Tailoring the mechanical properties of Selective Laser Sintered parts

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Abstract

The ~£1 million IMCRC-funded integrated project 'Personalised Sports Footwear: From Elite to High Street' is investigating the use of Rapid Manufacturing to produce personalised sports shoes, with the aim of enhancing performance, reducing injury, and providing improved functionality.

Research has identified that, for sprinting, performance benefits can be achieved by tuning the bending stiffness of a shoe to the characteristics of an individual athlete. This paper presents research to date on several novel methods of influencing the mechanical properties of Selective Laser Sintered shoe soles, with a particular focus on stiffness.

1.0 Introduction

1.1 Personalised Footwear Project

This research was performed as part of the IMCRC-funded project 'Personalised Footwear: From Elite to High Street. The project is investigating the use of Rapid Manufacturing, and in particular sintering technologies, to produce personalised out-soles for running footwear.

The personalisation of footwear may have performance benefits, particularly when considering elite athletes, but could also benefit the general public by reducing or preventing injuries, as well as providing improved comfort and fit.

1.2 Shoe Stiffness

Previous research[1] identified that on average, increasing the shoe bending stiffness increased sprint performance, but the stiffness each athlete required for his or her maximal performance was subject specific. It therefore follows that it would be possible to tune the stiffness of a shoe to an individual athlete, in order to optimise his or her performance. Further research[2] established a method of modifying the mechanical properties of sprint shoes through the application of selective laser sintering (SLS). Nylon-12 sprint shoe sole units were produced, and assembled to a standard upper. The longitudinal bending stiffness was controlled by varying the thickness of the sole unit. However, an increase in sole thickness necessarily adds weight to the shoe, and can change an athlete's perception of the shoe. It is also apparent that there is only a finite thickness increase viable before the comfort and size of the shoe become an issue.

Alternative methods of varying the stiffness are therefore under investigation. This paper highlights the use of varying proportions of glass filler in order to achieve the desired range of stiffness.

2.0 Experimental Procedure

2.1 SLS Part Production

2.1.1 Material Choice

Duraform PA and Duraform GF, both available from 3D Systems, are Nylon-12 and glass-filled Nylon-12 based powders respectively. The nominal stiffness of parts produced from Duraform GF is substantially higher than that for Duraform PA (4068 MPa as compared to 1586 MPa), and the processing parameters for both are very similar. It was therefore considered that by mixing different quantities of the two materials, and producing SLS parts from the resulting powder, parts with a range of stiffnesses could be produced. Powders with quantities of 0, 12.5, 25, 37.5 and 50 % glass filler by weight were produced in order to provide a wide range of values.

Mechanical mixing of nylon-12 and glass-filled nylon-12 was carried out for 30 minutes using an industrial mixer, ensuring an even distribution of glass-beads. To ensure consistency, the base powders were all taken from the same batch of materials.

2.1.2 Build Profile

Tensile and flexural test specimens were designed in accordance with the standards[34]. Additionally, five pairs of sole units were arranged within the build volume such that they were nested with their mediolateral axis parallel to the z-axis of the build. Compression samples were also produced, but the results are not available at the time of publication. Figure 1 shows an image of the build layout.

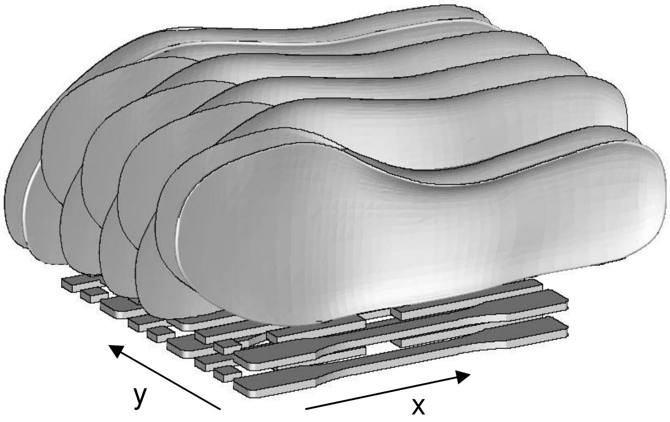

Figure 1 - Build geometry

2.1.3 Build Parameters

All specimens were produced on a 3D Systems SLS Vanguard machine with HiQ upgrade. Manufacturer default parameters for Duraform PA for 0 % and Duraform GF parameters for 50 % glass filler, as shown in Table 1. Where parameters varied between PA and GF, the values were interpolated between the two for each ratio of glass filler.

