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ScienceDirect

Procedia Structural Integrity 9 (2018) 295–302

Structural Integrity Procedia

www.elsevier.com/locate/procedia

IGF Workshop "Fracture and Structural Integrity"

Fracture behaviour of alloys for a new laser ranged satellite

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Abstract

A new laser-ranged satellite called LARES 2 (Laser Relativity Satellite 2) has been recently designed for accurate tests of Einsten's theory of General Relativity and space geodesy. Some high density alloys (8.6-9.3 g/dm3) have been studied and characterised for producing the LARES 2 passive satellite. The considered materials were Copper and Nickel based alloys that have been produced and characterised. Aim of this work was to analyse their fracture behaviour that is a requirement for materials to be used for space applications. Fracture tests have been carried out on several specimens and fracture surfaces have been analysed.

Peer-review under responsibility of the Gruppo Italiano Frattura (IGF) ExCo.

Keywords: Copper alloys ; Lares 2; material selection.

1. Introduction

LARES 2 is a passive laser-ranged satellite designed and developed for tests of Einstein's theory of General Relativity and space-geodesy (Ciufolini et al. (2017a, 2017b and 2017c)). In particular LARES 2 will provide the most accurate measurement of frame-dragging or Lense-Thirring effect (Ciufolini (2007)), a fundamental and intriguing phenomenon predicted by General Relativity with basic astrophysical application such as the generation of gravitational waves by two colliding black holes measured by the LIGO laser interferometers. A basic requirement in designing LARES 2 is the minimization of its cross-section-to-mass ratio to reduce as much as possible its orbital

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2452-3216
Peer-review under responsibility of the Gruppo Italiano Frattura (IGF) ExCo.
10.1016/j.prostr.2018.06.026

perturbations due to the non-gravitational forces acting on the satellite. The design of LARES 2 includes the choice of the base material made only on the bases of its density, while the specific alloy is chosen to meet the other requirements and constraints related not only to scientific issues but also to the certifications required for boarding the satellite on the launcher.

The main requirements are:

- Physical: density of about 9 kg/dm^3, low sensitivity to heating by irradiation, non-magnetic properties, high thermal conductivity.
- Technological: Good castability, good workability.
- Mechanical: hardness higher than 28 HRC (285 HV), yield strength 517 MPa and elastic modulus greater than 200 GPa.

The last requirement is derived from the previous LARES satellite for which it was used a completely different material (A.Brotzu et Al. (2015), A. Paolozzi et al. (2009b)), i.e. a tungsten alloy. The requirement was imposed to withstand the high pressure at the contact surfaces between the hemispherical heads of the separation system arms and the corresponding hemispherical cavities located at the equator of the satellite (A. Paolozzi et al. (2009a)). It has to be remembered that the pressure at the contact surfaces is a function of the Young modulus of the materials in contact and that therefore the requirement on the yield can be relaxed in case the satellite will be manufactured in copper alloy (A. Paolozzi et al. (2009b)). In fact the copper alloy considered for LARES 2 has a lower Young modulus than the tungsten alloy used for LARES. The separation system for LARES 2 is instead basically the same as the one of LARES. In particular the arms of it will again be made of steel 15-5-PH 1025. However, as will be described in detail later, the copper alloy under concern will fulfil the requirement on the yield the way it is.

Based on these requirements, some nickel and copper based alloys have been developed and studied.

Although nickel based alloys have considerably higher mechanical properties, they are more expensive and they do not have high thermal conductivity, which is an important science requirement to reduce thermal thrust perturbation on LARES 2 (I. Ciufolini et al. (2014)) .

For that reason, even though Nickel alloys, such as Haynes 242, have been studied and characterized as interesting candidates for the satellite, alternative copper based alloys, characterized by higher thermal conductivity, have been also taken into consideration.

Among copper based alloys we had to select one having acceptable values of yield strength and hardness. The most interesting candidates were copper-beryllium alloys but the toxicity of beryllium will introduce additional concerns which may bring the LARES 2 program off the schedule.

