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Toughness evaluation of LARES satellite tungsten alloy

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Abstract

LARES (LAser RElativity Satellite) is a passive satellite, it was launched on February 13, 2012 using the new European Space Agency (ESA) launcher VEGA, to measure with high accuracy the effect of the Earth angular momentum on the spacetime geometry that in turn affect the orbital motion of a satellite. This effect is called frame-dragging or Lense-Thirring effect. The reduction of the surface-to-mass ratio is the most important parameter in this respect. A tungsten alloy has been chosen as the best cost effective solution. The LARES 2 mission has been recently proposed aiming at the construction and launch of a second LARES satellite which, in one possible configuration, has a larger diameter and mass. During the LARES manufacturing some issues related to the low fracture toughness of tungsten alloys were evident, the most critical parts being the screws used in the retroreflectors mounting system. The aim of this work, on the basis of all these considerations, is to measure the fracture toughness of this alloy in order to evaluate, in a second stage, feasible thermomechanical treatments that should be able to increase safety margins.

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Keywords: Fracture toughness; Lares Satellite; Liquid sintering; Tungsten alloy.

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1. Introduction

Materials for space applications are aluminium alloys, polymeric composite materials and titanium alloys. However in small quantities also other materials are used. An exception is provided by the so-called passive geodetic satellites which are spherical in shape and usually very dense [1]. For instance the satellites LAGEOS 1, LAGEOS 2,

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Stella and Starlette, although made of aluminium alloys in the outer shell, contain a heavy metal mass (copper alloy for the first two satellites and depleted uranium for the other). LARES satellite is instead made of one single piece of tungsten alloy: among the largest piece ever manufactured and for sure the largest amount of tungsten mass ever launched in orbit [2,3]. The satellite has been successfully put in orbit on February 13, 2012 with the qualification flight of VEGA launcher [4]. The objective of the mission is to measure accurately the frame-dragging effect predicted by general relativity [5]: the orbital plane of LARES is dragged by the Earth rotation because it is spacetime itself to be twisted by the mass current of the Earth. The main difficulty of the experiment is to determine very accurately the effects of the classical perturbations so that frame-dragging is not masked by the non relativistic actions.

2. Satellite description

LARES is a massive sphere of tungsten alloy covered with 92 Cube Corner Reflectors (CCRs) [6] (Fig.1a). CCRs have the property to send back to a laser ground station a laser beam, regardless on the orientation of the satellite. Accurate time of flight of laser pulse estimation will provide positioning with an error that can be as low as few millimeters even at thousands of kilometers. This technique is called laser ranging technique and the ground stations are organized by the International Laser Ranging Service (ILRS) [7]. The diameter of the satellite is 364 mm with a total weight of 386.6 kg with a mean density of 15309 kg/m^3. This makes LARES the orbiting object in the Solar system with the highest mean density. But more important is that LARES has the lowest surface-to-mass ratio of any artificial orbiting object. This ratio is directly proportional to the acceleration induced on the satellite by non gravitational perturbations. Therefore LARES is the best test particle available in the solar system [8,9]. Of concern within the topic of this paper is the CCR mounting system (Fig. 1b), each one constituted by two plastic rings, a tungsten alloy retainer ring and three tungsten alloy screws. The CCR, made of high grade glass (Suprasil 311), is maintained in place loosely between the plastic rings. The mounting system is fixed on the satellite body with the three screws and the retainer ring. The main issues found during the manufacturing are relevant to the retainer rings but above all to the screws. The LARES 2 mission has been recently proposed aiming at the construction and launch of a second LARES satellite which, in one possible configuration, has a larger diameter and mass. The addition of this new satellite will improve the accuracy of the measurement of frame-dragging and Lense-Thirring effect [10].

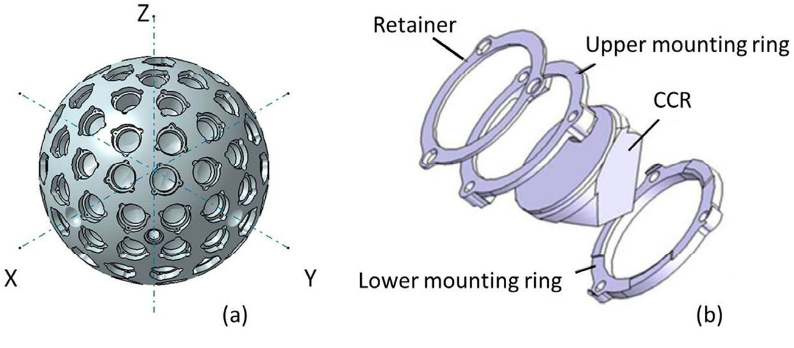

Fig. 1. LARES satellite drawing (a) and CCR mounting system (b).

