POST-PROCESSING OF DURAFORM™ PARTS FOR RAPID MANUFACTURE

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Abstract

In recent years layer manufacturing processes have evolved from Rapid Prototyping (the production of pre-production prototypes) to Rapid Manufacture (the production of end use parts) where limitations of the processes do not affect end use. There is no doubt that applications for Rapid Manufacture will grow in coming years, however there are a number of current limitations that will need to be addressed so as to maximise the scope for Rapid Manufacturing applications.

One of the main limitations for the adoption of Rapid Manufacturing is material properties of the parts produced. This research has looked at the possibility of increasing the range of material properties that may be achieved from parts made using current commercial Laser Sintering systems.

A series of tensile and impact test parts were built using Duraform™ powder on a 3DSystems Vanguard machine. These parts were then subjected to various form of post-processing including thermal treatment and infiltration with polymer infiltrants. The parts were subjected to tensile and impact tests with results showing that thermal post-processing achieved preferable results when compared with infiltration. Heating above the glass transition temperature yielded superior results though as the melt temperature was approached issues of deformation arose. These initial results have formed the basis for further work to consider how material properties for Rapid Manufacture by Laser Sintering may be improved.

Keywords
Rapid Prototyping, Rapid Manufacture, Selective Laser Sintering, Post-processing, Material properties.

Introduction

Rapid Prototyping (RP) is a relatively new family of technologies which emerged in the late 1980's. *Wohlers Report 2000*, defines it as: "A special class of machine technology that quickly produces models and prototype parts from 3-D data using an additive approach to form the physical models." [1]

Currently all commercially available RP processes build parts layer by layer. Thin, essentially 2D, cross sections of the part are built one on top of the other enabling parts to be built with geometries often impossible to achieve by machining and other methods. Such geometries include intricate internal structures, parts within parts, and very thin-wall features which are just as easy as building a simple geometry such as a cube.

Another important characteristic of RP processes is that they need no part specific tooling to produce parts. The manufacture of tooling for conventional manufacturing processes is expensive and time consuming. The lack of tooling therefore means RP processes can offer advantages from both time and direct cost points of view.

As the technology evolves production of parts for end use is becoming possible, rather than just for prototypes. Where RP technology is used to build parts for end use, the term 'Rapid Manufacturing' (RM) arises. RM has already found numerous uses for production of parts in relatively small quantities and where production of certain geometries is not feasible with conventional methods. Examples include Hearing-aid bodies [2], air handling systems [3] and electronics housings for Formula One cars [4].

The use of RP technology for RM is currently limited by a number of issues, and many of these relate to the physical properties of the parts. Parts tend to be weaker than parts made by conventional methods such as injection moulding, even when using the same materials. Also, repeatability of material properties is a serious issue with values varying throughout individual parts and between different parts according to the position within the build volume.

In order for RM to become more widely used the parts will ideally have at least the strength of parts made by conventional methods. This project looks at methods of post-processing to improve the mechanical properties (tensile and impact) of parts built from Duraform™ Nylon using the Selective Laser Sintering (SLS) process with the aim of facilitating the use of the material more widely in RM. The SLS process has been selected due to the versatility of the system and the wide range of materials available. Also important was the fact that many companies hoping to implement RM methods have already expressed particular interest in the SLS process and that it is already used in various industries to create end use products.

Theory & Analysis

Powder metallurgy (PM) has fundamental similarities with the SLS process. Both involve creating solid objects from compacted powder material using sintering/heating processes for bonding of the particles. Considering the similarity between the two, a logical progression can be made by applying basic PM principals to SLS: Parts made by such processes will usually contain voids or porosity and as such will be less dense than if there were no voids or porosity. A part with zero voids or porosity can be expressed as having 100% theoretical maximum density. The higher the density, the greater the part's tensile strength, elastic modulus and toughness. As such, the denser the part, the higher the 'strength'.

There are two main factors that cause decreased strength with lower densities. At densities less than 80% of maximum density, the size of inter particle bonds is the main factor and at densities of over 80% it is the pore size, shape and spacing which becomes the predominant factor [5]. This relates to the fact that porosity may consist either of a network of interconnected pores or of sealed holes, and that interconnected pores are generally found with densities less than 80% of maximum density [6]. This has major implications for infiltration since the material must be less than 80% dense otherwise infiltration will be unlikely to occur much further beyond the surface.

