OPTIMISATION OF HOLLOW GLASS FIBRES AND THEIR COMPOSITES

Mr. Martyn J.Hucker and Dr. Ian P. Bond

Department of Aerospace Engineering, University of Bristol,
Queen's Building, University Walk, Bristol. BS8 1TR.. U.K.

SUMMARY: Hollow glass fibre reinforced plastics have a structural performance niche in a class of their own. They offer increased flexural rigidity compared to solid glass fibre reinforced plastics, they offset the need for thin sandwich construction which is both difficult and expensive, and they provide an opportunity to develop laminates with improved or tailored characteristics. An experimental hollow glass fibre manufacturing facility is in operation at the University of Bristol. The facility is capable of drawing precision hollow glass fibres of various diameters with varying degrees of hollowness under precise parameter control. Hollow borosilicate glass fibres have been manufactured from tubular preforms with a variety of internal and external diameters which correspond to a range of hollowness values. In all cases, the resulting hollowness was reduced from that present in the preform state, regardless of drawing rate or furnace temperature. In fact, temperature has been demonstrated to be of paramount importance in controlling fibre hollowness due to the interaction between glass viscosity and surface tension effects. These results suggest that for a given temperature and draw rate there is a single condition where fibre hollowness is maximised and external diameter minimised.

KEYWORDS: hollow glass fibres, manufacture

INTRODUCTION

Hollow glass fibre reinforced plastics have a structural performance niche in a class of their own [1, 2, 3]. They offer increased flexural rigidity compared to solid glass fibre reinforced plastics (GFRP), they offset the need for thin sandwich construction (GFRP/syntactic foam/GFRP) which is both technically difficult and expensive, and they provide an opportunity to develop laminates with improved or tailored thermal insulation or sound attenuation characteristics.

Hollow glass fibres can be successfully manufactured and have been (but are no longer) commercially available [4]. Their useful mechanical properties mean that they are not wholly parasitic plies if combined with other types of higher performance laminate. However, the variability in fibre hollowness/concentricity and availability in only one geometrical form has limited their more widespread development.

Analytical and Finite Element modelling has shown that gains of greater than 200% in specific rigidity and transverse strength could be available by tailoring the combinations of fibre hollowness and matrix [5, 6]. Gains in rigidity are provided by the increase in section second moment of area for a given mass of glass reinforcement whereas gains in transverse strength are provided by the reduction in stress concentration between the fibre and matrix through elliptical deformation of thin wall hollow fibres. Recent work [7] has also shown their impact damage tolerance to be better than for an equivalent solid fibre system due to an energy absorbing mechanism whereby fibres are crushed under impact load.

An experimental hollow glass fibre manufacturing facility has been created at Bristol through prior collaborative work with DERA Farnborough [5]. The facility is capable of drawing precision hollow glass fibres of various diameters with varying degrees of hollowness under precise parameter control. Fig. 1 shows a cross section of some previously manufactured hollow silica fibres viewed using optical microscopy [5].

