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Cleaving of microstructured polymer optical fibres

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Abstract

The issue of how best to cleave PMMA microstructured polymer optical fibres (mPOF) is addressed. The impact of the following parameters on the cleaving process is considered: (i) temperature of the cutting blade, (ii) temperature of the platen holding the fibre, (iii) time allowed for thermal equilibration between fibre and platen, (iv) blade speed, and (v) blade condition. The strong influence of a temperature-dependent phase transition in the polymer on the cleaving process is established. Optically acceptable mPOF end-faces can be achieved but only over a limited range of cleavage conditions.
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1. Introduction

Microstructured polymer optical fibres (mPOF) may be fabricated by drilling a hole pattern in a preform which is then drawn down to a fibre containing the necessary refractive index profile for light guidance. Such fibres are increasingly being viewed as a realistic alternative to conventional (i.e. doped) polymer optical fibre, being potentially both cheaper and simpler to make while offering a diversity of optical properties through tailoring of the hole structure [1]. However an important issue with respect to successful commercialisation is cleaving the fibre to form an optical end-face for coupling. Commercial cutters exist for solid polymer optical fibres [2] but are not very effective when used on mPOFs. While UV-laser cutting has been shown to be potentially viable in the laboratory [3] it is unlikely to translate into a field-usable cutter. This paper reports on the results of preliminary work on mPOF cleaving using devices employing a razor blade. Results are presented on the effects of temperature (both fibre and cutting blade), blade speed and blade condition on the quality of the fibre end-face.

The fibres studied here were fabricated from amorphous polymethylmethacrylate (or PMMA)

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having a viscosity molecular mass (M_v) of 7.2×10^4. PMMA is usually regarded as a ‘glassy polymer’ – that is, an optically clear thermoplastic that is hard at room temperature but which can be worked viscoelastically above its glass transition temperature [4] (around 115 °C for the PMMA used in this study). However, PMMA can be anomalous in its mechanical behaviour. In particular, it can be significantly tougher/stronger than other glassy polymers. Kusy has shown [5] that the brittleness of bulk PMMA is strongly dependent on its M_v value with brittle behaviour occurring for $M_v < 10^4$ and ductile behaviour for $M_v > 10^5$. In addition, Matsushige [6] has reported that a ‘brittle to ductile’ transition can occur when samples are heated to around 50 °C, a level well below the glass transition temperature. This behaviour has been interpreted as evidence of a phase transition. In the brittle region, the fracture mechanics are both complex and molecular weight dependent [7] involving the formation of ‘crazing cavities’ ahead of the fracture tip [8]. The fracture surface energy also exhibits complex behaviour with respect to crack speed [9] which can affect the surface quality arising from any induced fracture. In the ductile region, interfacial shearing between (and deformation of) spherulites plays a major role in determining the properties of the exposed surface.

Currently the most successful method for cleaving an mPOF involves cutting the fibre with a razor blade [10]. Unsurprisingly, the effect of the blade changes with the mechanical properties of the PMMA. If it is brittle, the blade will initially form a notch which creates a stress concentration at the notch tip leading to the formation of a ‘craze’ region. As the blade cuts further and forces the notch sides apart, the crazing will extend and thin eventually forming a crack front. This in turn creates stress concentrations further into the fibre and more crazing ahead of the crack front. Eventually, a situation is reached where the blade tip is not in contact with the material, with cleavage now occurring via fracture due to the stresses caused by the opening of the crack by the blade (Fig. 1(a)). If the material is ductile however, the stress concentration is insufficient at the notch tip to initiate crazing and fracture. Here, it is the blade tip that is responsible for the cleavage (Fig. 1(b)). If the material is very ductile, then spherulites can be dragged out of the surface by the blade causing a smearing effect over the cut surface.

