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LOW-STRESS SOLDERING TECHNIQUE USED TO ASSEMBLE AN OPTICAL SYSTEM FOR AEROSPACE MISSIONS

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ABSTRACT

A high-precision opto-mechanical breadboard for a lens mount has been assembled by means of a laser-based soldering process called Solderjet Bumping; which thanks to its localized and minimized input of thermal energy, is well suited for the joining of optical components made of fragile and brittle materials such as glasses. An optical element made of a silica lens and a titanium barrel has been studied to replicate the lens mounts of the afocal beam expander used in the LIDAR instrument (ATLID) of the ESA EarthCare Mission, whose aim is to monitor molecular and particle-based back-scattering in order to analyze atmosphere composition. Finally, a beam expander optical element breadboard with a silica lens and a titanium barrel was assembled using the Solderjet Bumping technology with Sn96.5Ag3Cu0.5 SAC305 alloy resulting in a low residual stress (<1 MPa) on the joining areas, a low light-depolarization (<0.2 %) and low distortion (wave-front error measurement < 5 nm rms) on the assemblies. The devices also successfully passed humidity, thermal-vacuum, vibration, and shock tests with conditions similar to the ones expected for the ESA EarthCare mission and without altering their optical performances.

I. INTRODUCTION:

Solder joining using metallic alloys for the assembly and packaging of optical devices is an alternative to adhesive bonding or clamping methods. Soldering can guarantee a high level of cleanliness, avoids organic pollution and outgassing, whilst also assuring the high robustness and vacuum compatibility needed for the assembly and packaging of opto-mechanical space devices. Different laser based soldering techniques offering a localized input of thermal energy can be used to replace former space used optical-arrangements, for example: by bonding with laser beam transmission onto thin film solder layers [1], by a surface-mounted device assembly technique for small optics based on laser reflow soldering [2], with a method and device for connecting an optical element to a frame [3], or with a laser-based Solderjet Bumping technology [4]. Solderjet Bumping technology (Fig. 1.) allows for a flux-free and contact free processing of optical components allowing for 3D packaging by using various soft solder alloys (e. g. tin-based lead-free solders, low melting indium alloys or high melting eutectic gold-tin, gold-silicon or gold-germanium solders) in a spherical range diameter between 40 μm to 760 μm . Yet, Solderjet Bumping needs pre-applied metallization layers on the optical components (commonly non-metallic materials) in order to achieve good bond wettability and consequent high joining strength between the components to be assembled. Sputtered three layer systems using titanium as an adhesion layer, a platinum layer as a diffusion barrier, and a noble gold finish to prevent oxidization and acting as a wetting surface provide superb conditions for wetting of liquid solder droplets.

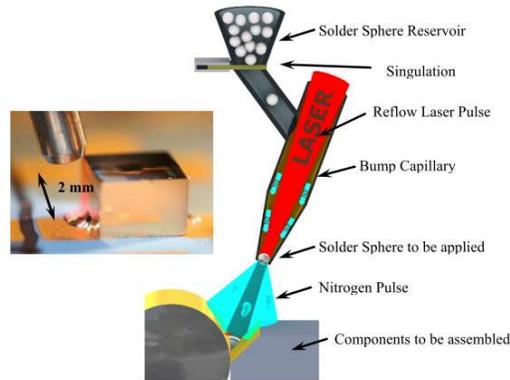


Fig. 1. The Solderjet Bumping device is mounted on a robotic articulated arm, allowing a rapid placement of the soldering alloys onto different 3D geometries. The soldering spheres ranging from 40 μm to 760 μm are transferred from the spheres reservoir to the bump tip capillarity where they are molten and jetted by nitrogen pressure onto the components to be assembled.