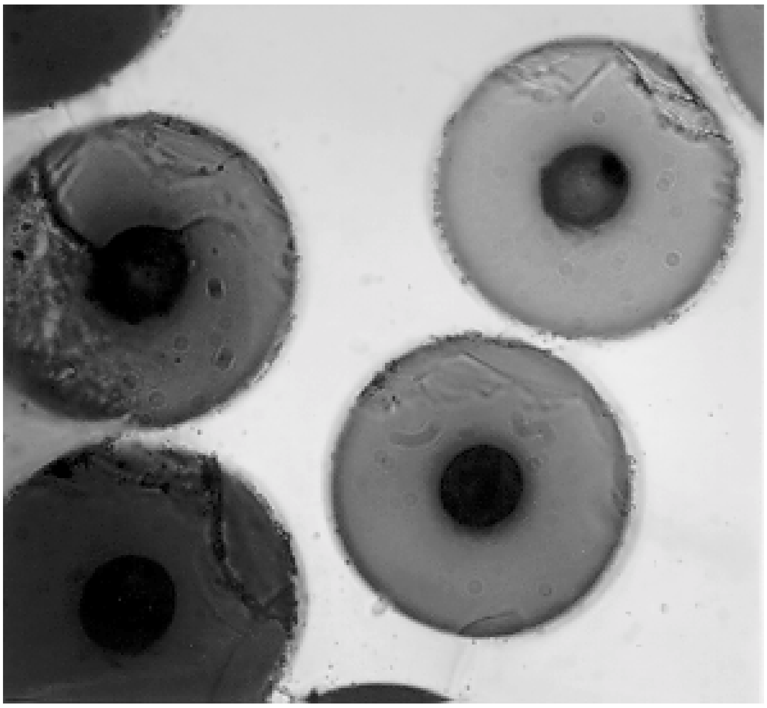


Fig. 1: View of 60μm external, 18μm internal diameter hollow silica fibre cross-sections using optical microscopy [5].

Building on previous experience, the current research effort is concentrating on the manufacture of continuous, consistent and concentric hollow filament from borosilicate glass. This was chosen as it is similar in composition to commercial glass fibres and affords more scope for process development. In addition, it is intended to adapt the manufacturing rig to produce a glass/epoxy 'pre-preg' tape for fabrication into test coupon material. Mechanical and physical properties of both fibre and composite are being characterised as part of a continuous feedback into the fibre development process.

Several investigations are currently underway into the unique characteristics of hollow fibres. For example, a study is being made of their dynamic behaviour for the development of highly damped or compliant composite systems. Efforts are also being made to fill the hollow cores with constituents which have additional functionality. It has already been shown that glass fibres with fine conducting metal cores [8] or particulate second phases [9] can be produced.

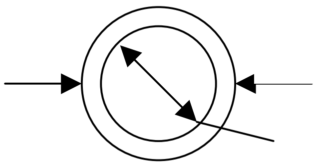
THEORY

Specific flexural rigidity and strength

From the analysis of hollow fibre composites by Burgman [2] and subsequent work by Watson [5] and Watson and Farrow [6], the flexural rigidity of a composite beam of width *b* and thickness *t*, which contains hollow fibres is given by:

$$R_h = \frac{E_s^*.b.t_s^3}{12\left(1-K^2\right)^2} \qquad (1)$$

where $E_s^* =$ effective modulus of the solid fibre laminate and
the fibre hollowness ratio is given by (refer to Fig.2):



$$K^2 = d^2 \big/ D^2 \qquad (2)$$

Fig. 2: Schematic of fibre cross-sectional dimensions

It can also be shown that the relative rigidity ratio (hollow to solid for equivalent glass mass) is given by:

$$\frac{R_h}{R_s} = \frac{1}{\left(1-K^2\right)^2} \qquad (3)$$

Because $\left(1-K^2\right) \leq 1$ we can conclude that for the same weight of glass, a hollow fibre composite will increase the rigidity and critical load at which buckling occurs.

The maximum bending stress ratio (hollow to solid) can be derived as:

$$\frac{\sigma_{\max h}}{\sigma_{\max s}} = \left(1-K^2\right)^2 \qquad (4)$$

and the ultimate strength ratio (hollow to solid) as:

$$\frac{\sigma_{ult\_h}}{\sigma_{ult\_s}} = \left(1-K^2\right) \qquad (5)$$

Table 1 summarises the gains for hollow fibre composites based on the above derivations. It shows that hollow fibre composites are more rigid and can withstand higher bending moments than solid fibre composites. For example, at a hollowness ratio of 0.5, a composite containing these fibres will be 300% more rigid and able to withstand a 100% increase in bending moment before failure occurs with only a slight increase in composite weight due to interstitial resin within the fibres.

