exhaustive test campaign aimed at investigating the properties of this material.

Key words: electro, deposited, copper, material, properties

1. Introduction

The properties of electro-deposited pure copper are considered as a crucial aspect for the design of the next generation’s experiments for the development of the ITER Neutral Beam Injectors, namely SPIDER (Source for Production of Ion of Deuterium Extracted from RF plasma) \cite{1}, MITICA (Megavolt Injector Concept Advancement) and ELISE (Extraction of Large Ion Source Experiment) \cite{2}. These devices feature components subjected to cyclic heat loads with high power densities (up to 20 MW m\textsuperscript{-2}). So reliable thermo-mechanical properties of this material are highly required, in order to carry out precise static, ratcheting and fatigue verifications.

As the material data available were scarce and not referred to a particular norm, a comprehensive test campaign has been planned and carried out in order to precisely investigate the properties of this material, in a metallurgical condition similar to the one of the components in fusion experiments. The main mechanical properties (Young’s modulus, yield strength, ultimate strength, elongation, reduction of area and fatigue life) and the main thermal properties (specific heat, thermal conductivity and thermal expansion) were evaluated. The most important parameters were investigated in function of temperature and metallurgical state. Particular care has been taken for the fatigue test campaign, which was carried out in strain control, inert atmosphere, both at room and at high temperature. The European (Euronorm) and American (ASTM) norms were observed for the test campaigns. Every phase of the activity was carried out in compliance with the quality requirements by Fusion for Energy (F4E).

Figure 1: Test set-up of the tensile tests: (a) Overview; (b) Specimen equipped with thermocouples and strain gauge.

Four plates were produced using the same process foreseen for the production of the components for the beam sources. From these, 116 specimens were milled (44 specimens for tensile tests and 72 for fatigue tests). It was chosen to adopt flat specimens, with dimensions and tolerances compliant to the considered norms, because most of the components to be manufactured with this material have a flat shape.

Finally, a comparison with the properties of pure annealed copper from the ITER database \cite{3} was carried out.

2. Tensile testing campaign

The tensile tests were performed according to the EN 10002 standard \cite{4, 5} in a temperature range between 20° C and 360° C using an Instron tensile testing machine, equipped with a climate chamber and a data acquisition system for recording the strain, load and temperature signals (see Fig. 1). The strain was measured with a strain gauge attached at the center of each specimen (giving a very precise measurement but limited to the
elastic part of the test), an extensometer (less precise but working also in the plastic part) and the displacement between the machine clamps (referred to the entire length of the specimen). In this way, a certain redundancy of signals was obtained, with the important advantage of cross checking the strain signals, and a consequent better reliability of the results. The test temperature was measured by means of two thermocouples (one at the center and one at the top of the specimen gauge section).

Two specimens were tested for each temperature, which showed very similar results. A stress-strain curve per each test temperature is reported in Fig. 2a. Interpolating curves for the tensile properties in function of temperature (see Fig. 2b), valid between 20°C and 360°C, are:

\[
\text{Ultimate strength [MPa]} = 274 - 0.58 \cdot T \\
\text{Yield strength [MPa]} = 235 - 0.49 \cdot T \\
\text{Young’s modulus [GPa]} = 129 - 0.16 \cdot T \\
\text{Elong. [%]} = 31.9 + 0.43 \cdot T - 0.003 \cdot T^2 + 4.9 \cdot 10^{-6} \cdot T^3 \\
\text{RA [%]} = -81.9 - 0.51 \cdot T + 0.006 \cdot T^2 - 1.1 \cdot 10^{-6} \cdot T^3
\]

It can be noted that for the curves at temperatures lower that 270°C there is a step in stress at a strain of around 8%. This step is due to a stroke rate variation from 1 to 4 mm min\(^{-1}\) (the rates were chosen in compliance with the maximum strain rates suggested by the norm). For tests at temperature higher than 270°C, the strain rate was kept constant and no step was recorded. As a consequence, two interpolating curves are drawn for the ultimate strength, and the lower one (corresponding to the tests at constant strain rate and represented as a continuous line in Fig 2b) is conservatively considered for the fitting Equation (1).

It can be observed that the yield strength is quite close to the ultimate strength, and is sensibly higher than the one of pure annealed copper (see [3]). For example, at room temperature it is 225 MPa, to be compared with 60 MPa of pure annealed copper. Also the ultimate strength is higher (262 against 200 MPa at room temperature), while the other tensile properties - Young’s modulus, Elongation (at failure) and Reduction of Area (at failure) - are found to be similar to the ones of pure annealed copper.

From Fig. 3, it can be observed that the behaviour of the material during tensile tests at different temperatures appears rather complex. Between 20°C and 170°C, elongation increases with increasing temperature while localized necking tends to become an uniform reduction of cross sectional area. Over 170°C, elongation decreases and localized necking disappears, being the reduction of sectional area uniform along the specimen. Further analyses and investigations are currently on progress to give an explication of this behaviour.

3. Fatigue testing campaign

In order to investigate the fatigue properties, fully reversed strain-controlled fatigue tests were performed according to the ASTM E 606 norm [6]. Tests were carried out for a selected set of strain levels ranging from 0.1% to 1% strain (peak-peak) adopting a sine shaped load, feedback controlled in strain, at room temperature (20°C) and high temperature (300°C). An MTS type 858 “Table Top System” servo-hydraulic testing machine was used to carry out the tests, equipped with a lateral
support (see Fig. 4a) built and added in order to prevent buckling of the specimen. An MTS 653.02 furnace was installed to maintain the specimen’s temperature stable at 300°C for the high temperature tests. Furthermore, a water cooling system was set-up for the clamps and a nitrogen venting system was installed for two reasons: to prevent specimen oxidation for tests at high temperature (300°C) and to maintain the specimen at 20°C during room temperature tests. The strain and temperature on the specimens were measured respectively by means of strain gauges and thermocouples. These signals were used to feedback control the load application, as well as the heating (furnace) and cooling (nitrogen venting) system.