By accurately measuring and weighing a cube sintered on the same SLS machine as the other parts and with the same build parameters, the density was found to be 87%. This was based on measured density of 0.96 g/cm^3 compared with a quoted maximum density for Duraform™ of 1.10 g/cm^3 [7].

Most materials generally contain structural imperfections and small cracks or voids. The presence of such voids causes high local concentrations of stress. It is mentioned above that, with parts made by SLS or PM, at different densities the voids will either be a network of interconnected pores or of sealed holes. It can be shown theoretically and practically that voids in the shape of circles (sealed holes) cause significantly less stress concentration than voids consisting of long ‘cracks’ [8]. This suggests why increased density would result in a tougher material.

Figure 1 shows a representation of particles of Duraform™ nylon modelled as contiguous spheres. They are drawn within cubes to indicate how they would be arranged cubically. This model was chosen for simplicity and would not represent the true packing characteristics, however it is sufficient for this explanation. The inter particle area of contact is shaded and it is shown that as the spheres become compressed, hence denser, the particles press against each other and deform and hence the area of contact increases (right). Also, it shows that as density increases, the free space, hence pore size, also decreases. It can be seen that in the loosely packed state the porosity is interconnected while in the tightly packed state the porosity takes the form of sealed holes. The arrows represent equal tensile forces being applied

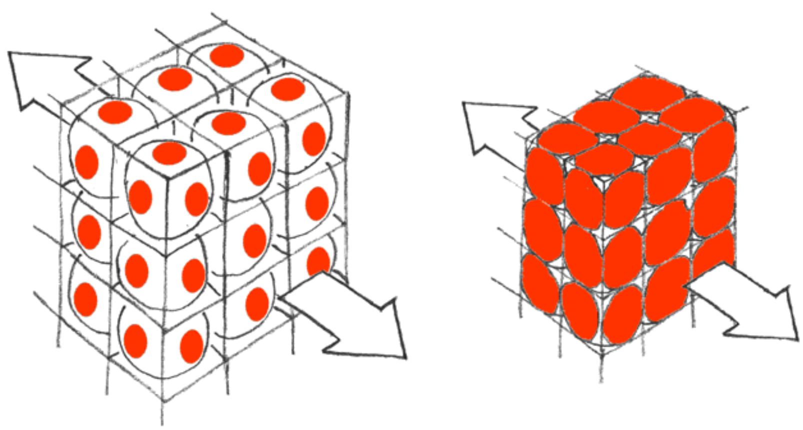

Figure 1. Inter particle contact area of loosely packed (left) and tightly packed nylon (right)

Under tensile loading the stress can be calculated simplistically by:

Stress (σ) = Force applied (F)/ Cross sectional area (A)

This shows that the higher the density is, the higher the total cross sectional area will be and hence the lower the stress within the material will be under the same applied load. Therefore the tensile strength of the material will be higher. Sheer strength and toughness would be affected in the same way.

When a semi-crystalline polymer such as Duraform™ is heated beyond its melting point (T_m = 184°C) it behaves like a highly viscous liquid

It is currently common practice to infiltrate the surface of SLS parts with 'Superglue' which allows a higher quality surface after finishing. Since this is a widely used method of post processing, this and other common infiltrants were investigated to assess their impact on physical strength properties of parts.

Methodology

The project consisted of the following practical stages:

1. Production of parts
2. Initial post processing and tensile/impact testing
3. Simple analysis of initial results
4. Further post processing and testing
5. Analysis of further results

The SLS Build process is outlined below:

1. Thin layer of heat-fusible powder deposited in part-build cylinder
2. Laser 'traces' cross-section matching corresponding layer in STL file, bonding particles to each other and adjacent layers
3. Roller mechanism deposits another powder layer
4. Platform in part-build cylinder moves part downwards a layer and process repeats.
5. Part removed and loose particles shaken off
6. Post-processing if required, such as infiltrating with superglue for improved surface finish.

The SLS machine used in this project was a 3DSystems Vanguard and the material was Duraform™ powder. Duraform™ is based on Nylon 12, a commonly used thermoplastic used in injection moulding and other plastics forming methods.

As mentioned above (step 5), the parts were removed from the SLS machine as a 'powder cake' containing the sintered parts held in the compacted but unsintered powder. While the parts were being removed from this 'cake' they were carefully numbered and photographed to record their position and orientation within the build volume.

