HIGH STRAIN-RATE MECHANICAL BEHAVIOUR OF A COPPER MATRIX COMPOSITE FOR NUCLEAR APPLICATIONS

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Abstract

Aim of this work is the investigation of mechanical behaviour of an alumina dispersion strengthened copper, known by the trade name GLIDCOP, subjected to dynamic loads: it is a composite material with a copper matrix strengthened with aluminium oxide ceramic particles. Since the particle content is quite small the material keeps the OFE copper physical properties, such as thermal and electrical conductivity, but with a higher yield strength, like a mild-carbon steel. Besides, with the addition of aluminium oxide, the good mechanical properties are retained also at high temperatures and the resistance to thermal softening is increased: the second phase blocks the dislocation movement preventing the grain growth. Thanks to these properties GLIDCOP finds several applications in particle accelerator technologies, where problems of thermal management, combined with structural requirements, play a key role. Currently, it is used for the construction of structural and functional parts of the particle beam collimation systems of the Large Hadron Collider (LHC) at CERN.

1 Introduction

The dispersion strengthened metal composites were studied [1] in order to achieve a combination of different material properties such as high thermal or electrical conductivity jointed with controlled thermal expansion, high strength, wear and arc erosion resistance and particular magnetic properties. This class of material is a fully dense powdered metal composite comprising a highly conductive metal (or metal alloy) matrix with a dispersion of discrete microparticles of a refractory metal oxide. The matrix is a preformed dispersion strengthened metal, while the second ingredient has the aim to confer the desired mechanical or physical properties to the composite. The additive material, generally, refers to metals, alloys or compounds presenting, in addition to that mentioned above, also high density and high melting point. In this work the attention is focused on the composite material GLIDCOP, which is a registered trademark of SMC Corporation. It is a dispersion strengthened copper (DSC) having discrete microparticles (smaller than 0.1 micron and in general in the order of magnitude of 100 Armstrong) of a refractory metal oxide uniformly dispersed throughout the matrix. In more details, the dispersed phase is consisting of microparticles of aluminium oxide, which are prepared by internal oxidation of aluminium, alloyed in the metal matrix. GLIDCOP is available in different grades, depending on the amount in weight of Al_2O_3 content: i.e., 0.3 wt.-% (AL-15), 0.4 wt.-% (AL-20), 0.7 wt.-% (AL-35) and 1.1 wt.-% (AL-

60). The number in the name represents the equivalent aluminium content, which is from 0.15 to 0.6 %. Here the mechanical behaviour of the GLIDCOP Al-15 is investigated both in temperature and strain-rate ranges, in order to better understand the deformation mechanisms that occur in these loading conditions. In more details, three sets of specimen are obtained and tested. The specimens arrive from two different batches of pristine material and a batch of material after heat treatment comparable with a brazing cycle (about 4 hours at 750°C with a ramp of 4 hours to reach the condition and a ramp of 8 hours to return to room temperature). The authors want to investigate the differences between the different material conditions.

Another important feature of dispersion strengthened metals is related to the stable microstructure. As a matter of fact, the presence of the ceramic particles in the metal matrix blocks the dislocation movement preventing the grain growth and conferring a fine structure to the material. In figure 1 the OFE copper and GLIDCOP AL-15 structures are reported. As it appears clear from the comparison, the grain dimension in GLIDCOP is more fine respect to copper one. The particular microstructure produces the effect of inhibiting recrystallization kinetics [2]. However, in DSC material, the recrystallization is generally possible but it is occurs only as result of annealing process, in which the material is kept at very high temperatures for a long period. This is not in accordance with the brazing process: the time for the annealing process in much longer than those required for high temperature brazing.