3. Material issues

During the LARES 1 manufacturing some issues related to the low fracture toughness of tungsten alloys were evident, the most critical parts being the screws used for anchoring the CCR system. A batch of screws was produced by means of a lathe machine that usually produces a poor surface finish. In fact Fig. 2a clearly shows several well visible cracks on the screw external surface that appears irregular. During mounting tests some screws, manufactured by means of this technology, broke up. The analysis of the fracture surface [11] revealed that this fracture probably started from cracks produced during the screw machining and then propagated following intergranular paths. Considering this experimental observation and considering the low fracture toughness of this material, it is apparent that the strength of screws can be increased by selecting a manufacturing technology that allows to avoid crack formation. The most interesting method seems to be the thread-rolling process that allows to increase strength by means of cold working. Fig. 2b shows the screw profile obtained with this technology. This figure highlights that the surface is smooth and only few cracks are visible. Thread rolling is then superior to other methods such as machining and is able to increase screw strength making them suitable even for more stressed CCR mounting systems.

The analysis of broken screws highlighted that the critical parts were not only the threads, but also the screw heads (Fig. 3). Other critical parts, although in a lesser extent, are the rings used in the CCR mounting system. All these components are critical during the satellite launch when they are subjected to high levels of acceleration and vibration. On the basis of all these considerations it is of paramount importance to measure the fracture toughness of this material in order to evaluate, in a second stage, feasible thermomechanical treatments that should be able to increase safety margins. This is necessary because all the satellite metallic components have to be made of the same alloy.

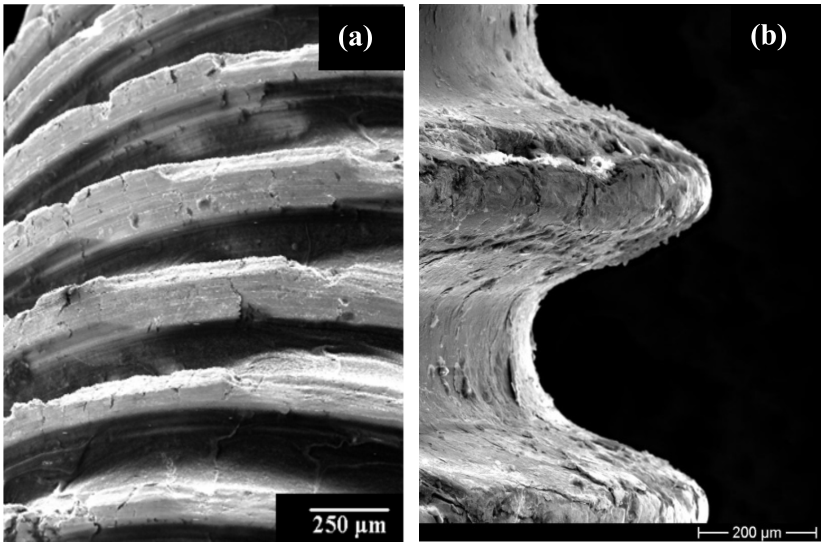

Fig. 2. SEM micrograph showing the screw manufactured by means of thread turning (a) and thread rolling (b).

Fig. 3. Macrograph showing the broken screws

4. Experimental

In this study W-Ni-Cu alloy specimens were ground to a mirror-like surface by SiC papers up to 1000 followed by 1 µm alumina. Metallographic structure of the studied material was inspected by means of optical and scanning electron microscope (SEM) and microanalyses were carried out by energy dispersion spectroscopy (EDS).

A sets of four specimens were made, in accordance with ASTM standard E399, by means electro discharge machining. ASTM E399 involves the testing of notched specimens either in tension or three-point bending. The three-point bending test has been performed in this work by using specimens shown in Fig. 4 and having the following dimensions: a=4.5 mm, W=9.1 mm, B=4.6 mm.

Fracture surfaces and crack propagation were analysed by SEM.

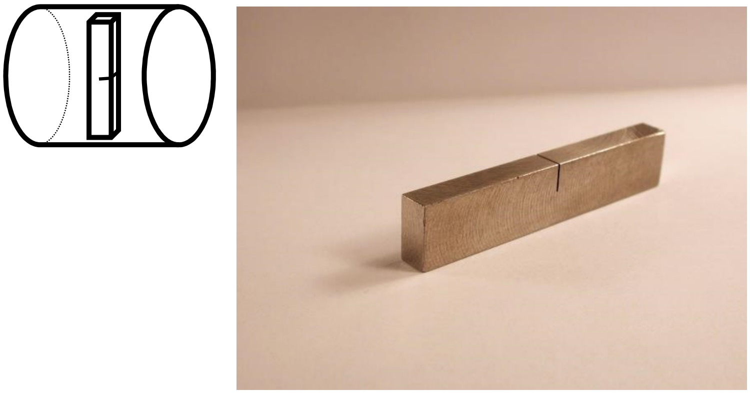

Fig. 4. Macrograph showing one of the specimens prepared in accordance with ASTM standard E399.

