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Study of CuCrZr alloy for the production of a passive satellite

A. Brotzu[a], F. Felli[a*], D. Pilone[a], V. Di Cocco[b], G. Sindoni[c], I. Ciufolini[d]

[a]*DICMA, Sapienza Università di Roma, Roma*
[b]*Università degli Studi di Cassino e del Lazio Meridionale, Cassino (FR)*
[c]*Scuola Ingegneria Aerospaziale, Sapienza Università di Roma, Roma*
[d]*Dipartimento Ingegneria dell'Innovazione, Università del Salento, Lecce*

Abstract

Fracture toughness and tensile tests have been carried out on a CuCrZr alloy to characterize its fracture behavior since it is considered a possible candidate for the construction of a passive satellite. Based on the satellite design requirements some copper-based alloys have been studied. These alloys are interesting candidates for the satellite construction because of their physical properties, such as high thermal conductivity and density, and because of their mechanical properties, in fact CuCrZr alloy is age hardenable. The low ductility and toughness of age hardened alloys are not a critical issue for the satellite body, but it could be a problem for the screws. For that reason, the study of the fracture behavior of this alloy is of crucial importance for material selection in the satellite design.

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Keywords: Copper alloy; CuCrZr alloy; Lares 2; Satellite material.

1. Introduction

This work was developed in the context of a wider research aimed at the study and development of alloys for producing passive artificial satellites. These alloys must have high density, high mechanical properties and high thermal conductivity as well as other less relevant features as main requirements. In 2012 a first satellite called LARES was produced and successfully launched, consisting of a metallic sphere (364 mm in diameter) made of a tungsten

* Corresponding author. Tel.: +390644585601
E-mail address: Ferdinando.felli@uniroma1.it

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alloy (W-3Ni-2Cu) obtained by means of liquid sintering technique (Brotzu et al. (2015)) for testing an intriguing phenomenon of General Relativity (Ciufolini et al. (2009)) called frame-dragging, performing other tests of gravitational physics and environmental monitoring (Pavlis et al (2015)). Frame-dragging, or dragging of inertial frames, consists in the change of orientation of gyroscopes, which determine the axes of the local inertial frames, due to mass-energy currents such as the rotation of the Earth (Ciufolini (2007)). The satellite was positioned at an altitude of about 1430 km by using the first qualification flight of the VEGA. Given the success of LARES, a new version of it (LARES 2) is to be launched on Vega-C's maiden flight and it is going to be positioned at an altitude of about 5900 km. This requires a lighter satellite having a greater diameter and the study of alternative alloys characterized by lower density than the one of LARES satellite and high mechanical properties, high thermal conductivity, good machinability etc. In the design of LARES 2 the choice of the base material must be done taking into account several requirements as described in Felli et al. (2018) and in Paolozzi et al. (2018). The selected material needs to have a density in the range 8000-9000 kg/m^3, low sensitivity to heating by irradiation, non-magnetic properties, high thermal conductivity. Moreover it must have good castability and good machinability. Our research group studied the properties of different alloys. Among them we considered the properties of a CuCrZr alloy characterized by an excellent combination of strength, electric conductivity and thermal conductivity (Li et al. (2009) and Morozova et al. (2018)). This property makes this alloy an interesting candidate also for dissipating for example heat generated by nuclear fusion experiments. These alloys are frequently used as engineering materials in various electric and electronic devices. CuCrZr alloys have high strength and electrical conductivity resulting from precipitation of dispersed particles (Zang et al. (2017) and Chbihi et al. (2012)). In fact these alloys are age-hardenable: heat treatment, constituted by solution treatment followed by quenching and aging, provides significant strength increase. Aged CuCrZr alloys possess high electric conductivity due to negligible electron scattering on solutes. Because of the low solubility of Cr and Zr in Cu the optimal contents of Cr and Zr in CuCrZr alloys are limited to 0.67 and 0.12 wt.% respectively (Bochvar et al. (2007) and Liu et al. (2017)). Although precipitation from liquid of Cr and Zr phases decrease the mechanical properties of the alloy a considerable strengthening of these alloys can be achieved by means of precipitation of secondary phases and thermo-mechanical processing. Plastic deformation can be performed by rolling, drawing, etc. Moreover CuCrZr alloys are studied because they are used for high heat flux applications in components of the ITER burning plasma device. CuCrZr is an interesting material for ITER because it exhibits high thermal conductivity, high strength, good ductility, radiation resistance, commercial availability, and low cost.

In this work we analyzed the mechanical properties of a CuCrZr alloy especially produced for evaluating its potential applications in the realization of the satellite.

