ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

Edited by Bruno Cugny, Nikos Karafolas and Zoran Sodnik

Mechanisation of precision placement and catalysis bonding of optical components

Christian J. Killow

Ewan D. Fitzsimons

Michael Perreur-Lloyd

David I. Roberston

et al.

International Conference on Space Optics — ICSO 2016, edited by Bruno Cugny, Nikos Karafolas,
Zoran Sodnik, Proc. of SPIE Vol. 10562, 105623W · © 2016 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2296078

MECHANISATION OF PRECISION PLACEMENT AND CATALYSIS BONDING OF OPTICAL COMPONENTS

Christian J Killow[1], Ewan D Fitzsimons[2], Michael Perreur-Lloyd[1], David I Robertson[1] and Henry Ward[1]
[1]*Scottish Universities Physics Alliance (SUPA), School of Physics and Astronomy, Institute for Gravitational Research, University of Glasgow, Glasgow G12 8QQ, UK. Christian.Killow@glasgow.ac.uk.*
[2]*UK Astronomy Technology Centre, Royal Observatory Edinburgh, Edinburgh EH9 3HJ, UK.)*

I. INTRODUCTION

Precision-aligned, ultra-stable optical assemblies are needed for an increasing number of space applications, in areas such as science, metrology and geodesy. A recent example has been the Optical Bench Interferometer for the European Space Agency LISA Pathfinder mission [1,2] for which novel alignment and bonding techniques were developed and used to construct the flight hardware.

LISA Pathfinder is currently in operation at the Lagrange point, L1. This mission is a technology demonstrator for a spaceborne gravitational observatory which is planned to address the ESA L3 science theme "The Gravitational Universe" [3]. LISA Pathfinder has two free-floating test masses shielded by a single spacecraft. The mission goal is to minimise residual forces on the test masses such that the variation in their separation is of order picometres over 1000s of seconds, and to characterise any remaining noise sources. A crucial subsystem for achieving this is the interferometric readout provided by the Optical Bench Interferometer [4]. This consists of a Zerodur baseplate of ~20 x 20.5 cm with 22 beam steering optics hydroxide catalysis bonded [5,6] to it, forming four Mach-Zehnder interferometers. The mission goals were extremely demanding, and necessitated control of the bonded optic position and alignment at the submicron and or order 10 microradian level. To achieve these accuracies a range of enabling techniques were developed in Glasgow [7,8]. The resulting optical assembly is ultra-stable at the picometre level and also UHV compatible by virtue of using a 'glue-less' chemical joining process.

The alignment process controls the out-of-plane optical alignment by: having ultra-stable input laser beams that are introduced to the system parallel to the baseplate; highly perpendicular reflecting-bonding surfaces; globally flat baseplates; and a very thin bond layer. The in-plane alignment is controlled by actively monitoring beam pointing whilst adjusting a component, as depicted in Fig. 1.

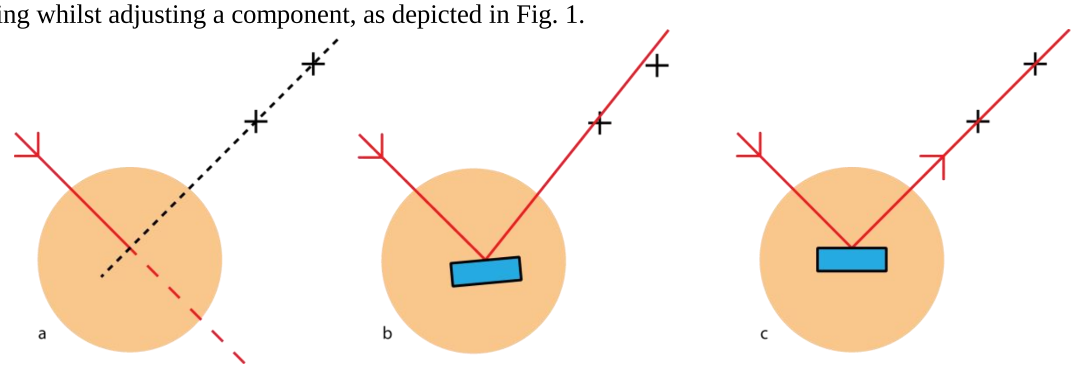


Fig.1 Schematic of component in-plane alignment, looking down through the bonding surface. The circles represent a baseplate to which the blue rectangle – the reflective component – is bonded. The red input beam, black dashed nominal reflected beam vector and target points (black crosses) are shown in 'a', a component during alignment in 'b', and a perfectly aligned component in 'c'.