5. Material Characterisation

The extreme high melting point of tungsten makes the production of mill products very difficult through melting and casting. For that reason the powder metallurgy was adopted from ceramics and used for producing tungsten components. Metallic alloys produced by VAR are used for applications where cleanliness and homogeneity of alloys are important to increase fracture toughness of the final components. Generally speaking, strategic industries such as aerospace and power generation require the high performance guaranteed by VAR remelted materials. Over the years this technology has been improved to increase the reproducibility of the metallurgical and mechanical properties of the final products. All these conditions justify the complexity of VAR technology, especially for big components such as LARES satellite. For refractory metals, such as tungsten, the VAR technique is widely used, but it is expensive and complex. The use of the process known as liquid sintering is becoming the most viable solution for producing big sound components. For this reason all the components for LARES program have been produced by means of this technology.

Tungsten alloys produced by liquid sintering are characterised by tungsten particles surrounded by a binder. The tungsten alloy used for LARES program is constituted by tungsten grains in a continuous Nickel-Copper matrix. In liquid phase sintering of the alloy used for LARES a mixture of tungsten and Nickel-Copper powders is heated at about 1500 °C at atmospheric pressure. The alloy cools down within the furnace with some circulated nitrogen. The alloy densification is reached mostly by rearrangement of tungsten particles that grow due to tungsten transport throughout the liquid. The interparticle bonding affects mainly mechanical properties such as strength and ductility.

As it can be observed in Figs. 5 and 6, the tungsten alloy is characterised by tungsten grains embedded in a matrix that was liquid at the sintering temperature. The tungsten particles have a size ranging from 20 to about 60 µm. Fig. 6 shows also that there are several interparticle necks among grains that are formed during the sintering process. EDS analyses carried out on the studied alloy showed that the particles are pure tungsten (Fig. 7a), while the binder phase, which surrounds the tungsten particles, contains 58% Ni, 17% Cu, 24% W and 1% Fe in weight % (Fig. 7b). The mean composition of the alloy is 92% W, 6% Ni and 2%Cu in weight %.

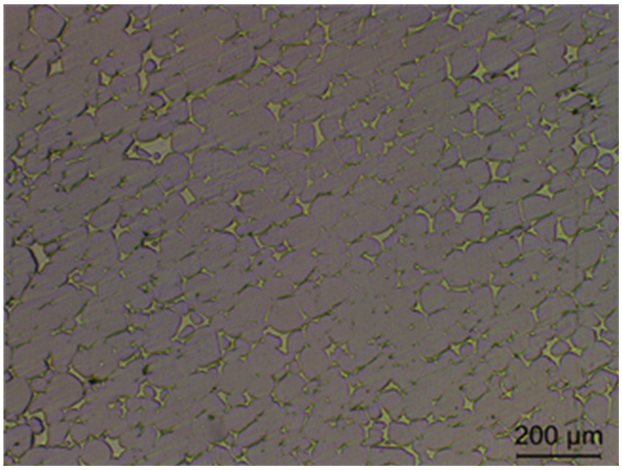

Fig. 5. Optical micrograph showing the alloy microstructure.