2. Experimental

CuCrZr was manufactured and was provided by Società Metallurgica Minotti. The nominal composition was 98.9 wt% Cu, 1 wt% Cr, 0.1 wt% Zr. The as-received material was forged and aged.

The performed heat treatments were: solution treatment at 1000 °C, quenching in water and aging at 450 and 500 °C. Hardness tests were carried out on specimens after different heat treatments while the Charpy and tensile tests were performed on the as-received alloy. The Charpy Impact Test was carried out by using ASTM E23 standards for a Type A specimen. Tensile tests were carried out for determining tensile strength, elongation and modulus. The fracture surfaces of both the tensile specimens and Charpy specimens were observed and characterized by using scanning electron microscope (SEM). Microstructural analyses were carried out by means of SEM and optical microscope on specimens etched by using ferric chloride reagent. Microanalyses were carried out by means of energy dispersion spectroscopy (EDS).

3. Results and Discussion

CuCrZr alloy is a PH copper alloy (heat-treatable alloy). Cr content must be lower than 1.5wt% to avoid the formation of coarse Cr particles. Zr, whose concentration is lower than 0.25wt%, increases the alloy hardness due to formation of precipitates and increases the alloy ductility avoiding intergranular fracture.

Specimens of the as-received alloy have been analyzed by means of EDS. Several analyses carried out on different specimens highlighted that, although they are not homogeneous, the actual composition is about 99.12 wt% Cu, 0.8 wt% Cr, 0.08 wt% Zr. SEM and optical microscope analyses of CuCrZr alloys revealed that the grain size is about 50 µm and that there is a phase distributed throughout the material (grey phase in fig. 1b). EDS analyses showed that it is a Cr rich phase. In fact it must be stressed that the highest equilibrium solubility of Cr in Cu is 0.71 wt.% at 1070 °C. Rapid solidification or severe plastic deformation are required to obtain a Cu-Cr supersaturated solid solution. On the other hand, the Zr solubility is very small (0.1 wt.%) even at a temperature close to the melting point. On the ground of these considerations, concentrations of Cr and Zr in CuCrZr alloys are usually limited to 0.67 and 0.12 wt.%, respectively. Obviously if the solidification stage is not properly controlled formation of primary precipitates can occur with consequent strength decrease of the alloy.

The CuCrZr alloy, whose microstructure is shown in Fig.1, has been provided in the heat treated conditions. Some preliminary conductivity tests showed that it is characterized by a very high electrical conductivity.

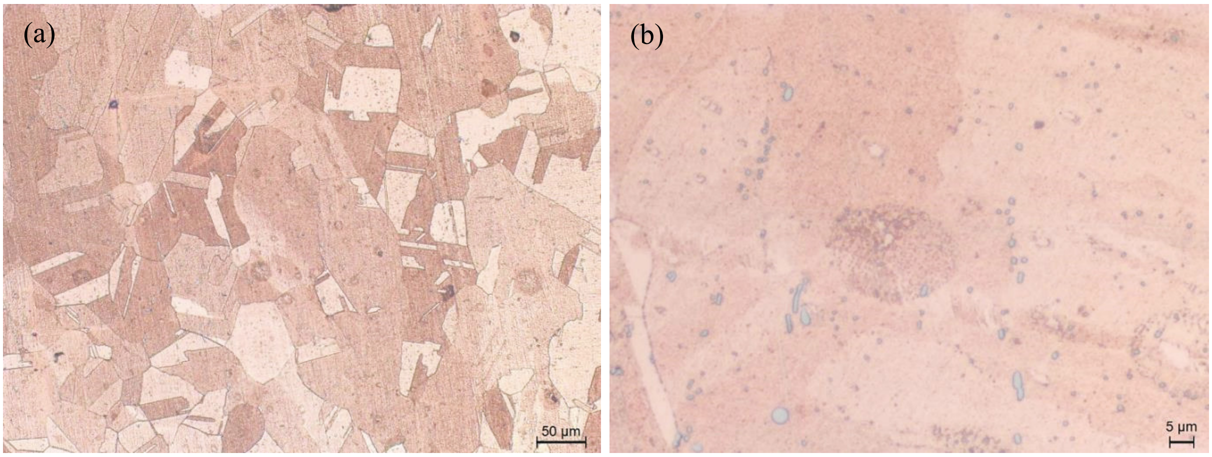

Fig. 1. Optical micrographs of the as-received alloy showing the grain structure (a) and a chromium rich phase dispersed in the alloy matrix (b).