Table 1: Comparison of relative property values for hollow and solid fibre composites.[6]

Relative values (hollow / solid)		
Hollowness Ratio (K^2)	Rigidity	Max. bending strength / Ult. tensile strength
0.0	1.00	1.00
0.1	1.23	1.11
0.2	1.56	1.25
0.3	2.04	1.43
0.4	2.78	1.67
0.5	4.00	2.00
0.6	6.25	2.50
0.7	11.11	3.33
0.8	25.00	5.00
0.9	100.00	10.00

Transverse strength

It has been suggested by Niederstadt [3] that under loading in the transverse direction, thin walled hollow fibre composites can deform elliptically (Fig. 3), reducing stress concentrations at the interface and consequently reducing interface cracking. Furthermore, with hollow fibres there is the potential to be able to match fibre geometry with the matrix deformation behaviour thus allowing a significant reduction in interfacial stress concentration. Watson [5] and Watson and Farrow [6] have used Finite Element Analysis techniques to make predictions of how effective this deformation could be in reducing fibre/matrix interfacial shear stresses in a composite.

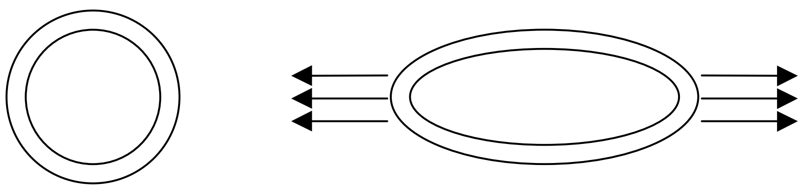


Fig. 3: Elliptical deformation of thin walled fibres under transverse load.

Boniface *et al.* [7] made a comparative study of the compression after impact behaviour of hollow, solid and hybrid glass fibre composites. They concluded that impact induced damage was reduced in all-hollow and hybrid laminates with hollow surface plies, due to transverse crushing of the hollow fibres during impact.

EXPERIMENTAL

Fig. 4 shows a schematic diagram of the main components in the fibre drawing rig at Bristol University. The fibres are manufactured by drawing down hollow glass preforms which pass through a graphite element tube furnace. Accurate dimensional control of the resulting fibres is achieved by balancing viscous flow and surface forces using careful temperature, preform feed rate and fibre draw rate selection. A ‘size’ layer, consisting of silane coupling agent, coating compound and lubricant, is applied to the fibres immediately after drawing to minimise any surface contamination or damage. Drawn fibre is incrementally laid down on a large rotating drum.

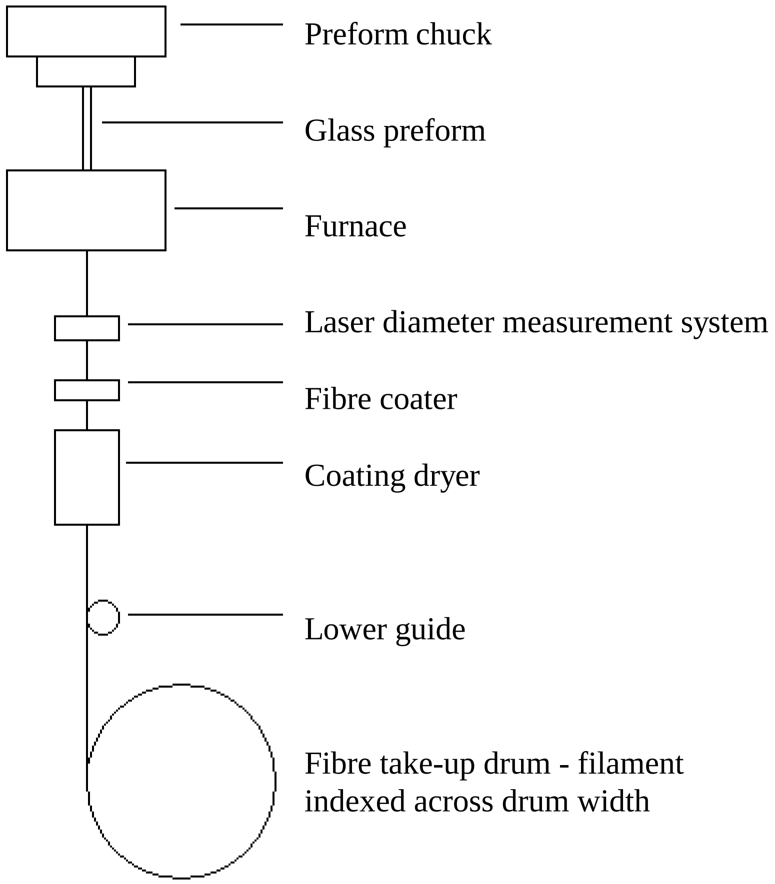


Fig. 4: Schematic of the main components of the fibre drawing rig.