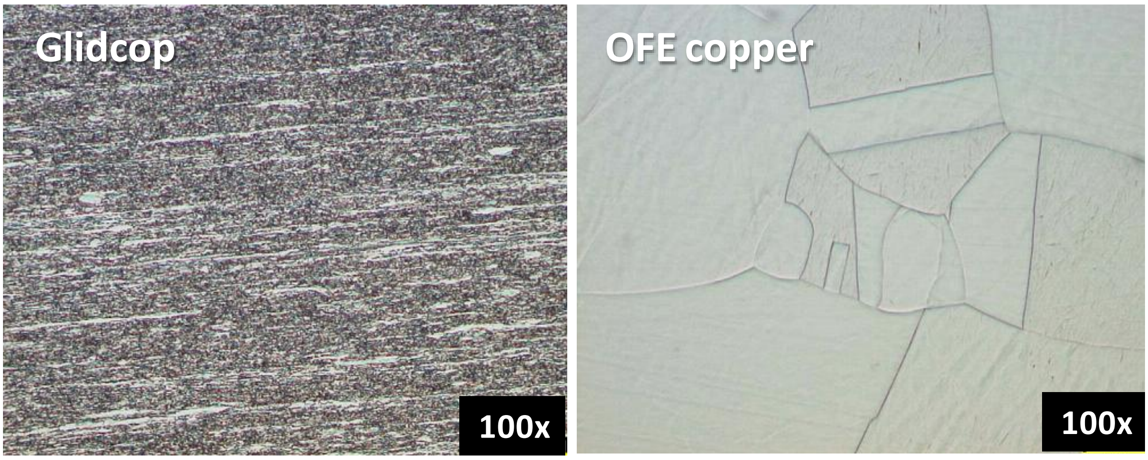

Figure 1. Images of the microstructures of GLIDCOP (left) and OFE copper (right).

The oxide particle content in GLIDCOP material is quite small. For this reason the material keeps the OFE copper properties, such as thermal and electrical conductivity, but with a higher yield strength, like a mild-carbon steel. Besides, with the addition of aluminium oxide, the good mechanical properties are retained also at high temperatures and the resistance to thermal softening is increased.

Thanks to these properties GLIDCOP® finds several applications in particle accelerator technologies [3, 4] and nuclear application fields [5, 6]. In these kind of applications problems of thermal management, combined with structural requirements, play a key role. Currently, GLIDCOP is used for the construction of structural and functional parts of the particle beam collimation systems of the Large Hadron Collider (LHC) at CERN (Geneva). The material could operate in extreme conditions especially in case of accident, in which high levels of stress, plastic strain, temperature and pressure are reached in a very short time (high strain-rate) [7]. This explains why it is fundamental to characterize the material in a wide range both in strain-rate and temperature.

In literature it is quite easy to find data and analyses performed by several authors about the influence of the temperature (i.e. [8, 9, 10]) or heat treatment (i.e. [11]) on GLIDCOP (in several grades). A lot of publications also deal with the analysis of the material microstructure (i.e. [2, 12]). Moreover a lot of studies were also performed to investigate the creep and fatigue behaviour (i.e. [13, 14, 15]). Finally, due to the application in nuclear fields, also a lot of works were done on the effects of the irradiation (i.e. [16]). In particular, a great amount of work was produced by Zinkle and his co-authors, especially, in the context of the Fusion Reactor Materials Program.

On the other hand it is quite difficult to find data about the material investigation at high strain-rate loading conditions. Some authors investigated this topic, mainly at very low strain-rate (i.e. [13, 17]), and most of the time the argument is correlated to the creep behaviour.

The authors previously investigated the GLIDCOP AL-15 both in temperature and strain-rates [18]. The temperature range investigated was between 20°C and 1000°C; the strain-rate varied between 10^{-3} and 10^{3} s^{-1}. Here a new tests campaign is performed in order to compare the results obtained for the first batch of GLIDCOP and the next ones.

2 Experimental tests

As mentioned before, the main goal of this work is the comparison of the results in terms of strain-rate sensitivity obtained with different batches of GLIDCOP AL-15: two pristine and one heat treated. The comparison is made using the Johnson-Cook model [19], which expresses the flow stress as:

$$\sigma_y = \left(A + B\varepsilon_{\mathrm{pl}}^{n}\right)\left(1 + C\ln\frac{\dot{\varepsilon}_{\mathrm{pl}}}{\dot{\varepsilon}_0}\right)\left(1 - T^{*m}\right) \qquad (1)$$

A is the elastic limit strength, *B* and *n* are the work hardening parameters, *C* and $\dot{\varepsilon}_0$ are the strain-rate sensitivity coefficients and T^* and *m* describe the thermal softening.

