Material and manufacturing issues of a laser ranged satellite

C. Vendittozzi, F. Felli,
Dipartimento Ingegneria Chimica Materiali Ambiente, "Sapienza" University of Rome, ITALY

A. Paolozzi,
Scuola di Ingegneria Aerospaziale, "Sapienza" University of Rome, ITALY

I. Ciufolini
University of Salento and INFN Lecce, ITALY

ABSTRACT. The LARES satellite is an Italian space mission funded by ASI, with CGS as prime contractor and Salento and Sapienza Universities as subcontractors. The LARES will be put into orbit by the European launcher VEGA during its maiden flight, foreseen in year 2011. The paper describes the general features of the material chosen for the manufacturing of the satellite and its components. Particular interest will be devoted to the manufacturing process and analysis of the screws.

INTRODUCTION

The Laser Relativity Satellite (LARES) is a high density satellite specifically designed to accurately measure (order of 1% accuracy) a theoretical prediction of Einstein general relativity, in particular the measurement of the Lense-Thirring (frame dragging) effect due to the Earth angular momentum and a high precision test of the Earth gravitomagnetic field [1-3]. Differently from most of the satellite structures, usually designed to minimize the mass of the entire system, LARES has been designed with the opposite philosophy [4] and in particular with the objective to maximize the mass-to-surface ratio; a high density and non magnetic material has been selected: tungsten alloy, [5-7]. LARES is manufactured from a single piece bulk material. This choice offers a simpler design and will reduce thermal gradients on the satellite surface. Tungsten alloys have never been used for the entire construction of a satellite. Therefore the need of manufacturing a first breadboard (BB), representative of a small portion of the satellite. This BB allowed to pin point a problem with the small screws of the Cube Corner Reflector (CCR) mounting system. In Fig.1 is reported a 3D representation of LARES satellite.

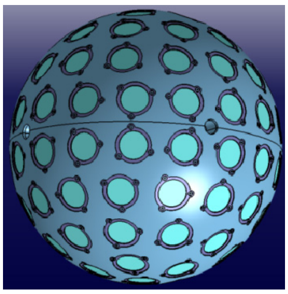

Figure 1: 3D representation of the LARES satellite.

ONE SINGLE PIECE SATELLITE OF 400KG

One critical parameter for a satellite to be used as proof-particle in the gravitational field of Earth is the maximization of the Mass-to-Surface ratio (M/S). That allow to make non gravitational perturbations acting on the surface of the satellite (such as atmospheric drag, thermal thrust and radiation pressure) small compared to the gravitational forces and consequently the experiment more accurate. Starting from a simple relation, valid for a perfect homogeneous sphere,

$$M/S = \rho r/3$$

where ϱ is the mean satellite density and r its radius, it is easy to deduce that the satellite should be very large. However due to obvious limitations on size and weight, the main constraint is in our case, the mass which has been established to be about 400 kg (launcher mass budget),

$$M = 4/3\,(\pi r^3)\rho = 400\ \text{kg}$$

consequently our optimization problem is solved by taking the highest value for ϱ. Among the highest density materials, a tungsten alloy was chosen (pure tungsten has a density of 19.350 kg/m^3), because pure tungsten is not workable. Tungsten alloys can reach a density of 18.500 kg/m^3. The LARES satellite will be the first orbiting object made entirely of tungsten alloy with the exclusion of the CCRs and the plastic mounting rings. A great challenge for the workability of such an alloy is that the satellite body is a monolith manufactured out of a single piece. Most of the laser ranged satellites have a core made of a material with a higher density with respect to the external part. The reason why a dense core is used, is because the density of the aluminum shells typically used for the external part, is too low for the scientific requirements (2.700 kg/m^3). It is hard, if not impossible, to obtain a sphere by casting without voids and flaws that may be generated by differential cooling: volumes near the center of the sphere solidifies last. For sintered material the absence of a liquid phase make the process possible. However sintered material does not guarantee a sufficient toughness and so the semifinished sphere has been manufactured with the so called liquid sintering technique in which the small quantity of Ni-Cu (about 5%) present in the alloy is brought to melting temperature, providing in the end the matrix inside which remains the unmelted tungsten particles. Also the other semi-finished components used to manufacture the CCR mounting systems have been prepared by the manufacturer using the liquid sintering technique. The chosen alloy is non magnetic to limit the interaction of the satellite with the magnetic field of Earth. In Tab. 1 are reported the main characteristics of the tungsten alloy chosen for LARES satellite construction.

SPECIFICATION	SAE AMTS-T-21014D;	CLASS 3 (NON MAGNETIC)
UTS	94.00 psi minimum	
0.2% YS	75.00 psi minimum	
% elongation in 1" gage section	1% minimum	
DENSITY	17.75 gm/cm^3	18.01 and 18.05 as misured
Hardness Rockwell C	34 maximum, typical is 28	
Microstructures	uniform at 200x	
%Tungsten	95 typical; balance Ni, Cu	Standard 95%W, 3%Ni, 2%Cu
Magnetic Permeability	<1.05 mu	measured <1.01 mu
Electrical Conductivity	<17% IACS	measured 16.94%

Table 1: THA-18N main features.