An accurate examination of literature data (J.Chalon et al. (2016), M.Gholami et al. (2017), Y.-L.Jia et al. (2013), Q.Lei et al. (2017), Q.Lei et al. (2017), J.R.Davis (2001)) suggested the use of either Cu-Ni-Si or Cu-P alloys. They have adequate mechanical properties: in particular two alloys, C70250 and C19500, were selected and were produced in the laboratory in order to test their properties. Unfortunately it has been found that the C19500 alloy was magnetic and that, after heat treatment, its hardness did not reach 28 HRC. On the contrary the C70250 alloy fulfilled all the requirements with the exclusion of the elastic modulus. In particular the mechanical properties, determined after different heat treatments, were hardness, yield strength and ultimate tensile strength. It must be stressed that the C70250 alloy is typically used as wrought alloy in commercial applications for small items, while in the studied application a semifinished sphere of about 415 mm in diameter with a mass of about 350 kg has to be produced. That can be easily obtained by direct casting. It is then of fundamental importance to determine the mechanical properties of this alloy in the as-cast conditions with different heat treatments in order to tune the processes to reach the required mechanical characteristics.

Aim of the present work is assessing possible critical issues concerning the toughness of the alloy subjected to different heat treatments. In particular for the satellite body the maximum hardness is needed in the areas in which the satellite is in contact with the separation system: in these areas a low fracture toughness should not be critical. On the other hand a greater fracture toughness is required for the screws used to fix the mounting systems of the cube corner reflectors (CCRs) on the satellite (I. Ciufolini and A. Paolozzi (1999)). CCRs, regardless on the attitude of the satellite, reflect laser pulses towards the laser ranging stations that sent the pulse. By counting very accurately the time of flight of the pulses, the station can measure the distance of the satellite with an accuracy that for the best stations can be better than 1 mm. Data from about 50 stations, located in different parts of the world, are collected and managed by the International Laser Ranging Service (ILRS) that make available data to scientists all over the world. The reconstruction of the orbit with accuracies of few centimetres allows to reach a few percent accuracy in the general relativity test using a satellite specifically designed to that goal (Paolozzi et al. (2015)). With LARES 2 it is expected to improve the accuracy by one order of magnitude so more attention has to be made also on the surface properties of the alloy that determine the temperature of the satellite (A. Paolozzi et al. (2012a)). A higher satellite temperature causes a higher temperature of the CCR which reduced the performances of the CCR (A. Paolozzi et al. (2012b)), consequently surface properties of LARES 2 satellite has to be chosen in such a way to minimize the temperature.

2. Experimental

The studied alloys were produced by the Materials Development Center (CSM) in a vacuum induction furnace by producing metal ingots in the range 5-12 kg.

Copper alloy specimens for aging tests, tensile tests and Charpy tests were obtained from an ingot of about 8 kg.

The performed heat treatments were: solution treatment at 900 °C, quenching in water and aging at 500 °C. Hardness and tensile tests were carried out on specimens after different heat treatments while the Charpy tests were performed only after aging treatment performed for 16-18 h at 500 °C.

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).

Screw surfaces were observed by means of SEM in order to evaluate any critical issues related to their production such as formations of cracks.

3. Results and Discussion

In Table 1 the actual alloy composition is compared with the nominal composition of C70250 alloy. As it can be seen the Ni content of the alloy is slightly higher than the nominal one.

Fig.1 shows the alloy hardness as a function of the time of aging carried out at 500 °C. This figure highlights that hardness increases with time, reaches a maximum value after 8/14 hours and then, due to overaging, it decreases.

Hardness, tensile and Charpy test results are reported in Table 2 for specimens subjected to the selected heat treatment for different times. It shows that the yield strength requirements are met when the selected copper alloy is aged for about 14 hours, although with this treatment elongation is only 2%. On the other hand after solution treatment the alloy elongation is about 35%, but the yield strength and hardness are not sufficient for the required application. The low ductility and toughness of the age hardened alloy is not a critical issue for the satellite body, but it could be a problem for the screws. A good compromise for the production of the screws, which need a good fracture toughness, is obtained in the overaged conditions in which the elongation reaches a value of 5% with a yield strength value of 520 MPa that is fully sufficient to guarantee an excellent screw tightening. Tensile tests allowed also the determination of the elastic modulus of this material: the measured value is 130 GPa, in accordance with literature data.

