VALIO

Executive Summary Report

Authors: Florian Müller, M.Eng.

Dr. Erik Beckert

Fraunhofer IOF (Prime)

Albert-Einstein-Straße 7

07745 Jena, Germany

Phone: +49 (0)3641 807 -306/- 338

Fax: +49 (0)3641 807- 604

florian.mueller@iof.fraunhofer.de

erik.beckert@iof.fraunhofer.de

Because of the short wavelength for X-ray and UV-optics narrow alignment tolerances are requested. Therefore, to ensure their optimum performance space optical instruments need to be assembled in close-to-work conditions. In some cases, this can include vacuum conditions.

Within the project "Novel In-Vacuum Alignment and Assembly Technologies for Optical Assemblies – VALIO" initiated by ESA, new technologies for alignment and bonding under vacuum conditions were developed.

With solderjet bumping and adhesive bonding two different joining technologies have been investigated. Solderjet bumping is a flux-less and thus clean laser based soldering process which needed to be adapted to vacuum conditions and tested under vacuum conditions. For the adhesive bonding 2k-epoxy with low outgassing were chosen and investigated. Furthermore, a suitable dosing technique for in-vacuum dosing was developed.

The following summary gives some details about the state-of-the-art of the chosen technologies, their adaptations, the test conditions, and the test results.

Solderjet bumping is a contact free Laser-based soldering technique. It was developed by Fraunhofer IZM. It has been transferred to industrial use and commercial setups are provided by PacTech Packaging Technologies. It is mainly used for electronical applications.

For solderjet bumping the solder comes as spherical preforms (balls) stored in a reservoir at the bond head. By a rotating device and gravitational force the solder balls can be separated and loaded in a capillarity. The solder ball is a few microns larger than the capillary, so the capillary is blocked. Nitrogen overpressure can be created in the capillarity. Now a laser puls with a duration of 10-25 ms is applied. The laser energy is absorbed by the solder ball closing the capillarity. The solder melts and is pushed out by the nitrogen. The melted solder is travelling under nitrogen flux to the target surface. At the target surface it spreads, solidifies instantly, and therefore creates a joint. This very localized bond has a very localized thermal effect to the joint partners and the bond surfaces. To improve the performance of the joint, a wettable surface on the target is required. A layer of noble metal, e.g. Au is preferable. Figure 1 shows a sectional view of the solderjet machine used at Fraunhofer IOF.

Fraunhofer IOF established this technology as a bonding technology also for nonelectrical components as shown in Figure 1. Therefore, also mechanical joints are created by solderjet bumping. It can be used to assemble different types of optics to metallic mounts. The technology has been used by ESA under Contract No. AO/1-5930/08/NL/NA for the mounting of laser mirrors on INVAR breadboards. It is the selected technology to assemble the green laser for the EXOMARS Raman-experiment.

The big advantages of the technology are the broad variety of solder which can be used allowing to adjust different properties of the bond. The contact free process allows to apply multiple solder bumps depending on the requested bond properties. To gain more degree of freedom in the positioning of the solder the solderjet bond head can be mounted onto a robot arm.

Nevertheless, to create a flux-less joint the targeted surface requests a metallisation layer. Especially for optical elements this can be a critical process. The flexibility of the device is limited in case of the location in space since the loading of solder requires gravitational force. A maximum tilt of 45° is recommended to assure a reliable loading.