The alignment and bonding techniques developed for LISA Pathfinder, which are now at TRL9, are considered state-of-the-art. Control of component alignment here was by using physical stops to define the position in which a component would come to rest when floated on a fluid, as described in [7] and shown in Fig. 2. Using this technique, component alignments at the submicron and 30 μrad level were achieved. However the processes involved painstaking effort by multiple skilled operators. Looking forwards to the assembly of more complex optical systems it is clear that reduced reliance on such skilled manual effort is mandatory. To address this work is now underway to "industrialise" the process, with the goals of increasing the rate and precision of component placement and bonding, and simultaneously reducing the risk in the overall assembly technique. The first step in this evolution has involved developing a component placement system that automatically brings an optic into contact with a substrate for bonding, whilst maintaining microradian-level alignment of the surfaces. In this article we report on this work that has already replicated the accuracies achieved during the LISA Pathfinder optical bench construction.

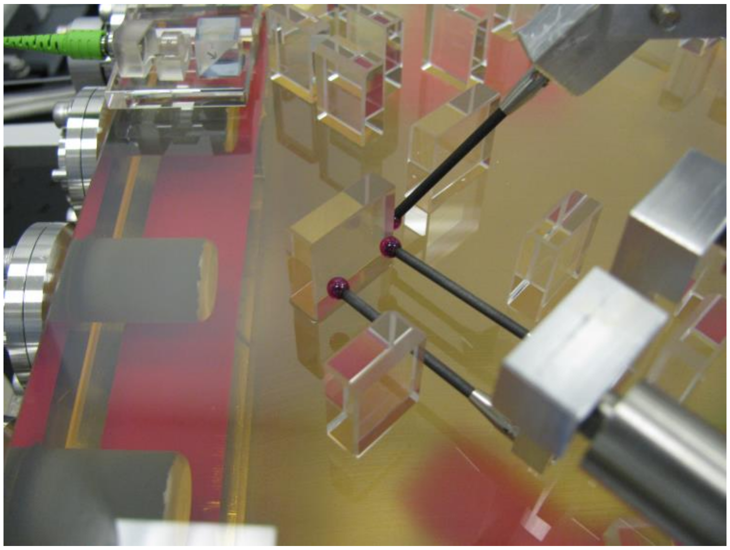


Fig. 2. Photograph of an alignment step for the LISA Pathfinder optical bench. The ruby balls (4 mm diameter) constrain the position of the optic being aligned. The Zerodur substrate is inclined at a small angle to provide a component of gravity to encourage the optic to rest against the stops. The ruby balls are mounted on styli that are in turn mounted on linear piezo actuators.

II. EXPERIMENT DESCRIPTION

A major consideration for mechanised hydroxide catalysis bonding of components is the ability to align the surfaces to be bonded with a very high level of parallelism, maintain this alignment whilst the reflective surface is aligned to a desired orientation, and continue to maintain both of these alignments while the bonding surfaces are brought into contact to start the bonding process. To this end a component holder was designed specifically to allow holding of a component with access to a probe beam which was used to provide an interferometric readout of the alignment of the two bonding surfaces using reflections from them. This holder was attached to a hexapod, allowing six degree-of-freedom alignment of the component with respect to the baseplate, and allowed for low-force unclamping to release the component. A photograph of the holder is shown in Fig. 3.