Considering that the specimen that has the highest hardness has also the lowest elongation, Charpy impact tests have been carried out in order to evaluate the impact energy that is about 90 J, according to the few data available in literature for copper alloys.

Table 1. Nominal composition of C70250 alloy in comparison with the composition of the experimental alloy

	Ni	Si	Mg	Mn	Fe	Zn	Pb	Cu
Nominal composition	2.2-4.2	0.25-1.2	0.05-0.3	0-0.1	0-0.2	0-1.0	0-0.05	Bal.
Actual composition	5	1.0	0.6	0.01	0.3	0.1	0	Bal.

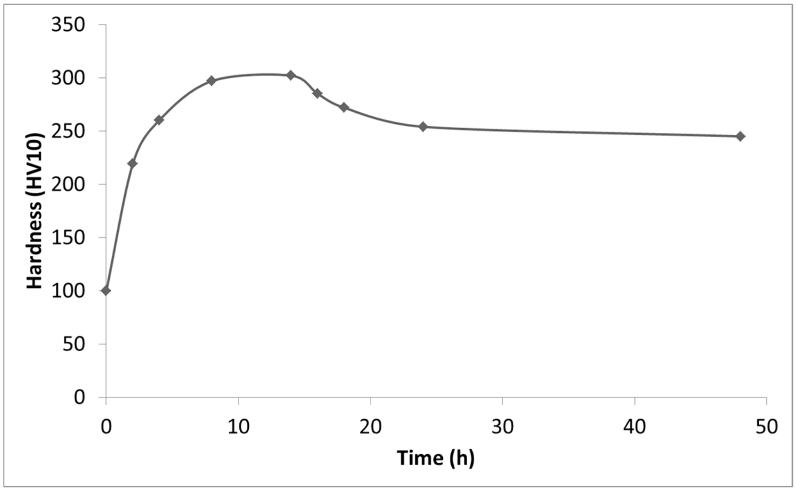

Fig. 1. Aging curve showing hardness values versus time

Table 2. Mechanical properties of the tested alloys

Heat treatment	Ultimate Tensile strength (MPa)	Yield strength (0.2%) (MPa)	Elongation (%)	Vickers Hardness (HV10)	Calculated HRC Hardness	Impact energy KV (J)
"As cast" alloy				160		
Solution treated (900°C) 2h + water quenched	250	103	35	100		
Aged (500°C) 2h				219		
Aged (500°C) 4h				260	24	
Aged (500°C) 8h				297	29	
Aged (500°C) 14h	654	542	1.9	302	30	
Aged (500°C) 16h				285	28*	82
Aged (500°C) 18h				272	26*	93
Aged (500°C) 24h	569, 581	519, 540	4.5, 4	254	23	
Aged (500°C) 48h	520	430	4.8	245	22	

* Measured values

An efficient design of the satellite requires a detailed understanding of the fracture behavior and of the mechanisms of failure of the selected material. SEM imaging of the fracture surfaces, of the specimens broken during tensile tests, show in the solution treated condition a ductile fracture morphology with typical dimples (Fig. 2). Fig. 3 highlights that the fracture surface morphology is different after aging. It can be seen that after aging at 500 °C for 14 h the alloy shows a mixed fracture mode: brittle interdendritic fracture areas coexist with ductile deformation areas.

