FIBER LASER PROCESSING OF THICK YTTRIA STABILIZED ZIRCONIA

Paper (2007)

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Abstract

A novel laser processing technique is demonstrated for cutting up to 13mm thick sections of Yttria-stabilized Tetragonal Zirconia Polycrystal (Y-TZP) ceramic. Y-TZP is a high toughness engineering ceramic which is extremely difficult to machine in its final state. However for some applications this is nevertheless desirable. As an example Y-TZP based dentures represent an example of mass-customization in which it is essential to machine the required shape from solid billets rather than to produce customized moulds. Currently this is done mechanically and necessitates the use of diamond tipped grinding and drilling tools, however this process is a very slow and suffers from problems of high tool wear.

In this work a Ytterbium fiber laser system has been used to achieve full thickness cuts via a novel controlled crack propagation technique. This results in a limited surface heat affected zone and no cracking is observed to propagate into the bulk material. Processing rates are substantially faster than alternative cutting techniques available for this material with feed rates of up to 1.8 mm/s demonstrated. A finite element model is used to achieve a better understanding of the cutting mechanism.

Introduction

Yttria-stabilised Tetragonal Zirconia Polycrystal (Y-TZP) is a particularly tough engineering ceramic; the high toughness arises from a crack arresting process that occurs due to a stress induced phase transition (tetragonal to monoclinic) at the crack tip [1]. This property makes it desirable for a wide range of industrial and medical applications including bone, tooth and joint implants, however it also makes the material very difficult to machine in its final state. For applications requiring customized and/or high precision components final state machining is often necessary. One example of this is for the manufacture of dental restorations such as dental crowns and bridges. An example of a typical dental bridge manufactured from Y-TZP is shown in Figure 1, this is the Y-TZP base and the finished item will have a glazed ceramic veneer to give a lifelike finish. This process is a perfect example of mass customization where large quantities are to be produced but each item is unique and subject to tight design tolerances. The item shown in Figure 1 was machined from a sintered block of Y-TZP by grinding using diamond tipped tools. The process gives a good end result but is very time and tool intensive. Laser machining represents a possible alternative process for machining this material which could potentially provide much more rapid processing times and avoid problems of tool wear. The material properties of Y-TZP, specifically its high thermal expansion coefficient (10.3×10^{-6}/°C) and low thermal conductivity (2.2 W/(m.K)) [2], make it a difficult material to machine using laser processes (typical comparative values for alumina are 8×10^{-6}/°C and 20 W/(m.K) respectively [3]).

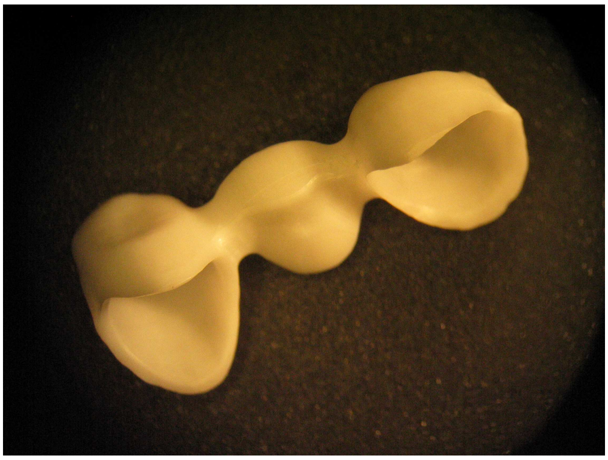

Figure 1: Dental bridge machined from Y-TZP

In previous work our group has successfully demonstrated laser machining of this material in the ms-regime [4] and the ns-regime [5]. Laser machining in the fs-regime has also been investigated by other authors [6]. In general laser processes at longer pulse durations can provide high material removal rates and are suitable for cutting and drilling operations. Using a ms-pulsed Nd:YAG laser material removal rates of 2.5 mm^3s^{-1} have been demonstrated in cutting operations (and 13 mm^3s^{-1} for drilling operations) producing through-cuts in material of up to 4.5 mm thickness and through-holes of up to 12 mm depth [4]. Such (relatively) high removal rates come at the expanse of surface finish and leave a significant surface heat affected zone (HAZ), surface finish is improved by moving to shorter pulse durations but at the expense of processing rate (2 mm^3min^{-1} for ns processing [5]). Different laser processes may be used in conjunction to combine the benefits of each individual process, for example in previous work a ns laser process has been used to remove the HAZ from ms laser-cut components. Additionally smaller feature sizes could be achieved with the ns-laser than are possible with mechanical machining [7].