The bulk characteristics of the material can be significantly modified by the fibre fabrication process. It has long been known that viscoelastic drawing of polymers creates anisotropy in the mechanical properties. In particular, the longitudinal fracture surface energy (a measure of the material’s resistance to cracking) is reduced while the transverse fracture surface energy is increased [11]. However quantitative data are limited and for draw ratios very much smaller than would be encountered in mPOF fabrication. The anticipated anisotropic behaviour together with an mPOF’s microstructure thus forms a classic crack-stopping structure [12] where the three-dimensional stress concentrations at the crack tip are only really able to form any significant crazing perpendicular to the crack direction – with the result that any crack arising from attempted cleavage turns through a right angle leading to a splintering process. The degree of anisotropy decreases with increasing draw temperatures and less splintering would be expected in such cases. However, the draw parame-

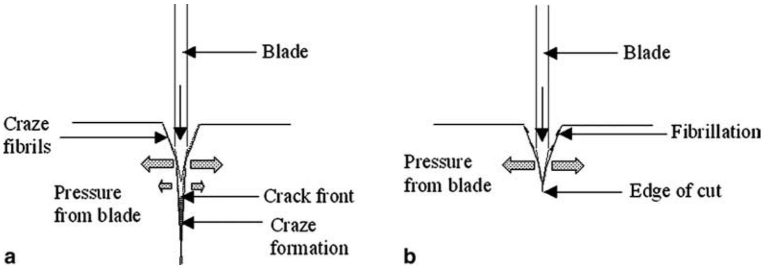

Fig. 1. Cleaving of: (a) very brittle and (b) very ductile material by a blade.

ters for an mPOF are set in response to a number of considerations (such as loss reduction [13]) with the result that fibres may well be drawn under conditions conducive to high anisotropy levels. Although little published data is available, it might also be expected that draw conditions would also affect other parameters such as the brittle/ductile transition temperature of the final fibre [14]. Clearly any generic method for cleaving mPOF must allow for this variation in material properties. Fortunately the key mechanical properties are temperature dependent with an increase in temperature typically reducing both the brittleness and the anisotropy of the fracture toughness [5,6].

2. Preliminary measurements

The first cutter used in this study was designed and constructed at the University of Auckland to study the effect of blade and base (or fibre platen) temperature on the end-face quality of cleaved mPOF. Fig. 2 shows a schematic of this cutter. A pair of independently heated blocks was joined by a hinge with a razor blade mounted in the upper block and a transverse groove machined in the lower block. The fibre is placed in the groove with its ends weighted to provide the necessary tension. The blade is then manually lowered to cut the fibre.

Many fibre samples were cut with the blade temperature ranging from 20 to 100 °C and base temperatures covering the range 50–100 °C (Fig. 3). Better quality cleavage was obtained with the fibre under modest tension although the level of tension was found to be unimportant. An acceptable end-face could not be achieved with a base temperature below 60 °C. Above this temperature, acceptable cleavage could be obtained with the most consistent results being for a base temperature between 85 and 95 °C and a blade temperature in the range 50 and 80 °C.

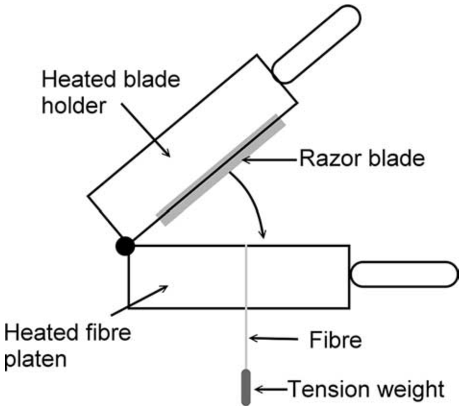

Fig. 2. University of Auckland fibre cutter.

Fig. 4 shows a scanning electron microscope (SEM) image of one such acceptable end-face. The cut was made from the upper left to the lower right. The upper part of the surface is the result of a ductile cut with lines marking the progress of the blade across the surface. However, the lower portion of the surface would seem more of a ductile fracture with 'river' lines (more visible under higher magnification) showing the path of the fracture edge. These river lines concentrate towards the lower edge and there is a 'halo' just above the lower edge. This latter feature is possibly due to a reflected shock wave (caused by fracture initiation) meeting the fracture edge. There is also some cracking of the inter-hole walls at the top of the structure. This preliminary work clearly demonstrated that it was possible to produce good quality optical end-faces if the base and blade temperatures were correctly chosen. However even when a 'good' cleavage was obtained, there was evidence that a number of different mechanisms were responsible for the overall cut.

