

AN HYBRID PROCESS SOLUTION FOR HETEROGENEOUS SURFACE BONDING

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Abstract

A hybrid assembly process combining molecular bonding and laser welding was developed to assemble optical components of standard quality. The method was tested on four material configurations relevant to space applications: two homogeneous assemblies, UV Fused Silica/UV Fused Silica and Zérodur[®]/Zérodur[®], and two heterogeneous assemblies, a glass/glass-ceramic assembly (UV Fused Silica/Zérodur[®]) and a glass/metal assembly (UV Fused Silica/Invar. The mechanical properties of the assemblies were evaluated at different stages of the assembly process, respectively contact bonding and laser welding. Mechanical characterization has allowed us to demonstrate mechanical strengths of the same order of magnitude as those described in the literature, but for adhesion surfaces larger than those reported therein. Overall, this protocol shows strong potential and warrants further investigation to achieve mechanical strengths comparable to those obtained in conventional bonded assemblies.

Keywords: Direct bonding, Laser welding, Fused silica, Zerodur[®], Invar, surface functionalization

1. INTRODUCTION

In photonics, space applications often utilize optical components assembled via adhesive bonding. However, these bonded components are subjected to temperature and pressure stresses that cause adhesive outgassing and the degradation of the adhesive's properties over time.

The objective of this project is to develop an adhesive-free assembly process combining molecular bonding and ultra-short pulse laser welding. This alternative approach aims to reduce surface-related constraints and enhance the mechanical integrity of the assemblies considering the use of standard polishing optical components. To develop this hybrid process, four assembly configurations were investigated. Two homogeneous assemblies—Fused silica/Fused silica and Zerodur[®]/Zerodur[®]—with a diameter of 50 mm and thickness of 1 mm target a contact area of 80%. Two heterogeneous assemblies—Fused silica/Zerodur[®] and Fused silica/Invar—with a diameter of 25 mm and thickness of 1 mm aim for a contact area of 50%. The materials used in the space sector each exhibit a low coefficient of thermal expansion (CTE). Respectively, CTE for fused silica, Zerodur[®] and Invar are $0.55 \cdot 10^{-6} \text{ }^{\circ}\text{C}^{-1}$, $0.2 \cdot 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ and $1.3 \cdot 10^{-6} \text{ }^{\circ}\text{C}^{-1}$. Their CTEs are also mutually compatible, helping to limit thermal stresses at the weld.

2. MOLECULAR ADHESIVE

Molecular adhesion is initiated via plasma surface activation, promoting the formation of hydrogen bonds and van der Waals bonds when the two surfaces come into contact. To enhance interface contact, the process is carried out in a controlled humid atmosphere to increase surface moisture levels. The plasma treatments may utilize argon (Ar) or oxygen

(O₂) plasma. Molecular adhesion is enhanced by a high-quality surface finish, characterized by an Sq roughness of less than 1 nm and a surface flatness of better than $\lambda/10$.

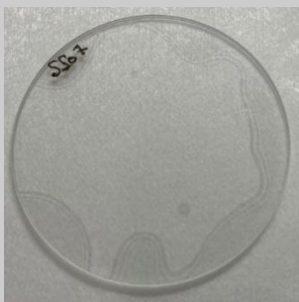
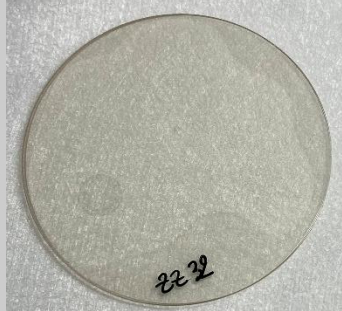
Two keys' parameters influence the adhesion process: surface hydrophilicity and roughness. Hydrophily is characterized using a goniometer by measuring the contact angle between a water droplet and the surface. Roughness is measured using an atomic force microscope (AFM). By studying how the contact angle and roughness change in relation to the type and duration of the plasma treatment, it is possible to determine the most suitable plasma treatment for each material. Table 1 shows the treatment selected for the three materials used in this study.

Table 1 : Selection of treatments based on the material, considering changes in roughness (Sq) and hydrophilicity (via contact angle) as a function of plasma type and duration

	Fused silica	Zerodur®	Invar
Plasma treatment	Ar – 2 min	Ar – 2 min	O ₂ – 15 min
Reference Sq (nm)	0,76	1,86	12,74
Sq after plasma treatment (nm)	0,66	0,59	4
Reference contact angle (°)	46,5 ±0,05	46,7 ±0,05	68,1 ±0,05
Contact angle after plasma treatment (°)	3 ±0,05	6,8 ±0,05	16,3 ±0,05

Once the treatments have been selected, the optical plates are bonded together. Table 2 details the surface characteristics—both initially and after plasma treatment—along with the molecular bonding results for homogeneous 50 mm diameter assemblies. The humidity level during bonding is also indicated. The images show the assemblies after molecular bonding; darker areas correspond to non-bonded zones containing air.