The hardness of this alloy was 132 HV10. In order to verify the effectiveness of the aging treatment, specimens of this alloy have been solubilized at 1000 °C for 1 h and then quenched in water. Aging treatments have been carried out at 450 and 500 °C to determine formation of precipitates like Cu_4Zr or $CrCu_2Zr$ (Chbihi et al. (2012)). The results are reported in Fig. 3. This figure shows that at 450 °C the hardness reaches a value of about 118 HV10, while at 500 °C it reaches the maximum value (133 HV10) after 1.5 h and for longer times it decreases due to overaging.

Tensile tests carried out on three specimens of the as-received alloy show that the alloy has the following mechanical properties: UTS 394 MPa, σ_y 180 MPa and E% 32.5.

Considering that the selected alloy must be used for producing screws, one of the main requirements is that that alloy needs to possess a good fracture toughness. Charpy impact tests have been carried out in order to determine it.

Three specimens of the as-received alloy have been subjected to Charpy impact tests and none of them broke as it can be seen from Fig. 4. Tests highlighted that the alloy fracture toughness is higher than 290 Joule and then that the tested alloy is very tough as already mentioned in literature.

The produced alloy showed lower strength in comparison with the ones reported in literature for heat treated CuCrZr alloys. On the other hand, it shows an excellent toughness highlighted by the results of the Charpy tests. As it can be seen in Figs. 1 and 2 a Cr rich phase is formed during solidification and its presence suggests that Cr solubilized in the Cu matrix is lower than expected and this affects the maximum reachable hardness. In fact, the aging curves show that hardness is never higher than 130 HV.

By observing fracture surfaces of specimens subjected to tensile tests (Fig. 5) it is apparent that this material is characterized by a very ductile behavior, in fact the alloy shows an evident necking (Fig. 5a) and a fracture surface characterized by dimples (Fig. 5b). Brittle fracture areas are not visible on these specimens.

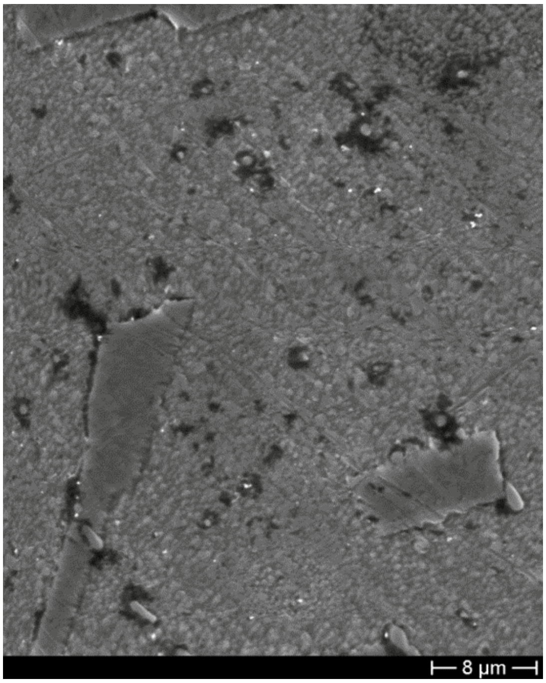

Fig. 2. SEM micrographs showing the Cr rich phase.

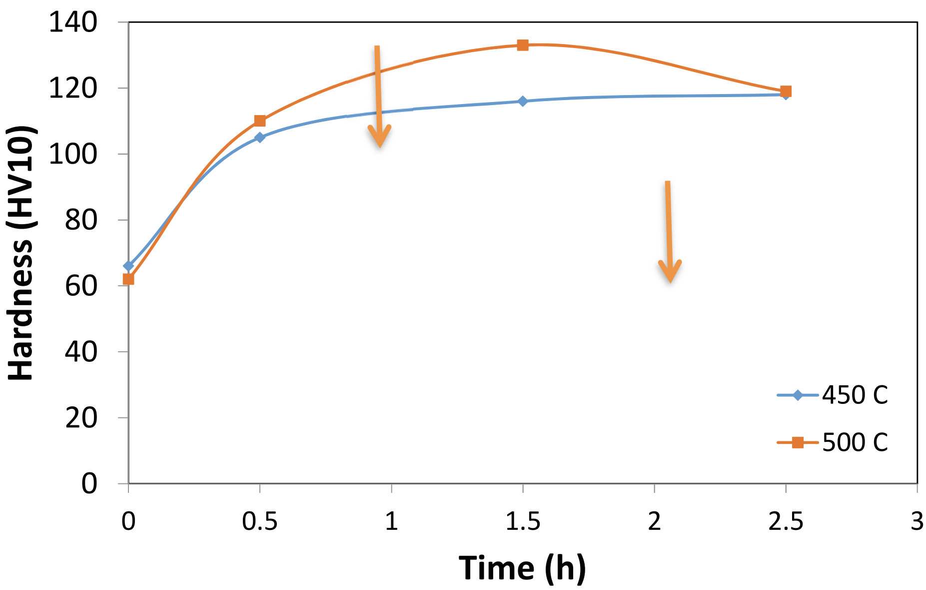

Fig. 3. Alloy hardness as a function of aging time for aging treatments carried out at 450 and 500 °C.