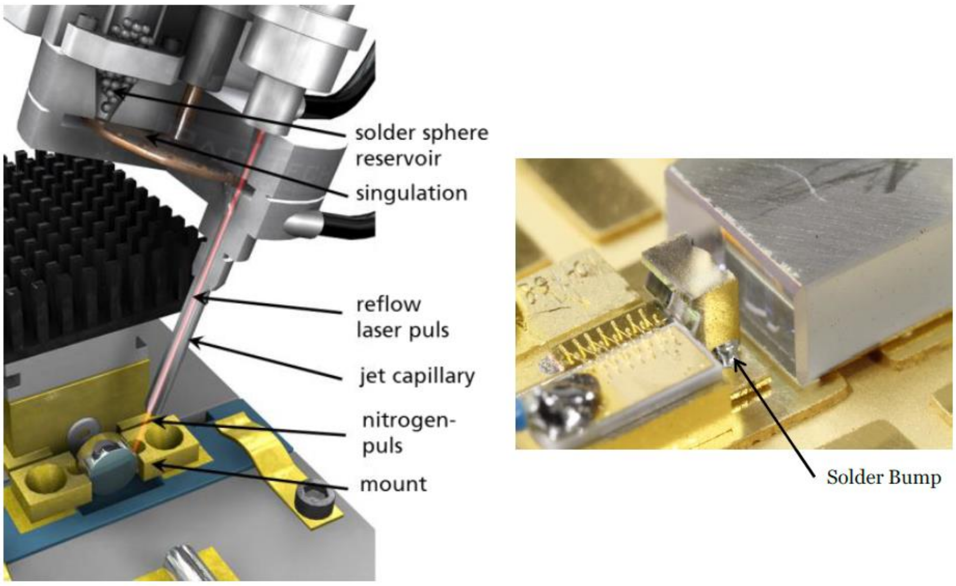

Figure 1 left: Schematic view of solderjet; right: optical component joint by solderjet bumping

Adhesive bonding based on polymer adhesives is one of the most common technologies for the fixation of optics. Depending on the adhesive used, different bonding properties can be achieved. It is possible to create flexible joints with damping abilities as well as stiff constructive joints. High thermal and electrical conductivity can be realized depending on the used adhesive.

Because of their viscosity adhesives can adapt to nearly any 3D volume. By sample design a very precise bonding area and volume can be determined allowing specific bond properties and strength.

The disadvantage of adhesive bonding is often the limitation concerning work temperature. Especially the often-used UV-curing adhesives are not stable at temperatures of more than 120 °C. For a bonding process performed in vacuum most of the adhesives are not suitable since they contain volatile components that create voids inside the adhesive volume. Only a very limited number of adhesives shows an acceptable stability in their uncured state under vacuum conditions.

To apply adhesives different technologies are used. For a precise dosing often a time-pressure dosing system is used. Therefore, the adhesive is filled to special cartridges which can be connected to the dosing device. To apply adhesive the volume is applied with pressurized air (0-7 bar depending on adhesive) for a defined time. By varying time and/ or pressure the dosed adhesive volume is regulated.

Pretesting of adhesives was done to select adhesives with a sufficient vacuum stability in their un-cured state. Most of the common adhesives contain volatile components and are not suitable for the targeted dosing environment. In addition, the number of space graded adhesives is limited. To select two suitable adhesives for the bonding campaign several tests were carried out. Possible adhesives for the VALIO- test campaign were Loctite Ablestik 285 (Catalyst 9), Loctite Ablestik 55 (Catalyst 9), Epotek 301-2 FL, Epotek 302-3 Black and Scotchweld EC2216 B/A. To qualify their bonding ability small volumes of the adhesives were dosed onto soda-lime-glass. An additional sample set was manufactured by bonding silicon-chips to soda-lime-glass using the same adhesives. All samples were shear tested after curing of the adhesives. Figure 2 shows a photograph of the samples. Both types of samples were cured equally in atmosphere- and vacuum-condition.