ELECTROCHEMICAL DISCHARGE MACHINING

To meet the scientific requirements, the material workability and the design mechanical tolerances were fundamental. Several solutions were weighted in terms of alternative technologies for machining the satellite body surface and, particularly, for all the cavities manufactured on it. Among them preliminary tests were carried out for electrochemical discharge machining (EDM). EDM is a combination of two different machining methods to remove material, electrochemical dissolution of the material combined with a thermal erosion by electrical discharges that occur between the electrodes. This technique leaves a burr free surface and the lack of tool forces prevents distortion of the part. Generally EDM is used for machining complex cavities in hard and high strength materials. Tests for the LARES satellite have been carried out by performing electrochemical machining of specimens made of liquid sintered W-Ni-Cu alloy. After machining, specimen surfaces have been analyzed by SEM in order to evaluate the surface finish. As it can be seen in Fig. 7 the results are not satisfactory, in fact the EDM produces a bad surface finish probably due to the, already mentioned, double-phase nature of the sintered tungsten alloy. During the process the Ni-Cu binder phase dissolves first, leaving loose tungsten grains that come off from the surface. Fig. 2 shows in fact the specimen surface that appears uneven due to Ni-Cu alloy selective dissolution and to grain detachment.

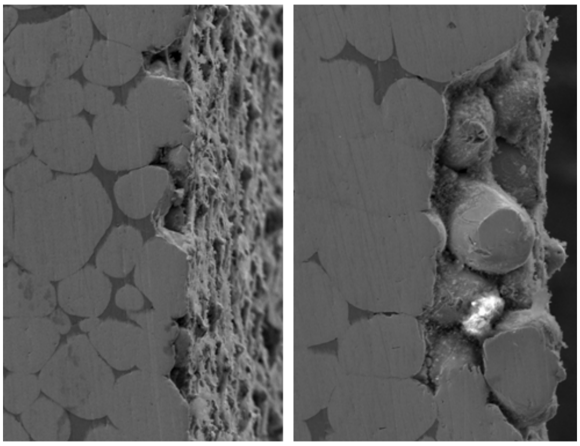

Figure 2: Micrograph of the surface obtained by means of EDM.

MICROSTRUCTURE ANALYSIS

The CCR mounting system screws (Fig. 3) represent a very critical point for the manufacturing process. Since the material is very hard to work we had to fix a lower limit (i.e. 3mm) for the diameter of the threaded screws. A smaller diameter does not allow to make the internal thread of the screw inside the satellite body. To verify the feasibility of sintered tungsten screws with M3 metric thread, a BB has been realized. In Fig. 3 the components (the screws, the satellite body, represented by a cylinder, and the retainer ring), are shown. A metallographic structure analysis has been performed by microscopy (SEM) on a W-Ni-Cu alloy specimen, polished by means of SiC paper and 0.3 μm alumina.

Figure 3: Mounting System Screws and rings.

The tungsten alloy (Fig. 4) realized by means of liquid sintering has a structure substantially different than a structure obtained by casting or, in the case of the tungsten, by Vacuum Arc Remelting (VAR). Such a structure is characterized by tungsten particles of about 30 µm embedded in a Ni-Cu phase. EDS analyses revealed that the binder phase contains 58% Ni, 13% Cu and 29% W (weight %). In fact during the sintering process, part of tungsten diffuses through the Ni-Cu liquid phase. This class of structure has a weak point for what concern toughness and fracture resistance, making the material susceptible to intergranular brittle fracture. This mechanism of fracture is particularly critical in the case of production of screws with this alloy. In this situation, screws produced by means of a lathe machine produces a poor surface finish, as it is shown in Fig. 5, the screw surface appears jagged and characterized by cracks. After several mounting tests one of the screws, manufactured by lathe machining, broke. The SEM analysis of the surface of the fracture, carried out in order to understand the failure mechanisms, indicates the presence of two different mechanisms due to the coexistence of two different phases. Tungsten grains tend to come out (crumble for intergranular cohesion) from the matrix formed by the Ni-Cu binder phase, which tends to deform plastically, showing a dimpled fracture surface. The fracture was almost certainly triggered by a crack formed into the thread during the machining by the lathe machine (Fig. 6), then propagate rapidly by exploiting adjacent intergranular paths. This observation suggests that an alternative manufacturing process need to be found, i.e. rolling-thread.

Usually, rolled threads increased tension, shear, and fatigue strength. The cold formed screws have shown a higher density of material grains, especially where they have been compacted. The rolled screw profile is shown in the micrograph reported in Fig. 7 which shows that the thread surface finish is very smooth with only few cracks. This highlights that thread rolling is superior to other methods such as lathe-machining.

