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Shrinking of bumps by drawing scintillating fibres through a hot conical tool

SciFi Project

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Abstract

The LHCb SciFi tracker will be based on scintillating fibres with a nominal diameter of 250 μm. A small length fraction of these fibres shows millimetre-scale fluctuations of the diameter, also known as bumps and necks. In particular, bumps exceeding a diameter of about 350 μm are problematic as they can distort the winding pattern of the fibre mats over more extended regions. We present a method to reduce the diameter of large bumps to a diameter of 350 μm by locally heating and pulling the fibre through a conical tool. The method has been proven to work for bumps up to 450 – 500 μm diameter. Larger bumps need to be treated manually by a cut-and-glue technique which relies on UV-curing instant glue. The bump shrinking and cut-and-glue processes were integrated in a fibre diameter scanner at CERN. The central scanning and bump shrinking of all fibres is expected to minimise bump related issues at the four mat winding centres of the SciFi project.

1. Introduction

The LHCb Scintillating Fibre (SciFi) tracker will be based on round scintillating fibres of type Kuraray SCSF-78 with a nominal diameter of d_n = 250 μm. The fibres, as delivered by the supplier, show certain diameter variations on a length scale of centimetres, referred to as bumps ($d > d_n$) and necks ($d < d_n$), which potentially compromise the packing pattern, when such fibres are wound to staggered multi-layer mats. The winding pitch is 275 μm, leaving a gap of 25 μm on either side to the adjacent fibre [1]. Experience has shown that bumps up to 0.35 mm diameter cause only minor local deteriorations of the winding pattern.

Bumps, as defined above, are to be distinguished from diameter variations on larger length scales (tens of centimetres or metres), which can be caused during the fibre production by glitches in the regulation of the drawing speed and temperature. Such diameter variations are observed very rarely.

There is a number of phenomena which can lead to bumps:

1. Inclusion of solid particle (e.g. a splinter of glass), in the core and/or cladding of the fibre.
2. Inclusion of soft (organic) material (e.g. a cotton fibre or a dust particle).
3. Non-uniformities in the core and cladding base materials.

While the first two sources of bumps have been reduced by the fibre producer by taking effective measures at the various process steps, the third source has been addressed by attempts to obtain ingredients of higher purity, but could not be fully eliminated.

Up to now, bumps with diameters exceeding 350 μm were foreseen to be handled during fibre winding at the four SciFi winding centres. Two methods have been developed at winding centres.

The first method consists of cutting out the bumpy fibre section by choosing the cut positions such that they fall into the zone in which the completed (polymerised) fibre mat will be transversely cut in order to release the mat from the wheel. In this case, the two respective fibre ends need only to be aligned geometrically but not form an optical joint. The loose fibre pieces are attached by cyanide super glue to the adjacent fibre on the winding wheel.

The second method consists in cutting the bumpy section a few tens of centimetres before the winding wheel. The two ends are geometrically aligned and joined head-on by cyanide super glue. Both methods interrupt the winding process for about 10-15 minutes and bear a small but controllable risk to pollute the winding machine with glue, damage the already wound fibres or form a new bump consisting of excess glue.

2. A new method to shrink the bump diameter

In the following we describe an alternative approach to reduce the diameter of a bump to an acceptable limit rather than eliminating it. First rudimentary attempts to reduce the bump diameter consisted in heating the tensioned fibre with a hot air blower. However they proved unsuccessful as the position and temperature of the heated spot could not be controlled well enough.

Recently we developed a method which consists in drawing the fibre through a hot drawing tool (see Figure 1) with a conical profile at the entrance and a well-defined minimum diameter of d1 = 0.35 mm. Similar tools are used for industrial wire drawing. Bumps exceeding this diameter will become temporarily stuck in the entrance cone. The tool is kept at a constant temperature of about 100°C. Starting from the contact surface the fibre will heat up and soften thanks to the thermoplastic nature of polystyrene and polymethylmethacrylat (core and cladding materials). Under a pull force of about 100 cN the fibre will start to creep through the hole, which reduces the maximum fibre diameter to about 0.35 mm.

It is clear that the method will fail if the bump diameter largely exceeds the hole diameter. Furthermore, bumps containing inclusions, particularly solid ones like glass bits, will most likely not shrink but remain stuck and eventually break. Finally, the method will also fail for long segments with excess fibre diameter (resulting e.g. from process regulation issues). A solution to these limitation is discussed in section 5.