The drawing tower utilises a non-parametric analogue control system for setting of the various processing parameters, calibration of which has been performed by experimental measurement. Furnace temperature is measured by a pyrometer which also acts as feedback for the furnace controller. Fibre external diameter measurement is performed in real-time with a laser diameter measurement system. A PC based system is currently under development which will upgrade the existing control and measurement methods. This will allow on-line monitoring and recording of preform feed rate, fibre draw rate, furnace temperature and fibre external diameter. Techniques for estimating draw tension in the fibre and internal diameter are also being examined.

RESULTS AND DISCUSSION

Fig. 5 is an SEM micrograph showing a bunch of fibres with external diameter of 55μm and hollowness ratio of 55% drawn from an 18mm external/15.3mm internal diameter hollow preform at a temperature of 1400°C. The concentricity of the bore with the fibre axis and the regularity and uniformity of the fibres are all clearly visible. Fig. 6 shows fibres drawn from an identical preform but at a higher temperature of 1580°C. The resulting fibres are of approximately the same external diameter, 54µm, but hollowness is much reduced to 11%.

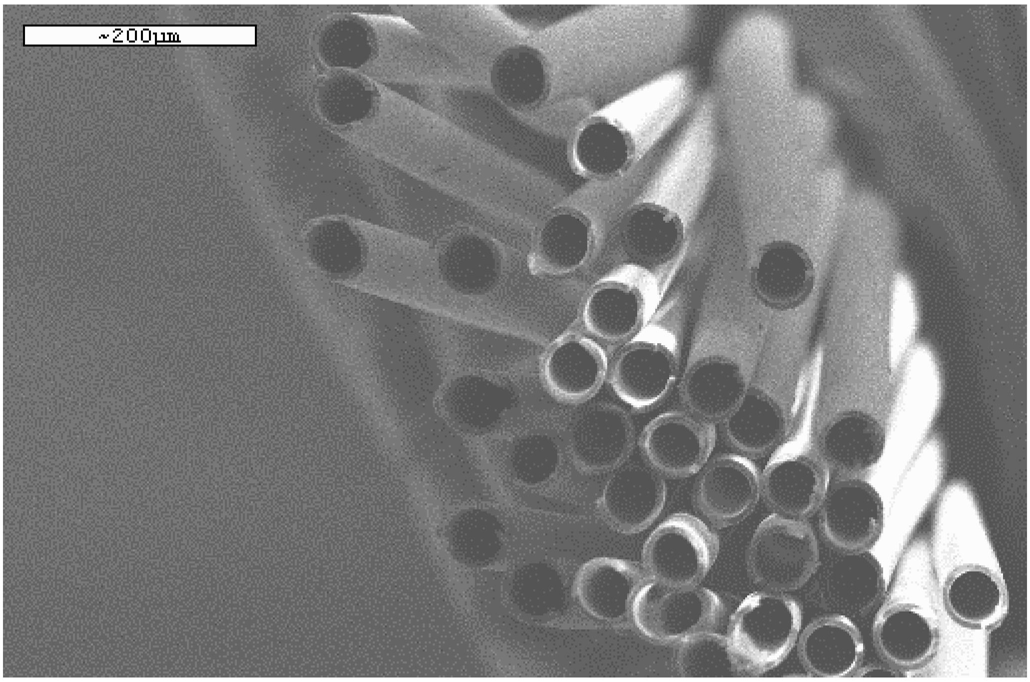


Fig. 5: SEM micrograph of borosilicate glass hollow fibres of 55µm external diameter, drawn from 1.3 mm wall thickness preform with external diameter of 18 mm at 1400°C. The fibre has a hollowness of 55%.