The work presented in this paper demonstrates the use of a high average power fiber laser as a tool for bulk processing of Y-TZP blocks. Although limited in terms of peak power compared to a Q-switched laser a fiber laser can produce a high fluence by virtue of its high beam quality single mode operation that enables the output to be focused to a small beam diameter with a long depth of focus. This laser was operated in the ms-regime by modulating the output; however the results demonstrated are a substantial improvement upon previous Q-switched ms laser work.

Experimental Work

The laser used in this work was an YLR-1000-SM Ytterbium fibre laser system manufactured by IPG. This is a continuous wave (cw) laser capable of delivering up to 1 kW at 1075 nm. The output may be modulated at up to 50 kHz with an arbitrary duty cycle. The fiber core diameter is 14 µm and a 7.5 inch (190.5 mm) focusing optic was used to give a beam waist diameter of approximately 45 µm.

Figure 2 illustrates the experimental set-up used for machining. Fiber-optic beam delivery is incorporated into the laser system and this is mounted onto a fixed assembly containing focusing optics and a gas flow system. The gas flow serves both to protect the optics from debris and to assist with material removal from the work piece. Oxygen was used as an assist gas at a pressure of 6 bar with a stand off of 2 mm between the nozzle tip and the workpiece. Oxygen was chosen as in previous work [8] it was established that discoloration produced in this material by laser machining as a result of oxygen depletion at high temperatures could be avoided by using oxygen as an assist gas. The sample was mounted on precision translation stages synchronized with the laser to enable the sample to be located and moved under the beam.

This work focused on processing blocks of dental grade sintered Y-TZP. Billets of dimensions 8×18×44 mm are the standard size from which a dental bridge would be manufactured; the largest size billet generally used is of dimensions 13×18×44 mm. These two sizes of billets were used in this work.

Low initial absorption of Y-TZP at 1075 nm and the granular nature of the material created an intermittent problem with back reflections to the laser (triggering a safety cut-off switch). It was found that coating billets with a thin layer of graphite (colloidal spray) to provide a consistently absorbing surface both solved this issue and significantly improved the consistency of results due to improved initial absorption.

To start with the capability of the laser to drill holes in the Y-TZP blocks was assessed in single pulse and later multiple pulse operation. The main aim however was to produce consistent full thickness cuts. A novel and effective cutting mechanism was developed. To achieve a better understanding of this cutting process a model was developed using the finite element modeling (FEM) software package, Abaqus.

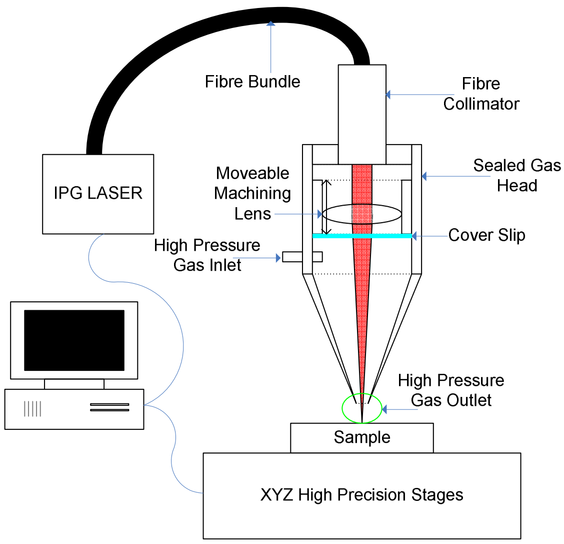

Figure 2: Diagram of experimental set up incorporating fibre laser, focusing optics, gas flow apparatus and precision stages.

Results and Discussion

Drilling

The laser was found to easily drill through 13mm thickness of material. The on-time was modulated to find the shortest time required to penetrate this thickness. It is desirable to find the lowest parameters in terms of power and pulse length to minimize the thermal impact on the material. By stepping the output directly (rather than ramping the intensity) to 400 W it was found that a minimum laser-on-time of 26 ms was sufficient to consistently penetrate 13mm thicknesses.