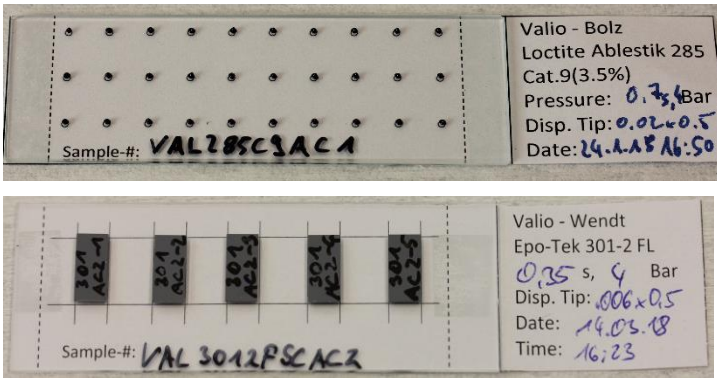

Figure 2 Samples for adhesive selection; top: single droplets on soda lime glass; bottom: silicon chips bonded to soda lime glass

The tests show significant differences concerning the in-vacuum use of the adhesive. Epo-Tek-301-2-FL is not curing under vacuum. Also, Scotchweld 2216 B/A grey and Ablestik 55 cat.9 show significant outgassing effects of their volatile components when bonding the silicon chips to the glass. For the fully vented droplets these effects do not occur. However, since the later bonded geometry cannot be vented these adhesives were considered not suitable for in-vacuum processing. Because of their high stability Ablestik 285 cat.9 and EpoTek 302-3m black were the preferred adhesives for the following test campaign. Figure 3 shows the measured shear resistances for both adhesives.

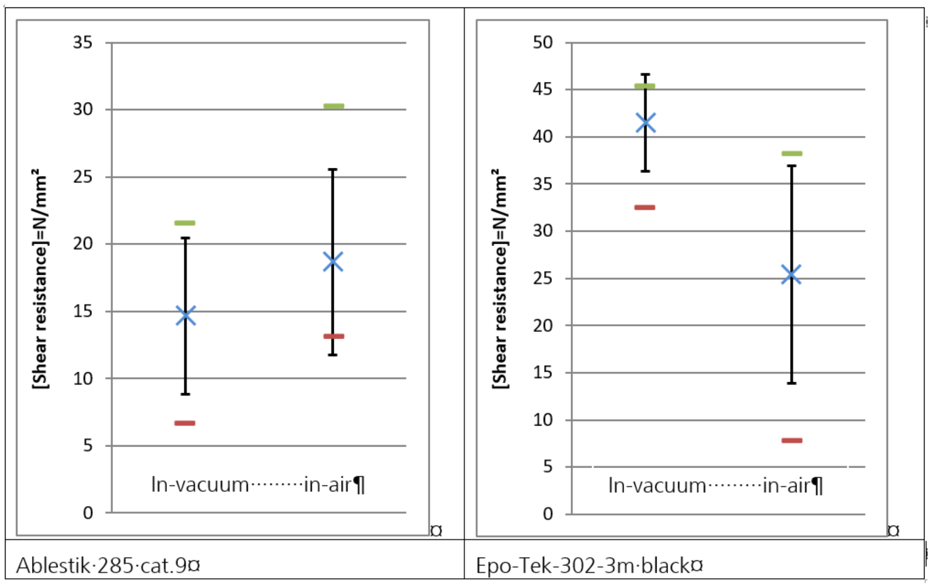

Figure 3 Shear resistances of preferred adhesives

To perform the in-vacuum bonding tests, specialized samples have been design. The designed samples had similar mechanical properties (DOF, material) like the pins used for the Athena mounting. In addition, the bond strength had to be similar. The original mounting is bonded by EC2216 B/A grey reaching 1248 N bond strength.

Each sample has been divided into two separate parts: a pin and a mounting plate. The material of both parts is Invar. The design is shown in Figure 4.