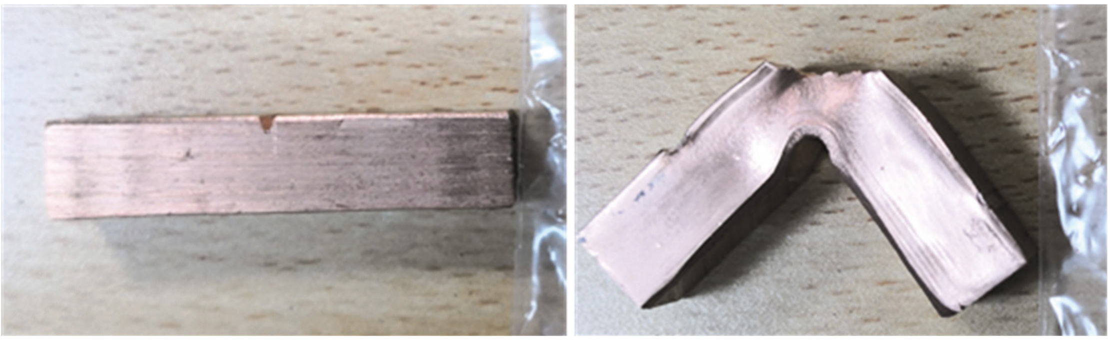

Fig. 4. Charpy specimen before (left) and after (right) the impact test.

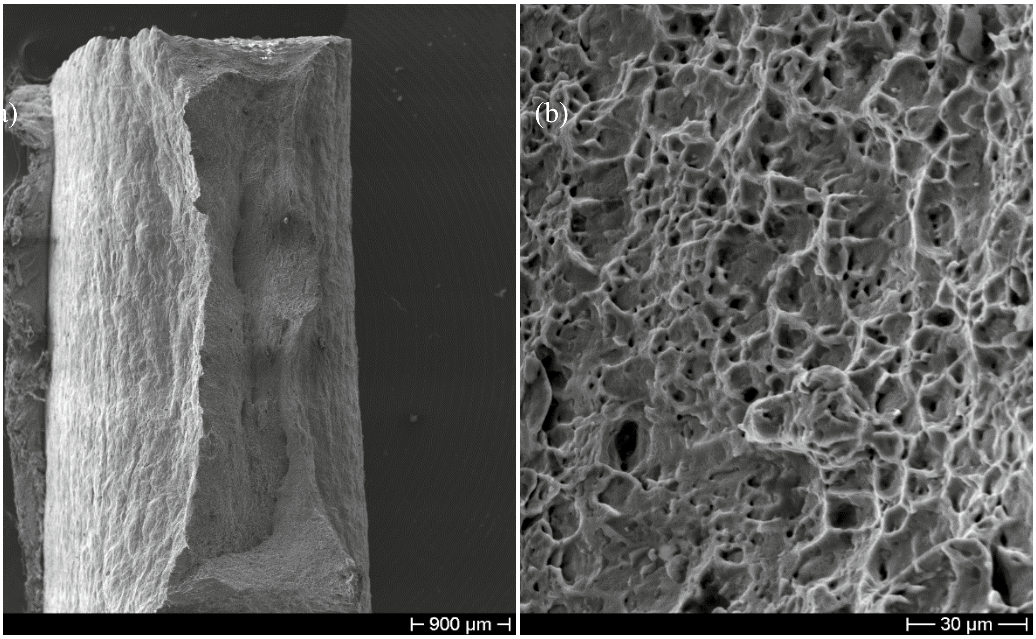

Fig. 5. SEM micrograph showing the fracture surface of the specimen after the tensile test.

A careful examination of fracture surfaces after Charpy impact tests shows that, even at higher load application rates, the alloy behavior is always very ductile as it can be seen in Figs. 6 and 7. In this case shear dimples are observed: they are oriented following the material deformation during the test.

Fig. 6 highlights that the studied alloy, before separation, has an intensive local extension and necking down. The stresses during plastic deformation and the material displacement before fracture determine the alignment of the dimples (Fig. 7 a and b). The studied material doesn’t show, after impact tests, mixed mode of cleavage and dimpled fracture. Moreover there is not intergranular fracture and this confirms the effect of Zr that avoids intergranular fracture. By observing fracture surfaces the coarse Cr particles do not seem to affect the fracture behavior of the alloy.