Fill laser power	12W	12W
Scan spacing	0.15mm	0.15mm
Scan speed	5ms$_{-1}$	5ms$_{-1}$
Part heater set point	174°C	175°C
Left feed set point	135°C	140°C
Right feed set point	135°C	140°C

Table 1- SLS build parameters

3.0 Results

3.1 Tensile properties

All parts were conditioned at 20 °C (+/- 1 °C) and 50 % (+/-5 %) relative humidity. Tensile tests were performed using a Zwick Z030 tensile testing machine fitted with an extensometer. E-Modulus was measured using a 1 mm/min strain rate, and Tensile Strength and Elongation at Break were measured at 5 mm/min.

3.1.1 Young's Modulus

Figure 2 shows the Young's Modulus recorded for each ratio of glass filler.

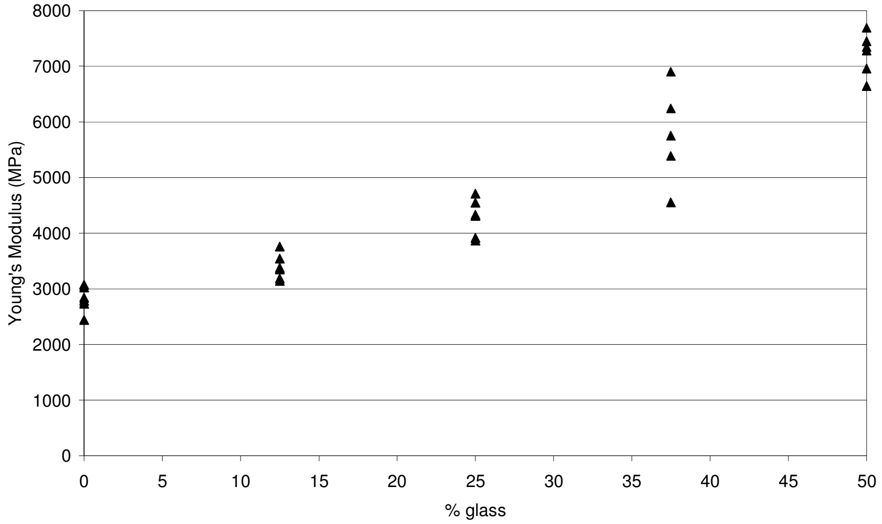

Figure 2 - Young's Modulus

It can be seen that an increase in glass filler lead to an increase in Young's Modulus, with an increase from 2816 MPa to 7227 MPa (157 %) between 0 and 50 % glass.

3.1.2 Tensile Strength

Figure 3 shows the Tensile Strength values recorded at each ratio of glass to nylon.