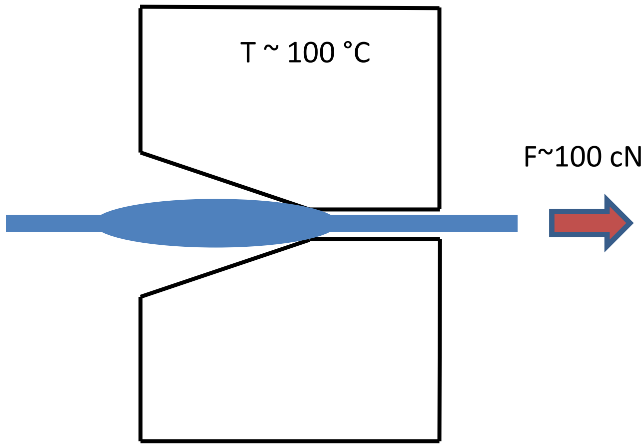

Figure 1: Principle of bump shrinking by means of a hot drawing tool.

3. Technical realisation

The drawing tool

The feasibility of the method was demonstrated with a manual tool containing a set of conical holes with graded diameters. Such tools are used in jewellery making for the thinning of gold wires. A set of tests allowed to find the temperature and tension ranges for successfully shrinking a bump.

For a dedicated set-up, which could potentially be integrated in the fibre diameter scanner, a specialised wire drawing tool was purchased. An illustration of such a drawing tool is shown in Figure 2. The inner part, the so-called die nib, is made of tungsten carbide and has a conical hole with the smallest diameter of d1=350 µm. The die nib is press fitted in an outer ring with an outer diameter of 28 mm. The tool is mounted in a cylindrical heating element (150 W) which allows to keep it at constant temperature.

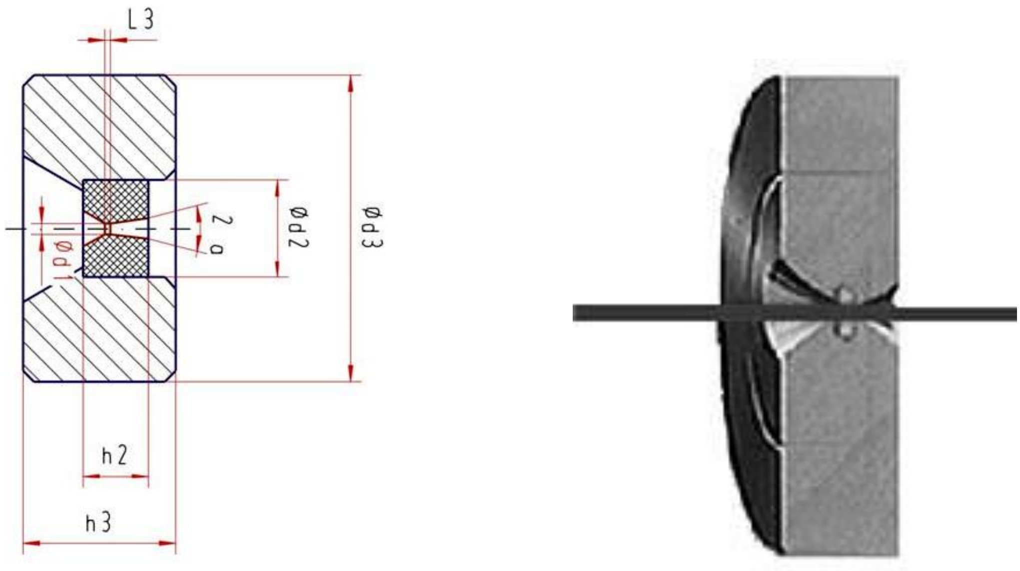

Figure 2: Illustration of typical geometries of wire drawing tool. The drawing direction is from right to left.

Integration and automation in the fibre diameter scanner

The bump shrinking set-up, shown in Fig. 3, consists of the heated drawing tool and a set of three wheels (D = 10 cm). The fibre runs at moderate speed from left to right towards the rewinding spool. The middle wheel is mounted on a pivoting arm. The mass of the arm is adjusted such that it requires a force of 200 cN (200 gram) to lift it. If a bump becomes stuck in the tool, the arm lifts up and creates a tension in the fibre of 100 cN. At a height of approximately 10 mm, the lifted arm opens an electrical contact which leads to the abrupt stop of the rewinding motor (and also of the small feeder motor which ensures proper side-by-side placement of fibres on the spool). The unwinding motor, not shown in the sketch, acts accordingly to maintain a tension of 50 cN upstream of the drawing tool. As soon as the heated fibre has sufficiently softened and the fibre can creep through the tool, the arm lowers and all motors restart. The whole shrinking process takes typically 1 s.