As mentioned earlier, part properties vary throughout the build volume but using data generated by other research [9] compensation factors where generated which theoretically eliminate the effects of property variation as a factor of part bed distribution. The data available was for positions across the 'face' of the build but not for different depths. However, the build of parts (3 horizontal layers) and selection for each variation of PP meant that for each variation there were 6 parts used, from 2 locations across the face of the build, each with 3 parts, one from each height. Because of this, effects of property variation due to different build heights were practically eliminated. In addition, although compensation factors were used, the selection of the 2 locations on the face of the build for each variation was carried out to ensure an even 'distribution' as much as possible, so that, for example, if the first location was central then the second would be near the edge. These steps were essential to stop factors relating to build position interfering with the results of the post processing.

It is common practice for unsintered powder from the 'powder cake' to be mixed with virgin powder for further use to minimise waste. However, since this is a potential source of variation only virgin powder was used in this project.

Conventional heating was carried out in a Zwick temperature chamber using a controlled heating and cooling cycle to avoid potential issues of thermal shock. Thermocouples placed in the oven were used to measure temperatures rather than having them attached to parts. This was done primarily due to the need to maximise the use of the limited parts from a single build and that a significant number of parts would be un-testable if they had thermocouples attached. It was considered acceptable since all parts were heated in the same positions hence for the purpose of an 'initial' relative comparison' there should be no problems. In addition the small internal volume of the oven and high rate of air circulation should theoretically result in a relatively even temperature distribution compared with other conventional ovens.

Initial testing suggested further processing by varying heating times beyond 1 hour with temperatures in the approximate range of just below the glass transition temperature to as close to the melt temperature as possible. Table 1 shows the temperatures and times that parts were subject to after building on the SLS machine. The temperatures selected for the 3 hour heating were based on initial results from 1 hour heating.

Time (Hours)	Temperature (^oC)				
	155	165	175	180	183
1	✓	✓	✓	✓	✓
3			✓	✓	✓

Table 1. Heating parameters employed for post-processing

Infiltration was performed using 'Superglue' (Loctite 406), 'Thomsons Water Seal' (for sealing bricks/mortar against moisture ingress), and 'MDF sealer' (for protecting MDF wood). These are all polymer based. Due to the Superglue's high cost per volume and low viscosity the method used was to place the parts on a rack and place drops of the liquid along the faces which spread evenly on its own. This took place in an extraction bay because of irritant fumes. For the 'Thomsons' and MDF sealer the parts were submerged in the liquids for durations of 2mins, 1 hour and 24 hours.

Initial testing suggested further processing by infiltrating with Superglue and Thomsons, but not MDF sealer.

Testing was carried out as per ISO standards as follows.

Impact testing: BS EN ISO 180:2001
Tensile testing: BSI EN ISO 527-1:1996

The impact tests were notched Izod and the notches were 'built in' to the STL file.

Results & Discussion

Methods of post processing are compared with 'original' un-post-processed parts from the same build and textbook values for Nylon 12 (equivalent to Duraform™) and Nylon 6 (another very widely used Nylon). Mean values for each set of 6 samples are shown on the graphs as well as the max/min range.

Figure 2 shows the effects of post-processing on the impact strength of parts. Conventional heating yielded significant improvement especially with higher temperatures and longer times. Improvements from 180°C to 183°C were significant given the small increase in temperature. Heating at 183°C for 3 hours resulted in an improvement in impact strength of 60% over standard Duraform™ parts and at a value over that for Nylon 6. However the melt temperature is 184°C and hence at 183°C the parts deformed considerably (see Figure 3). All methods of infiltration resulted in slight increases in impact strength over standard Duraform™ parts. Shorter soak times for Thomsons resulted in marginally higher values than the longer soak times though the relatively high spread compared with this increase means this finding is not conclusive.