Holes drilled in the Y-TZP blocks were typically 150 µm in diameter, approximately three times larger than the spot diameter at focus with an aspect ratio of 93.3:1. A HAZ extended a further 70 µm into the bulk material, this is apparent in Figure 3 in which radial cracks can be clearly seen extending from the hole. In Figure 4 a layer of re-deposited molten material is apparent as well as a layer of material that has suffered thermal damage. The material removal process is very similar to that investigated previously for a ms-pulse duration laser system and a closer examination of the HAZ is available in that work [4]. Material removal rates compare well to the Q-switched ms-pulse duration used in previous work (of ~13 mm^3s^{-1}). Approximately 0.41 mm^3 of material was removed in a 26ms pulse creating an effective material removal rate of 15.71 mm^3s^{-1}.

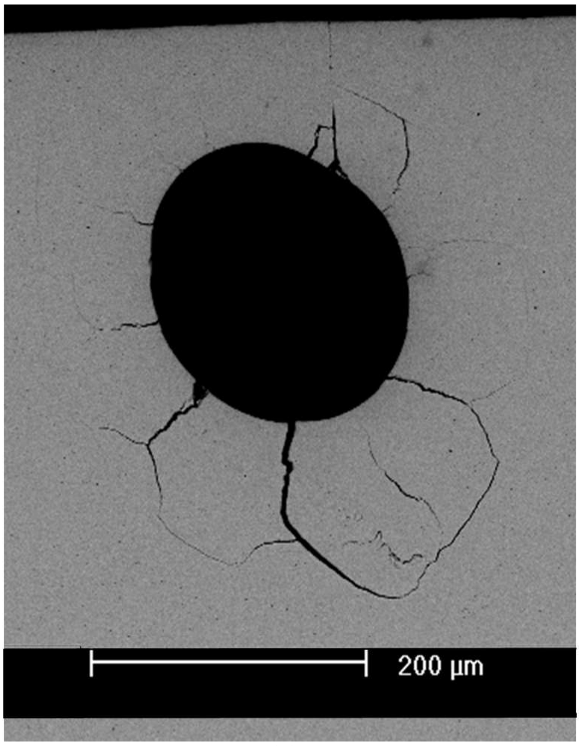

Figure 3: ESEM image of fibre-laser drilled hole in Y-TZP (section taken at mid-depth). Cracks can be seen to propagate radially into bulk.

Thicker sections of material were used to investigate the laser penetration at greater depths by increasing the laser-on-time in steps. The maximum depth achieved for a single pulse was 15.4 mm by operating the laser at 1 kW for 56 ms. Longer duration pulses did not produce deeper holes. It is believed that this is due the limitations in expelling the molten material from the top of the hole and the interaction of the laser with this material. For long laser on times a cavity is formed around the hole as the laser energy is absorbed by melt in this region without penetration to greater depths.

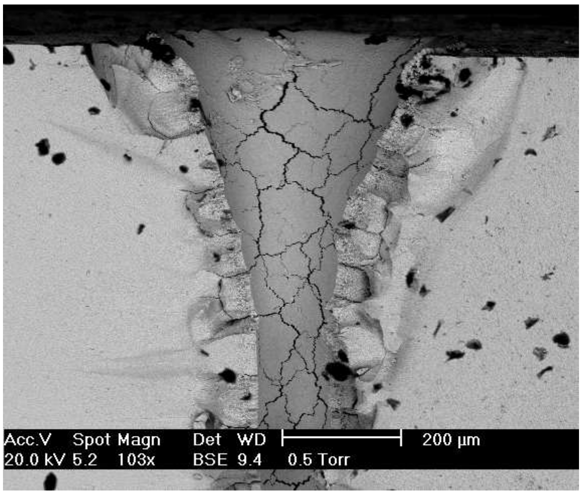

Figure 4: ESEM image showing cross section of fibre-laser drilled hole in Y-TZP. Re-cast material is visible on the hole walls and a HAZ extends into the bulk.

Drilling with multiple pulses gives time for material to be removed from the hole between pulses and reduces the average power used. This enabled deeper holes to be machined without bulk cracking. Best results were achieved for four laser pulses of 25 ms at 1 kW with a 250 ms delay between pulses. These parameters consistently produced a through-hole in 18 mm thick billets. Increasing the pulse duration or the number of pulses for thicker material sections produced limited increases in depth. For example, 12 pulses of 25 ms with a 250 ms delay produced a blind hole of approximately 23 mm depth. This does not compare well to a through hole of 18mm depth from 4 pulses. Attempts to drill to greater depths generated too much thermal shock within the billet and resulted in bulk fracture.