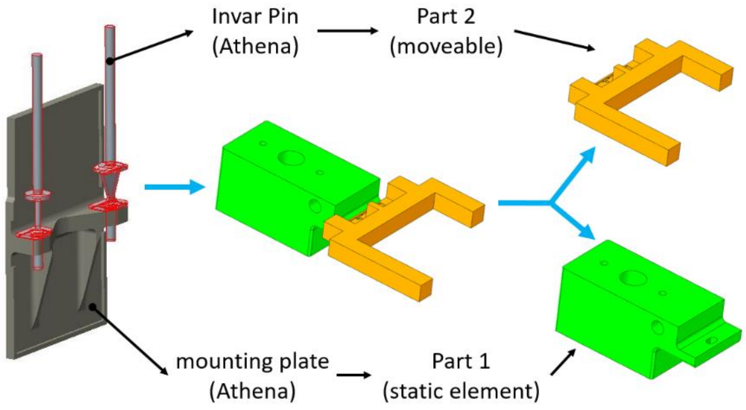

Figure 4 Sample design of the used test samples

Depending on the kind of bonding two different sample's part 2 have been designed. Each design has been approved by FEM simulation.

For adhesive bonding a bonding area of 136,2 mm^2 has been chosen to guarantee at least 1245 N of maximum force to be applied on the sample. This bond area between sample part 1 and part 2 was filled through 3 separate holes.

For the soldering a necessary bonding area of 31 mm^2 has been calculated. This area was splitted into 8 slotted holes. However, with this design the target maximum force is 815N. The solder used for the campaign was SAC 305.

Regardless of the bonding technology the samples were mounted in a sample holder allowing a precise alignment of both sample parts. In addition, capacitive sensors were used to monitor the alignment of both parts during the bonding process.

To align the bonding devices (solderjet/ adhesive cartridge) a vacuum compatible hexapod was used. It allowed an alignment of the bonding system in 6 DOF which was important for a precise alignment and bonding. The hexapod as well as the sample holder were placed inside a vacuum chamber.

Adhesive tests have been done at normal atmosphere and under vacuum conditions. For both test campaigns the similar setup inside the vacuum chamber has been used. For the in-air tests, the time pressure dosing system is directly connected to the adhesive cartridge mounted on the hexapod platform. In contrast for the in-vacuum tests additional valves have been implemented, allowing to depressurize the pipes of the dosing system inside the chamber. This was important to guarantee a precise stopping of the dosing (pressure in chamber 10^{-4} mbar vs. pipe dosing pressure 4 bar). High efforts were taken to make sure the chamber pressure of $< 10^{-4}$ mbar was not compromised during the venting.

For the test campaigns in air 15 samples per adhesive have been provided (including 3 storing samples). The investigation of all samples showed no visual issues.

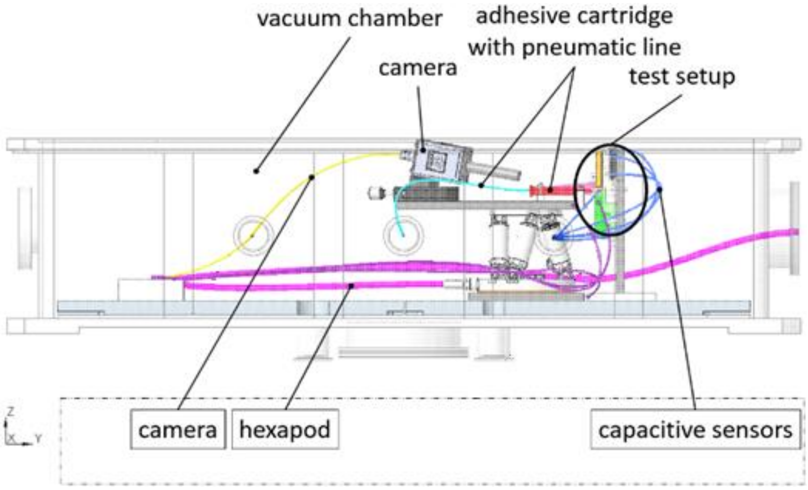

Figure 5 Schematic view of adhesive bonding setup

For the adhesive campaign under vacuum conditions 21 samples should be produced per adhesive (3 to store). For the samples of Ablestik 285 cat. 9 the test plan could be fulfilled. No critical issues occurred during the bonding. The test campaign with EpoTek-302-3m black had to be stopped after a few samples. Regardless of the described pre-tests the adhesive showed a massive outgassing of its volatile components. Neither a precise dosing nor a stable bond could be created. A possible reason to explain such findings during the test campaign and not during the pre-tests is the difference in the handled and applied volume. Furthermore, the adhesive volume in the pre-test was much better vented, so that the outgassing could not be visually detected. Epo-Tek 302-3m black was not suitable to create in-vacuum joints under the observed circumstances.

