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Innovative Lightweight Substrate for Stable Optical Benches and Mirrors

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ABSTRACT

High precision space optics, such as spectrometers, relay optics, and filters, require ultra stable, lightweight platforms. These equipped platforms have on one side to survive the launch loads, on the other side they have to maintain their stability also under the varying thermal loads occurring in space. Typically such platforms have their equipment (prisms, etalons, beam expanders, etc.) mounted by means of classical bonding, hydro-catalytic bonding or optical contacting.
Therefore such an optical bench requires to provide an excellent flatness, minimal roughness and is usually made of the same material as the equipment it carries (glass, glass ceramics).

For space systems, mass is a big penalty, therefore such optical platforms are in most cases light weighted by means of machining features (i.e. pockets). Besides of being not extremely mass efficient, such pockets reduce the load carrying capability of the base material significantly.

The challenge for Oerlikon Space, in this context, was to develop, qualify and deliver such optical benches, providing a substantial mass reduction compared to actual light weighted systems, while maintaining most of the full load carrying capacity of the base material.

Additionally such a substrate can find an attractive application for mirror substrates. The results of the first development and of the first test results will be presented.

1. INTRODUCTION

The original idea for the development presented in this paper is to combine the best performance of different types of already widely used structural and opto-mechanical solutions to achieve ultrastable, lightweight platforms, which can be used as structural elements for optical benches or substrates of mirrors in space applications.

Space environment is driven by a harsh induced mechanical environment during launch followed by significant temperature excursions in orbit. Typical launch loads correspond to several hundred times the Earth gravity for optical components like mirrors, lenses, etc. Temperature variations are very often ranging between -50°C to +80°C for non-operating cases and may be narrower, depending on the degree of stabilization, for operational cases. Furthermore, for any space systems, mass is an extremely scarce resource, which is controlled with high importance.

Any optical system which has to perform in space has therefore to be integrated in a way such that during the launch phase the integrity of the optical elements is guaranteed and that, in operating conditions, the alignment and the geometrical stability of the optical layout is always compatible with the required performance.

The combination of those requirements was the starting point for a project originally carried out by Oerlikon Space as internal Research and Development activity. The aim was to develop benches to be implemented as supporting base-plate for high performing optical systems.
Such benches, in addition to the above mentioned requirements, have to allow the alignment of the optical components, as well as the verification of all performance parameters under all environmental conditions.

2. SPECIAL ASPECTS: MATERIAL

A good material for optical benches, which have to provide dimensional stability over a wide temperature range, is Zerodur, because of its near zero coefficient of thermal expansion (CTE). But, in order to provide the necessary stability against bending effects and the required mechanical stiffness, an optical bench made out of Zerodur needs to provide a substantial thickness, typically more than 10% of its lateral extension. Consequently, as the density of Zerodur is 2530 kg/m3, the mass of such a bench becomes prohibitively high.
Before discussing possibilities to reduce the mass of an optical bench, an assessment of the strength of Zerodur is appropriate. If we look into the technical publication [1] of Schott, the supplier of Zerodur, a bending strength of 10 MPa is given for parts with normal surface conditions, without scratches and flaws. This value is probably quite conservative, but as Zerodur is a glass-ceramic material, its mechanical strength depends on different factors, like the microstructure and area of the surface which is exposed to tensile stresses, the rate of stress increase, the time under load and the environmental conditions [1].
A case by case evaluation of Zerodur strength for given conditions can be performed where test results are available and evaluated using the so called Weibull distribution. This statistical strength assessment needs a very large number of samples and the resulting Weibull plots indicate failure probabilities for given loads, instead of minimum strength

data, as usually given for metallic materials. But as such results are not available in a datasheet, the strength assessments have usually to be made using the proposed 10 MPa.

One possibility to reduce the weight of a Zerodur part is the machining of pockets or similar features into the back side of the optical bench. One drawback of this solution is the fact that the geometry of such pockets can lead to stress concentrations, which reduce the mechanical properties of the structure. Additionally this process is extremely delicate, as cracks, generated during this operation, could potentially lead to failure, or at least to a significant reduction of the material strength. Due to these risks, the machining costs are very high. Combined with the high costs of the raw material, of which most is machined away, this leads to an expensive solution.

Furthermore such a light weighting can bring a reduction of the mass up to 80%.