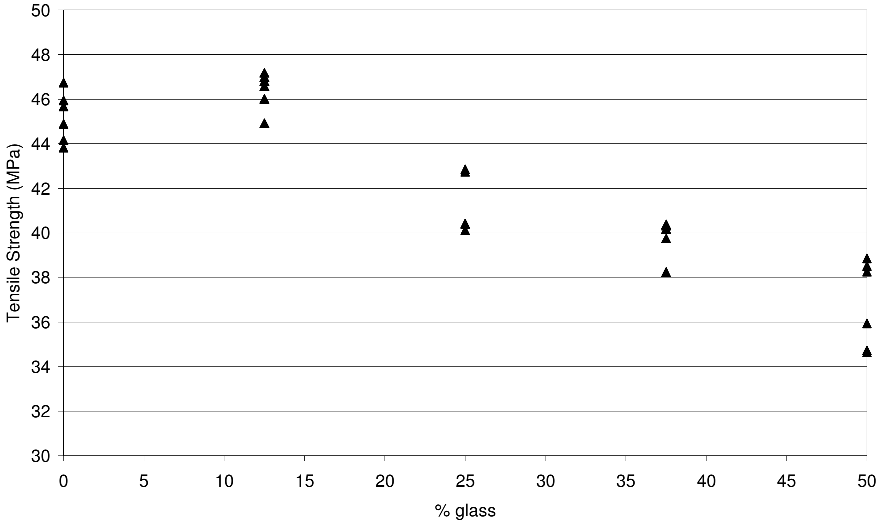

Figure 3 - Tensile Strength

In this case it was seen that the Tensile Strength decreased over the range tested. However, the variation over the range was substantial less than for the Young's Modulus, showing only an 18 % decrease between 0 and 50 % glass.

3.1.3 Elongation at Break

Figure 4 shows the effect of glass-filler ratio on the Elongation at Break.

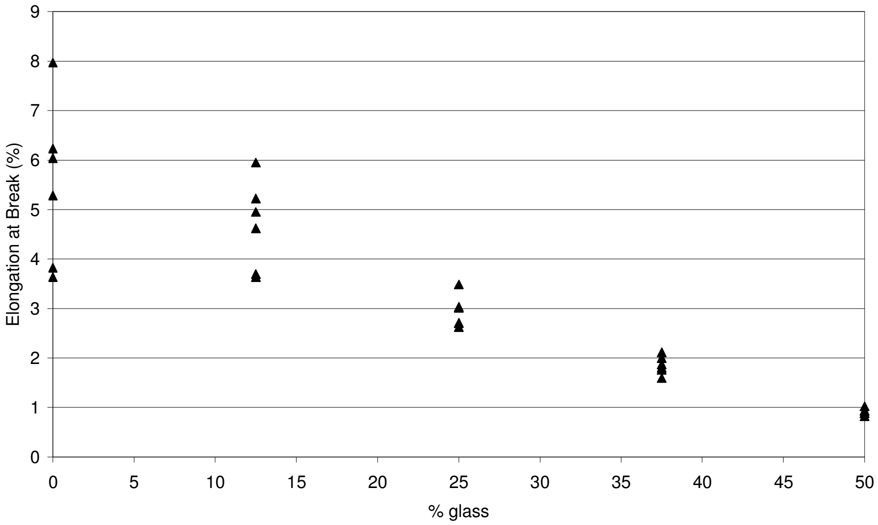

Figure 4 - Elongation at Break

It can be seen that an increase in proportion of glass filler led to a decrease in Elongation at Break (ductility), showing an 84 % decrease when increasing the filler content from 0 to 50 % glass. It also appears that there is a substantial increase in repeatability of the results when using higher levels of filler.

3.1.4 Summary

The results presented in this section have shown that, over the range tested, an increasing proportion of glass filler will cause a corresponding increase in stiffness. The large increase in stiffness achievable, with a relatively small decrease in Tensile Strength, is promising when considering the requirement to tailor the stiffness of SLS shoe soles. However, the fairly large decrease in Elongation at Break may prevent the use of very high ratios, as discussed further in subsequent sections.

3.2 Flexural Properties

3.2.1 Flexural Modulus

Figure 5 shows the effect of glass filler content on the Flexural Modulus.