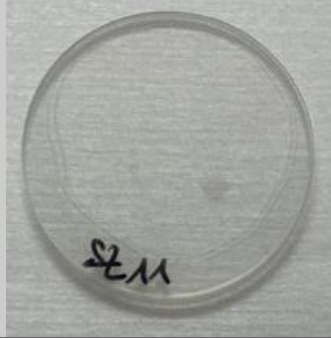
Table 2 : Result of molecular adhesion for homogeneous assemblies.

	Fused Silica/ Fused Silica	Zerodur®/Zerodur®
Initial Sq (nm)	1	2
Flatness	$\lambda/4$	$>\lambda/20$
Diameter (mm)	50	50
Humidity rate	86 %	86 %
Image result		
Contact bonding surface rate	85 %	77 %

The bonded surface percentages align with the project objectives. However, certain constraints arose during the process. The first relates to the presence of dust in the working environment; the cleanroom is rated ISO 5. The presence of dust is indicated by interference fringe patterns. The second constraint is specific to the Zerodur® discs. Indeed, the flatness of the

discs exceeds $\lambda/20$, with a concave curvature of 100 m. Pressure application methods were implemented to counteract this curvature.

Table 3 : Result of molecular adhesion for heterogeneous assemblies.

	Fused Silica/ Zerodur [®]	Fused Silica/ Invar
Initial Sq (nm)	1 / 2	1 / 12
Flatness	$\lambda/4 / >\lambda/20$	$\lambda/4 / >\lambda/20$
Diameter (mm)	25	25
Humidity rate	86 %	86 %
Image result		
Contact bonding surface rate	70 %	0 % - optical contact

The results for the 25 mm diameter heterogeneous assemblies are detailed in Table 3. For the Fused silica/Zerodur[®] assembly, the bonded surface area is 70%, which is 20% above the project target of 50%. For the Silica/Invar assembly, molecular bonding did not occur; however, the presence of interference fringes indicates optical contact, which can facilitate laser welding. This result is attributed to the Invar, which—following internal polishing—exhibits a high initial roughness of 12 nm and flatness exceeding $\lambda/20$, with a convex curvature of -20 m.

A preliminary bonding protocol prior to the laser welding stage was established for each assembly. Encouraging optical contact results were demonstrated, despite various constraints; indeed, standard surface polishing quality and sample thickness do not facilitate molecular bonding. However, the overall project aims to develop a hybrid process combining molecular bonding and laser welding. A key limitation of laser welding, identified early on, is the lack of optical contact between the two surfaces. In this instance, however, each assembly exhibits optical contact, which appears promising for successful welding.

3. FEMTOSECOND PULSE LASER WELDING

Following the molecular bonding stage, the assembly was reinforced via ultrashort-pulse laser welding. A femtosecond-pulse laser beam was focused on the assembly interface, as illustrated in *Figure 2*. At the operating wavelength of 1030 nm, the laser pulse energy underwent non-linear absorption, triggering a permanent state change—in this instance, fusion at the interface of the two materials. To perform the weld, the beam followed a spiral path, representing in *Figure 2*. Four process parameters were varied according to the material combination: translation speed, repetition rate, spiral pitch, and pulse energy. Parameters and results for homogeneous assemblies following welding are listed in Table 4, while those for heterogeneous assemblies appear in Table 6.

All four assemblies yielded successful welds, despite the beam passing through zones characterized by interference fringes—indicative of optical contact rather than bonding. The pulse energy was adjusted to suit the specific material combinations under study.

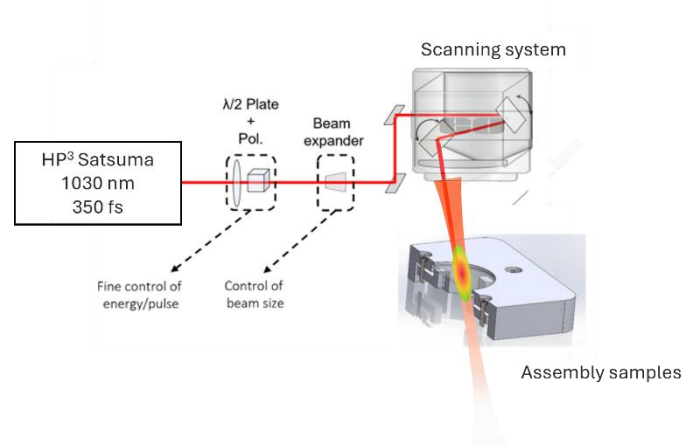


Figure 1: Scheme of setup for laser welding at the interface of assemblies.

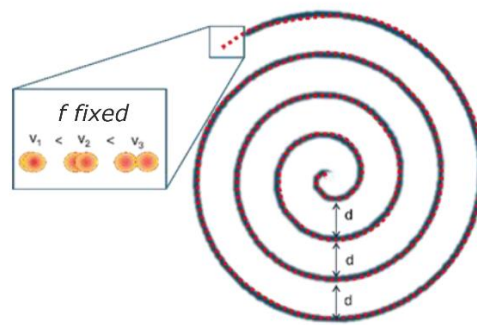


Figure 2: Scheme of the spiral path used during laser welding at the interface of each assembly.