The J-C material model is uncoupled in plastic strain, strain-rate and temperature effects. According to this, the experimental tests can be managed exchanging one parameter at a time. For this reason, experimental tests could be performed at different speeds at room temperature and different temperatures at quasi-stating loading rate. For each loading condition at least three repetitions are performed.

The problems concerned to the damage and the failure of the specimen are neglected. In this way, under the hypothesis that the mechanical behaviour of the material is the same both in compression and in tension, it is chosen to carry out only the compressive test.

Quasi-static loading condition is obtained via general purpose electro-mechanical testing machine while high strain-rates compressive tests are carried out with a standard Split Hopkinson Pressure Bar (SHPB) setup.

2.1 Thermal sensitivity

In [18] experimental tests at different temperatures were performed starting from room temperature up to 1000 °C. The tests were quasi-static compression tests, performed on an electro-mechanical testing machine using an induction heating system, controlled in a feedback closed-loop by means of thermocouples welded on the specimen surfaces or a thermo-camera (fig. 2). The thermal softening parameters were identified on the basis of a numerical inverse method.

In this work, the temperature influence in no further investigated. The results obtained in [18] for the identification of the temperature dependency are used and compared with the data available in literature [3, 13, 20]. Figure 2 reports the diagram in which the 0.2% yield stress is plotted vs. temperature: the data obtained by the authors in the previous work are in trend with the results obtained from other research centres. This confirmed the validity of the previous results and justifies the use of those results in the next section.

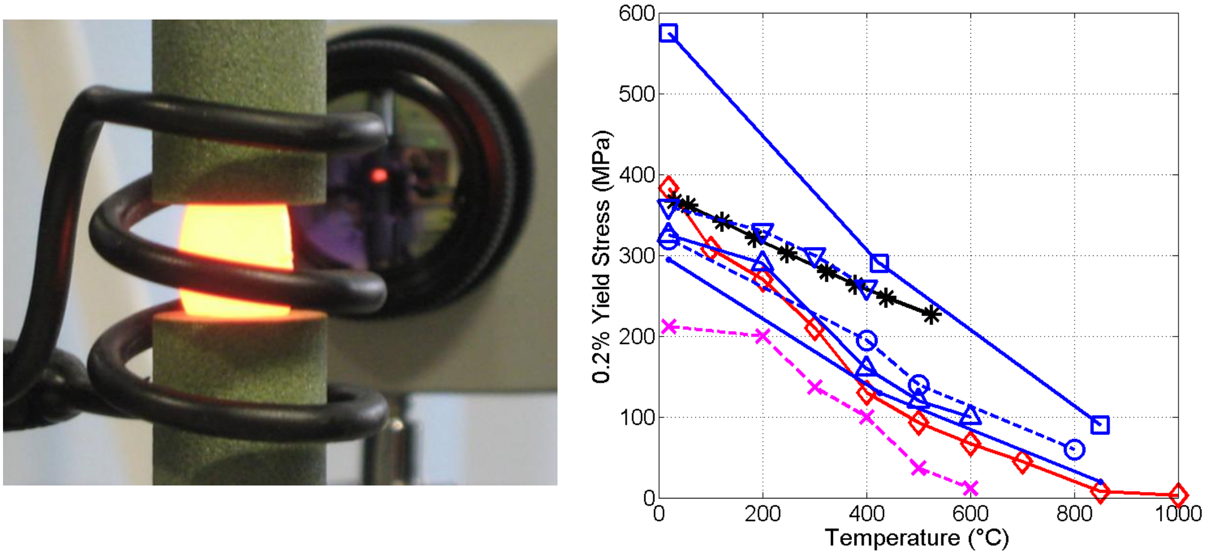

Figure 2. Images of the compression test performed at 850 °C (left); comparison between the results available in literature [3 (□,▽,△,○, •), 13, 20 (∗)] and those obtained in [18 (◊)] in terms of 0.2% yield stress vs. temperature. The marker (×) represents the pure copper data.