Figure 6 In-vacuum adhesive bonded sample

Soldering tests in air and in vacuum have been performed on similar setups. The tests in air have been carried out on a state-of-the-art soldering station. In total 15 samples had been soldered. The bond head is angled under 45° to the vertical, to allow a better comparability to the in-vacuum tests where the bond head needed to be angled due to space limitations. Figure 7 shows a soldered sample.

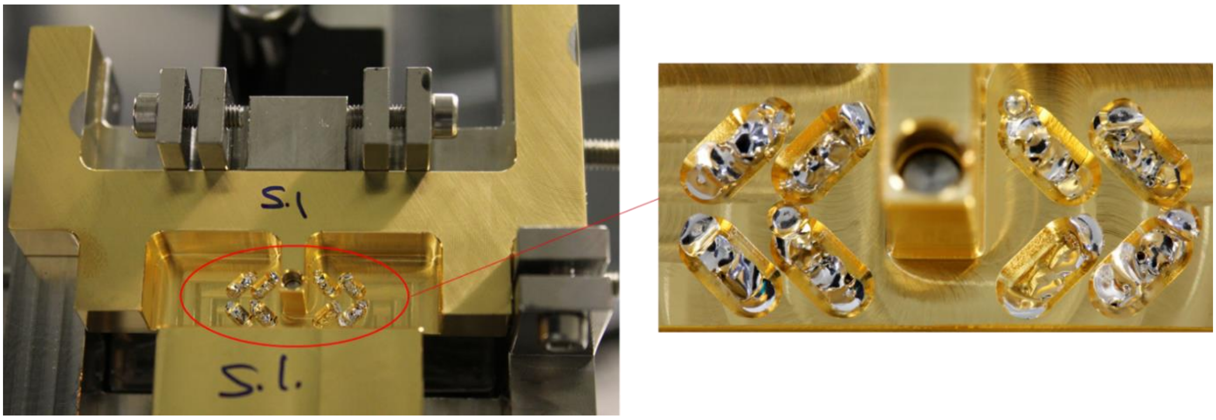

Figure 7 Soldered Sample

For the soldering in vacuum several changes had been done to the bond head to guarantee the vacuum is not compromised by any non-compatible material. The solderjet head was mounted onto the hexapod. Under camera view the capillary could be aligned with reference to the sample. Per slotted hole an average of 9,16 solder balls have been applied to reach a good visually appealing bond.