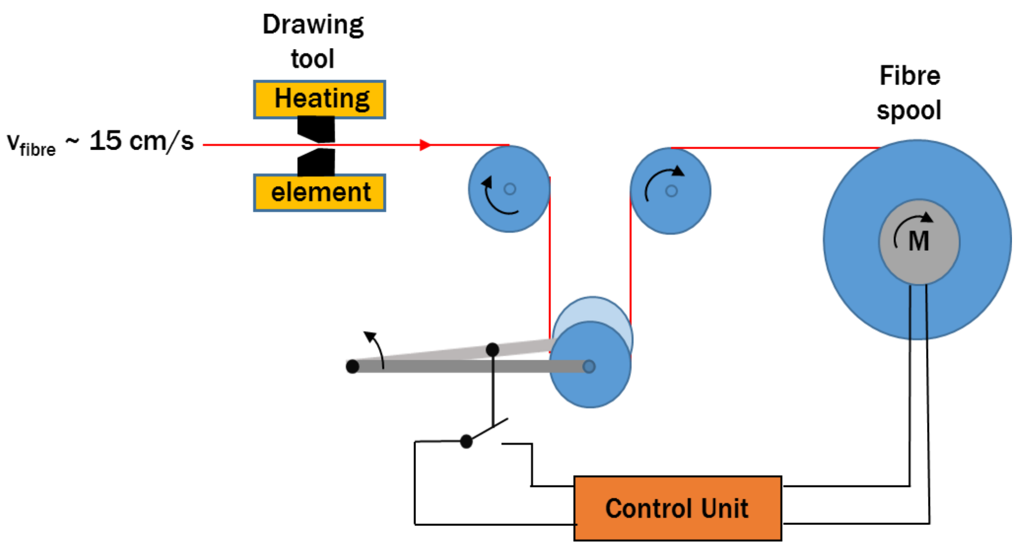

Figure 3: Illustration of the bump shrinking set-up.

As shown in Figure 4, the bump shrinking set-up was integrated in the fibre diameter scanner [3]. It was placed in between the Lump & Neck Detector (LN) and the AccuScan (AS) Laser Micrometer. In case the LN detects a variation of the fibre diameter of more than ±25 μm, it triggers a reduction of the fibre speed from 100 cm/s (nominal speed) to 15 cm/s. The chicane (not visible in Figure 4) ensures a delay of several seconds such that the bump will run into the hot drawing tool at a speed of 15 cm/s.

After the shrinking, the bump passes – still at the reduced speed of 15 cm/s – the Laser Micrometer and its diameter profile is precisely recorded.

The control of the bump shrinking set-up is integrated in the micro processor based control system of the fibre diameter scanner. This allows to tune speed and time delay in order to optimise the shrinking process. The programme also foresees a so far not implemented option, namely to remove during the bump shrinking process the default tension of 50 cN which pulls the fibre backward through the drawing tool and which has to be overcome by the 100 cN generated by the lifting arm.

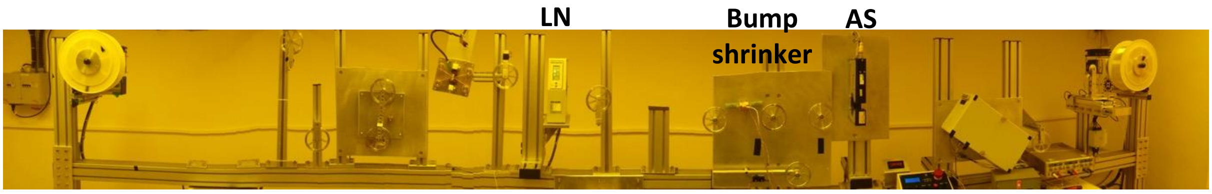

Figure 4: Panoramic photo of the fibre scanner at CERN after the installation of the bump shrinker. The set-up extends over a width of 6 meters.

The temperature of the drawing tool is controlled by a separate PID regulator. It features a ramp function which is set to a slope of 25 K per minute. The ramp of the temperature setpoint avoids overshoots when the temperature of the tool is raised from ambient to 100°C. A Pt100 sensor is tightly positioned in a hole drilled into the drawing tool. A temperature of 100°C has found to be optimal for the bump shrinking process. Lower and higher temperature were tested leading in both cases to unsatisfactory result: 90 °C was insufficient to soften the fibre, while temperatures higher than 110 °C caused excessive damage to the fibre geometry.

4. Results

The typical diameter profile of a shrunk bump shows a neck at the position where it had previously the largest diameter. Under the applied tension, the soft fibre elongates by typically a few mm. It appears that the fibre is reshaped without changing its volume. In order to visualise the effect of the bump shrinking method we plot the diameter of the fibre, as measured by the AccuScan and assume that the fibre to be fully symmetric.