Table 4 : Welding parameters and weld results for homogeneous assemblies

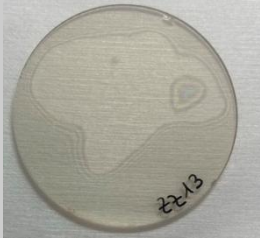
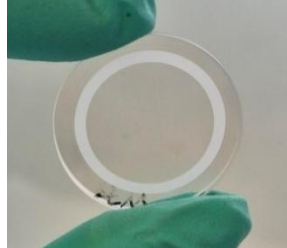
	Fused Silica/ Fused Silica	Zerodur®/Zerodur®
Speed (mm.s ⁻¹)	5	5
Pulse Frequency (MHz)	1	1
Spiral step (μm)	2	2
Pulse energy (nJ)	1 000	300
Before weld		
After weld		

Table 5 : Welding parameters and weld results for heterogeneous assemblies.

	Fused Silica/ Zerodur®	Fused Silica/Invar
Speed (mm.s ⁻¹)	5	5
Pulse Frequency (MHz)	1	2
Spiral step (µm)	2	2
Pulse energy (nJ)	700	400
Before weld		
After weld		

4. MECHANICAL CHARACTERIZATIONS

Two mechanical test setups were used to measure adhesion energy via the "crack method" and shear strength using a shear test rig.

Regarding adhesion energy, the Fused silica/Fused silica, Zerodur®/Zerodur®, and Fused silica/Zerodur® assemblies yielded state-of-the-art results, as shown in Table 6.

Several measurement campaigns were conducted using the shear test rig. Shear strength was measured and compared for Fused silica/Fused silica, Zerodur®/Zerodur®, and Fused silica/Zerodur® assemblies—specifically those that were bonded-only, welded-only, and bonded-then-welded—with the results presented in Table 7. The shear strength of the bonded-then-welded assemblies is significantly higher than that of the bonded-only or welded-only assemblies. This comparison highlights the merits of the hybrid process.

Table 6 : Adhesive energy of Fused silica/Fused silica, Zerodur®/Zerodur®, and Fused silica/Zerodur® assemblies.

	Fused silica/ Fused silica	Zerodur®/Zerodur®	Fused silica/ Zerodur®
Adhesive energy (mJ.m ⁻²)	1 823	6 303	2 945
Adhesive energy in literature (mJ.m ⁻²)	2 000 ^[1]	2 500 ^[2]	2 500 ^[2]

Table 7 : Comparison of shear strength according to the joining process: bonding, welding, and bonding followed by welding.

	Shear strength (MPa) Adhesion	Shear strength (MPa) Welding	Shear strength (MPa) Adhesion + welding
Fused silica/ Fused silica	0,12	0,4	6,77
Zerodur[®]/Zerodur[®]	0,29	1,3	6,6
Fused silica/ Zerodur[®]	No measure	0,7	3

The second measurement campaign was conducted using a sample-holding tool better suited to the shear test rig. Consequently, the shear strengths of the various assemblies were higher than those recorded in the initial measurements. In Table 8, these results are compared with the state of the art and existing literature on bonded assemblies. The shear strength of samples prepared using the hybrid protocol aligns with literature findings for surfaces joined via molecular bonding or welding. However, the contact areas cited in the literature are smaller—on the order of hundreds of micrometers—compared to the contact areas studied in this project, which are on the order of tens of millimeters. The larger the bonding surface, the greater the risk of imperfections.

Finally, while the shear strength of bonded assemblies exceeds our results, potential process improvements are being considered to enhance mechanical performance. The molecular bonding step could be improved by working in an ISO 3 cleanroom to reduce dust levels. Although laser welding is currently performed in the MHz regime, a future project could explore welding in the GHz regime.

Table 8 : Shear strength measured for our four assemblies and then compared with results from the literature.

	Shear strength (MPa) Adhesion + Welding	Shear strength (MPa) Literature: adhesion/welding	Shear strength (MPa) Literature: glue
Fused silica/ Fused silica	23,7 ± 7,5	73 ^[3] 57,15 ^[4]	51 ^[9]
Zerodur[®]/Zerodur[®]	19 ± 12	20 ^[5]	33 ^[10]
Fused silica/ Zerodur[®]	9,3	6,9 ^[6] – ULE/Zerodur [®]	35 ^[11]
Fused silica/Invar	12,8	10 ^[7] – Fused silica/Copper 16,39 ^[8] – Fused silica/stainless steel	30 ^[12]

5. CONCLUSION

In conclusion, a hybrid process combining molecular bonding and ultrashort-pulse laser welding was successfully developed. This process is suitable for the studied materials and can be applied to standard-quality surfaces. Mechanical characterization revealed bond strengths comparable to those reported in the literature, but over larger bonding surface areas than previously reported. Finally, while this protocol shows promise, further development is required to bring the bond strengths closer to those achieved with adhesive bonding.

Acknowledgements

J. CARCREFF and ALPhANOV acknowledged funding from R&T CNES (contract number 5700009488).

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