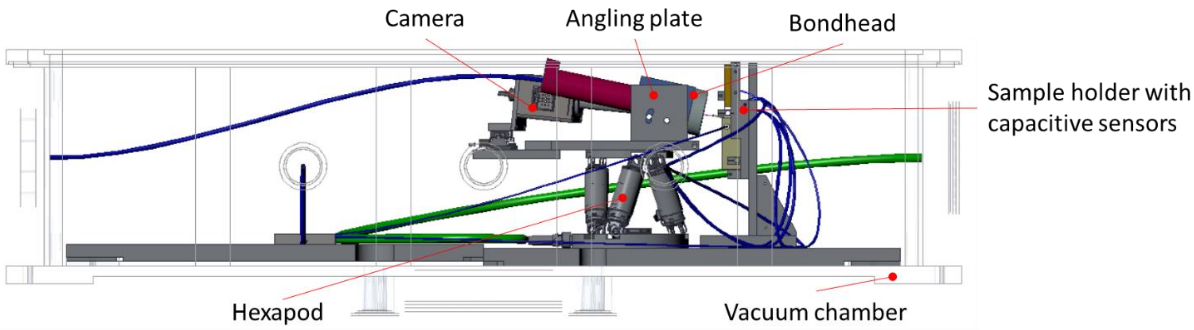

Figure 8 Schematic view of soldering setup

To test the environmental stability of the bonds half of the samples underwent an additional thermal cycling in vacuum. The temperature was ranged from -40°C up to +65°C. In total 8 cycles with a ramping of 1°C/min have been performed. The pressure was reduced to 10 mbar during all cycles. Afterwards, no visual effects could be detected on the samples.

To measure their bond strength all samples underwent a destructive push test. The samples were pushed apart in 3 different axis (X, Y & Z). The setup is displayed in Figure 9.

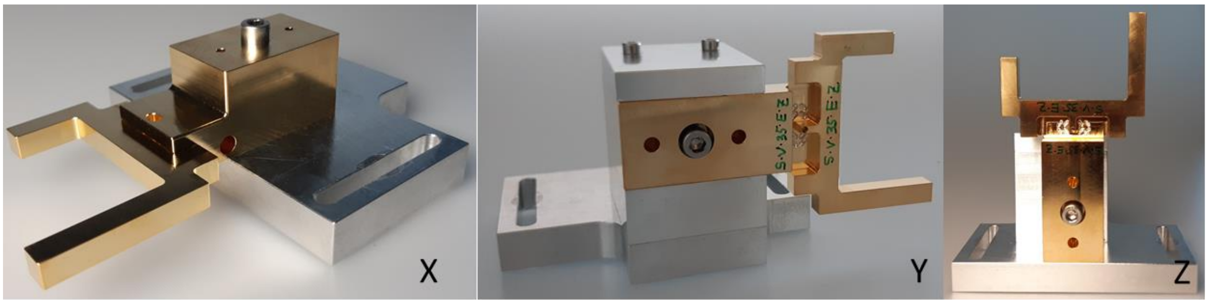

Figure 9 Push test tools for different axis

For the X-direction the load is mainly tensile. In Y- and Z-direction it is shear load. In Figure 10 sheared samples for every bonding technology are displayed.

		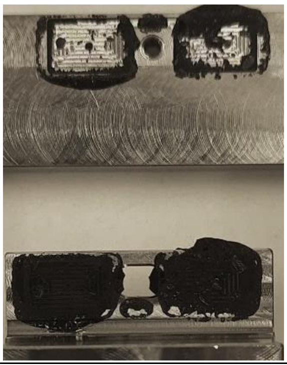	
Soldered Sample sheared in X	Soldered sample shered in Y	Ablestik 285 cat9 shered in X vacuum bond	Ablestik 285 cat 9 sheared in X in-air bond

Figure 10 Visualisation of sheared samples

The soldered samples show a difference in the push direction. For the tensile load in x-direction the solder is pulled threw the slotted holes and stays at the static part. For the y- and z-direction the solder is sheared inside the bond. Solder appears on both parts of the sample.

For the adhesive samples bonded under vacuum conditions a mixed bond failure occurred. Most parts of the adhesive delaminated at the sample surface. However, in some areas a breakage inside the adhesive volume was detected. At these areas the adhesion force between metal and adhesive is very high and the bond can be considered sufficient. The delamination and therefore the weak adhesion on the other areas might be caused by the compatibility of the used adhesive and the substrate material. To improve the adhesion a primer could be applied to the bond surfaces prior to the adhesive application. Also roughening of the metal parts would increase the bond surface area and can increase performance of the adhesion on the substrates.

The measured shear forces are shown in Table 1.

The adhesive bonding campaign in air lead to a high variation of the measured shear forces. Therefore, the process was considered instable. We estimate that contamination issues are the main reason for the high scattering of the values. The material combination (adhesive to plain invar) might not be ideal as well. An additional cleaning right before bonding as well as the application of a primer prior to the adhesive application could improve the adhesion and stabilize the bonding process.