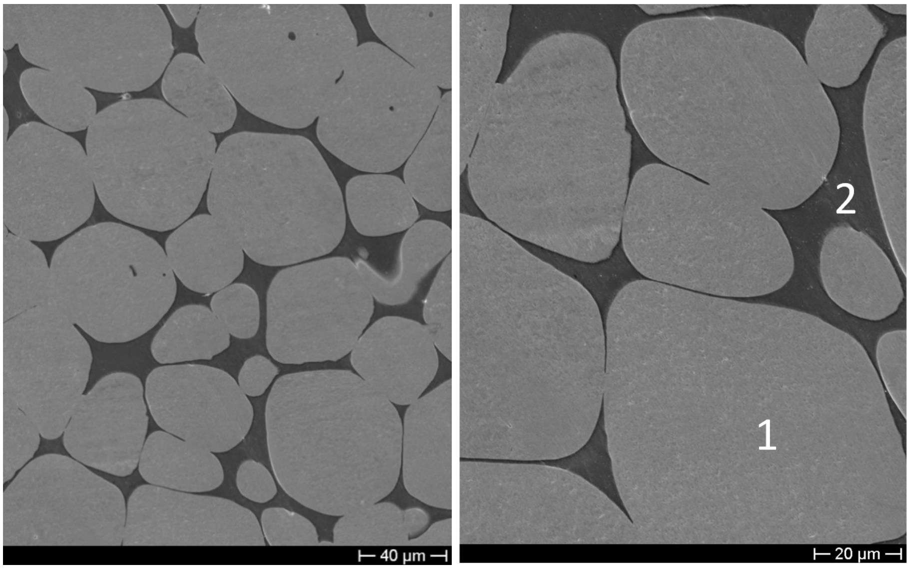

Fig. 6. SEM micrographs of the alloy microstructure. 1- tungsten grains, 2-Ni-Cu binder.

Considering that in literature there are very few data available we determined the fracture toughness of the material used for producing screws using the ASTM E399 testing that concerns the determination of the plane-strain fracture toughness (K_{IC}) of metallic materials by using different fatigue-cracked specimens. The K_{IC} determined by this test method gives indications about the resistance of a material to fracture in presence of a sharp crack under severe tensile constraint.

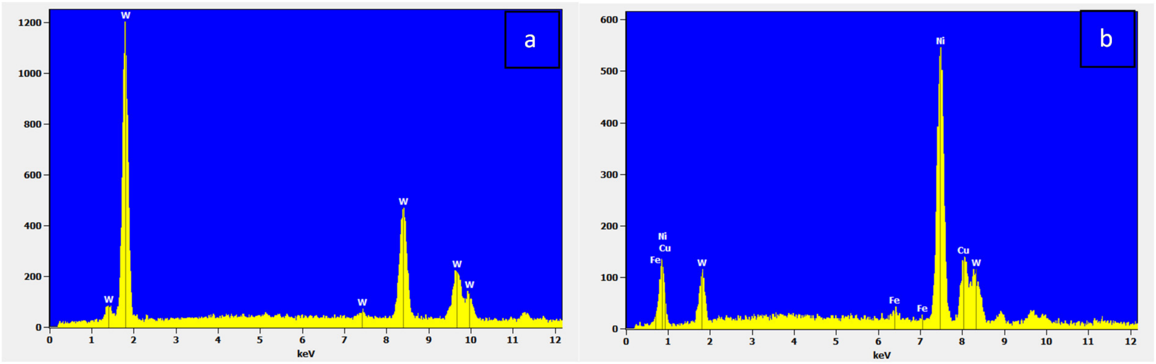

Fig. 7. EDS spectra showing: (a) the composition of tungsten grains (point 1 in Fig.3) and (b) the composition of the binder phase (point 2 in Fig.2).

This value may be useful to evaluate the relationship between failure stress and defect size for a material in service that could be subjected to severe stress. Fracture toughness tests gave the load-deflection curves reported in Figure 8, while the K_Q calculated values are reported in table 1.

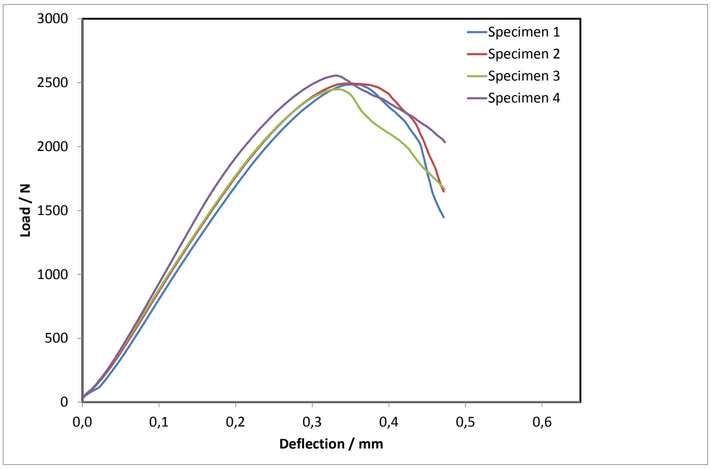

Fig. 8. Representative load-deflection curves of four specimens of the analysed tungsten alloy.