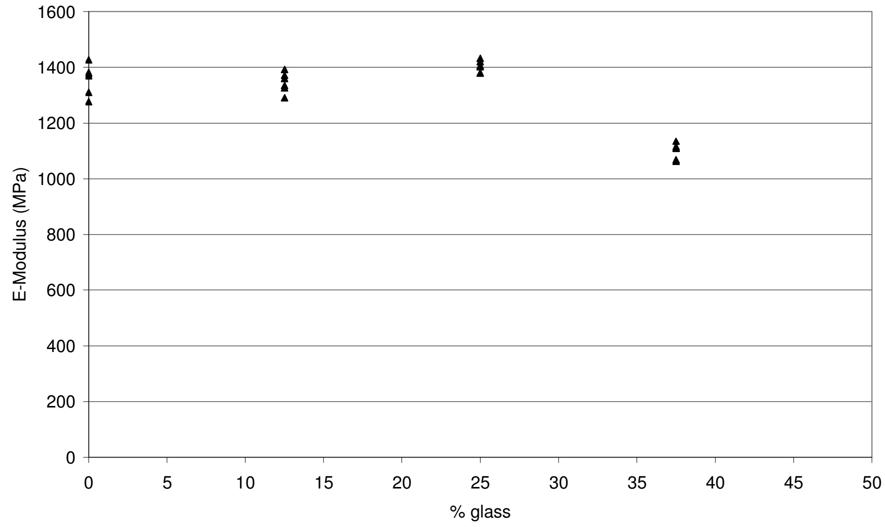

Figure 5 - Flexural Modulus

It can be seen that the Flexural Modulus remained relatively constant (average of 1369 MPa) between 0 and 25 % glass. After this point there appears to be a reduction in modulus, although the data for the 50 % values was unavailable.

3.2.2 Flexural Strength

Figure 6 shows the effect of varying the proportion of glass filler on the Flexural Strength.

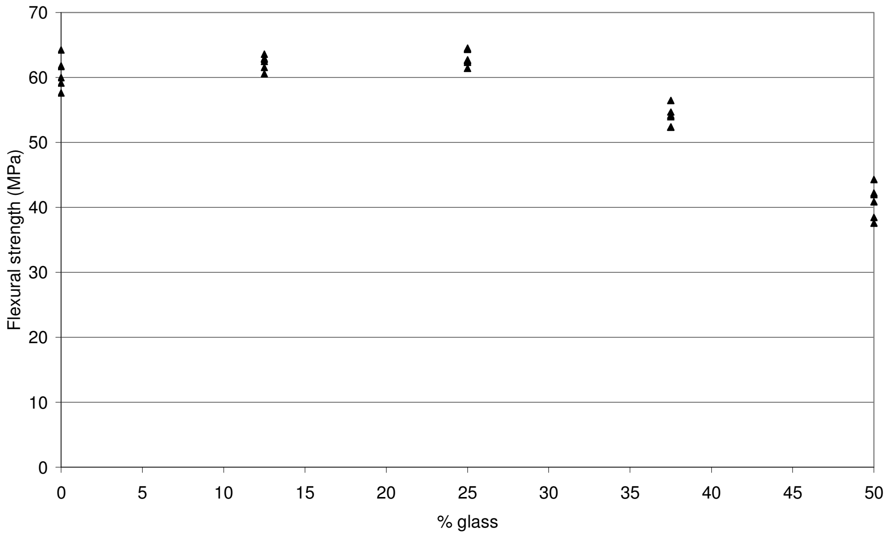

Figure 6 - Flexural Strength

As for the Flexural Modulus, the Flexural Strength was not influenced by the proportion of glass filler until after the 25 % level, with values remaining at an average of 62 MPa. In this case there was a definite reduction in the values recorded once the 25 % level was surpassed.

3.3 Testing of Shoe Soles

Mechanical testing of the sole units was carried out using a purpose built fixture, designed in accordance with ASTM standard for flexibility of running shoes[5]. Force measurements were recorded in extension and flexion with each sole unit fixed at 70% shoe length from the rear. For extension the sole units were pulled vertically upwards using a stirrup system and for flexion the sole units were compressed vertically downwards. The speed of the test machine was fixed at 1000mm/min and five test cycles in extension and flexion were recorded. The data presented is a mean of the last 3 cycles for the left and right units.

3.3.1 Extension Tests

Figure 7 shows the experimental set-up for the extension tests.