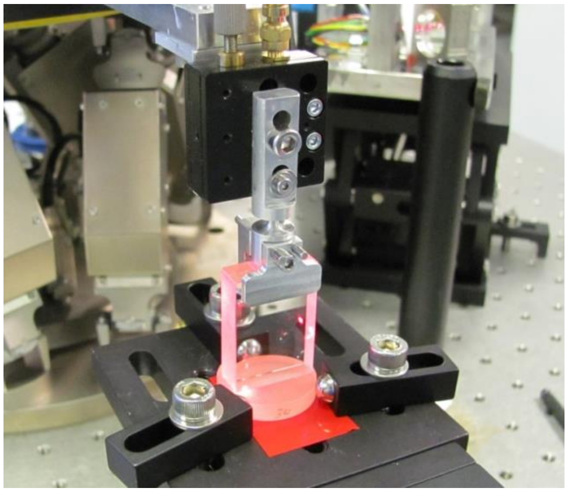
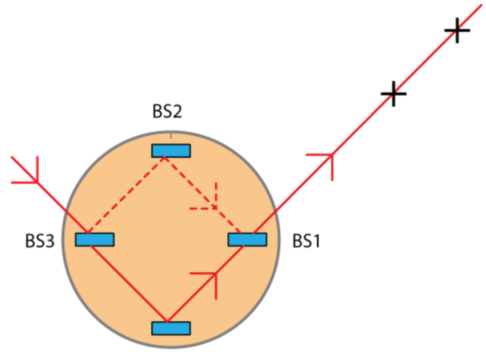


Fig. 3. Photograph of the component holder which is attached to a hexapod. Here, the rectangular beamsplitter has been bonded to the 1” diameter Zerodur disk below.

In order to arrive at a measure of how well a reflected beam can be aligned, in-plane, whilst mechanically bringing a component into contact with a baseplate and bonding it in place, a Mach-Zehnder type optical arrangement was constructed. A sketch of this and a photograph of the completed assembly are shown in Fig. 4.



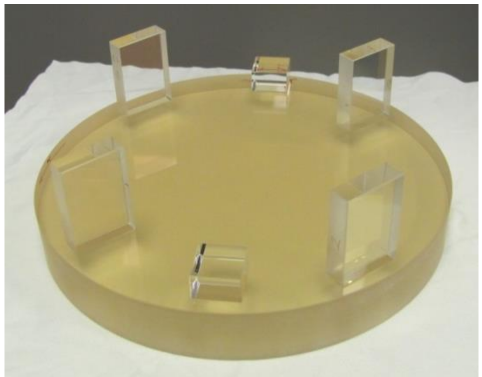


Fig. 4. (Left) Diagram showing the optical layout of the assembly to demonstrate alignment capability. The dashed red line and solid red line represent the two different laser beam paths, and the alignment of these compared to the targets (black crosses) can be measured independently. (Right) Photograph of the bonded assembly on a 6” diameter baseplate with four beamsplitters and two reference cubes.

An input laser is split in two by BS3 and the resulting beams are reflected off BS2 and BS1 for the beam shown as a dashed line (which will be referred to as the ‘reflected beam’), and reflected from BS4 and transmitted through BS1 for the beam shown as a solid line (the ‘transmitted beam’). The component alignment described here is that of BS4 – the last component to be bonded – as measured by the relative centering of the reflected and transmitted beams at the target points, represented by the black crosses in Fig. 4.

The system is set up with the partially bonded assembly – just lacking BS4 – and input beam pre-aligned such that the reflected beam is reasonably centered at the target points. In reality the target points consist of a beamsplitter with a quadrant photodiode after each port: one ~2 cm away and one ~14 cm away. This target is based on the one described in [8]. The measure of alignment success is how coaxial the reflected and transmitted beams can be kept while BS4 is aligned and bonded.

The signals from the two quadrant photodiodes during component alignment were used to inform the alignment process, and were recorded. During alignment the centering of beam position at the near photodiode was prioritised and then the angle was optimized using the additional information of beam position on the second photodiode. The full set up for this bond is shown in Fig. 5.