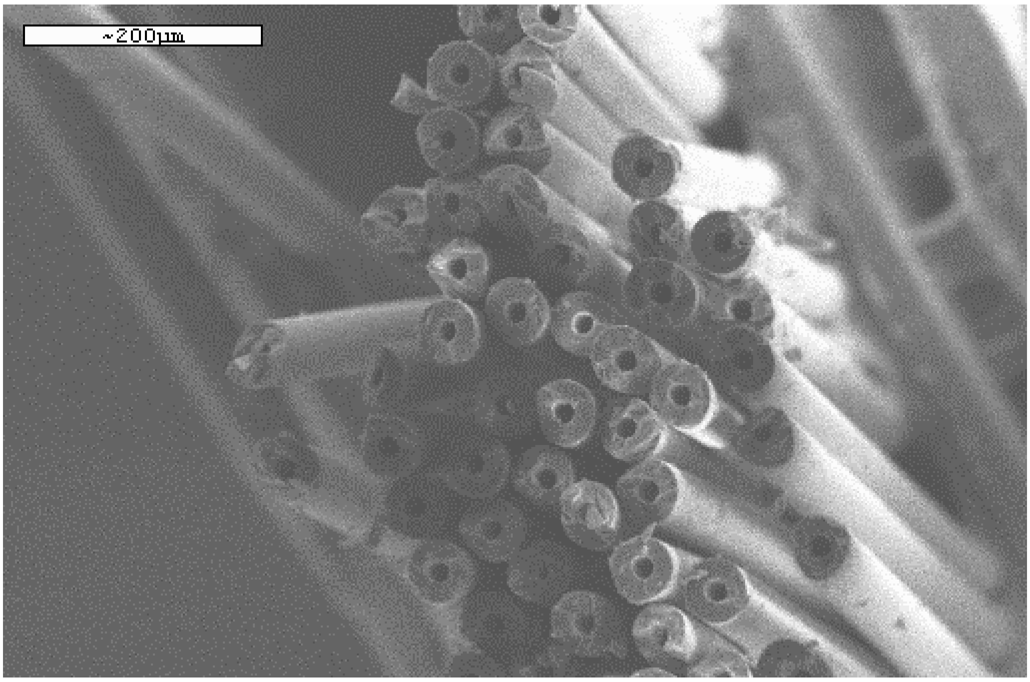


Fig. 6: SEM micrograph of borosilicate glass hollow fibres of 54µm external diameter, drawn from 1.3 mm wall thickness preform with external diameter of 18 mm at 1580°C. The fibre has a hollowness of 11%.

Table 2: Details of hollow borosilicate fibres so far manufactured.

Preform OD / ID (mm)	Preform K^2 ratio (%)	Fibre OD (μm)	Fibre ID (μm)	Fibre K^2 ratio (%)	$\frac{\text{Fibre } K^2}{\text{Preform } K^2}$	Draw rate (ms^{-1})	Feed rate (mms^{-1})	Temp (°C)
18/12.5	48.2	105.0	68.0	41.9	0.85	0.67	0.0500	1400
18/12.5	48.2	70.0	47.0	45.1	0.91	1.47	0.0250	1460
18/12.5	48.2	40.0	20.0	25.0	0.51	4.1	0.0125	1480
18/15.3	72.3	45.0	32.0	50.6	0.70	1.08	0.0125	1480
18/15.3	72.3	55.0	40.9	55.2	0.76	0.94	0.0125	1400
18/15.3	72.3	53.6	17.7	10.8	0.15	0.52	0.0125	1580
18/15.3	72.3	28.3	9.5	11.3	0.16	1.42	0.0125	1580
18/15.3	72.3	25.4	7.4	8.5	0.12	1.96	0.0125	1580
18/15.3	72.3	19.5	6.8	12.2	0.17	2.77	0.0125	1580