2.2 Strain-rate sensitivity

In this work the attention is mainly focused on the second term of the equation 1, which expresses the trend of the ratio between static and dynamic flow-stress curve (σ/σ_{st}), fixing the temperature. It describes the increase in the material strength consequent to the increase in strain-rate. The relation represents a line in the plane σ/σ_{st} vs. strain-rate in a semi-log plane in the abscissa. The parameter C is the slope of the line. In more details, the authors use the strain-rate expression considering $\dot{\varepsilon}_0$ as a threshold, in accordance with the model implementation in a lot of commercial finite element code, such as LS-DYNA [21]. The parameter $\dot{\varepsilon}_0$ is the lower strain-rate values for which there is a strain-rate effect on the flow stress. For strain-rates lower than this value, any influence is neglected (σ/σ_{st}=1 for every strain-rate).

The strain-range investigated cover six order of magnitude from 10^{-3} and 10^{3} s^{-1}. The quasi-static tests are performed on the device Zwick-Roell Z100, that is an electro-mechanical universal testing machine able to apply a maximum load of 100 kN at a maximum velocity of 300 mm/min. The experimental tests at high strain-rate are performed on a Split Hopkinson Pressure Bar equipment. The facilities layout for the compressive tests is the standard one (fig. 3). The apparatus was actuated by a pneumatic gas-gun (1.5 m long) and was composed of two bars made in high strength steel (17-4PH) of 10 mm diameter and 3.4 m length. The striker bar used in these tests was 500/1000 mm long: with this setup the impact velocity is in the range 10-20 m/s. This implies that with the adopted specimen diameter (which determines the ratio between transmitted and incident waves) and lengths (which determine the strain-rate once the reflected wave has been measured), the actual strain-rates is between 500 s^{-1} and 5000 s^{-1}. Measurements of strain in the bars is performed with KYOWA semiconductor straingages. Acquisition is made with a 2.5 MHz NI acquisition board managed by a LabView program.

The specimens used in the experimental tests are nominally 5 mm of diameter and 5 (L) or 2 (S) mm long.

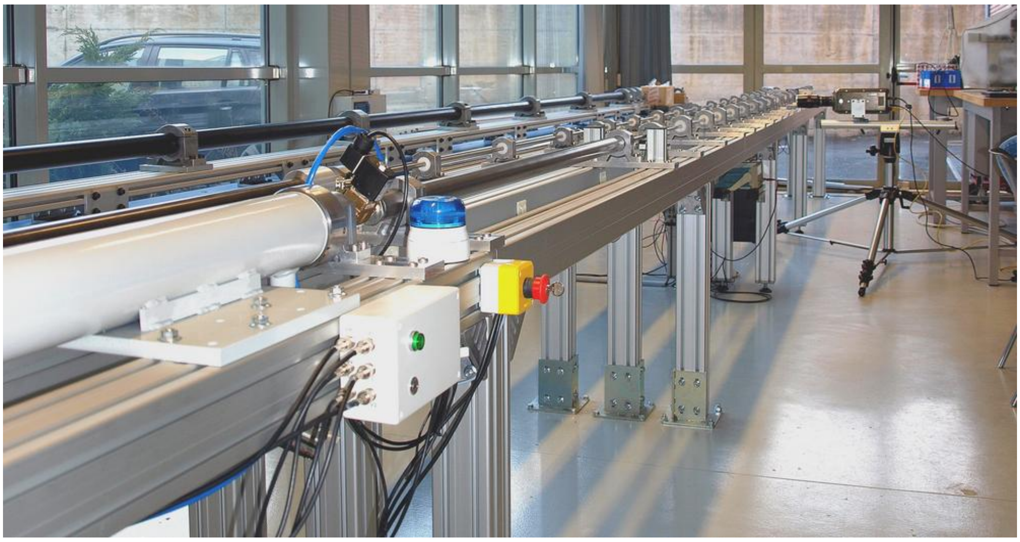

Figure 3. SHPB setup used for high dynamic tests.

In figure 4 (left) the engineering stress-strain curves obtained in quasi-static and dynamic regimes are shown for both small and long specimens of the first batch. It appears evident that there is a geometrical effect, which influences the material response. In figure 4 (right) the same curves obtained for the heat treated specimens are reported. Comparing the two diagrams it is possible to conclude that the thermal cycle made on the GLIDCOP does not produce a significant reduction of the material properties as expected and anticipated in the introduction. Small influence can be noticed in the first part of the curve just over the yield point.