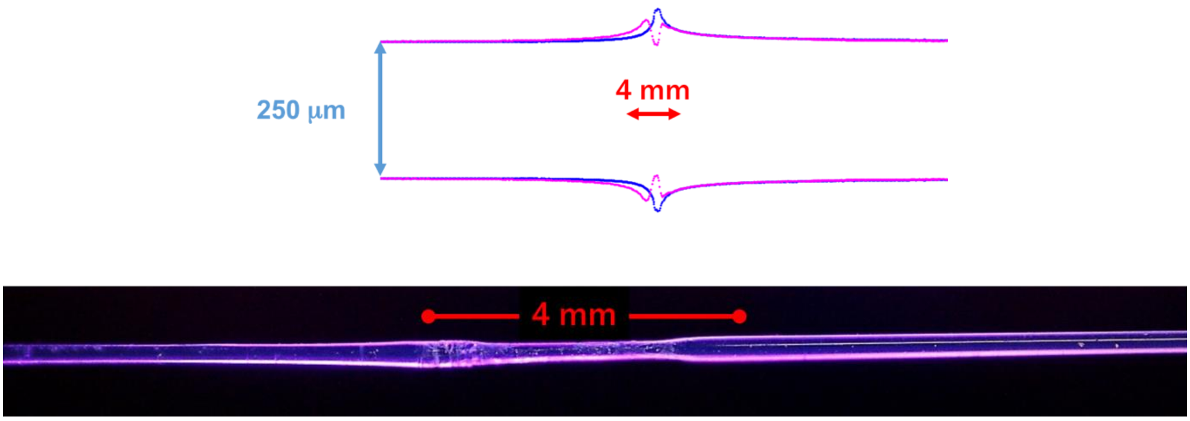

Figure 5: Fibre bump before (blue) and after (magenta) shrinking. The profile was measured by the laser micrometre and, after the shrinking, a photo was taken with a microscope. Please note that plot and photo do not show the same length segment of the fibre.

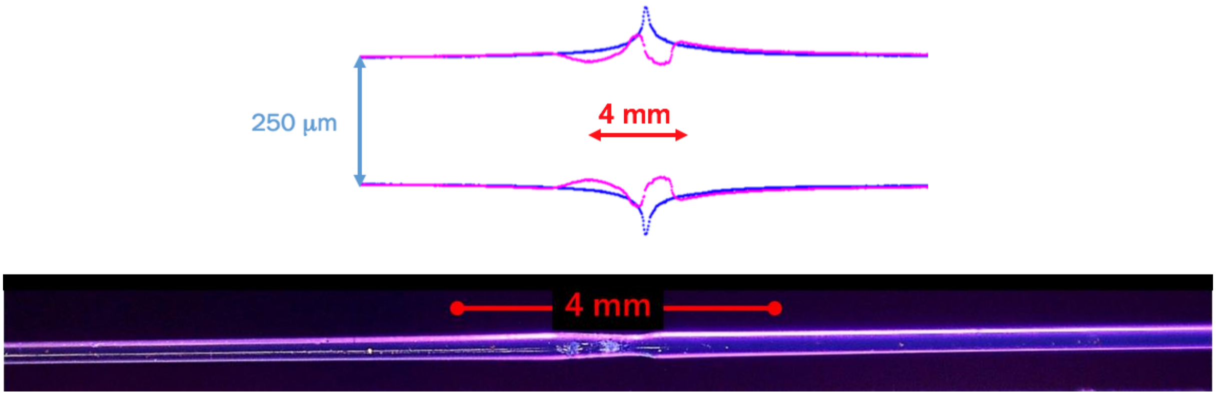

Figure 6: A further example of a bump before and after shrinking.

Figures 5 and 6 show two measurements of bumps before and after the shrinking process. Note that the x and y-scale of the drawings are very different, such that the fibre appears much thicker than in reality. In addition, photos of the shrunk fibre were taken with a microscope, where the fibre was excited with UV light (390 nm). The amount of luminescence light leaking out of the fibre is small, which proves that the light guiding mechanism of the fibre remains largely unaffected.

Single versus double tool

In a 12.5 km spool, 10-20% of the bumps have a diameter larger than 450 µm. In order to treat as well this category of bumps, the initial plan was to install two tools in sequence with d1 = 400 µm and d1=350 µm, respectively. The tools were mounted one after the other in a common heating element. Experience showed that if a bump becomes stuck in one of the tools, the fibre touches also the hot wall of the other tool which may produce necks at previously 'bump-free' sections, as shown in Figure 7.