A range of fibre geometries have been fabricated in order to investigate the controlling parameters and determine the practical limits of the fibre manufacturing equipment. Two preform tubes of similar external but differing internal diameters have been used to manufacture fibres in an attempt to determine whether the proportion of hollowness remains constant during the drawing process. As can be seen from Table 2, in all cases the process of drawing a fibre results in a reduction in hollowness. In the case of very small external diameter fibres, drawn at high temperature (1580°C), the level of hollowness has decreased by 85% from the preform value (see Fig. 6). To counter this effect, preforms of hollowness (K^2) greater than 75% are used, however, for practical reasons it is not planned at this stage to alter preform geometry to increase this value. Fig. 7 shows the correlation between fibre internal and external diameters. The relationship can be described as being reasonably linear although the relationship between fibre and preform hollowness cannot yet be explained as only two conditions have been investigated so far.

Fig. 8 attempts to correlate the fibre external diameter with the fibre hollowness (K^2) value. Again, for the limited data so far a linear relationship could be argued. The target is to be able to manufacture fibres of external diameter less than 30μm with hollowness values greater than 40%. Fibres manufactured so far have met the specification for either suitable external diameter or suitable hollowness, but not both at the same time. The shaded zone on the plot indicates the fibre geometries that are desirable for structural reinforcement in composites and highlights the advances in fibre manufacture that are required.

Fig. 9 shows draw rate (ms^{-1}) versus hollowness (K^2) for fibres drawn from identical preforms (18 mm external, 15.3 mm internal) at three different temperatures, as labelled. The resulting external fibre diameters are also included as data labels. The plot clearly shows that temperature is the predominant factor affecting fibre hollowness, draw rate having little apparent affect except on external diameter.

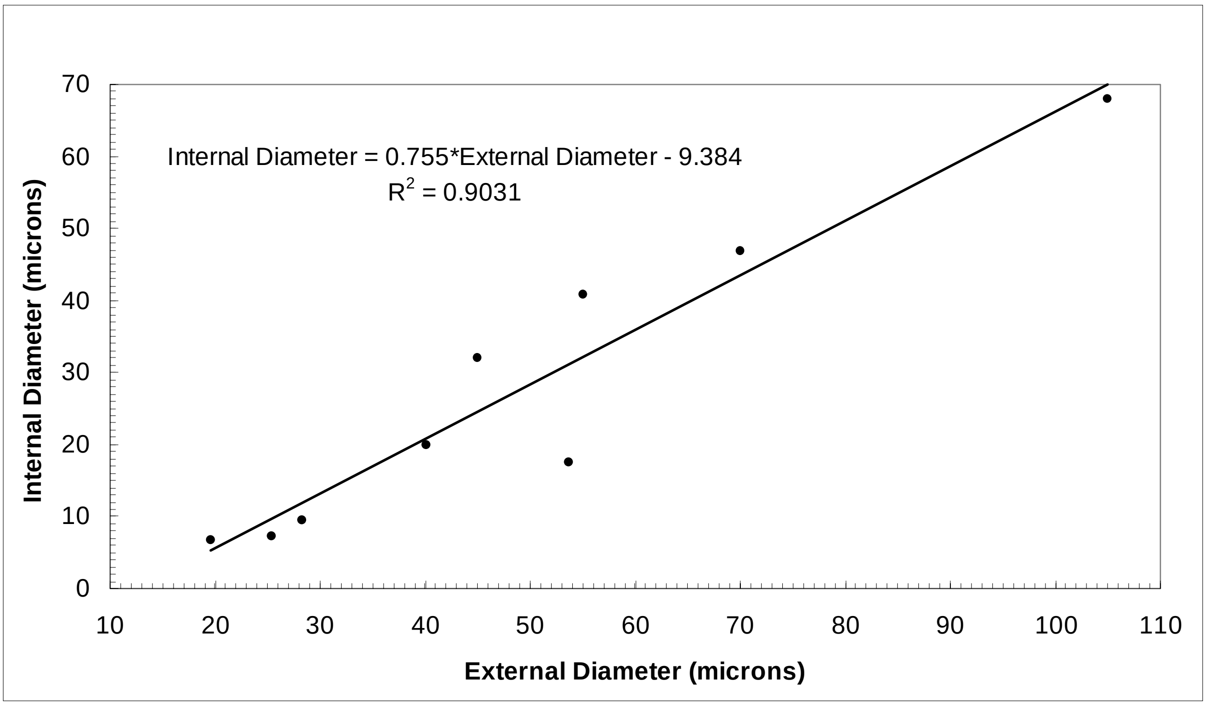


Fig. 7: Correlation between external and internal fibre diameters (μm).