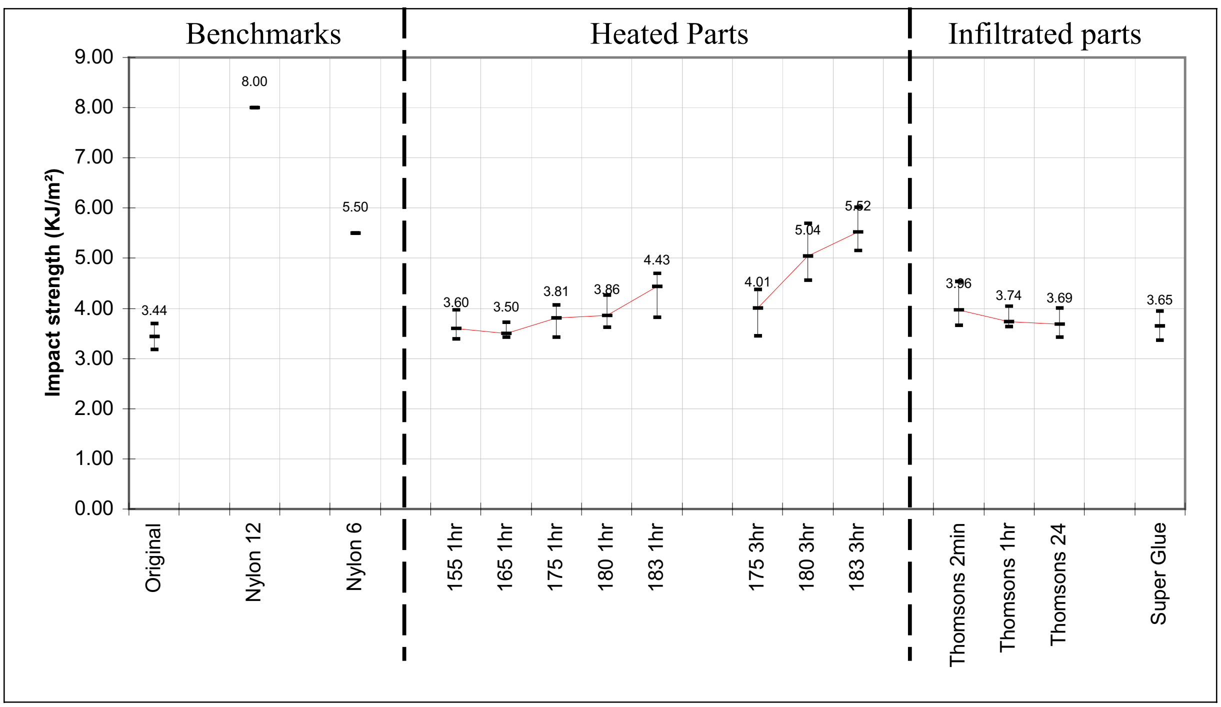

Figure 2. Impact strength results

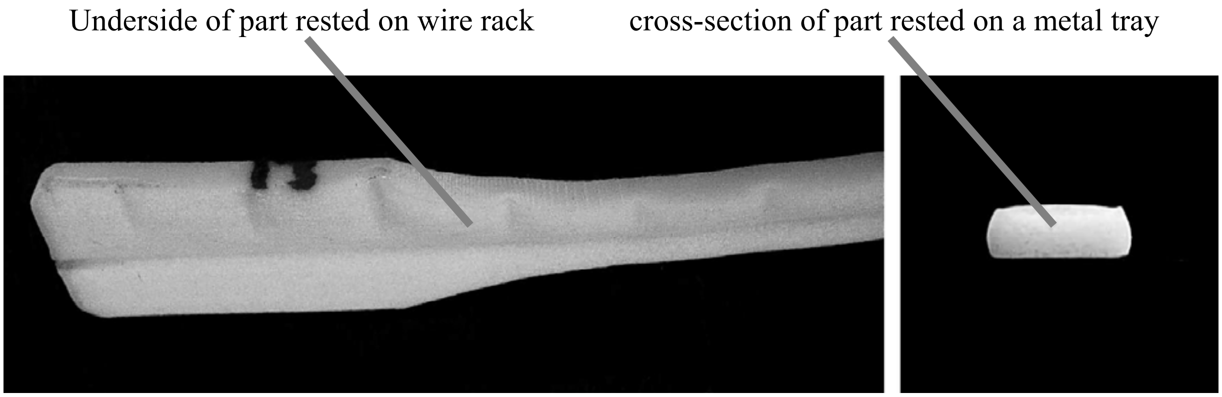

Figure 3. Deformation of parts heated to 183°C for 3 hours

Figure 4 shows that Young's Modulus for standard Duraform™ parts is higher than those for moulded Nylon 12 parts and that heating increased the stiffness further. Higher temperatures resulted in higher stiffness though prolonged heating for 3 hours yielded no improvements on the 1 hour heating indicating an optimum heating time (to achieve maximum stiffness) is under 1 hour. The effects of infiltration on stiffness appeared to be negligible, probably due to the minimal depth of infiltration.