Optical elements used for space applications such as those used at the European Space Agency LIDAR (Light detection and ranging) EarthCare Mission whose aim is to monitor molecular and particle-based back scattering to analyze atmosphere composition needs to be fixated in a robust and stable way without altering the optical performances [5] but also assuring high levels of cleanliness in order to avoid laser induced contamination (LIC) and laser induced damage (LIDT) [6]. For our purpose, we investigated the assembly of a high grade fused silica lens (see L1 in Fig. 2.) of 26.5 mm diameter assembling it to a titanium (Ti-6Al-4V) barrel. The assembly by means of the laser soldering technology Solderjet Bumping had to meet several requirements for the mission purpose [5]:

- high centering accuracy (<0.1 mm),
- high stability (sub-micron range), low stress and non-deformation of the optical shape, otherwise the instrument response will fluctuate, birefringence will be induced and the data/image will be distorted,
- high cleanliness - chemical pollution has to be avoided as interaction of contamination with the high power laser that could reduce the optical performance, and eventually cause catastrophic failure (molecular: level A MIL- STD-1246 $<0.05 \cdot 10^{-6} \text{ g/cm}^2$; particles: <50 ppm),
- no organic compounds, the instrument will be mounted in a controlled atmosphere with only noble materials to avoid pollution and outgassing.

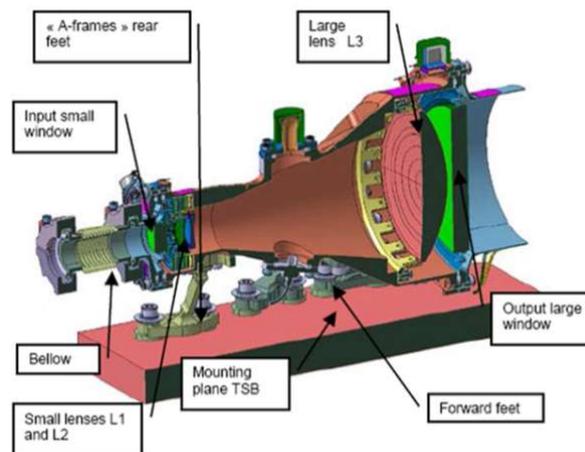


Fig. 2. Opto-mechanical setup for a beam expander of the earth atmosphere monitoring LIDAR (ATLID ESA Mission).

At the same time the opto-mechanics must operate reliably in harsh space environments (Fig. 3.):

- long life time (typically 20-30 years, taking mission and manufacturing times into account),
- ultra-high reliability (no possibility to repair during mission),
- high range thermal cycling: -40 $^{\circ}\text{C}$ /+60 $^{\circ}\text{C}$,
- compatibility with vacuum, Proc. of SPIE Vol. 10562 105620Q-3

- high joint strength to withstand vibrational load during rocket launch (typically 100 g).

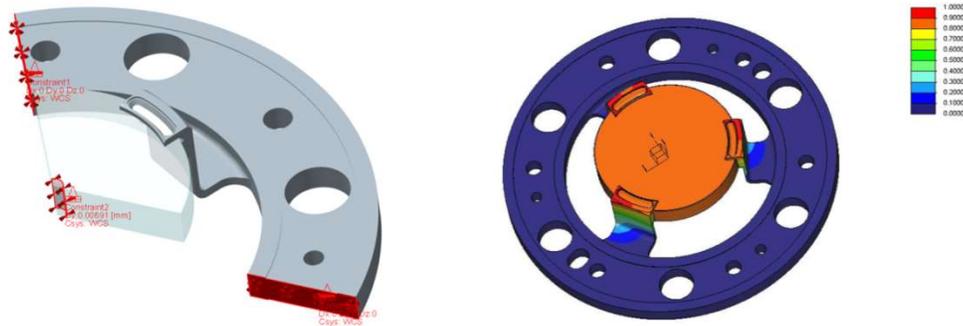


Fig. 3. Initial FEM simulations performed to verify if the assembly can withstand and operate under harsh space environments. Left, thermal simulation applied on 120° segment showing thermal mismatch and constant displacement on the three axis. Right, first vibrational eigenmode at 3168 Hz, meeting requirements for the modal analysis (following expected eigenmode frequencies were 3180, 4180 and 5983 Hz).

II. EXPERIMENTAL ASSEMBLY DETAILS:

A beam expander optical element incorporating a fused silica lens (SQ1) and a Titanium (Ti-6Al-4V) barrel was assembled by the use of jetted droplets of diameter 760 μm soldering alloy Sn96.5Ag3Cu0.5 (SAC305); chosen because of its thermo-mechanical properties.