Therefore, for the adhesive bonding campaign in vacuum, the samples underwent a separate cleaning procedure. Therefore, the resulting shear force values are more reliable and even higher (see Table 1). Nevertheless, the values do not reach the target. These deviations can be explained by the formation of bubbles inside the cartridge as well as in the applied adhesive volume. The bubbles form because of outgassing of volatile components of the adhesive in the vacuum environment.

Table 1 Mean shear values for bonded samples

Probe set	Axis	Environmental tested		non-environmental tested	
		mean shear force in N	σ in N	mean shear force in N	σ in N
Soldering in air	X	853	38	467,7	257,9
	Y	945	51	888	32
	Z	878	19	1025	5
Soldering in vacuum	X	899,71	84,66	902,67	199,77
	Y	809,9	74,22	835,8	34,94
	Z	792,48	44,04	801,44	71,89
Ablestik 285 in air	X	620	0	126	15
	Y	n/a	n/a	958	23
	Z	727	139	604,5	244,5
Ablestik 285 in vacuum	X	518,8	12,21	349,9	50,8
	Y	808,43	42,81	878,13	30,82
	Z	434,35	94,25	555,4	44,6
EpoTek 302-3m black in air	X	1540	0	275	55
	Y	168,9	168,9	1460	60
	Z	1735	65	1042,5	407,5

An investigation via microscope (see Figure 11) showed several of the mentioned small bubbles inside the adhesive volume. Because of such bubbles the effective bond area is reduced. This affects the shear strength of the bond so it will break earlier than expected.

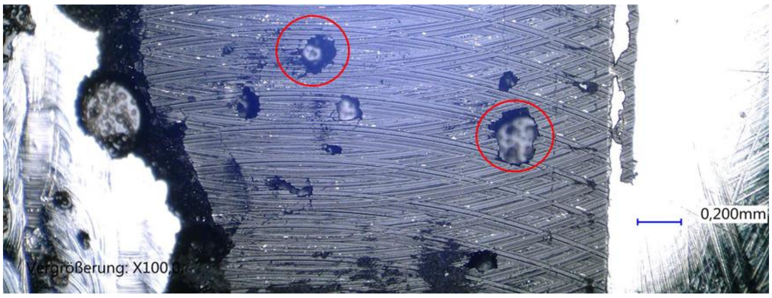

Figure 11 Microscope view of Ablestik 285 cat. 9 bond created in vacuum

The bond strength of the soldering is not affected by the environment the joint has been created in (air or vacuum). The values are very similar and within the standard deviation of the other sample set. This proofs the high stability of the soldering process. In addition, no negative influences by environmental testing could be detected.

The high reliability and process stability of the soldering technique is shown in the diagram in Figure 12. The maximum force needed to break the solder bond is applied over the average of applied solder bumps per slotted hole in one sample. The diagram shows all soldered samples independent from the bonding environment. On average 9,16 solder balls per hole have been applied leading to a mean shear force of 839 N. The scattering around this average is very small.

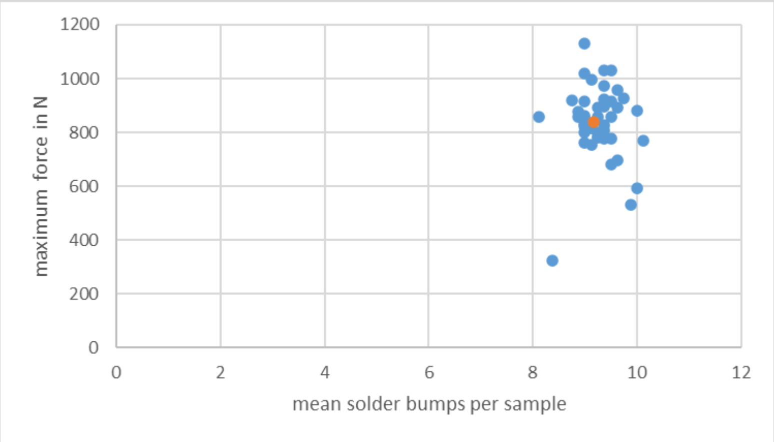

Figure 12 maximum shear force over amount of solder bumps (average marked orange)