Bump shrinking with a single tool of 350 µm inner diameter has proven to work for bumps up to 450 and often even up to 500 µm. Figure 8 shows a typical example.

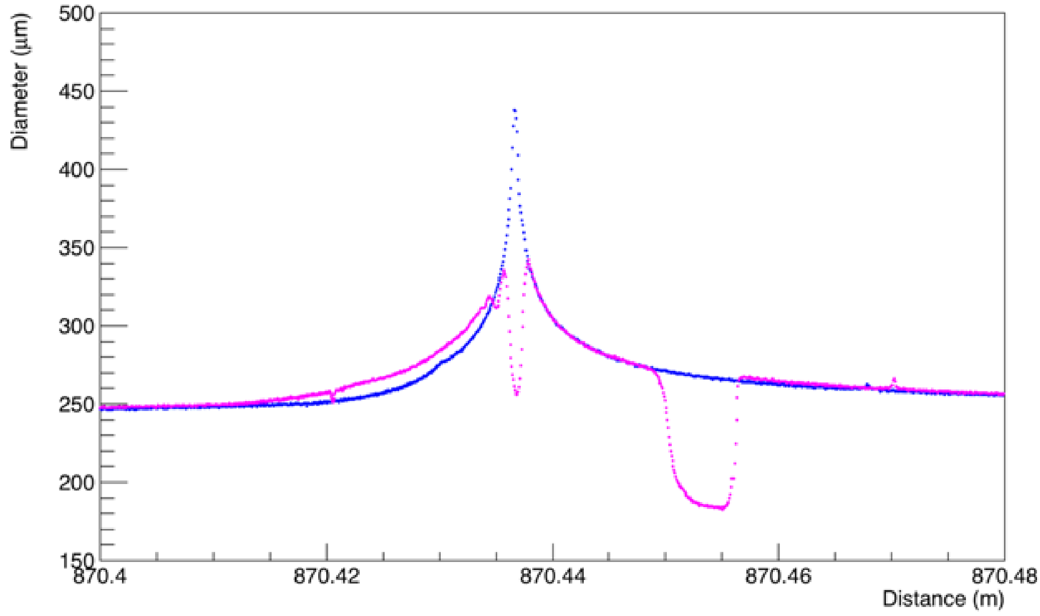

Figure 7: Measured fibre diameter profile before (blue) and after (magenta) bump shrinking with a double tool. The collateral damage in form of a neck at 870.45 m is clearly visible.

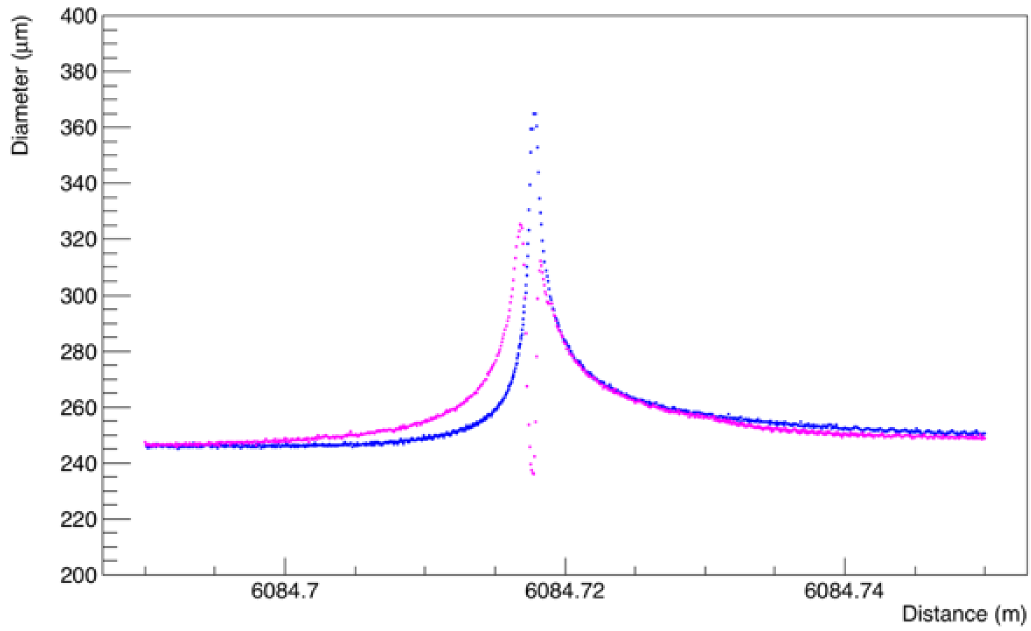

Figure 8: Measured fibre diameter profile before (blue) and after (magenta) bump shrinking with a single tool. The shrinking process reduced the height of the bump and also slightly elongates the fibre. The diameter of the central neck, here at 6084.72 m, is usually comparable to the nominal fibre diameter.