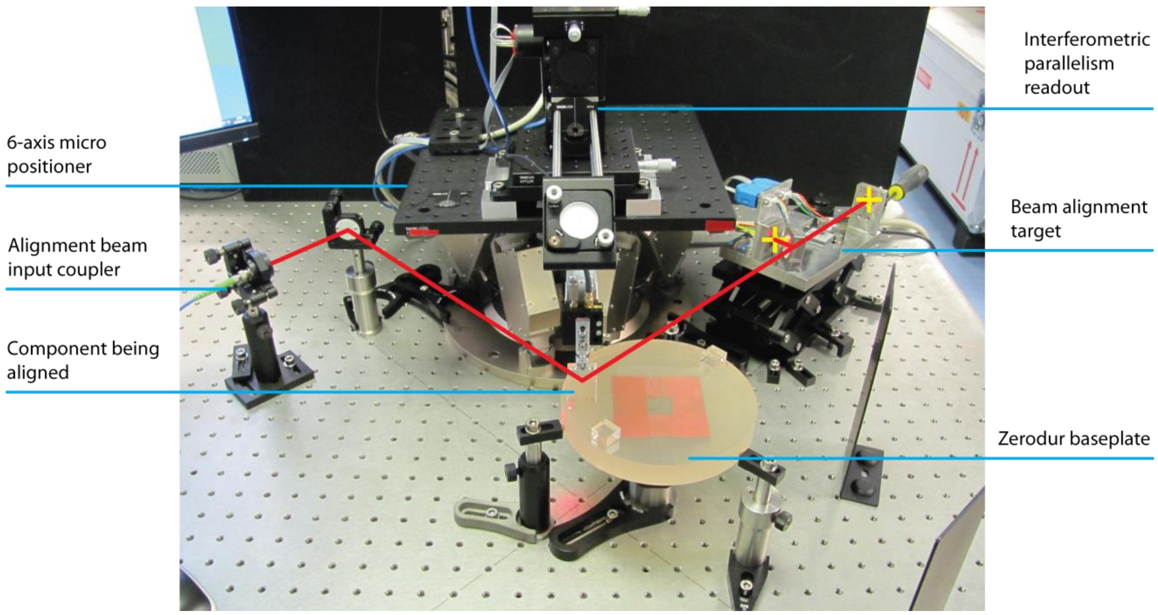


Fig. 5. Photograph of the set up during a precision bond.

The interferometric readout of the parallelism of bonding surfaces enabled alignment of the surfaces as they approached prior to bonding of ~1 μrad, leading to a maximum height difference between the two surfaces, for a 2 cm wide component, of 20 nm. This should be compared to the global flatness specification of the component surfaces of 63 nm. The probe beam has diameter of ~1 mm, meaning our measurement resolution is sufficient to define the parallelism of the surfaces to better than their global flatness.

III. RESULTS AND DISCUSSION

The data collected from the two photodiodes during alignment and bonding was used to compute the beam angle, and this, along with the beam position at the first photodiode were compared for the reflected and transmitted beams. The distance from the component to the near photodiode was 220 mm. The difference between the *stationary* reflected beam and the transmitted beam that was being *steered* is compared as this removes signals from sources common to both beams, such as input beam wander, or drift in the position of the calibrated target, for example. By investigating the differential motion between the two beams we are only sensitive to motion of BS4 alignment with respect to the baseplate. The differences in the beam position and angle between the two beams are plotted in Fig. 6, with the evolution of the beam position and angle shown for spot measurements immediately before and after the bonding surfaces were brought into contact, and as the bond cured for ~7000 seconds.