3. Controlled mPOF cleavage

The development of an mPOF cutter suitable for commercial applications required a more complete understanding of the cutting process and the various parameters that affect the end-face quality. For example, one key factor is the physical condition of the cutting edge of the blade. Fig. 5 demonstrates the effect of cutting fibre with a heated steel razor blade. Fig. 5(a) shows a pristine blade edge while Fig. 5(b) shows that a cold fibre significantly chips the cutting edge of a hot blade. Softening the fibre by raising it to 80 °C reduces damage to the blade (Fig. 5(c)) but does not eliminate it entirely.

In addition to the deleterious effect of a damaged blade edge on the cleavage quality, the impact of debris from the cutting process needs

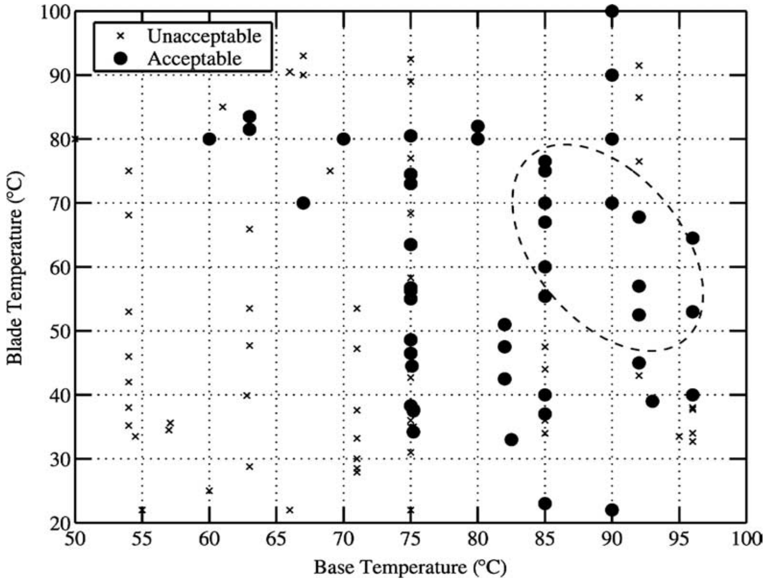

Fig. 3. Cleave quality as a function of base and blade temperatures.

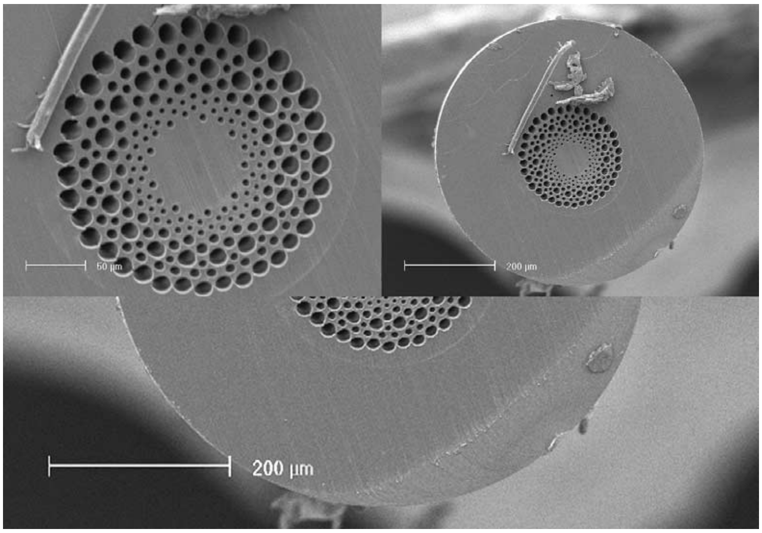

Fig. 4. SEM images of a hot blade/hot fibre cut fibre.

to be considered. Fig. 6 shows such PMMA debris on the cutting edge of a blade used to cleave cold fibre. Such debris is potentially as damaging to the cleavage surface as a worn blade edge.