Success rate

While testing the bump shrinking procedure, 80-90% of the bumps with a maximum diameter of 450 – 500 μm were successfully removed. A strict diameter limit cannot be specified, since also length, shape and roundness of the bump play a role. However, there are three categories of bumps which generally fail to be shrunk:

- Bump larger than 450 – 500 μm: the bump remains stuck in the tool for tens of seconds without minimal progress. Usually, after some time the fibre breaks.
- Long bumps: bumps exceeding a diameter of 350 μm over a length of more than a few mm, have difficulties to creep though the tool as the amount of material to be reshaped is too large.
- Filled bump: if a bump contains solid particles, like e.g. bits of glass, it will not be able to shrink and remains stuck in the tool.

The limited experience which we could collected so far, shows that 80-90% of the bumps exceeding 350 μm diameter are shrinkable without manual intervention. On a 12.5 km spool, as delivered by Kuraray, we find typically between 0 and 3 bumps which fail to be shrunk and require to be dealt with manually (see sec. 5).

Light loss across a shrunk bump

The light losses across shrunk bumps was assessed by performing an attenuation length measurement [1]. For this purpose three fibre samples of 3 m length were selected which contained each a shrunk bump with an original (before shrinking) diameter above 350 μm. The plots in Figs. 9 - 11 show the measured photocurrent as a function of the excitation distance for the three samples. In each plot the green points were fitted with one exponential and the red points were fitted with another exponential, while the blue points are not fitted. The light leak Δ at the position of the bump derived from the difference of the photocurrent values extrapolated from the two fitted curves before and behind the bump. The resulting light leaks were consistently found smaller than 20%, which corresponds to a light transmission bigger than 80%.

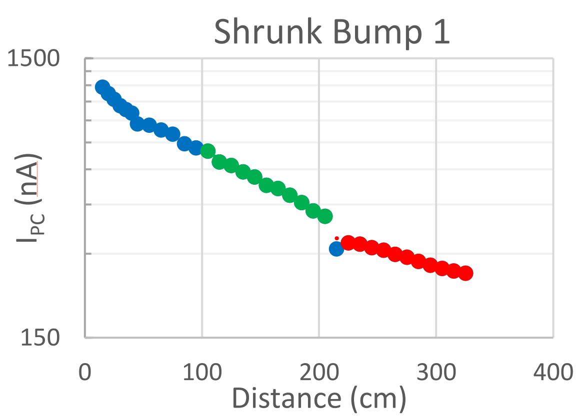

Figure 9: Photocurrent as function of the excitation distance for the first fibre sample. Δ = 50 nA = 12.5%.

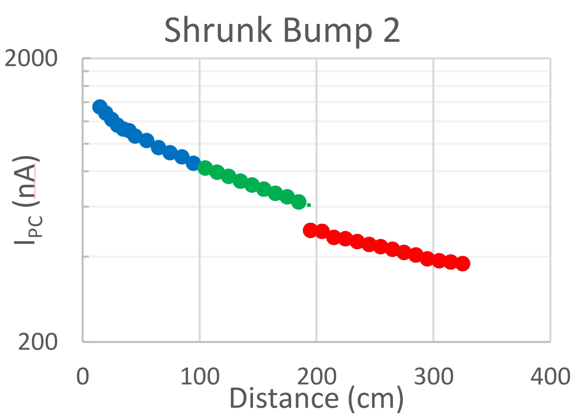

Figure 10: Photocurrent as function of the excitation distance for the second fibre sample. Δ = 110 nA = 18%.

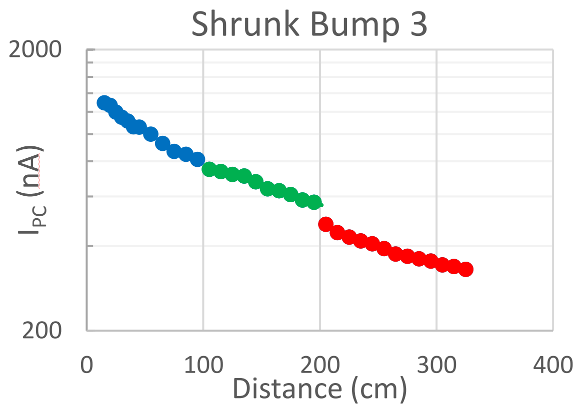

Figure 11: Photocurrent as function of the excitation distance for the second fibre sample. Δ = 100 nA = 18%.