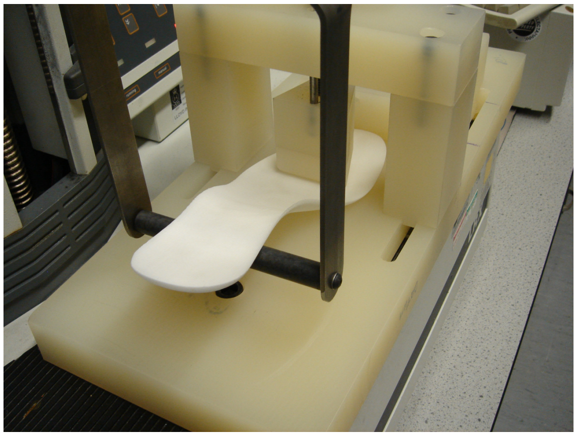

Figure 7 - Extension rig

Figure 8 shows the results of these tests.

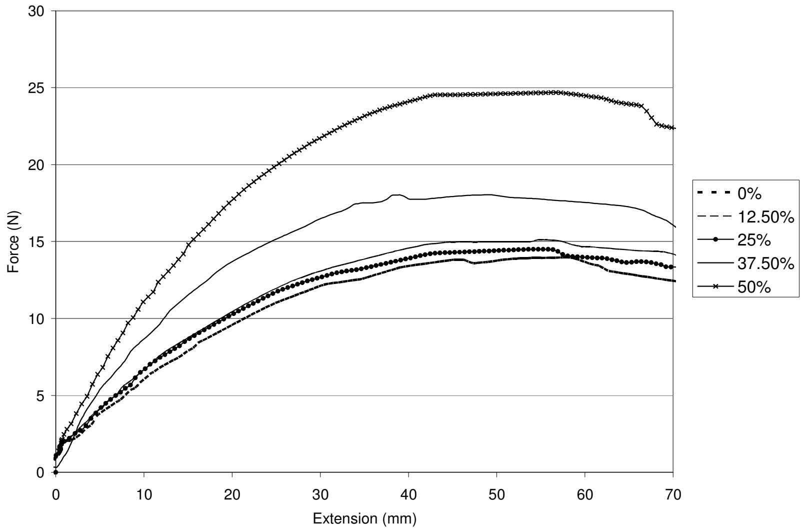

Figure 8 - Extension test results

It can be seen that there was no significant variation between the data recorded at the 0, 12.5 and 25 % levels of glass filler. However, above the 25 % level, there was an increase in bending force with filler content. The maximum force recorded for the 25 % glass soles was just over 15 N, compared with the maximum at 50 % filler of almost 25 N, an increase of approximately 66 %.

3.3.2 Flexion – sole unit compressed vertically downwards

Figure 9 shows the experimental set-up for the flexion tests.

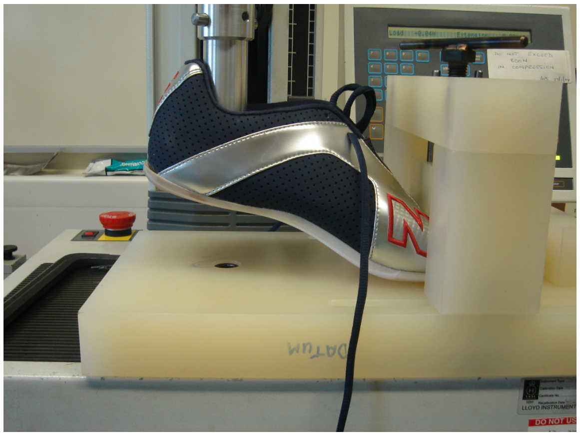

Figure 9 - Flexion rig

Figure 10 presents the results of these tests.