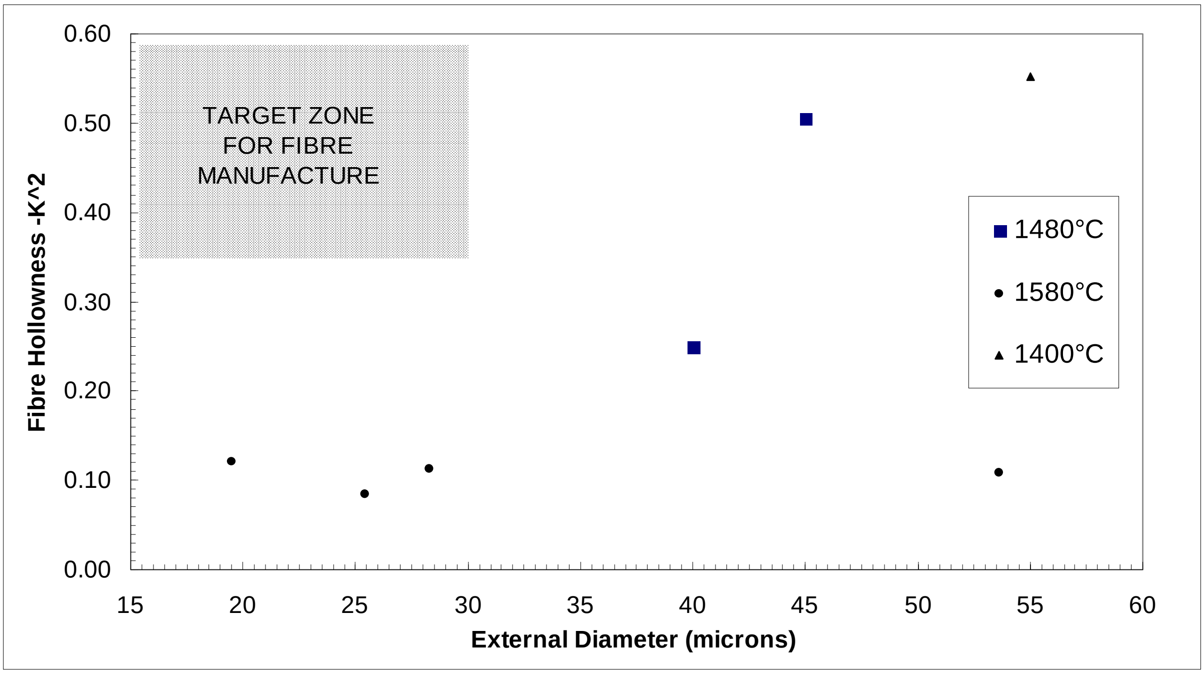


Fig. 8: Correlation between fibre hollowness (K^2) and fibre external diameter (μm).

The findings so far suggest that to be successful in fabricating fibres with a high level of hollowness (i.e. $K^2 > 50\%$), low operating temperatures are required. This increases glass viscosity markedly, inhibiting surface tension effects on the inner wall which otherwise lead to fibre collapse. This is compounded by the fact that draw rates must be much higher to produce small external diameter fibres at lower temperatures, typically greater than 2 ms^{-1} for the preforms used. The high glass viscosity and draw rate combine to give relatively large tensile forces in the fibre during drawing, leading to increased fibre breakage during the drawing process. A further problem associated with low temperatures (and high viscosity) occurs due to reduced flow rates in the necking region. The volume of fibre being drawn is higher than the volume of preform entering the furnace thus it eventually results in viscous rupture in the necking region. The combined effect of these various processing parameters is to create a conflict between achieving small external diameter and high hollowness. It can be hypothesized that a single 'optimum' fibre geometry (maximum hollowness and minimum external diameter) will exist for each combination of furnace temperature and draw rate.