Pull tests

The mechanical strength of the fibre pieces containing shrunk bumps was tested. The test was performed using the three fibre samples described above and a fine-scale force gauge as illustrated in Figure 12. The fibre was fixed on a spool at one extremity and on the force gauge on the other extremity. A force was applied on the force gauge until the fibre broke. In all three cases the force at break was above 300 cN. The fibre never broke at the bump position, but rather at the extremity of the sample. This is explained by the fact that the diameter of the fibre at the bump is usually larger than nominal and the fibre therefore more resistant. As pointed out by the fibre producer[1], a further strengthening effect may come from the combined application of heat and tension. The polystyrene chains will align themselves to the fibre axis and improve the mechanical properties of the fibre. The fibre becomes what is usually referred to as an S-type fibre

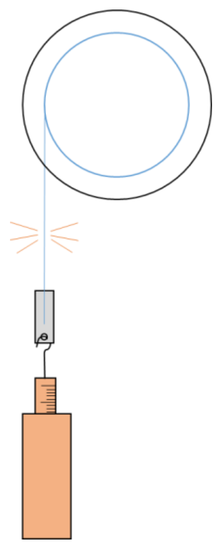

Figure 12: Illustration of the fibre's mechanical strength measurement.

[1] O. Shinji, Kuraray Co. LTD, private communication May 2016.

5. Limitations and solutions

As described earlier, the bump shrinking method fails for certain large or long bumps. We developed a cut & glue method, which relies on a UV curing instant glue. In addition to its superior tensile strength of approximately 20 N/mm^2 (this is about double the value of a standard cyano acrylate glue), the glue offers the possibility to optimise the glue quantity and to precisely align the fibre ends (with glue applied) before the activation of the curing.

The method consists of the following steps: Once the defect is stuck in the drawing tool, the scanner is put on hold and the heating of the drawing tool is switched off. The defect is removed from the fibre by a simple scissors cut, however the two fibre ends are then treated with a guillotine-like fibre cutter which produces orthogonal cuts of reproducible quality. As soon as the drawing tool temperature has fallen below 60°C, the fibre can be threaded through the drawing tool and the two ends mounted on a 2-stage x-y table, which allows for a precise head-on alignment of the two ends (see Figure 13). A small amount of UV curing glue[2] is applied to both fibre ends and the fibres ends are brought gradually in contact. The amount of glue and its distribution as well as the alignment of the fibre ends are controlled via a USB microscope and can still be corrected (within 1-2 minutes). The curing is initiated by exposing the glue to a 300 mW UV light source[3], emitting at 365 nm. The typical exposure time is 12 – 15 s at a distance of about 1 cm. A typical gluing sequence is shown in Figure 14.

A series of pull tests, shown in Figure 15, revealed an average force at break of about 130 g. This represents a reasonable safety margin considering the standard pull force during spooling and fibre mat winding of 50 g.

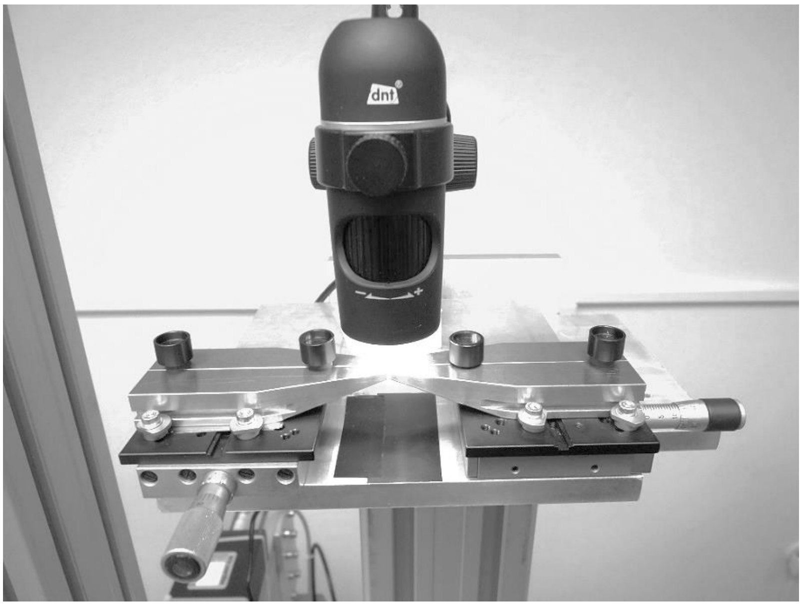

Figure 13: Gluing station consisting of two translation tables (in x–y configuration) and a USB microscope. The fibres are held by soft magnets in the V-grooves of the two mounting plates.