Table 1. Thermo-mechanical properties of the used materials.

Material parameter	Units	Silica lens	SAC305	Ti-6Al-4V
Density	Kg/mm ³	2.20E-06	7.38E-06	4.43E-06
Young's modulus	kPa	7.00E+07	4.4E+07	1.10E+08
Poisson ratio		0.167	0.3	0.34
Shear stiffness	kPa	2.99E+07	1.69E+07	4.10E+07
Coefficient of thermal expansion	1/K	5.10E-07	2.24E-05	9.30E-06
Thermal conductivity	W/(m·K)	1.3	56.3	7.1

The lenses were only locally metallized with the sputtered three-layer system (titanium/platinum/gold) in order to assure maximum free aperture usage besides guaranteeing the required bonding strength; the titanium barrel was fully metallized since no additional constraints were required. Later, the silica lens was positioned under the titanium barrel flexures (Fig.4., right) through spring-type mechanical stops that secured the lens axial (for tip and tilt adjustment) and radial centering accuracy of 0.1 mm during the soldering process (Fig. 4.).



Fig. 4. Left, designed and manufactured tool for the lens positioning during soldering process. Right, detail of the spring-type mechanical stops that secured the lens center accuracy.

The spherical SAC305 solderjet bumps have been melted by a 1064 nm laser with a pulse energy of 1600 mJ [7]. Before and during the assembling process we measured the lens soldering applied stress with a polarimeter (StrainMaticR M4/60.13 zoom, Ilis GmbH, Germany) to ensure that no damage on the silica lenses arises; the test showed a final stress always under the boundary value of 1 MPa (Fig. 5.).

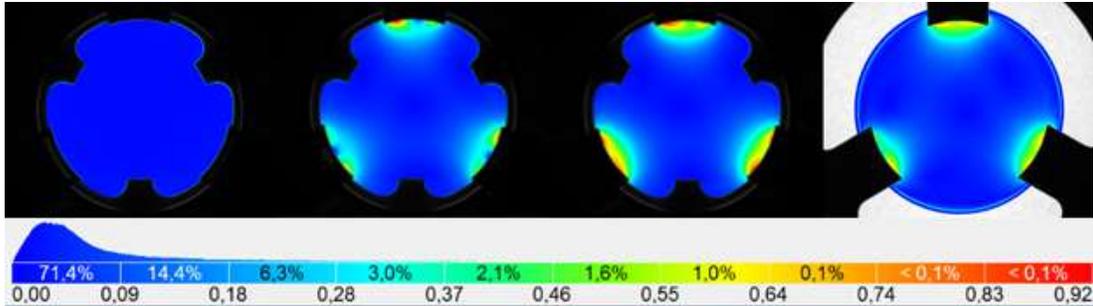


Fig. 5. Polarimeter measurements of caused stress during the soldering process. The first three images show the stress before and during the soldering process with the titanium barrel and the fused silica lens inside the positioning tool shown in fig. 4. The last image shows the final stress of 0.92 MPa after the assembling process (without the positioning tool).

III. ASSEMBLY CHARACTERIZATION AND ENVIROMENTAL TESTING:

The general aim for this optical system is to expand the 26.5 mm collimated beam from the 354 nm laser source module to the final 120 mm diameter beam used to characterize the atmosphere; in order to prove that no significant changes occurred on the silica lens that lead to depolarization, distortion, or alteration of the lens optical performances, the assemblies were optically tested by a wave-front error (WFE) measurements. The WFE measurements in a double pass configuration at 354 nm have been carried out thanks to a characterization optical bench set-up using a laser source, collimation optics and a wave-front analyzer (Fig. 6.). Results shows that the transmitted (one pass) WFE is <11 nm rms (root mean square error of the wave-front error with respect to the best plane) and a WFE focus removed <3 nm rms_i (root mean square error of the wave-front as respect to the best sphere i.e. without focus) as specified by mission requirements (respectively 15 and 5 nm rms).