3. THE ALTERNATIVE SOLUTION

The idea for the developed alternative solution is quite simple: combine the excellent thermo-elastic performance of Zerodur with the effective mechanical and low mass properties of a structural solution widely used in spacecraft, namely the sandwich.

Zerodur is used for the face sheets and therefore in a planar shape, a solution which retains as much as possible the strength of the Zerodur material in a state practically free from microcracks. Thanks to the planar shape of the face sheets, they can be polished to a high degree, therefore leading to a higher load carrying capability.

The properties in plane of the optical bench are given by the properties of the face sheets, as the modulus of elasticity of the core material is negligible in this direction. That means that the bending characteristics are defined as well by the face sheet material.

For our applications it turned out that Aluminum honeycomb is optimally suited as core material. Its rather high CTE of 23 ppm plays only a role across the optical bench, which typically is a non-issue. In plane, as said above, the Zerodur properties are dominant.

Very important to underline is that the density of an Aluminium core, can be as low as 16 kg/m^3 depending on the cell size and wall thickness, which is about 160 times less than of Zerodur bulk material!

In the case, that the third dimension is also of importance, there are possibilities to either use a near zero CTE core material (for example CFRP), or to use specific mounting techniques, which stabilize the more important face relative to its optically relevant counterpart.

Although Zerodur is the material of choice for the faces of thermostable benches, other materials have been tested by Oerlikon Space. Fused silica for example is a possibility, if a small CTE is required, e.g. in the case of affine optical designs.

4. APPLICATION: SANDWICH BASE_PLATE FOR ALADIN Mie SPECTROMETER

Oerlikon Space AG has sized, built and tested the Zerodur-Aluminium sandwich optical bench, in the frame of the Aladin programme as supporting base-plate for the Mie Spectrometer Unit.

The base-plate shown in Fig. 2 and Fig. 3 represents a great improvement for the unit in term of mass. In comparison with the same sized plate made out of light weighted Zerodur, 30% of the mass of the total unit could be saved, maintaining the same optics mounted on it. Such type of base-plate proved an extremely high load carrying capability taking into account that at its center a mass of 1.03Kg was concentrated on an area of 16.6 cm2.

The fully equipped unit, and therefore its base-plate, successfully underwent a full qualification programme consisting of vibration test (high sinus up to 30 g and random excitation) and thermal cycling.

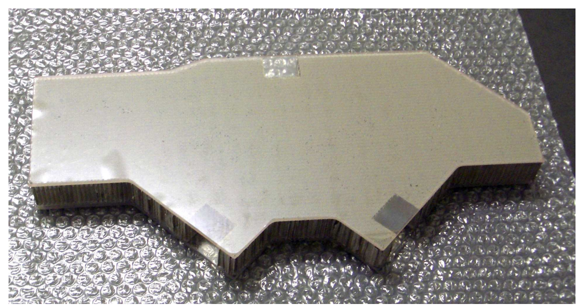

Fig. 2 Picture of the Base-plate built for the Aladin Mie Spectrometer

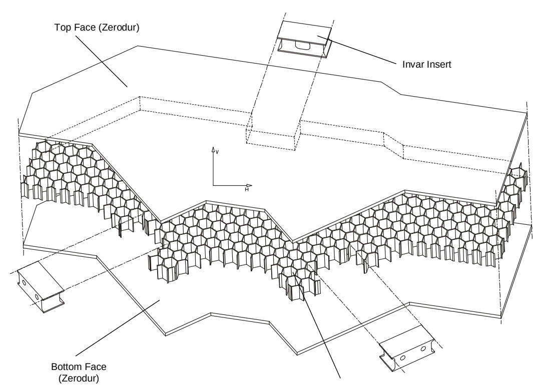

Fig. 3 Exploded view of the Base-plate built for the Aladin Mie Spectrometer

Furthermore such a base-plate provided the high stability required by the optical elements for the alignment, during integration and under all environmental conditions. In Fig. 4 the set-up for the verification of the base-plate planarity before integration of the optics is shown and in Fig. 5 one of the interferometric measurements is presented.