[2] Loctite 4305 LC
[3] APM UV – Cure (LED 365 nm), APM Technica, CH-9435 Heerbrugg, Switzerland.

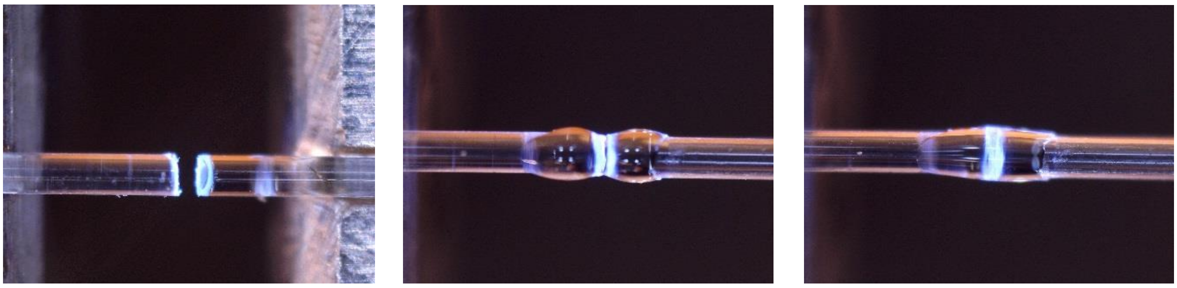

Figure 14: Alignment and glue distribution at the glue joint. The slight glue excess leads to a formation of a sleeve-like reinforcement, which improves the stability. In order not to act as bump, its total diameter must stay below 350 μm.

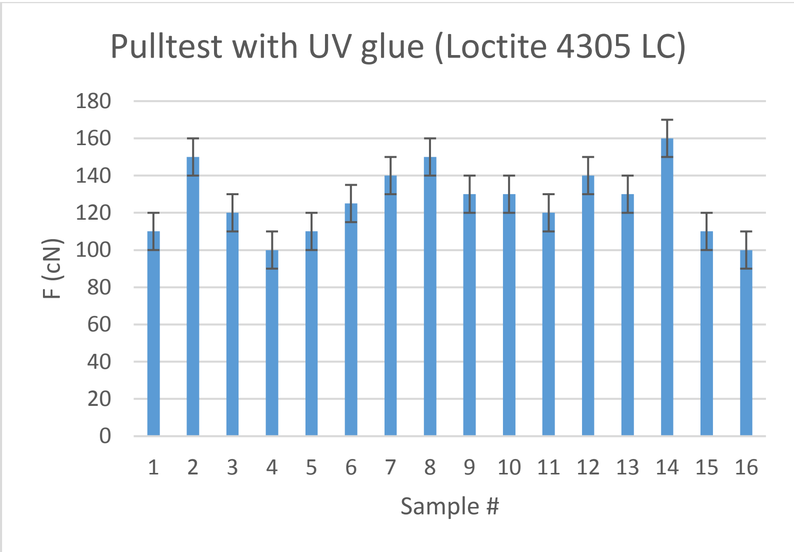

Figure 15: Force at break (cN) of fibre joints glued by UV curing Loctite LC 4305 glue.

6. Exclusion of adverse effects on the fibre properties

The bump shrinking method implies that the complete fibre (i.e. the full 12500 m length of a spool) passes through the hot tool. During most of the time the fibre passes at relatively high speed of about 1 m/s. The region of about 1 m before and after the bump passes at a speed of about 15 cm/s. Even if the tool is well aligned to the theoretical fibre axis, it cannot be excluded that the fibre touches the hot tool wall as the nominal clearance is only 50 μm. The length of the contact zone L3 (see Fig. 2) is less than 1 mm, i.e. the contact time at the slow speed of 15 cm/s is below 10 ms.

Before applying the bump shrinking method during the series production of the fibres (11’000 km), any negative impact from the mechanical contact with the tool and the temporary heating on the fibre properties had to be excluded. The critical fibre parameters are the attenuation length and the light yield following ionising radiation. Both could degrade from overheating the fibre. Furthermore, the integrity of the 2 x 7.5 μm thick cladding structure which could be affected by scratches or detaching from the core. This would lead at the same time to a change of the fibre diameter. Lastly, the mechanical stability of the fibre could degrade due to thermal or geometrical effects.

All possible degradations and failures were investigated and found to be insignificant (see [4]).

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