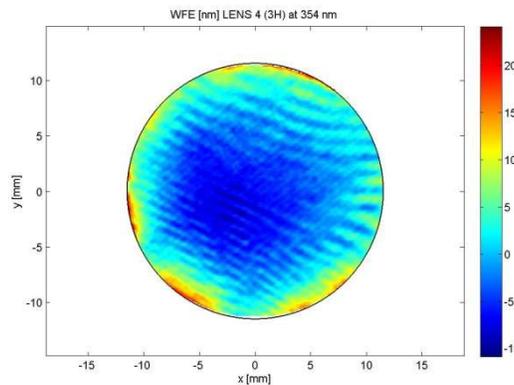


Fig. 6. Example of lens WFE measurement in transmission results on one of the assembled silica lenses.

The maximum lens depolarization ratio by mission requirements was established to be $2 \cdot 10^{-3}$. The maximum depolarization ratio measured (Fig. 7.) for the assembled lenses by using a highly polarized laser beam was $1 \cdot 10^{-4}$ (measurement threshold).

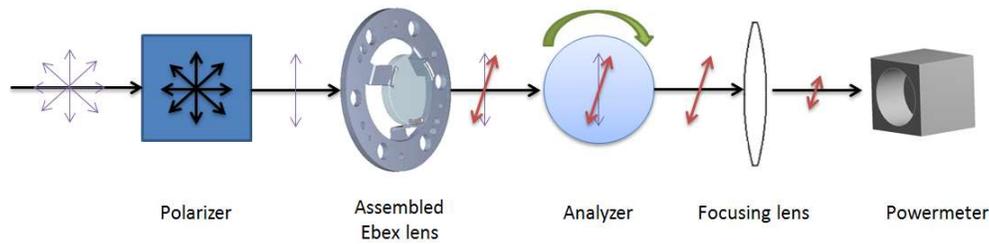


Fig. 7. A highly polarized laser beam passes the assembled components, a double 90° analyzer and it is focused to a power meter. This system enables one to measure the ratio of the power along the polarization direction parallel and perpendicular to the input beam polarization.

Thermo-mechanical tests were later performed on the assembled components in order to confirm that they can withstand similar aerospace mission conditions as the ones for the ESA EarthCare Mission. The devices were initially inserted in a climatic chamber at 45°C, 95% relative humidity for 48 hours. The devices were then inserted in a vacuum chamber for 10 cycles between -40°C and +60°C at a pressure lower than $1 \cdot 10^{-5}$ mbar before being inserted into a climate chamber for 20 cycles between -40°C and +60°C with a plateau length of 2 hours. At last, vibrations with a maximum level of 33 g_{rms} have been applied for one minute along the three axes, and shock level of 600 G for 0.5 ms have been also successfully applied three times over each axis (Fig. 8).

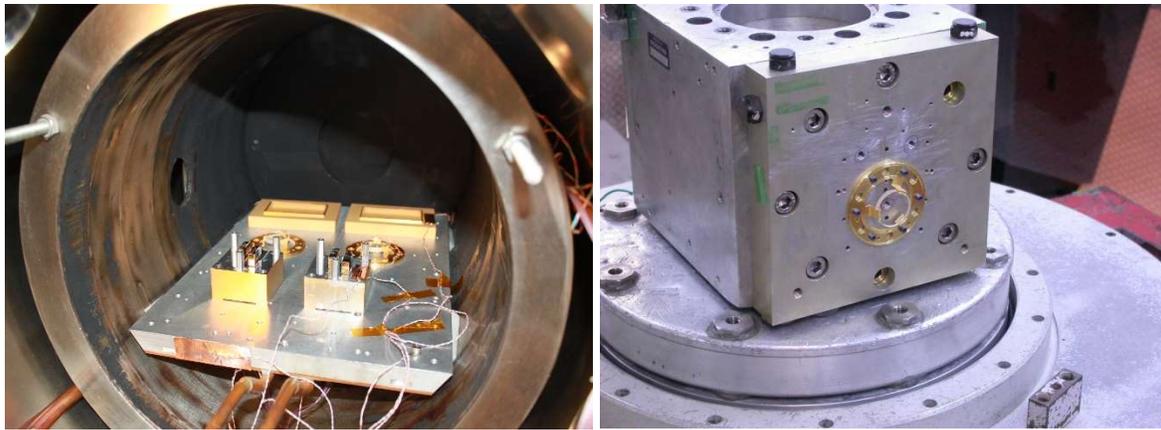


Fig. 8. Details of lenses thermal tests (left) and vibrational tests (right).