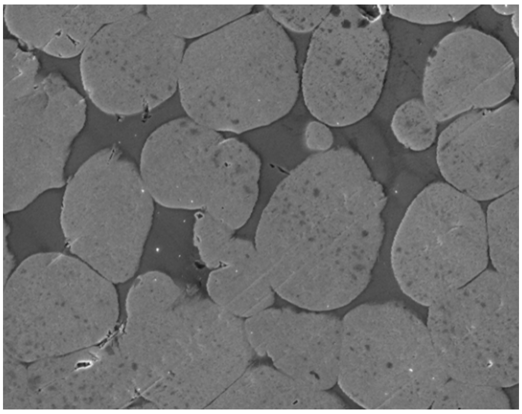

Figure 4: W-Ni-Cu Alloy microstructures.

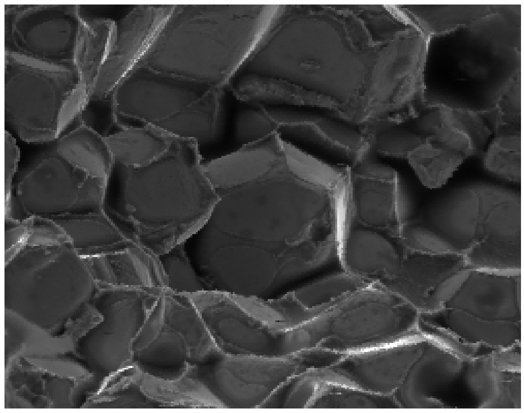

Figure 5: Micrograph of the fracture surface.

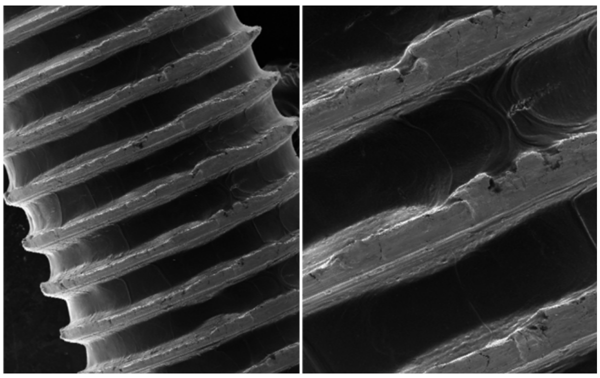

Figure 6: Screw obtained by means of a lathe machine.

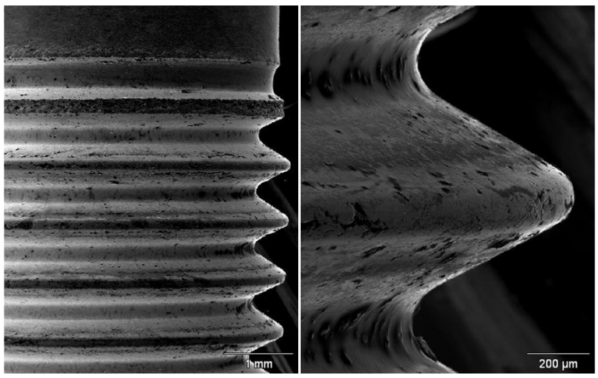

Figure 7: Screw obtained by thread rolling.

Conclusions

The micrographic analysis performed in particular on the LARES satellite screws, showed the defects produced using a lathe-machine, on the other hand the thread-rolling process brought a significant increase in hardness through cold forming, and a better surface smoothness. In the evaluation of alternative methods for cavity manufacturing on the satellite body, the EDM has been discarded: the irregularity and fragility of the surface obtained by applying this process to a liquid sintered alloy, such as the one selected for the satellite, is in contrast with the mission requirements.

REFERENCES

[1] Ciufolini, E. C. Pavils, Nature, 431 (2004) 958.
[2] Ciufolini, Nature, 449 (2007) 41.
[3] Ciufolini, J. A. Wheeler, Gravitation and Inertia, Princeton University Press, (1995).
[4] A. Paolozzi, I. Ciufolini, C. Vendittozzi, I. Peroni, In: XX AIDAA Congress, Milano, Italy, (2009).
[5] A. Paolozzi, I. Ciufolini, F. Felli, C. Vendittozzi, A. Brotzu, D. Pilone, F. Passeggio, In: XX AIDAA Congress (2009).
[6] Missione LARES: progettazione del corpo del satellite e dei suoi componenti, Tesi di Laurea,C.Vendittozzi, Relatore Prof. A. Paolozzi, Correlatori Prof. I. Ciufolini, F. Passeggio.
[7] A. Paolozzi, I. Ciufolini, F. Felli, A. Brotzu, D. Pilone. In: 60th International Astronautical Congress, Daejeon, Republic of Korea (2009).