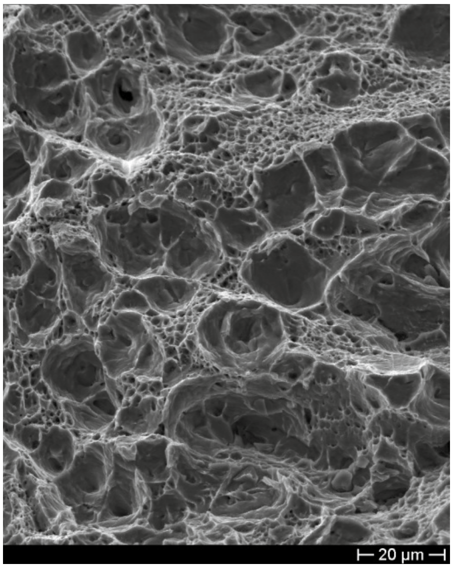

Fig.2 . SEM micrograph showing the fracture surface on a specimen treated at 900 °C for 2 h and water quenched.

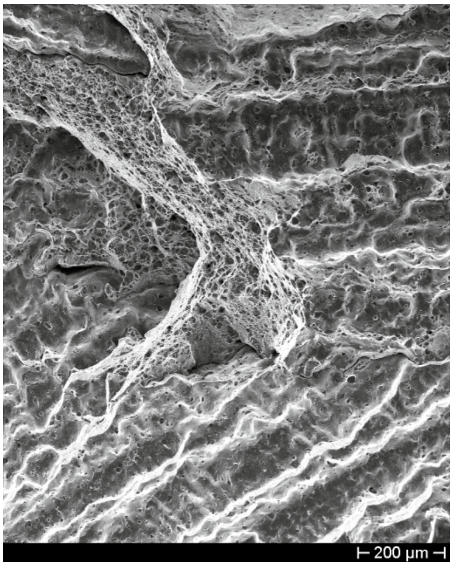

Fig.3 . SEM micrograph showing the fracture surface on a specimen aged for 14 h at 500 °C.

In the overaged conditions (Fig. 4) SEM analyses show again a mixed fracture mode with the presence of dimples in the areas with a ductile behaviour, while other areas are characterized by a brittle interdendritic fracture. It can be highlighted that in none of the considered samples a clear brittle fracture can be visible, in fact plastic deformation is always observable on fracture surfaces.

In order to evaluate if the overaged C70250 alloy is a good candidate for screw production it is important to analyse the Charpy specimen fracture surfaces. Figure 5 reports SEM micrographs, at two different magnifications, of the fracture surface of a V-noched specimen used for the Charpy test. These micrographs show an intermixed mechanism with very small dimpled zones and brittle fracture zones very close to each other. This observation confirms that the selected alloy in the overaged conditions has a good toughness and that it is a suitable material for screw manufacturing.

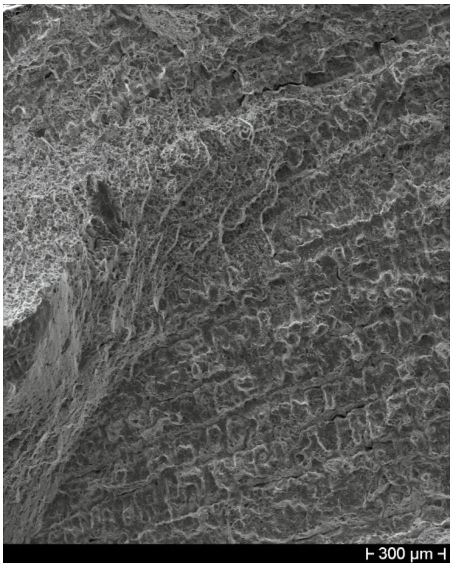

Fig.4 . SEM micrograph showing the fracture surface of a specimen aged for 24 h at 500 °C.