Fig. 7 shows a rig designed at the University of Sydney to refine our understanding of the mPOF cutting process. In addition to independent control of blade and platen temperature, the blade is mounted on a stepper-motor driven linear stage to enable the speed and cut depth to be controlled. To eliminate the effect of changes in blade condition, the fibre platen is mounted on a screw-driven slide and moved before every cut. The angle of the blade can also be adjusted.

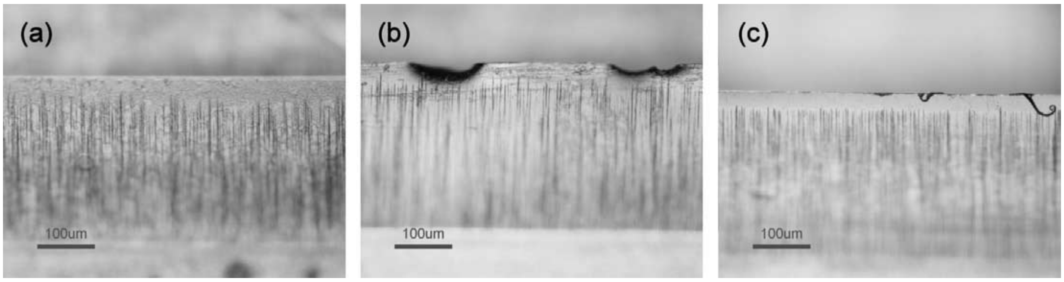

Fig. 5. Damage to a steel razor blade caused by cutting PMMA fibre. (a) A pristine blade. (b) Damage from cutting room temperature fibre with a hot blade. (c) Damage from cutting hot fibre with a hot fibre.

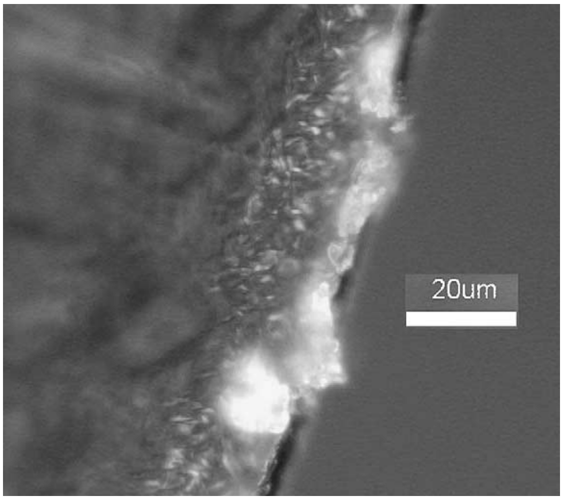

Fig. 6. PMMA debris on a blade used to cut cold fibre.

Initially, a 2-mm slot was provided for the blade to drive into, but it was found that this allowed the fibre to deform under pressure from the blade. Subsequently, this slot was replaced with a 1-mm cross-groove to allow the blade to pass completely through the fibre whilst minimising the unsupported length of fibre (Fig. 8).

4. Effect of fibre equilibration time

The fibre used for preliminary testing was a Graded Index microstructured Polymer Optical Fibre (GImPOF) which was fabricated by drilling the required hole pattern in a cylinder of high purity PMMA. This cylinder was then drawn to a 6-mm rod and 'sleeved' with lower quality PMMA to produce a 12-mm diameter preform. The latter was then drawn to fibre with an outer diameter of 400 μm at a temperature of 220 °C and under 45 g of tension. This high temperature, low tension draw gave a fibre with relatively low material anisotropies but with somewhat distorted holes. The boundary between the inner, high purity material and the sleeve material is visible in all the images.