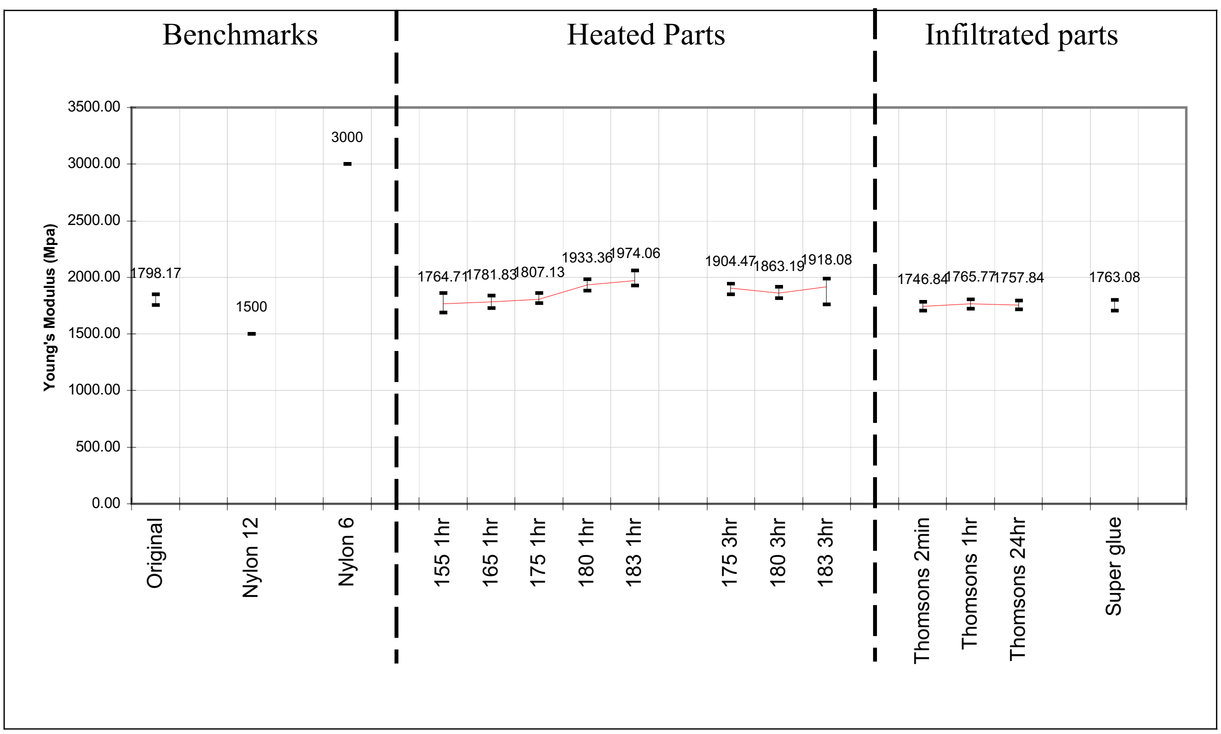

Figure 4. Young's Modulus Results

Figure 5 shows that standard Duraform™ parts have a slightly lower UTS than moulded Nylon 12 although heating close to the melt temperature increases the UTS so that it just surpasses that of Nylon 12. As with Young's modulus, the optimum heating time would appear to be less than an hour, again this is of particular significance for RM. Infiltration appears to have a slightly detrimental effect on the UTS of Duraform™ parts, although it is not clear why this occurs.