Cutting

Initially attempts at laser cutting were in the cw regime however the results were poor, the main problem appeared to be related to removal of melt from the cut. The good beam quality and narrow cuts produced by the laser was actually detrimental to the process as little space was available to effectively eject melt from deeper cuts. Trapped molten material then inhibits further cutting

Moving to a pulsed regime proved far more successful as can be seen from Figure 5. A process was developed in which a series of through-holes were machined in a line across the billet. For appropriate parameters cracks or fractures were caused to propagate in a controlled way between holes. These fractures extended to the full thickness of the material and joined holes to make a cut. In this way full thickness cuts could be produced in 13mm thick Y-TZP.

Holes were drilled using 400 W for 26 ms, as discussed previously, to give consistent through-holes. The off time between holes and the hole separation within the material are important to the success of the process. A 3.6% duty cycle (26 ms on, 694 ms off) was found to be most effective. This gives sufficient time for material to cool between laser pulses so as to avoid uncontrolled cracking while maintaining sufficient pre-heating to drive the fracture process after the following pulse. Using these laser parameters a maximum feed-rate for successful cutting was shown to be 1.8 mms^{-1} corresponding to a hole separation of 1.3 mm.

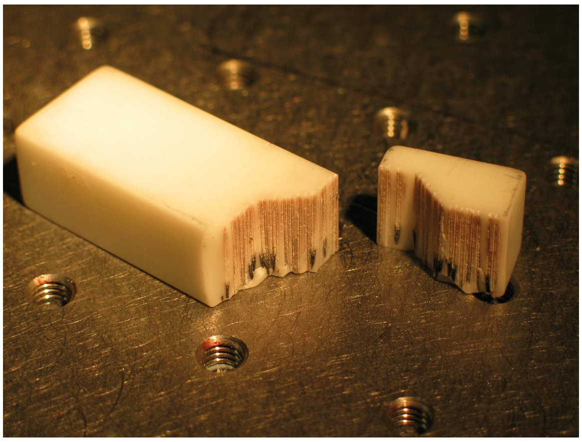

Figure 5: Profile cut of 13 mm thick Y-TZP using a 1 kW fiber laser.

Figure 6 shows a close up view of the cut surface; the individual laser-drilled holes are clearly seen in cross section. In this instance holes were drilled from the right of the image to the left. Cracks are visible on the surface to the right of the holes extending towards the previously drilled hole. It is believed that these are the initiating points of the fracture that occurs between the holes indicating that the fracture travels from the newly machined hole back towards the previous hole.

From Figure 7 the origin of the cracks is apparent. This image shows the top of a hole at the side of a laser machined cut. Cracks propagate radially from the hole to a depth of approximately 100µm into the bulk material, this is a result of the rapid heating and cooling that occurs in this region and the steep temperature gradient that is induced here. On the left side of the image it appears that one of these cracks has acted as an initiation point for fracture that extends away to the previously drilled hole to the left.

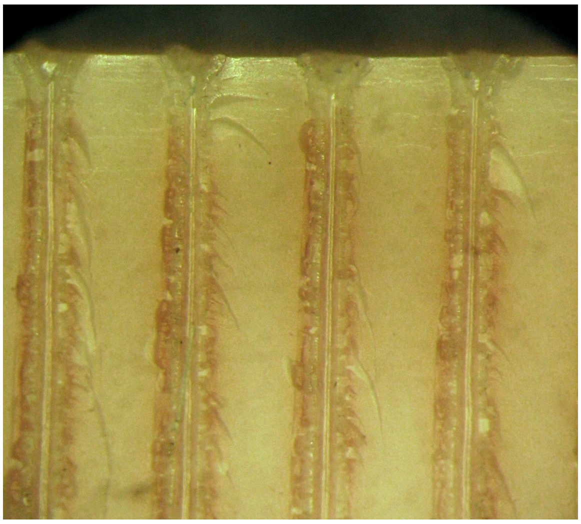

Figure 6: Close up view of cut surface. The laser was moving from right to left relative to this image.