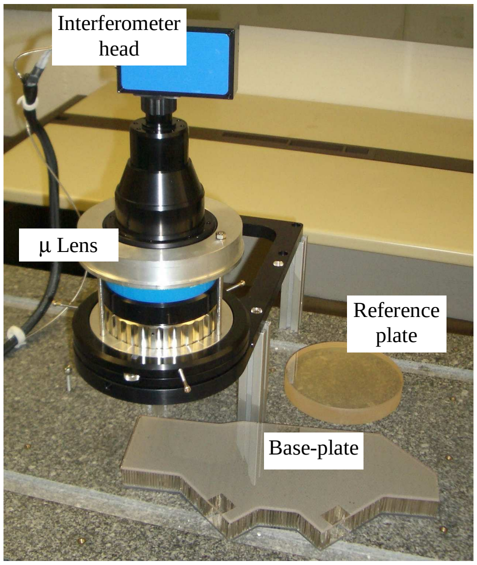

Fig. 4 Set-up for interferometric verification of the base-plate

Flatness requirement:

3λ = 1.899 µm

Measured flatness; PtV:

1.889 µm

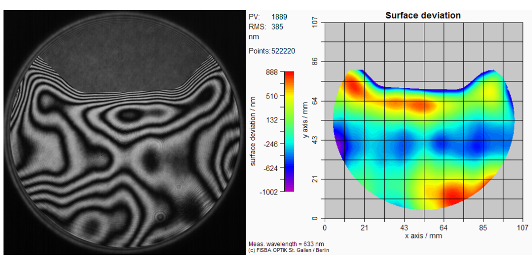

Fig. 5 Example of interferomteric measurement of the base-plate surface

5. MANUFACTURING AND TESTING

A dedicated process for the manufacturing of the base-plate sandwich was developed. The bonding of the Zerodur plates to the Aluminum honeycomb core was performed using an epoxy film adhesive, which was cured under elevated temperature and pressure. In order to be able to mount the optical bench to the instrument structure some attachment points were required. This was solved by bonding inserts into the edges of the optical bench, i.e. by having local cut-outs in the honeycomb core, in which the inserts were bonded, using room temperature curable adhesive.

Different mechanical and dimensional tests and inspections were performed. The bonding strength between honeycomb and Zerodur plates was evaluated using 40x40 mm flatwise-tensile test samples. In a second step the bonding strength of the titanium-inserts and their influence on the surface flatness of the base-plate were evaluated on larger samples (Fig. 7). The measured strength values for the inserts and the sandwich bonding were found to be well within the structural requirements for the given application in the Aladin instrument.

The evaluation of the flatness after bonding of the sandwich and the titanium inserts was also found to be within the requirements (Fig. 8). Nevertheless, as some distortions are induced by the bonding of the titanium inserts, the functional surface of the optical bench should be limited to the non-distorted area away from the insert locations.

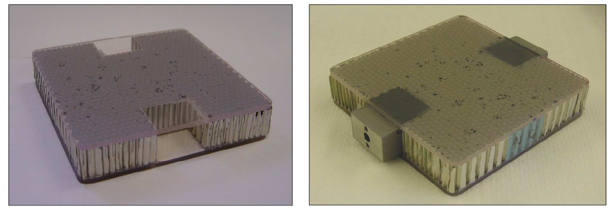

Fig. 6: Zerodur sandwich sample before and after bonding the inserts

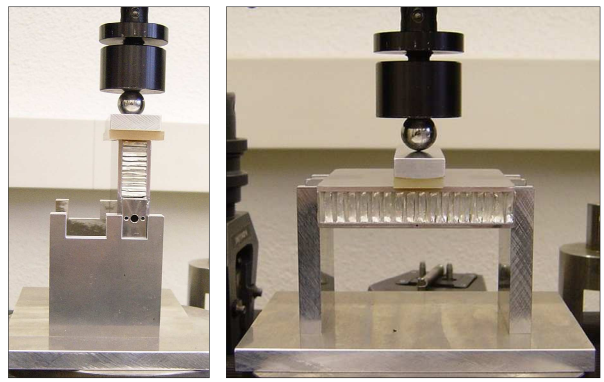

Fig. 7: Baseplate insert shear and bending strength test setup

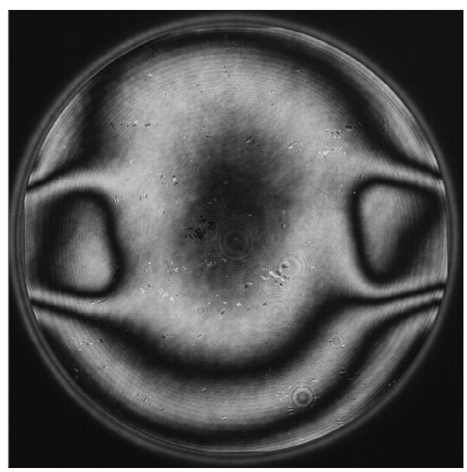

Fig. 8: Interferogram and surface after insert bonding

6. FROM BENCHES TO MIRRORS

The optomechanical performance of the sandwich optical bench turned out to be excellent.