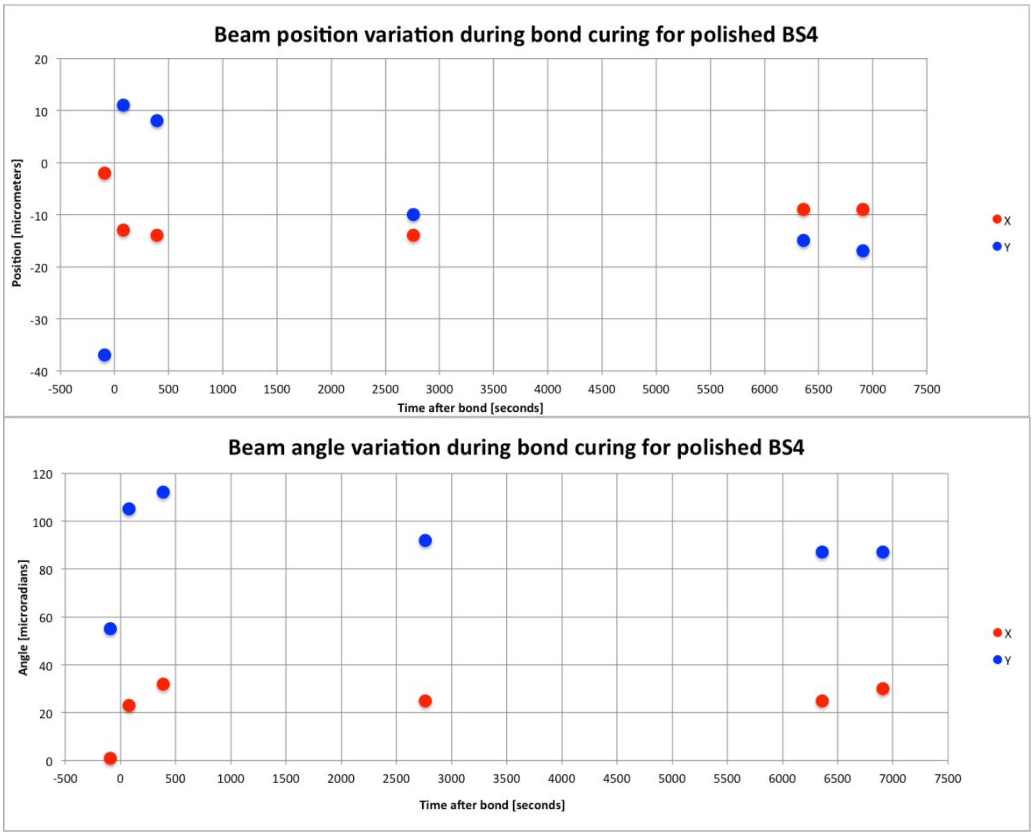


Fig. 6. Plots of the beam position (top) and angle (bottom) on the target for polished BS4. This data is for the beam reflected from the component being adjusted and has had the fixed beam data subtracted from it. The final data points are after the component had been unclamped. X is in-plane and Y is out-of-plane.

The following features of these plots warrant specific discussion:

- In-plane control of a reflected beam during mechanised bonding of <10 μm and 30 μrad is shown. This is at the level achieved by the more complex alignment techniques used in LISA Pathfinder. The alignment is seen to deviate during the process of bringing the surfaces into contact and tends towards recovering the pre-contact position as the bond cures.
- The out-of-plane alignment is not controlled during the bonding process, it is a 'dead reckoning' alignment. The difference between alignment pre-contact and alignment after bonding was ~40 μm and ~30 μrad, although the data suggests this value may have still been decreasing.
- The movement of the bonded component during bonding provides an interesting view of the behaviour of a macroscopic component as the chemical processes involved in bonding occur. When the precise location of the component being bonded is of interest, as it is here, this is an important phenomenon to be aware of and further investigations to charaterise this are planned.

IV. ENVIRONMENTAL TESTING

The optical assembly was environmentally tested to demonstrate the relevance of the processes for space flight. The processes are closely related to those used in the construction of the LISA Pathfinder optical bench, and the mechanically bonded assembly described here was subject to testing at a similar level to that for the LISA Pathfinder optical bench.

A. Thermal vacuum testing

Once the assembly had been cured it was subjected to thermal vacuum cycling. This is particularly relevant for composite assemblies such as these due to the difference in coefficient of thermal expansion of the baseplate and the optics. The lack of a compliant material at the interface, as there is with epoxy joins, means the materials and the bond between them must survive directly the forces induced. The science payloads for space missions often operate at around 20°C, but the survival temperature is generally 10’s of degrees either side of this.

The temperature cycling was conducted over a period of ~70 hours in a vacuum of between 0.1 to 0.01 Torr, and the temperature data is presented in Fig. 7. No change in the assembly or its alignment was seen as a result of these tests.