Displacement To monitor the position of the samples during any version of the bonding, capacitive sensors are used. During the whole process of bonding the relative positions of both sample parts are monitored. The following Table 2 shows the maximum and minimum rotational displacement during soldering and adhesive bonding under vacuum environment.

Table 2 rotational displacement during bonding

Bonding condition	Rotation Axis	Max. rotation in mrad	Min. rotation in mrad	Span in mrad
Soldering vacuum	Rx	0,8000	-1,2536	2,0536
	Ry	0,7967	0,0169	0,7798
	Rz	0,4912	0,0297	0,4615
Ablestik 285 vacuum	Rx	1,4887	-0,7321	2,2208
	Ry	1,4083	0,0000	1,4083
	Rz	3,7608	0,0002	3,7606
Soldering air	Rx	0,4917	-1,3229	1,8146
	Ry	0,2174	0,0174	0,2000
	Rz	1,8229	0,0042	1,8187
Epotek air	Rx	0,3958	-0,0312	0,4271
	Ry	0,7217	0,0000	0,7217
	Rz	0,2771	0,0000	0,2771
Ablestik 285 air	Rx	0,8000	-1,2536	2,0536
	Ry	0,7967	0,0169	0,7798
	Rz	0,4912	0,0297	0,4615

The rotational displacement for soldering and adhesive bonding show significant differences. Especially the displacement (span value) in Ry and Rz are within the factor ~3.5 bigger for adhesive bonding then for the soldering. For rotational displacement in Rx the values just slightly divergent.

Since the soldering process is an contactless process creating an instant bond, the relative position of sample part 1 and sample part 2 are fixed immediately with the solder. Rotational displacement cannot fully excluded by the setup and the design of the samples. Both samples are aligned in that way, that both surfaces are planar and in contact. When applying the solder on the first hole, the position of both sample parts will be fixed. Due to thermal induced stress within the bond, small dislocations of both samples occur.

By applying the adhesive, higher forces can be estimated on the samples during the process. The dosed amount of adhesive is pushed into the gap between the two sample parts applying force to both parts of the sample. This can create a dislocation of both sample parts. The outgassing issues of the adhesive increase the negative effect on the sample.

In summary two bonding techniques were tested regarding their feasibility and process stability when performed in vacuum. Both, solderjet bumping as well as adhesive bonding are operational in vacuum environment. However, in this environment solderjet bumping has several advantages over adhesive bonding. The bond created by solderjet bumping is neither influenced by the pressure condition (vacuum vs. air) nor by the environmental test on the sample. The soldering process is faster than adhesive bonding and guarantees a stable bonding strength. The targeted maximum shear force of 815 N could be reached for all bonded samples. Adhesive bonding on the other hand requires long curing times of up to 24 h. In addition, in vacuum all investigated adhesives tended to build bubbles in the adhesive volume during curing. This reduced their bond strength and the reliability of the whole bonding process.

With Ablestik 285 cat.9 bond strengths in the range of 2,57 N/mm² up to 6,45 N/mm² could be achieved when the bonding was performed in vacuum. In contrast for soldering the values are in the range of 25,56 N/mm² up to 29,12 N/mm². Therefore, for a certain bond strength the necessary bonding area is much smaller for soldering than for adhesive bonding.

Soldering is a very precise and reliable technique for high performance bonding. Nevertheless, also adhesive bonding should be considered as an option. Especially if the samples cannot be metallized or are very temperature sensitive adhesive bonding can be an alternative to soldering.

End of Document