This encouraged us to take another ambitious step: investigate the possibility to polish the sandwich to make, in a first instance, flat mirrors out of it.

SESO (Societé Européenne de Systèmes Optiques), which are cooperating with Oerlikon Space in this development, have achieved remarkable results with the polishing of a sandwich sample.

Using traditional polishing technique, on a 130 x 130 mm sample a quality of lambda/3 PTV and lamba/14 RMS (45 nm RMS!) has been achieved (see Fig.9), removing edge effect 8 mm around the boards. The samples proved to be very stable also during the polishing process therefore, being the above results just the first trial, SESO is confident that the polishing can be further improved.

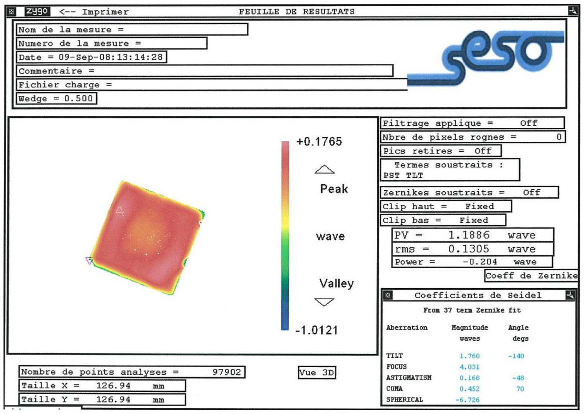

Fig. 9: Interferogram of the polished sample removing edge effects

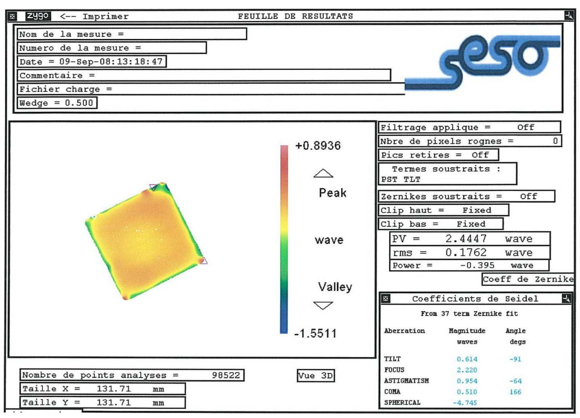

Fig. 10: Interferogram of the polished sample including edge effects

7. OUTLOOKS

The promising results of the performed polishing trials are regarded by both of us, Oerlikon Space and SESO, as an encouraging starting point.

After further improvement of the polishing, the "coatability" of the faces will be investigated, to determine the quality achievable for mirrors.

Due to the excellent weight ratio, such mirrors are interesting for gimbaled applications as in coarse pointing assemblies.

In a next step then mirrors with power shall be investigated, either as single pieced mirrors, for small sized ones, or as element of segmented and deployable mirrors for large telescope for both space and ground based application. The identification of the best approach for the manufacture of the sandwich and the polishing of the curved mirror will have to be identified and validated.

8. ACKNOWLEDGEMENT

The development of this innovative sandwich technology has been performed within an Oerlikon Space Research and Development program. The first flight implementation was under the EADS Astrium contract 60217 for the Aladin experiment of the ESA Aeolus mission.

The polishing process investigations and trials have been carried out by SESO.

Special acknowledgments and thanks go to the development team for the innovative ideas that led to the success of this technology, as well as to the companies' management for their constant support.

We like to thank the ESA and Astrium ALADIN team for supporting the implementation of the Aluminium-Zerodur sandwich base-plate in the spectrometer unit.

9. REFERENCES

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[2] United States Patent 7167631: Highly stable and very light optical bench and extra terrestric use of such an optical bench.

[3] European Patent EP1593951: Very stable and very light optical bench and its use in outer space.