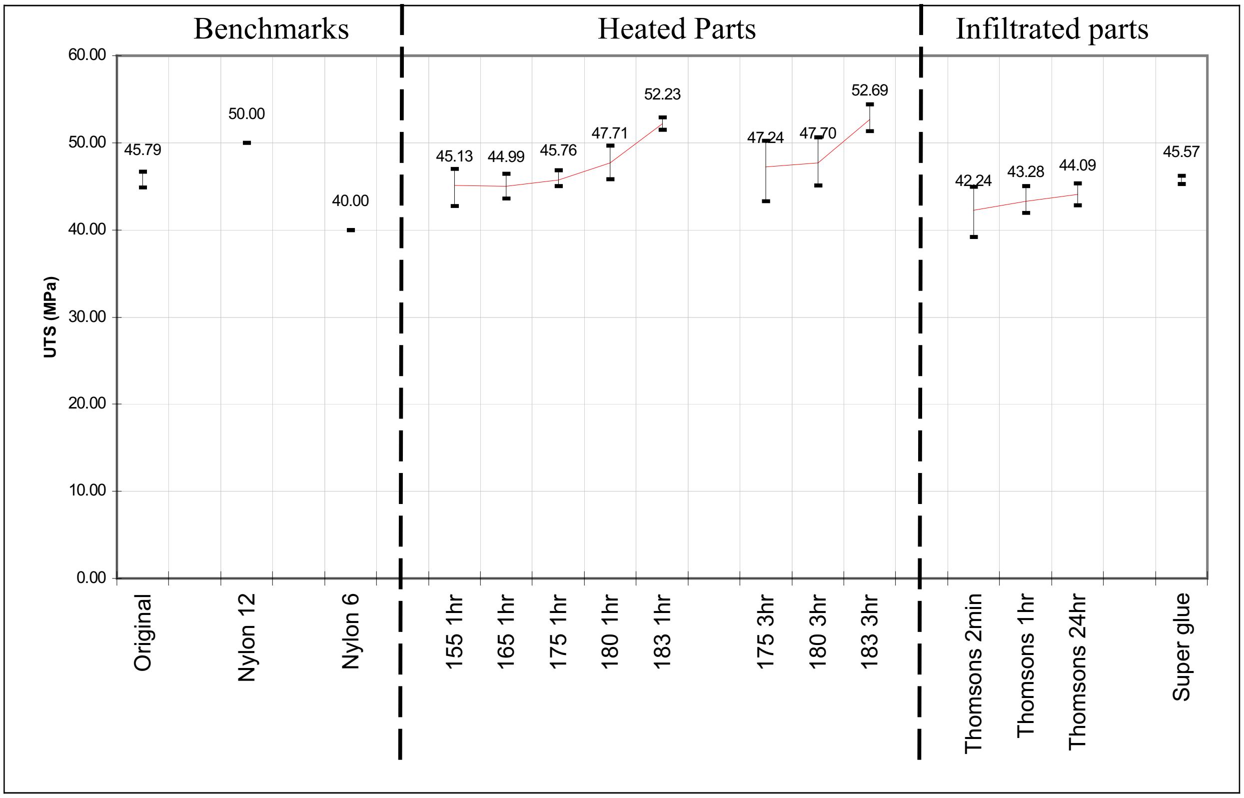

Figure 5. UTS Results

Figure 6 shows that standard Duraform™ parts are considerably less ductile than moulded nylon parts and that elongation at break decreased marginally when parts were heated to temperatures below 180°C. Marked increases at 183°C are shown however it was observed by visual inspection that these parts did neck before failing where as other parts did not. Figure 7 shows a tensile sample that had been heated to 183°C for 3 hours. There is some necking, however moulded nylon would show considerably more elongation. The responsible mechanism may be related to re-solidification and that the lower the viscosity reached when heating then the greater the degree of parallel chains/lamellae formation and hence increased crystallinity and thus increased ability for polymer chains to align under stress. However, it is interesting to note the extremely high elongation since it suggests that Duraform™ necks far less than Nylon 12 which in many cases is a desirable property. It suggests the true yield stress for Duraform™ is significantly higher than that of Nylon 12. As with the other tensile results, infiltration had a negligible effect on elongation at break.