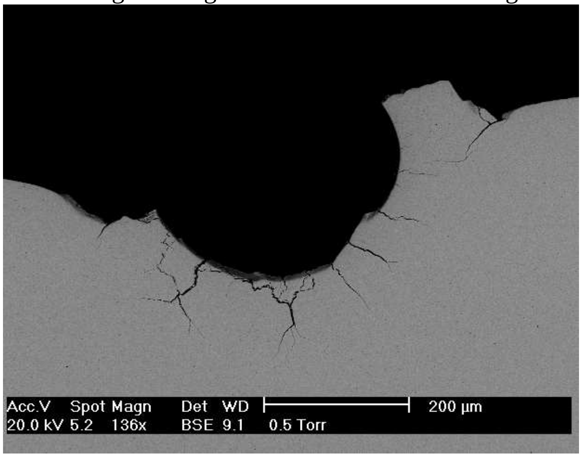

Figure 7: ESEM image of individual hole on cut edge. The laser was moving from left to right relative to this image.

Directional variation is possible with this process as demonstrated by the shaped cut in Figure 5. This is important as it means that profiled cuts are feasible. Limitations in term of maximum angular variation and curvature have not currently been investigated fully.

There does however appear to be a minimum limit on the width of cut sections of approximately 3 mm. When machining within 3 mm of a surface parallel to the cutting direction there is a tendency for fractures to propagate towards the nearest edge rather than towards the next laser drilled hole.

The material available to test provided a choice of thicknesses for cutting that was limited to 8 mm, 13 mm or 18 mm. As discussed previously it was possible to drill through the 18 mm thick material but this required multiple pulses (4 pulses at 1kW, 25ms on 250ms off). A cut was attempted by drilling separated holes through this thickness of material however this was unsuccessful, with the block shattering as the second hole was drilled.

Modeling

To gain a better understanding of the mechanisms at work in this process finite element modeling work has been carried out to represent the thermal- and stress-field evolution proceeding single and double laser pulses. Y-TZP has a melting temperature of 2700°C, data on temperature dependent mechanical properties is available up to around 1500°C [9,10]. However in this temperature range the material is starting to become susceptible to significant plastic creep [11]. Neglecting the effects of this creep in this fast process of heating and cooling cycle, temperature dependent variables were approximated for the FEM. A coupled temperature displacement model was adapted to mimic the temperature and residual stress distribution caused by the laser processing. As the emphasis in this work was on the understanding of heat transfer between the two neighboring laser drills, element deletion was not adapted to model the laser to drill the hole. Instead, holes of the correct dimensions were assumed to be drilled by the laser, and appropriate boundary conditions applied to mimic the temperature distribution on the inside of the hole geometry. Due to symmetry, only half of the geometry was modeled with appropriate boundary conditions, as shown in Figure 8, where in the first step, the hole on the left hand side gets heated up to the appropriate temperature of the material within 26ms. The laser then moves to the second hole on the right hand side in the second step and applies heat for the 26ms period, whereas the boundary conditions of the first hole are modified to mimic the cooling process. Finally, in the third step, the whole body is allowed to cool to room temperature within the next few minutes.

In terms of the crack propagation caused by the internal stresses in the material, the cracks seen in Figure 3 and Figure 7 which were initiated by the laser drilling can propagate from the second hole to first either in tension or in shear. Figure 8 shows the typical tensile stress distribution (σ_{33}) perpendicular to the surface of the cut at the end of step 2. It can be appreciated from the figure that the stress distribution caused by both holes is localized near the holes at this time period, and covers the entire thickness of the sample. However in between the two holes there is also stress distribution which drives the cracks from the second hole to the first during the cooling process. This is further clarified in Figure 9, where a funnel shaped stress distribution is apparent between the holes. This stress field moves from the direction of second hole to the first during the cooling period (third step).

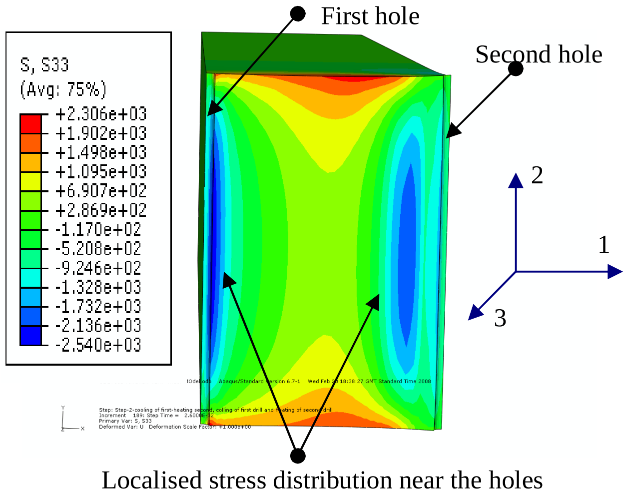

Figure 8: Model geometry and localized stress distribution (σ33) at the end of second step.