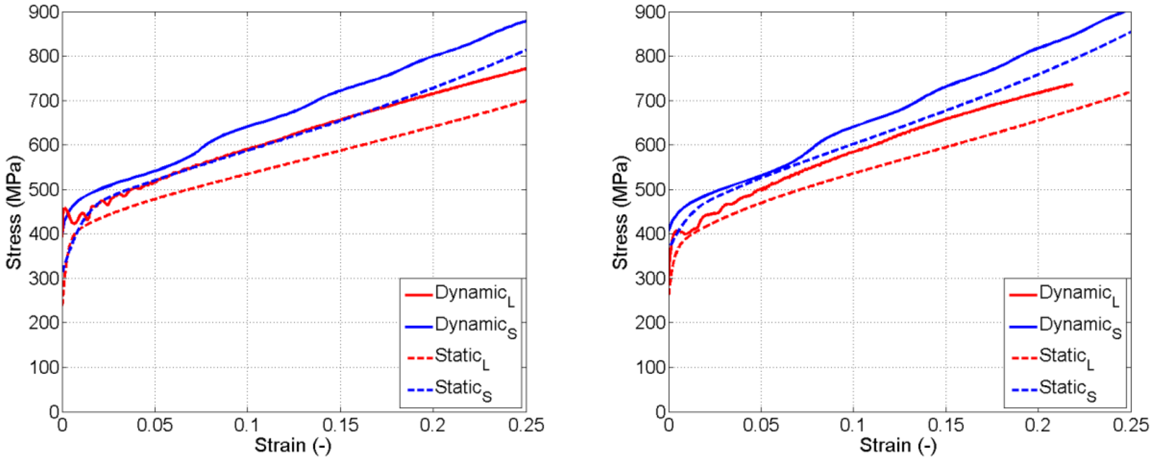

Figure 4. Comparison between quasi-static (dashed line) and SHPB (solid line) for long (red) and short (blu) specimens in case of pristine material (left) and heat treated material (right).

In order to obtain the *C* parameter of the J-C strain-rate expression the ratio between the stress of the dynamic curves and the static ones has to be evaluated. First of all, due to the consideration just made, each dynamic curve is divided with respect to the static one referring to the same length of the specimen. Moreover, each batch of specimens is treated separately. This procedure is performed for two different levels of strain: 0.05 and 0.2.

An important consideration has to be done for the temperature. Thermal softening is essentially due to heat conversion of plastic work occurring at high strain-rate deformations. For strain-rate over 10^2 s^{-1} thermal phenomena (diffusion and conduction) can be neglected and thermal softening can be evaluated under adiabatic assumption. Given this last hypothesis and the further assumption of uniform stress, strain and temperature fields, the material temperature can be analytically computed as a function of plastic work as shown in expression (2).

$$T = T_r + \frac{\beta}{\rho \cdot C_p} \cdot \int_0^{\varepsilon_p} \sigma(\varepsilon, \dot{\varepsilon}, T) \cdot d\varepsilon \tag{2}$$

In expression (2) ρ is the material density, C_p is the specific heat at constant pressure and β is the Taylor-Quinney coefficient [22, 23] that represents the portion of plastic work that is converted into heat (for metals about 0.9, in this work it is assumed equal to 1).

In accordance with this, the σ/σ_{st} values obtained for all the SHPB tests are corrected. In more details, starting from the experimental data the σ/σ_{st} reported in figure 4 are calculated as follows:

$$\frac{\sigma}{\sigma_{st}} = \frac{\sigma_{exp}}{\sigma_{exp,\ static}\left(1 - T^{*m}\right)} \tag{3}$$

where T^* and m are those obtained in [18].