Table 1. K_Q values calculated from three point bend tests

	P_{max}	P_Q	K_Q	Acceptance criteria	
	(N)	(N)	$(MPa\sqrt{m})$	Pmax/Pq < 1.10	$2.5 (K_Q/\sigma_y)^2 < B$
Specimen 1	2486	2218	12.3	1,12	1,11
Specimen 2	2494	2229	11.8	1,12	1,02
Specimen 3	2448	2222	12.0	1,10	1,05
Specimen 4	2555	2202	12.0	1,16	1,05

As it can be seen in the table the ratio P_{max}/P_Q for specimens 1, 2 and 4 is slightly higher than 1.10, while the value of the expression $2.5 (K_Q/\sigma_y)^2$ is always less than both specimen thickness and crack length. The σ_y value of this alloy is 586 MPa. Table 1 shows that the K_Q values are very similar to each other and that the mean calculated

K_Q value is 12 MPa√m. Considering that for specimen 3 K_Q is equal to K_{IC} it can be assumed that 12 MPa√m is the fracture toughness of the studied alloy. By comparing this value with those available in literature [12], it can be verified that it is quite similar to those measured for some as-sintered tungsten alloys. This toughness value could be increased by manufacturing processes such as rolling, forging or drawing that could then increase screw strength.

SEM examination of fracture surfaces highlighted that the fracture is mostly intergranular close to the notch, while many cleavage fractures are visible far away from the notch (Fig. 9). By analysing the crack path (Fig. 10a) it is evident that fracture follows a composite pattern of cleavage fracture of tungsten particles and ductile fracture of the binder. Earlier investigations [13] suggested that during deformation, the tungsten grain embedded in a soft matrix phase is subjected to a hydrostatic stress and that the alloy behaviour changes by changing the grain contiguity and the tungsten-matrix interface. Figure 10b shows that close to the crack tip microcracks nucleated both at the grain-matrix interface and within the grains.

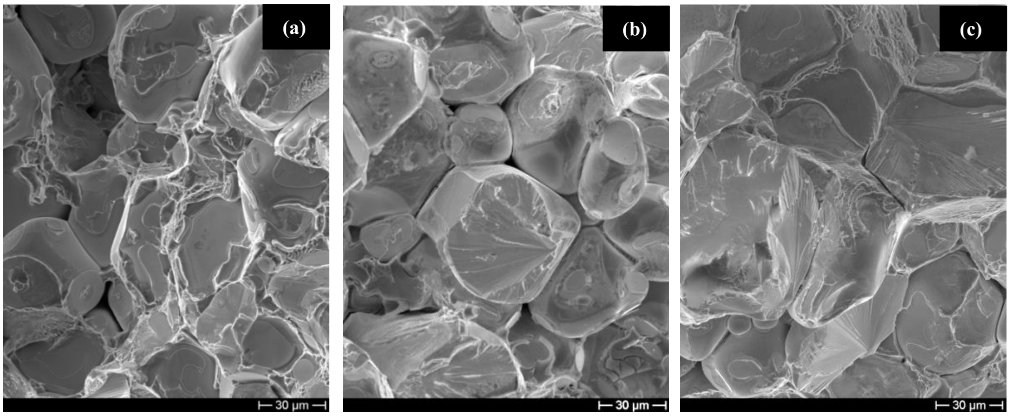

Fig. 9. SEM micrograph showing the fracture surface morphology of the three point bend specimen close to the notch (a), in the central part (b) and in the final part (c) of the fracture.

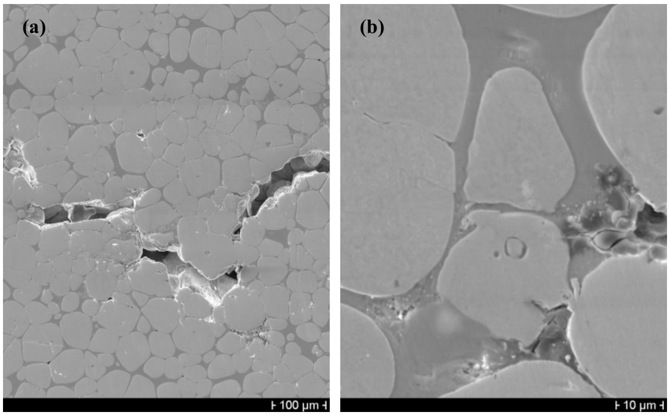

Fig. 10. SEM micrograph of the crack path (a) and in the area close to the crack tip (b).

6. Conclusion

Test results gave values of fracture toughness extremely repetitive, the mean value is 12 MPa √ m. These values are quite close to those available in literature on similar tungsten alloys, although the values obtained in the test presented here are slightly higher. On the basis of our results it will be possible to study feasible thermomechanical treatments aimed at increasing the alloy toughness as already suggested by literature data for similar alloys.

As far as the propagation mode is concerned the crack grows with a mixed mode that is initially intergranular and then partially transgranular with cleavage fractures throughout the tungsten grains. This is due to the possible compression of grains by the matrix phase.

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