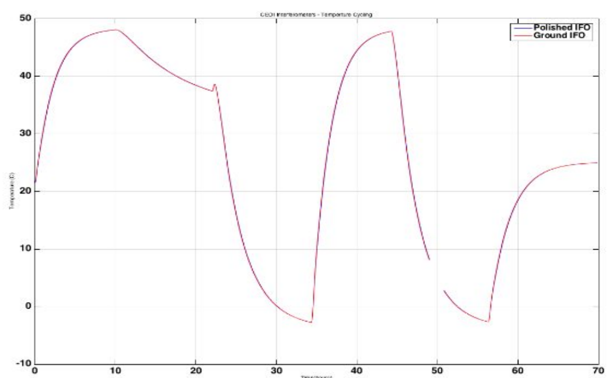


Fig. 7. Temperature in Celsius against time in hours for the thermal vacuum testing.

B. Shock and vibration testing

Unlike the LISA Pathfinder optical bench, the assembly constructed to demonstrate mechanised bonding described here does not have a stress-free mounting system. A mounting solution was designed using a clamp to hold the optical assembly, as shown in Fig. 8. The mounted assembly was hard-mounted to a shaker table and the qualification levels it was tested to are shown in Tab. 1, 2 and 3.

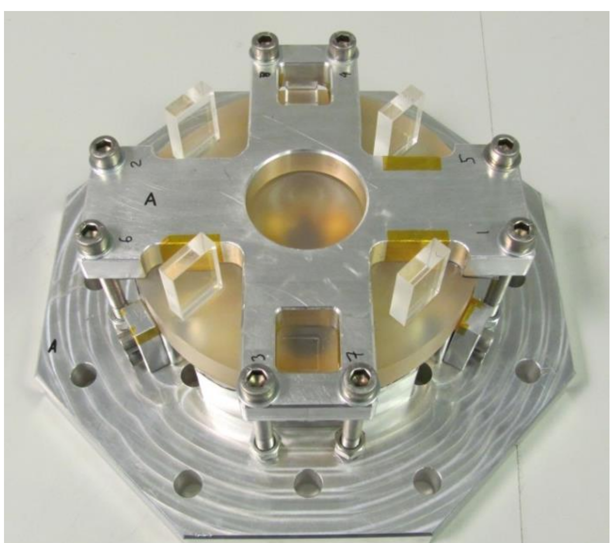


Fig. 8. Photograph of the optical assembly in the vibration mount.

Tab. 1. Sine Requirements

Frequency (Hz)	Qualification X-axis		Frequency (Hz)	Qualification Y-axis		Frequency (Hz)	Qualification Z-axis
5	8mm 0-pK		5	9.3mm 0-pK		5	13.6mm 0-pK
20	13g		20	15g		20	22g
70	13g		40	15g		60	22g
90	18g		60	20g		80	27g
100	18g		100	20g		100	27g
Sweep rate 1 sweep up	2 octaves per minute		Sweep rate 1 sweep up	2 octaves per minute		Sweep rate 1 sweep up	2 octaves per minute

Tab. 2. Random Vibration Requirements

Frequency (Hz)	Qualification in X- and Y- axes, g^2/Hz		Frequency (Hz)	Qualification Z-axis, g^2/Hz
20	ramp up with +6dB/oct		20	ramp up with +6dB/oct
80	0.13 g^2/Hz		100	0.5 g^2/Hz
400	0.13 g^2/Hz		150	0.5 g^2/Hz
2000	ramp down with -7dB/oct		200	ramp down to 0.08 g^2/Hz
Total	8.9g, rms		700	0.08 g^2/Hz
Duration	120 sec		2000	ramp down with -7dB/oct
			Total	11.1g, rms
			Duration	120 sec

Tab. 3. Shock Test Requirements

Frequency (Hz)	Shock levels in X and Y, SRS, g (Q=10)		Frequency (Hz)	Shock levels in Z, SRS, g (Q=10)
70	5g		70	5g
1000	200g		700	50g
10000	200g		10000	50g

During vibration testing the baseplate to which the optics were bonding suffered a failure, leading to one component being removed from the assembly. The remaining three components survived all testing, indicating that the processes used can be suitable for space flight hardware. It is likely that the mounting setup of the Zerodur baseplates was problematic, leading to the baseplate failure. Fig. 9 shows the separated parts of the failed baseplate, with crack propagation having passed through a bond layer and a beamsplitter, leaving a shard of component still bonded.