Early testing considered the effect of the time between laying the fibre on the platen and subsequent cleavage. Fig. 9 shows the results from one such test series where the blade and platen temperatures were known to produce a good end-face if the fibre were allowed time to come up to temperature. For times under 40 s, the end-face quality is poor and characteristic of the low temperature cleavage (i.e., below 60 °C) obtained previously with the simpler cutter. For times above 40 s, the end-face quality is characteristic of the previously seen 'sweet zone' shown in Fig. 3. Consequently, any fibre was left to equilibrate on the platen for at least 60 s before cutting.

5. Effect of platen temperature

Fig. 10 shows fibre samples equilibrated with the platen at temperatures from 25 to 100 °C cut with a blade at 60 °C and moving at 0.05 mm/s. All end-faces suggest ductile behaviour with a cut upper surface and a ductile fracture at the lower edge. At 25 °C the cladding surface is badly scored and the fracture zone at the bottom is strongly banded and rough. In addition, the outer holes in the core area have been damaged although the

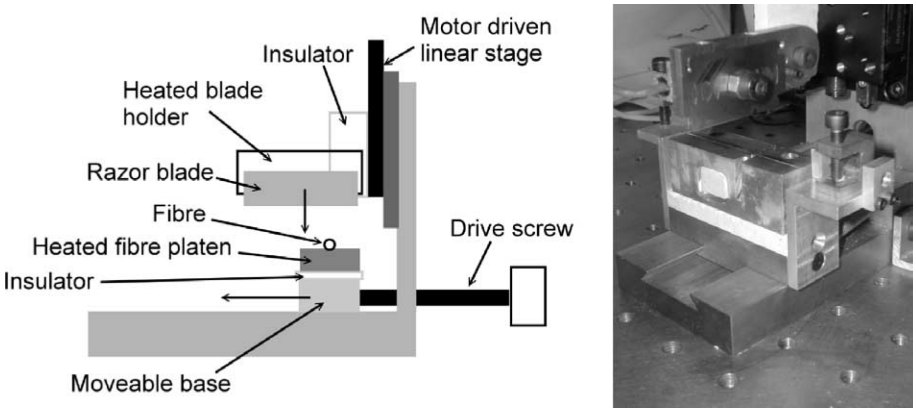

Fig. 7. The University of Sydney fibre cutter.

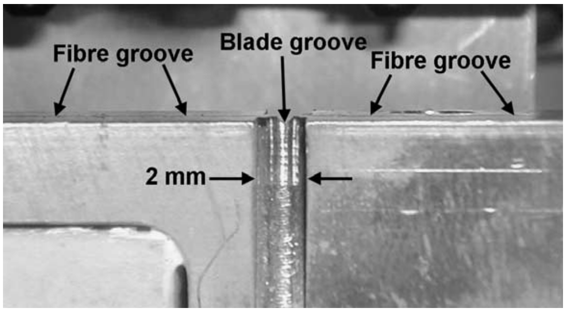

Fig. 8. Cross-groove in fibre platen.

core is still centred. At this temperature both damage to the blade and PMMA debris would be expected to contribute to poor end-face quality. As the platen temperature rises, so scoring and banding get worse while the core is dragged away from the cladding, becoming distorted and off-centre. It seems likely that the new type of roughness observed here around 50–60 °C – a 'crumbly cheese' surface appearance – is caused by distorted spherulites within the PMMA. However, the situation improves as temperature is increased further and by 70 °C the surface quality is close to being acceptable. There is some scoring on the cladding