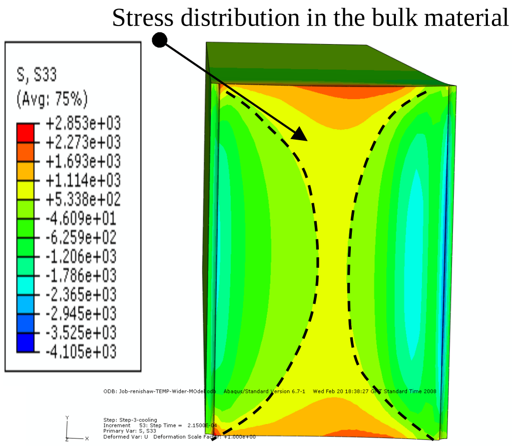

Figure 9: Stress distribution driving cracks from second hole to first during the cooling period; the funnel shown in the dotted line progresses from right to left in the figure driving the cracks.

These results indicate that the temperature distribution and diameter of the holes drilled by the laser, cooling provided by the oxygen, and spacing between the holes is critical for controlling the crack propagation and enabling a clean cut between the two holes.

Conclusion

The use of a fiber laser has been evaluated for processing Y-TZP in its final state. Laser drilled through-holes have been demonstrated for a thickness of 18mm and a novel cutting process has been developed relying on controlled crack propagation between laser drilled holes. Both empirical evidence and modeling work suggest that cracks propagate from a laser drilled hole back to the previously drilled hole. Modeling work indicates how the process is driven by the thermally induced stress field that arises in the material as a side effect of the laser drilling.

Profile cuts have been demonstrated through 13 mm thick Y-TZP. Compared to other techniques for cutting this material in its final state this laser process is much faster than any mechanical technique available and cuts through significantly greater thicknesses than alternative laser processes with no evidence of undesired bulk fracture. While the surface finish is of limited quality a two stage process could be envisaged in which the fiber laser is used for profile cutting and a secondary process (short pulsed laser or mechanical) is used for finishing and fine detail. Advantages in machining time compared to an all mechanical process would still be substantial.

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Meet the Authors

Jon Parry graduated in 1999 from Nottingham University with a BSc(Hon's) in Physics before joining Point Source to work on fibre delivery systems. He was awarded an MSc in 2002, jointly by Heriot-Watt and St Andrews Universities and a PhD by Heriot-Watt University in 2006. The PhD investigated fibre-optic delivery of high-peak-power laser light for fluid flow measurements. Jon is currently working at Heriot-Watt as a Research Associate, working primarily on laser processing techniques for ceramics.

Fraser Dear - "from a wee town called Kirriemuir" - received a MPhys in Optoelectronics and Laser Engineering from Heriot-Watt University in 2004. During his undergraduate degree he gained experience and interest in laser micro-machining by undertaking a project at Oxford Lasers. He was recently awarded a PhD in "Short pulse laser micro-machining of engineering ceramics" by Heriot Watt and has now taken a position at AWE.

Rehan Ahmed is a lecturer in mechanical engineering within the school of Engineering and Physical Sciences (EPS) at Heriot-Watt University. Prior to this appointment in 1999, he held a post-doctorate research position at Cambridge University. Dr Ahmed completed his MSc and PhD from Brunel University. His research interests include Tribo-mechanical modelling and evaluation of surface engineered

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Jon Shephard graduated in Engineering from Cambridge University after which he joined Pilkington Plc, UK, working within R&D. He returned to study for his MSc (Eng) and PhD within the Department of Engineering Materials, University of Sheffield. His work concentrated on the development of mid-IR transmitting optical fibres and waveguides, where he subsequently undertook a Research Associate position. He has recently been appointed Lecturer/RCUK Fellow in Mechanical Engineering at Heriot-Watt.

Duncan Hand graduated from the University of St Andrews in 1986 with a BSc in Physics with Electronics, and from the University of Southampton (Optical Fibre Group) in 1991 with a PhD. In 1991 he moved to Heriot-Watt University, initially employed as a Research Associate to work on optical fibre interferometric sensors. In 1997 he was appointed Lecturer in Physics and subsequently promoted to Reader (2001) and Professor of Applied Photonics (2003). His work on manufacturing includes laser precision machining and laser joining of microsystems.