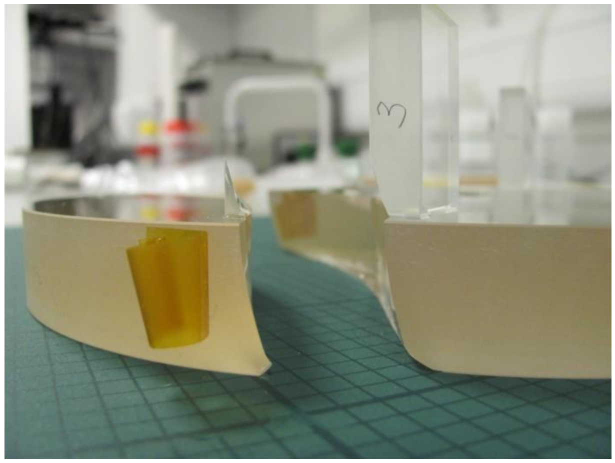


Fig. 9. Photograph of the separated parts of the failed baseplate. Note the shard of component still bonded after the crack propagation passed through the bond layer and component.

V. SUMMARY

The LISA Pathfinder optical bench construction demonstrated submicron and of order 10 microradian level component alignment and hydroxide catalysis bonding. The processes used have been shown to be suitable for space flight optical assemblies, and to perform in an ultra-stable manner. The work described here demonstrates the first steps towards providing a higher level of automation of this process, which will reduce risk and assembly time. Alignment accuracies equivalent to those achieved for LISA Pathfinder have been demonstrated with the mechanised bonding technique. Further automation of the process, including the introduction of a measurement of absolute distance between bonding surfaces, is underway.

ACKNOWLEDGMENTS

This work was funded by the UK Space Agency by a NSTP Fast-Track grant, contract number RP10G0348A04. We acknowledge support by the University of Glasgow, the UK Astronomy Technology Centre, and the Scottish Universities Physics Alliance.

REFERENCES

[1] F Antonucci, *et al.*, "LISA Pathfinder: mission and status", *Class. Quantum Grav*. 28, 094001 (2011).
[2] Armano M, *et al*., "Sub-Femto-g Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results", *Phys. Rev. Lett*. 116, 231101 (2016).
[3] P Amaro Seoane *et al*., "The Gravitational Universe, a white paper describing the science theme addressed by the proposed eLISA gravitational-wave mission", arXiv:1305.5 (2013).
[4] D I Robertson, E D Fitzsimons, C J Killow, M Perreur-Lloyd, H Ward, J Bryant, A M Cruise, G Dixon, D Hoyland, D Smith and J Bogenstahl, "Construction and testing of the optical bench for LISA Pathfinder", *Class. Quantum Grav*. 30 085006 (2013).
[5] Gwo D-H "Ultra-precision and reliable bonding method", United States Patent no US 6,284,085 B1 (2001).
[6] A. van Veggel, and C. Killow, "Hydroxide catalysis bonding for astronomical instruments", *Advanced Optical Technologies*, 3(3), pp. 293-307 (2014).
[7] Christian J Killow, Ewan D Fitzsimons, James Hough, Michael Perreur-Lloyd, David I Robertson, Sheila Rowan and Henry Ward "Construction of rugged, ultra-stable optical assemblies with optical component alignment at the few microradians level" *Appl. Optics* 52 (2) pp177-181 (2013).
[8] Ewan D. Fitzsimons, Johanna Bogenstahl, James Hough, Christian J. Killow, Michael Perreur-Lloyd, David I. Robertson, and Henry Ward, "Precision absolute positional measurement of laser beams", *Appl. Optics*, 52 (12) pp. 2527-2530 (2013).