The work to date has concentrated on understanding fibre manufacture. The next phase of the work will be to investigate their mechanical properties, both as individual fibres and as reinforcements within polymer matrices.

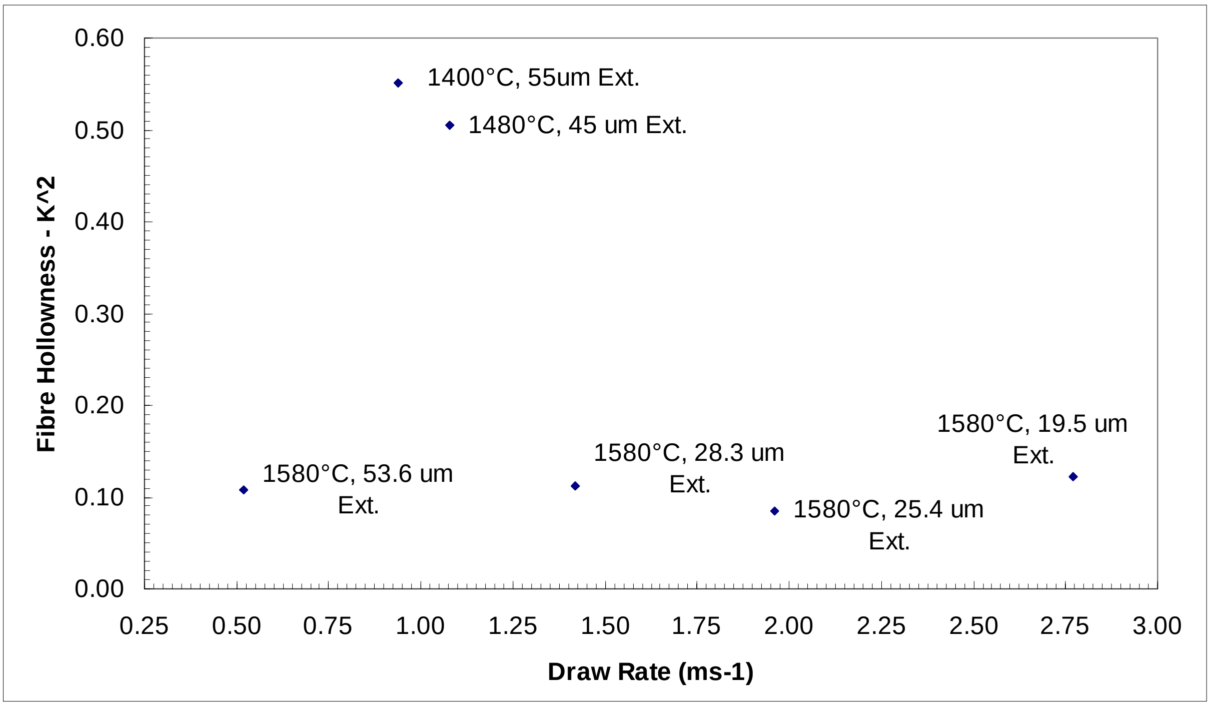


Fig. 9: Correlation between fibre draw rate (ms^{-1}) and the resulting fibre hollowness (K^2). The labels indicate the fibre drawing temperature and the resulting fibre external diameter.

CONCLUSIONS

Hollow borosilicate glass fibres have been manufactured from tubular preforms with a variety of internal and external diameters which correspond to a range of hollowness values. In all cases, the resulting hollowness was reduced from that present in the preform state, regardless of drawing rate or furnace temperature. In fact, temperature has been demonstrated to be of paramount importance in controlling fibre hollowness due to the interaction between viscosity and surface tension effects. These results suggest that for a given temperature and draw rate there is a single condition where fibre hollowness is maximised and external diameter minimised.

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