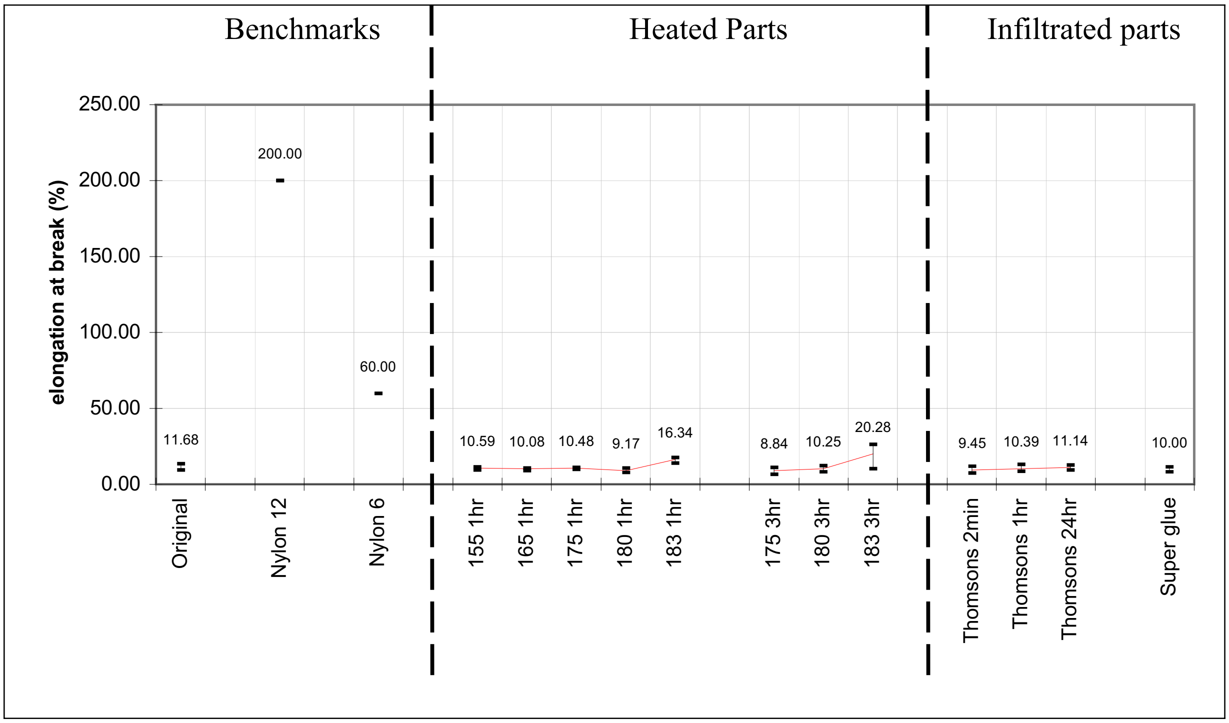

Figure 6. Elongation at break results

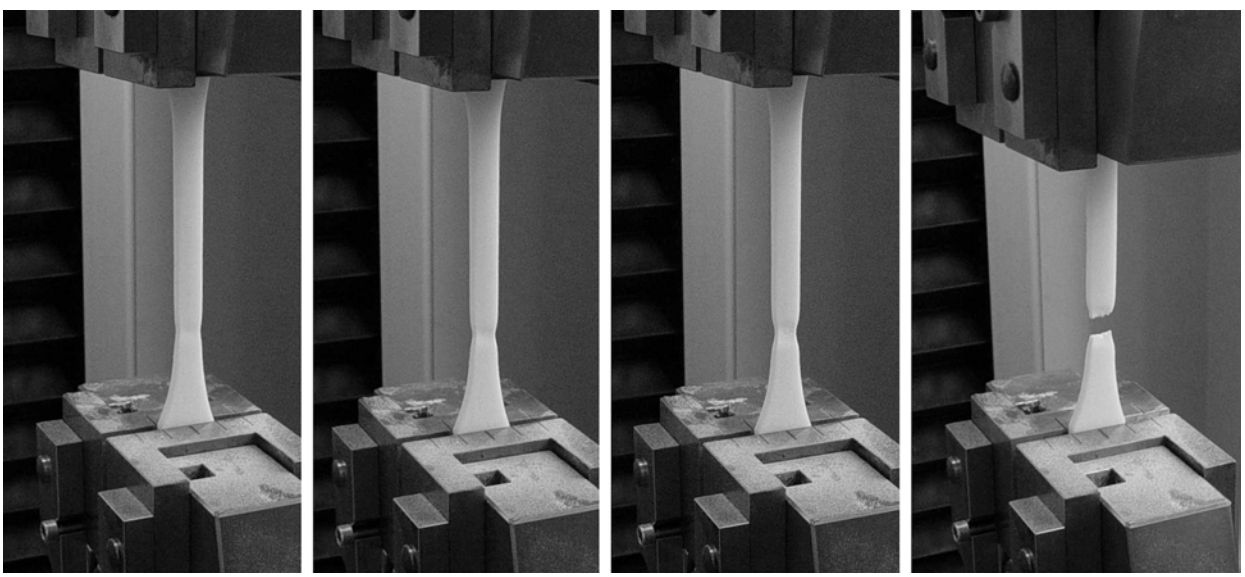

Figure 7. Necking observed in tensile test part heated to 183°C for 3 hours

Conclusions & Recommendations

The objective of this project was to investigate post-processing methods to improve tensile and impact properties of SLS Nylon parts for further investigation. The investigation suggested methods of increasing inter particle contact area would result in improvements and heating of the parts yielded significant increases in both impact and tensile ‘strength’. Heating just below the melt temperature resulted in significant improvements compared with lower temperatures. The higher the temperature the better the results though close to the melt temperature issues of part distortion and necking of samples arose. Surface infiltration, commonly used to improve surface properties, was shown to have little effect on bulk properties even though the ratio of surface area to volume was quite high.

This initial research demonstrates that it is possible to modify certain properties of SLS parts to match and in some cases exceed those of comparable polymers, processed by conventional means which is very important in relation to the objective of developing RP for RM.

The two major physical attributes of parts are strength and accuracy/surface finish. When altering SLS build parameters, improvements in one will often result in detriment to the other, so that, for example, the strongest parts tend to have low accuracy and poor surface finish [10]. Therefore, a compromise set of build parameters is usually selected. However, since accuracy/surface finish appear less affected by build position a logical approach would be to bias build parameters towards maximising accuracy/surface finish and then use separate post processing to improve the part strength. This may result in parts that are accurate, strong with constant strength characteristics throughout the build. It is recommended that this is investigated by applying parts from identical build locations to different forms of post processing. A separate build would therefore be required for each PP method and spread of results could then be compared.

Some other recommendations for further investigations can be made:

- Microwaving was investigated briefly but due to difficulties encountered was not investigated further and the results not presented. Problems encountered related to lack of heating followed by extreme localised heating of parts resulting in rapid melting. However, based on microwave theory and initial findings, it is predicted that effort focussed on this could overcome the problems that arose.
- Pressing was not investigated though it could be, and is predicted would yield improvements.
- Coloured infiltrants could be used to determine accurately the degree of part penetration. Build parameters could be modified to produce parts with densities considerably below 80% to enable complete infiltration.
- Methods to compensate results for variations due to build position are vital so further research in this field would be useful.
- Combining methods of post processing such as heating and pressing could also be investigated.
- Deformation observed at high temperatures could be addressed by supporting parts in glass balls which is standard when post-processing laser sintered polymer coated ceramics.

References

1. Wohlers, T., 2000, ‘**Wohlers report 2000’,** *Colorado Wohler associates*
2. Caloud, H., Pietrafitta, M., Masters, M., 2002 ‘**Use of SLS technology in direct manufacture of Hearing aids’,** *2002 SLS users group conference*
3. Palumbo, B., 2002. ‘**Use of Duraform™ GF in customized Manufacturing of Air Handling Systems**’, *2002 SLS users group conference*
4. Stocker, M., 2002, ‘**From Rapid Prototyping to Rapid Manufacturing**’, *Auto Technology,* vol. 2 2002, pp38-40
5. Agarwala, M., Bourell, D., Beaman, J., Marcus, H., & Barlow, J., 1995, ‘**Post-processing of selective laser sintered metal parts**’, *Rapid Prototyping Journal*, vol. 1, number 2, pp36-44.
6. Kalpakjian, S., 2001, ‘**Manufacturing Engineering and Technology’,** *Prentice-Hall*
7. Bugeda, G., Cervera, M., Lombera, G. 1999 ‘**Numerical prediction of temperature and density distributions in selective laser sintering processes’** *Rapid Prototyping Journal*, vol. 5, number 1, pp21-26
8. John, V.B., 1992, ‘**Introduction to engineering materials**’, *Macmillan Press Ltd*
9. Saleh, N., 2003**, ‘Duraform™ heat zones’,** *Loughborough University*
10. Gibson, I., Dongping, S. 1997, ‘**Material properties and fabrication parameters in selective laser sintering process**’ *Rapid Prototyping Journal*, vol. 3, number 4, pp129-136