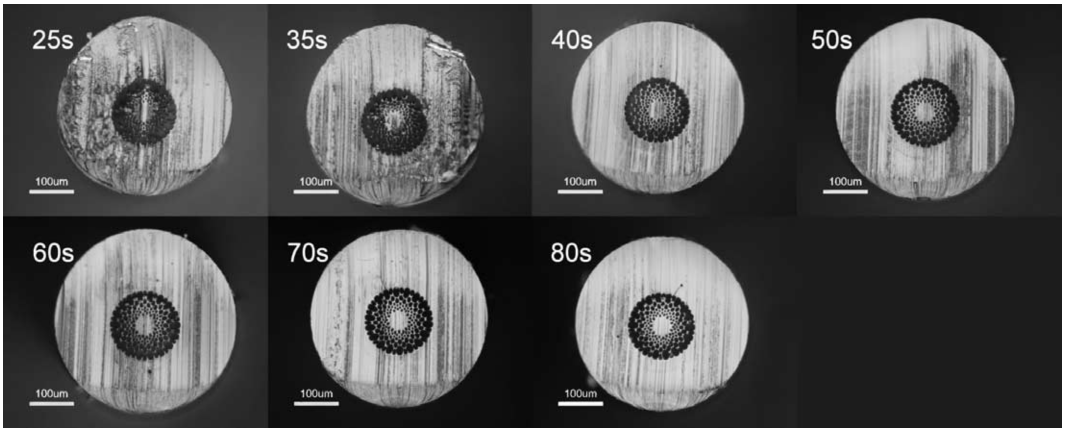

Fig. 9. End-faces cut with a platen temperature of 80 °C, a blade temperature of 60 °C and a blade speed of 0.5 mm/s for different delays between fibre placement and cutting.

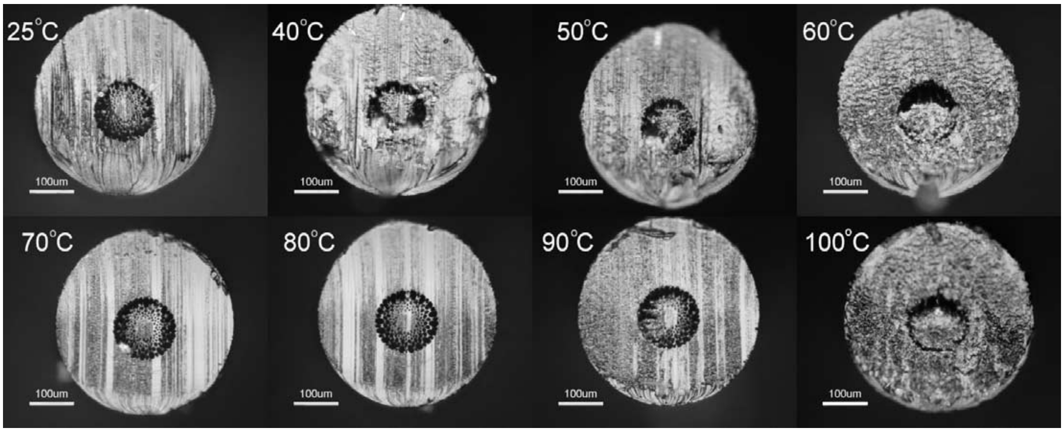

Fig. 10. End-faces cut at increasing platen temperatures from 25 to 100 °C with a blade temperature of 60 °C and a blade velocity of 0.05 mm/s.

but this is much finer than at 25 °C, the core is in position, and the fracture zone is now quite smooth and small. This sudden change in end-face appearance is felt to be due to a phase change in the PMMA, possibly related to the 'brittle-ductile' transition reported by Matsushige [6]. Acceptable surface quality is maintained until 80 °C. Above this temperature however the surface gradually deteriorates until by 100 °C it is as poor as at 60 °C.

6. Effect of blade speed

Platen temperature was restricted here to three 'good' levels (i.e., 70, 80 and 90 °C) with an additional series of cleaves at 65 °C to examine the sharpness of the suspected phase transition between 60 and 70 °C. Blade speed was varied from 0.03 to 7 mm/s. Fig. 11 shows the results obtained in a matrix form.

Despite a few anomalous results, the overall trend is one where acceptable quality end-faces are achieved with an increasing blade speed as the temperature rises. This observation is consistent with a requirement for a minimum localised cleavage force on the grounds that as the temperature rises so the material softens and a higher blade speed is needed to generate the force necessary to sever the atomic bonds within the PMMA.

End-face quality at 65 °C is good for low blade speeds (i.e., up to 0.2 mm/s), indicating that the transition previously postulated as being responsible for the smearing effect observed at 60 °C ends quite sharply.