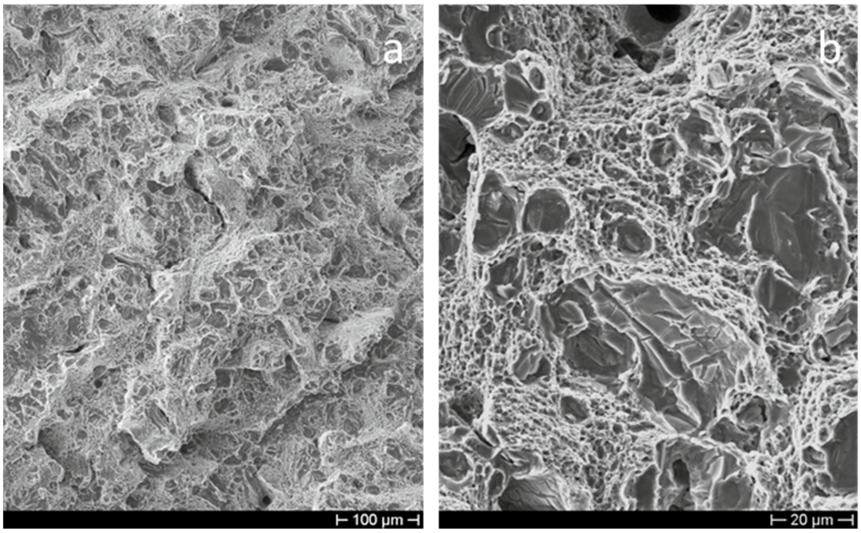

Fig.5 . SEM micrograph showing the fracture surface of a specimen aged for 16 h at 500 °C after the Charpy test.

Once decided that the best solution for the screw production is the use of the selected alloy in the overaged conditions, screws have been produced by means of machining in order to evaluate the alloy workability. Figure 6 shows the screw surface: as it can be seen it is even and smooth, without either cracks or irregularities. This indicates that the C70250 alloy aged at 500 °C for 24 hours is characterized by a good machinability and then that it is suitable for screw production and application.

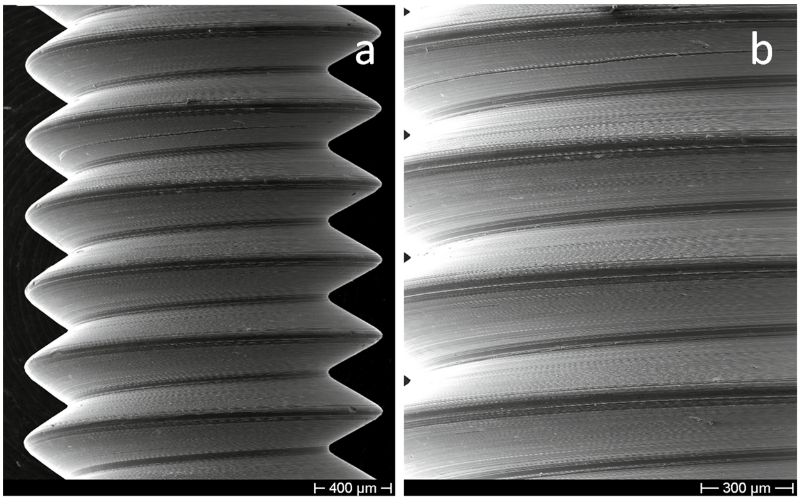

Fig. 6. SEM micrographs showing the surface of an M2 screw made of C70250 alloy at two different magnifications.

4. Conclusions

In this work the results of a research campaign aimed at the selection of the most suitable alloy for the production of the new LARES 2 passive laser-ranged satellite for testing General Relativity are reported and discussed. The obtained data suggested that an interesting candidate for the satellite is the C70250 copper alloy that in the age hardened conditions meets all the design requirements. In particular the selected alloy, aged at 500 °C for 14 h, seems to be the best candidate for the satellite body for which the low alloy deformability is not a critical issue. In fact fracture surface analyses highlighted that all the specimens show plastic deformation. Screws, that need a material characterized by a good workability and fracture toughness, together with an acceptable yield strength, should be produced by using the alloy aged at 500 °C for 16-24 h. The results of the Charpy impact test, carried out on the overaged alloy, confirmed that it is a suitable material for screw production.

Acknowledgement

The authors thank the Italian Space Agency for the support of the LARES and LARES 2 space missions under agreements No. 2017-23-H.0 and No. 2015-021-R.0 and the International Laser Ranging Service (IRLS) for its availability to track LARES 2 satellite.

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