Heat transfer to the specimen via radiation was found to be very low, due to the high reflectivity of copper. Hence, in order to reach the required temperature of 300°C on the specimen, the furnace would have been required to run at very high temperatures (higher than 800°C). This temperature was above the operational limits for the employed strain gauges and related glue and cabling. A solution to the problem was found by improving the heat transfer to the specimen by using additional heating elements (FHCs - Finned Heat Collectors). These aluminium elements (see Fig. 4c), have proved to be very efficient in absorbing heat by radiation and transferring it by thermal conduction to the specimen. Radiation absorption was enhanced by adopting a design with fins (similarly to the cooling systems for electronic circuits) and by coating them with a black high temperature paint, while conduction was improved by filling the gap between FHCs and specimen with conductive paste. Pre-tests have shown that the installation of such elements has no influence on fatigue life time evaluation; in fact, no scratches or surface damage could be detected after the tests.

The strain-life results are reported in Fig. 5a, where they are interpolated separating the elastic strain from the plastic strain, as suggested by the Manson-Coffin theory (see for example [7]). The corresponding equations are:

\[ \Delta \varepsilon_{\text{tot},20^\circ C} = 77.37 \cdot N_f^{-0.63} + 0.94 \cdot N_f^{-0.12} \]  \hspace{1cm} (6)

\[ \Delta \varepsilon_{\text{tot},300^\circ C} = 1903.8 \cdot N_f^{-0.87} + 0.72 \cdot N_f^{-0.11} \]  \hspace{1cm} (7)

where \( N_f \) is the number of cycles to failure, the first addends are the plastic contributions to the total strain (prevailing at low number of cycles) while the second addends are the elastic contributions (prevailing at high number of cycles). It can be observed that the strain controlled fatigue life is higher at 20°C.
than at 300°C for strain levels lower than 0.3%, while the situation is reversed for strain levels higher than 0.3%. This could be due to the reduction of the Young’s modulus at high temperature, which implies lower stress than at room temperature with the same strain level.

In Fig. 5b the cyclic stress-strain curves are plotted for the two considered temperatures. The stabilized stress amplitudes were recorded at the half-life of each constant strain fatigue test, with the same approach adopted in [3]. These curves are fundamental for the thermo-mechanical analyses, in order to simulate (for example with Finite Elements models) the elasto-plastic behaviour of the material during cyclic loading.

Comparing the results with the one of pure annealed copper [3], it can be observed that strain controlled fatigue life of electro-deposited copper is sensibly larger than pure annealed copper (for example, about double for 0.2% strain), while cyclic stress-strain curves are sensibly higher (this effect is more evident at 20°C than at 300°C). Both these aspects make electro-deposited copper a better material than pure annealed copper when subjected to cyclic heat loading.

4. Effect of heat treatments

A test campaign was carried out in order to investigate the effect of annealing heat treatments on the properties of electro-deposited copper. In fact some fusion components made of this material could be subjected during operations to high temperatures (up to about 300°C). Hence, tensile tests (according to [4, 5]), hardness tests (according to [8]) and grain size measurement (according to [9]) were carried out on a set of specimens (2 per each metallurgical condition) without heat treatment and after annealing in vacuum for 5 hours at 175°C, 275°C and 375°C. These temperatures cover the typical operating range of a heat sink material in fusion experiments.

As visible from Fig. 6, mechanical properties of electro-deposited copper are decreased by the annealing treatments at 275°C and 375°C, while they are not changed after annealing at 175°C. This suggests to foresee a maximum operating temperature lower than 175°C for the components made of electro-deposited copper in order to be sure to preserve its mechanical properties. Moreover, a clear link was found to exist between heat treatments, yield strength, hardness and grain size. Namely, annealing was generally found to bring a lower yield strength, a lower hardness, and a larger grain size. As hardness and grain size are non-destructive tests, the obtained correlation could be useful in the future for acceptance test on the components made of this material.

5. Thermal properties

An analysis of the main thermal properties (specific heat, thermal conductivity and thermal expansion) was carried out at room temperature. The values were found to be almost identical to the ones of pure annealed copper reported in [3]. Hence, no influence of the microstructure was found regarding the thermal properties.

6. Conclusions

An exhaustive thermo-mechanical test campaign was performed on electro-deposited copper, a crucial material for fusion engineering. Comparing the properties of electro-deposited copper with the ones of pure annealed copper, the following considerations can be made:

- mechanical properties of electro-deposited copper are sensibly better than the ones of pure annealed copper;
- fatigue life of electro-deposited copper is larger than the one of pure annealed copper.

These advantages could be due to the very small grain size obtainable with the electro-deposition technique and make this material an optimal choice as heat sink, suitable for applications in many components for fusion experiments, in particular for SPIDER, MITICA and ELISE devices.

Acknowledgements

This work was set up in collaboration and financial support of Fusion for Energy.

References

[5] EN 10002 - 5, Metallic materials; tensile testing; part 5: method of testing at elevated temperature.