7. Additional causes of surface damage

Fig. 12 is a close up of an end-face for a platen temperature of 80 °C, a blade temperature of 60 °C and a blade speed of 0.5 mm/s. The draw conditions for this fibre were such that significant distortion of the hole shapes has taken place during fabrication with a concurrent thinning of the walls between the holes. Despite this thinning process, the core is in position and in good condition, with walls of less than 1 μm thickness having survived the cutting process. Horizontal lines are visible on the end-face in both the core and cladding. These lines are 2–2.5 μm apart, a separation that suggests their origin as being the 2.03 μm movement of the stepper motor that drives the blade.

Fig. 5 clearly shows that the surface of a blade is not flat but displays grinding marks. To test the possibility that these could be an additional source of scoring on an end-face, the last 'nick' in a blade was located and photographed. This image was flipped horizontally, inverted to a negative to compensate for the fact that the blade faces the fibre,

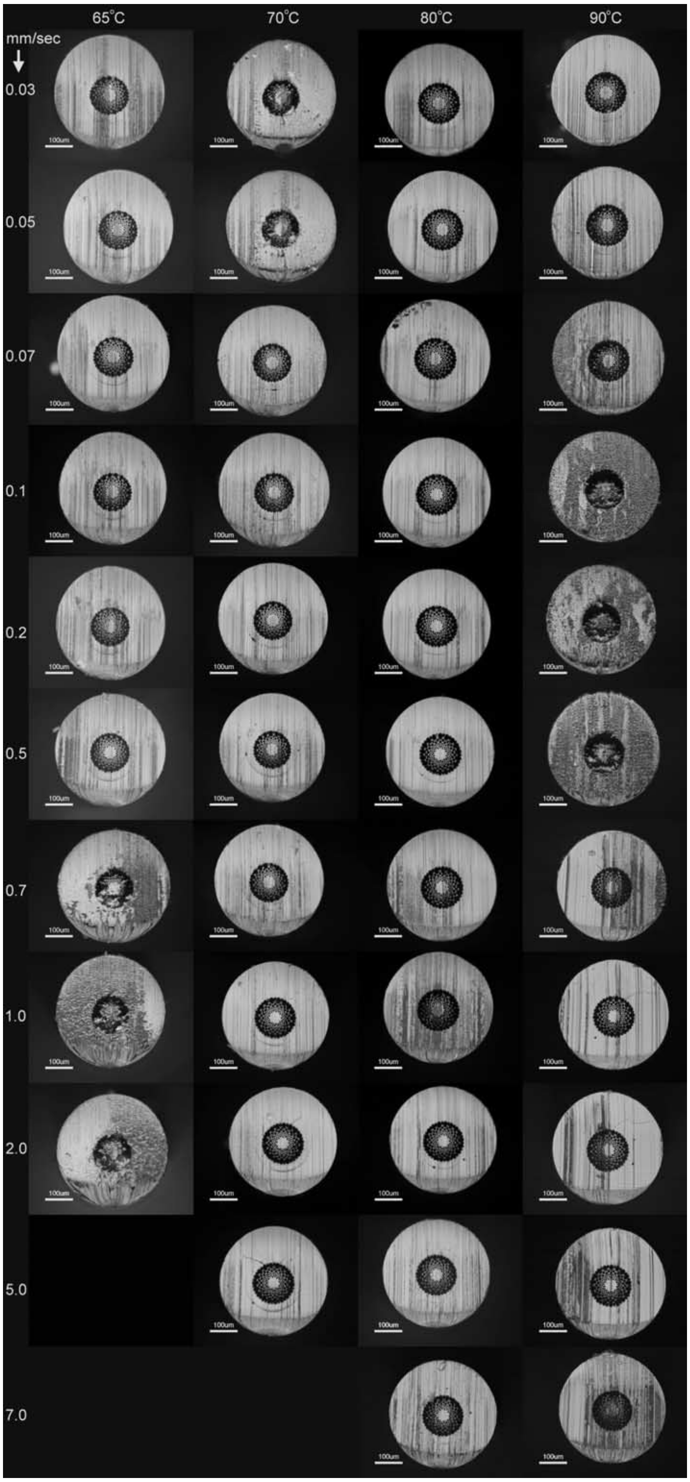

Fig. 11. Effect of blade speed on end-face quality for platen temperatures of 65–90 °C.