The assembled lenses optical testing was repeated after passing the thermo-mechanical tests to check for any change of the optical functionality; the WFE measurement (rms and rms_i) and the depolarization ratio did not show any change from the above mentioned tests. In addition, no visual evolution of the solder joints (Fig. 9) or cracks on the glass have been detected; moreover, the lenses centering stability has shown an accuracy after all the process of $<1 \mu m$ from the barycenter of the titanium barrel. The results demonstrated that the mounting and assembly techniques are compatible with state of the art optical quality in terms of injected stress, birefringence and WFE before and after passing tests replicating the requirements needed for the ESA EarthCare mission.

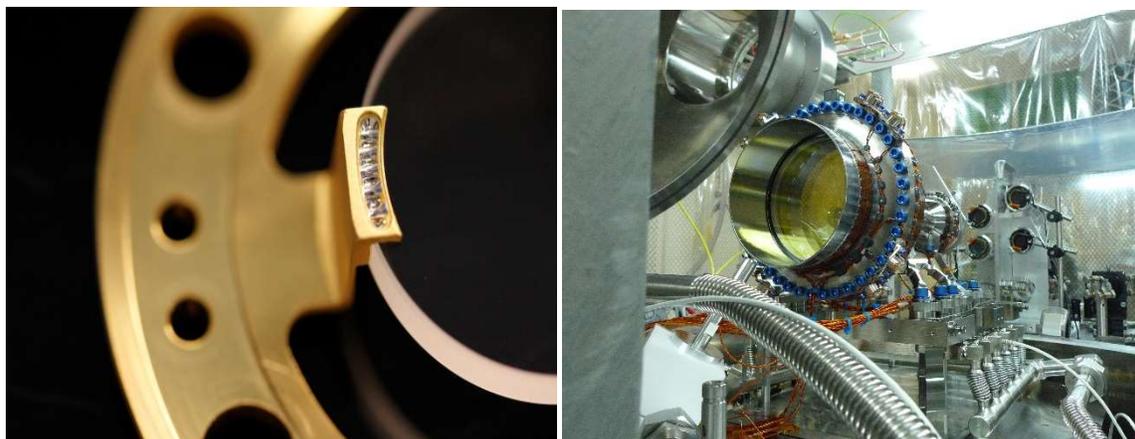


Fig. 9. Left, detail of the solder bumps joint evolution inspection. Right, lens optical tents inside a similar to LIDAR opto-mechanical set-up seen in Fig. 2.

IV. CONCLUSIONS:

A high-precision opto-mechanical lens mount similar to the LIDAR EarthCare mission has been assembled (Fig. 10.) with a minimized and localized stress (<1 MPa on less than 1% of the lens optical surface). The assembly has been performed by the use of soldering alloys and avoiding any kind of organic and outgassing pollution. The joined silica lens and titanium barrel has revealed outstanding performances in terms of WFE (<5 nm rms_i) and depolarization ($<0.02\%$); and it has successfully withstood humidity test, thermal-vacuum cycles (from -40 to $+60$ °C) vibration (up to 33 g_{rms}), and shock (600 g) with a high centering stability below 1 μ m.

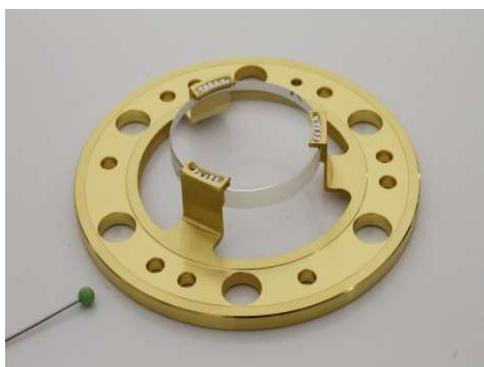


Fig. 10. Assembled lens by means of Solderjet used as representative prototype of the one used in ATLID Mission.

Solderjet bumping technology has demonstrated the ability to assemble high-precision and advanced optical systems made with different materials [8] being able also to withstand harsh environments required for space missions [9].

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