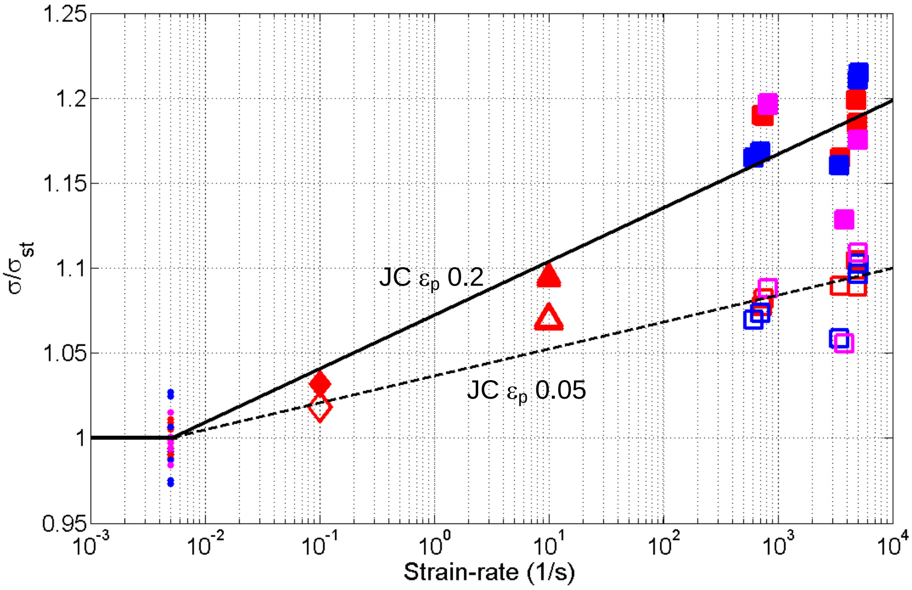

Figure 5. Ratio between the stress of each curve and the mean on the static one in the same condition (geometry and material). The empty markers refer to 0.05 of strain, the filled marker to 0.2 of strain. The markers meaning is: •=quasi-static, ◊ and△ medium [18] and □ SHPB tests.

In figure 5 the data for the three batches of specimens are reported in the same diagram σ/σ_{st} vs. strain-rate. There is a certain level of dispersion, generally, greater than the differences in the batches. This justifies the unique interpolation for all the data with the piece-wise J-C model. For the interpolation, the threshold $\dot{\varepsilon}_0$ is set equal to the strain-rate of the static tests (5×10^{-3} s^{-1}).

The J-C model formulation implies that for different strain levels the strain-rate influence is the same. Looking the results of figure 5, it is clear that the two strain levels do not produce the same strain-rate effects. This means that, probably, the J-C model is quite inaccurate for this type of material

The future developments of this work will be using different material models. Physically-based material models, as a matter of fact, are maybe more suitable since based on the dislocation theory for evaluation of the flow stress at different temperatures and strain-rates. Models, such as Zerilli-Armstrong [24] or those proposed in [25], use different formulations in function of the lattice structure. The reason is related to the fact that the dislocation glide are governed by different factors varying the class of metal. Finally, it seems to be of importance to considered a model in which strain, strain-rate and temperature dependences are treated in a coupled manner.

3 Conclusions

In this work the mechanical behaviour of a metal matrix composite was investigated. The material objective of the study was GLIDCOP AL-15, which is a dispersion strengthened copper with alumina particle. The oxide particle content is quite small: the material keeps the OFE copper properties, such as thermal and electrical conductivity, but with a higher yield strength, like a mild-carbon steel. Besides, with the addition of aluminium oxide, the good mechanical properties are retained also at high temperatures and the resistance to thermal softening is increased.

Three different batches of the same material were tested: two were pristine and one was heat treated in accordance with the thermal cycle proper of a brazing process. For what concerns the temperature sensitivity, data available in literature are used to support and confirm previous results from the authors. The main part was the identification of the strain-rate influence for the different materials. Experimental compression tests were performed starting from quasi-static tests up to high strain-rate loading conditions. Different sizes of the specimens were used and the geometrical effects introduced were suitably taken into account. The Johnson-Cook model was used in order to investigate the loading rate influence on the flow stress. To do this, it was necessary the evaluation of the ratio between each dynamic curve and the correspondent static one obtained for the same geometry and on the same batch. The data obtained were corrected in order to take into account also the temperature increase consequent to the heat conversion of the plastic work. From the analysis it was possible to assert that the three materials have the same strain-rate dependence using a Johnson-Cook approach. Moreover, the J-C model appeared to be quite inaccurate for this type of material, since different strain-rate parameters were obtained varying the strain level at which the calculations were done. Future development will be the use of more complex, physically-based model.

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