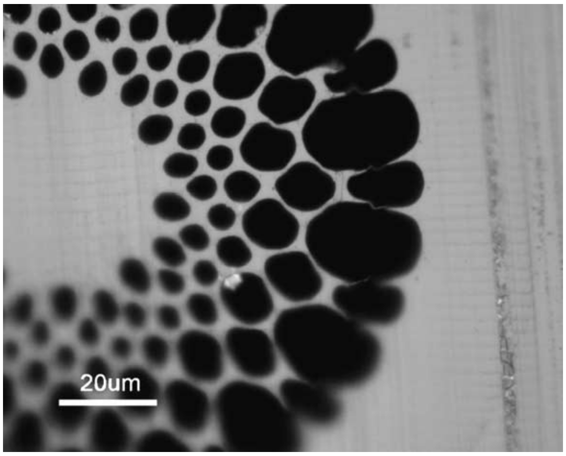

Fig. 12. Close up of the core region of an end-face cut with a platen temperature of 80 °C, a blade temperature of 60 °C and a blade speed of 0.5 mm/s.

then superimposed on the image of the last end-face to be cut (Fig. 13).

While not conclusive, the alignment of the grinding marks on the blade and the scoring on the end-face lends support to the possibility that the blades themselves are responsible for some of the damage to the end-face of a cut fibre.

8. Conclusions

This study has shown that it is possible to consistently cleave microstructured polymer optical fibres to produce an acceptable end-face via cutting with a fine blade. For the fibre used this process is ductile over the range of temperatures studied. The 'best' conditions identified for PMMA appear to involve the fibre temperature being above an apparent phase transition at around 60 °C. A platen temperature of 70 °C with the blade temperature around 10 °C higher would appear to be near optimum. Translation of the blade relative to the fibre is also essential to ensure that a virgin section of blade is used each time. It would also appear that to maintain end-face quality, blade speed should be increased with fibre temperature.

While these preliminary results were obtained for fibres fabricated under a wide range of conditions, the fibres used here for the detailed analyses were all drawn at relatively high temperatures and low tension, thus displaying a low level of anisotropy in their mechanical properties. Fibre drawn at lower temperature and higher tension does however display significant anisotropy and is prone to splintering, particularly when cut at low temperatures [10]. Work thus far on such fibre indicates that the anisotropy is significantly reduced as the platen (and thus the fibre) temperature increases and that it too can be successfully cut over the range 70–90 °C.

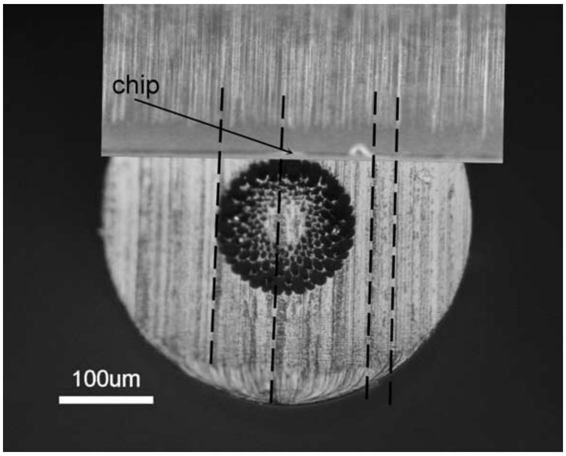

Fig. 13. The region around the last chip on a razor blade matched to the last fibre end face to be cut.

Planned extensions of this preliminary study include examining the effect of blade temperature and blade angle on end-face quality, as well as the impact of scoring on optical transmission through the end-face surface. The influence of mPOF fabrication conditions on the mechanical properties of the fibre will also be studied, particularly with respect to their effect on optimal cleaving conditions.

Acknowledgements

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