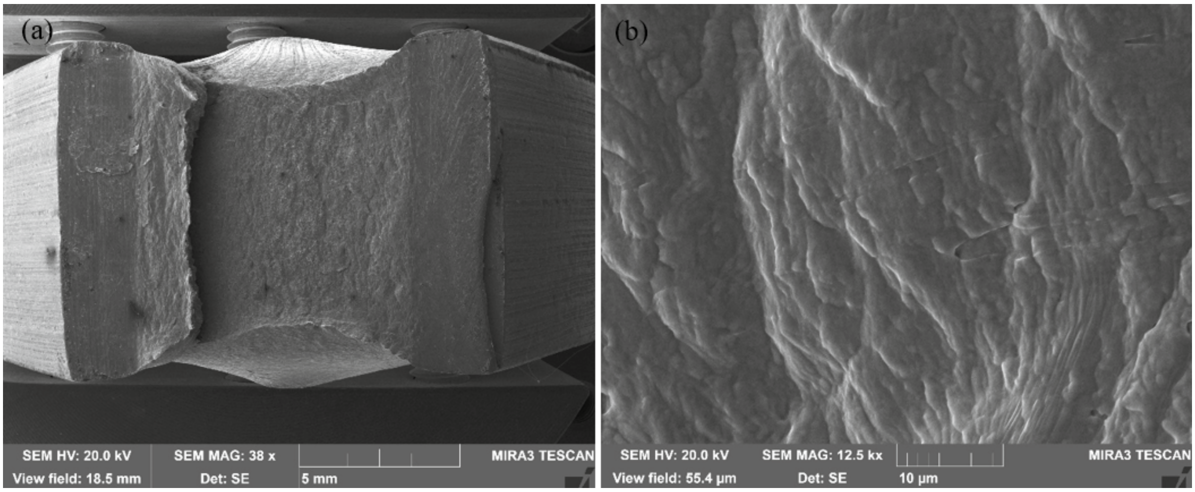

Fig. 6. SEM micrograph of the specimen fracture surface after Charpy impact test.

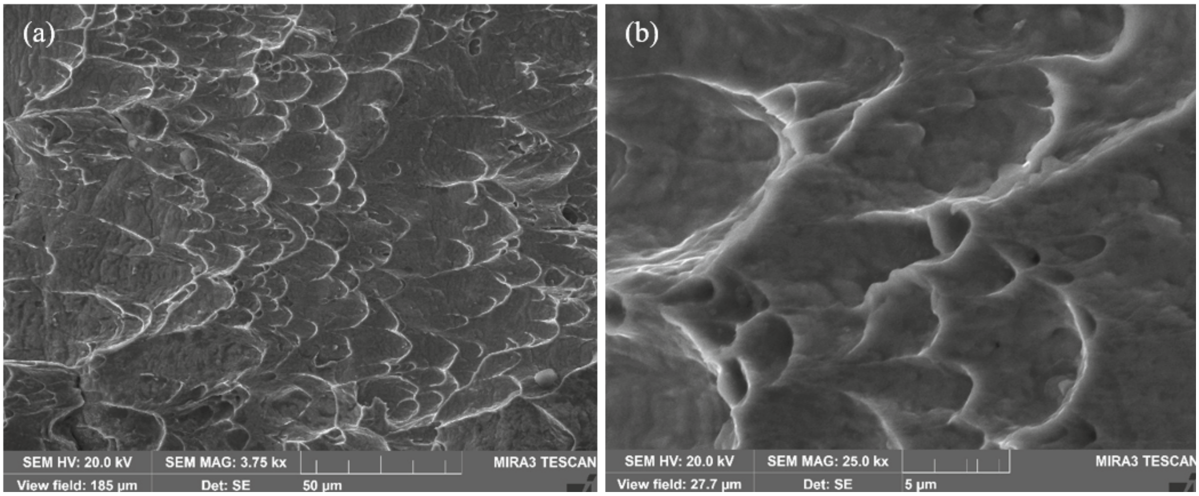

Fig. 7. SEM micrograph showing the morphology of the fracture surface.

4. Conclusions

The study performed on the CuCrZr alloy for its possible application in the construction of a passive satellite revealed that this alloy doesn't show suitable mechanical properties (UTS, σy, HV), although it shows very good conductivity and toughness and possesses the required density. Despite these results, this alloy could be an interesting material for other applications such as electric, nuclear and physical devices.

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