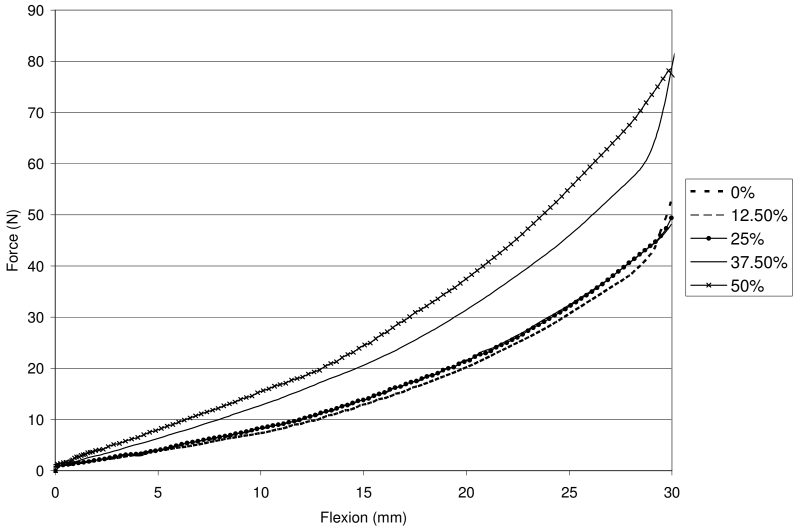

Figure 10 – Flexion test results

As for the extension tests, no significant variation was recorded between the soles produced with 0%, 12.5% and 25% glass filler. Once again it was seen that above this threshold an increase in glass filler led to increase in bending force. Taking an arbitrary point of 20 mm, it can be seen that the force increase from 21.3 N to 37.5 N, an increase of approximately 75 %.

3.4 Comparison with Mechanical Property Tests

The results presented here suggest that, in order to provide an indication of the effect of a factor on the behaviour of a shoe sole, the tensile stiffness (Young's Modulus) would be more suitable than the flexural stiffness. In both flexion and extension, the shoe soles showed an increase in bending stiffness with increasing proportion of glass filler, which is consistent with the results recorded for Young's Modulus.

However, whilst the Flexural Modulus showed the opposite effect, it also recorded no discernable difference between the parts produced with the lower proportion of glass filler, which correlates more closely with the results of mechanical testing of the shoe soles than the tensile property results.

These results highlight the fact that standard testing of mechanical properties has substantial deficiencies when attempting to predict the actual behaviour of shoe soles.

The decrease in Elongation at Break with increasing proportion of glass filler was consistent with the results of the shoe sole testing. Increasing the percentage of glass filler, came at the expense of ductility. Under extension and flexion the sole units with 50% glass filler suffered catastrophic failure. A crack was initiated on the medial aspect of the perimeter at the primary point of flexion and propagation rapidly occurred until failure on the fourth cycle.

4.0 Conclusions

Results have shown that it is possible to vary the stiffness of shoe soles by adding controlled proportions of glass filler to standard Nylon-12 SLS powder. Whilst the inclusion of increasing amounts of glass filler have been shown to increase the stiffness of both standard tensile specimens and actual shoe soles, when 50% glass filler was included, the related decrease in ductility led to catastrophic failure of the sole units. This suggests that there is a maximum level of filler, between 37.5 and 50 %, beyond which it is impractical to produce the soles.

It has also been shown that, when physically testing shoe soles, there was no discernable difference between the forces required until the proportion of glass filler was 25 % or higher.

Further work will be required in order to identify the range of filler ratios within which the stiffness can be controlled and modified, but without compromising mechanical integrity, and to understand the fatigue behaviour of the shoe soles.

5.0 References

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[2] Toon, D., Hopkinson, N. and Caine, M. Design and construction of as sprint spike with a selective laser sintered nylon sole unit, 8th Footwear Biomechanics Symposium, Taipei., 2007

[3] ISO 178:2001 : Plastics - determination of flexural properties

[4] BS EN ISO 527-2:1996 : Plastics – determination of tensile properties

[5] ASTM F-911 – 85 : Standard Test Method for Flexibility of Running Shoes