Investigation into the mechanical properties of Rapid Manufacturing materials

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1 Abstract

During the past few years, there has been a move to convert Rapid Prototyping (RP) processes into Rapid Manufacturing (RM) machines to produce end-use parts for different industries. However, in order to make Rapid Manufacturing possible, there is a need for designers to have comprehensive information relating to the mechanical properties of new materials at different intervals of ageing, temperature and humidity. This is in order for them to have confidence in specifying the materials in their designs.

This paper will discuss the progress of the Design for Rapid Manufacture project that is currently being undertaken at Loughborough University, and give details of the mechanical properties of new range of Stereolithography (SL) materials that are currently being extensively evaluated.

2 Introduction

Rapid Prototyping (RP) technologies are used to build prototypes directly from 3D CAD models using layer by layer building techniques without any need for either moulds or tools. One of the main objectives of RP is to reduce the time taken to produce a prototype by eliminating all the sequences that are used in conventional techniques. There are many processes that are used in RP (more than 20) [1], however, this paper is concerned with two specific processes namely:

i) Stereolithography (SL), which emerged in 1987 [2]. In this process, a laser beam scans and solidifies the surface of liquid resin to convert it to a solid object.
ii) Laser Sintering (LS), which uses a similar method to SL but for a material that is originally in a powder form.

Due to the marked development in the different aspects of RP technologies during the past 15 years, some of the RP processes have started to be used as Rapid Manufacturing (RM) systems to produce end-use parts in different applications such as [2]:

i) Boeing’s Rocketdyne (California) has successfully used LS to manufacture hundreds of glass-filled nylon parts for the International Space Station and the space shuttle fleet; also the company uses RP to manufacture parts for F-18 fighter jet.
ii) Align Technology (California) uses Stereolithography to produce custom-fit clear plastic aligners that are used to straighten teeth.

RM applications are increasing all the time; however there are some limitations that impede the RP processes to be employed in their best or maximum use as RM machines, such as:

i) The limited number of materials *(around 46 SL & 15 LS materials in USA & Europe*), which is considered to be very small compared to other manufacturing techniques such as Injection Moulding that has thousands of materials available to it.

ii) The very limited information about the mechanical properties of the materials at different temperatures, humidties and ageing, which is one of the main reasons for designers to be under-confident in specifying RP materials.

iii) The machines are designed for prototyping, not for manufacturing which means that they are working at slow speed, low accuracy and produce parts with poor surface finish [3].

iv) Current high cost of machines (*typically £400,000 - £750,000*) and materials (*£160 / KG SL resin*) [3].

v) The available CAD systems are not user friendly due to the complexity of use, as they need lots of training and experience.

Due to these limitations, there is much research work that is dedicated to improve the RP processes to enable them to be used as manufacturing systems. One of these researches is the Design for Rapid Manufacture project.

3 Design for Rapid Manufacture project aim and objectives

The aim of the project is to investigate how the advent of RM will affect the design and manufacturing stages of complex plastic components. This project commenced at Loughborough University (UK) in 2001 and it is funded by EPSRC. The project partners include (in alphabetical order): 3D Systems, Bafbox, Delphi Automotive, Jaguar Cars, MG Rover, RimCast and Vantico, those have great experiences in dealing with the different RP branches (*part designers and manufacturers; RP machines suppliers and RP materials suppliers*) [4].

The assumption is made that the problems of accuracy, surface finish, speed, etc. have been resolved and that the RP processes have been converted to fully manufacturing machines. Within the project, current RP machines are used in the place of future RM systems. It is recognised that there are some limitations with these processes, but it is the principle of additive manufacture, that is important, not the actual machines used. The main areas of the project are:

3.1 Design Freedom

Without the restriction of removing a product from the tool, designers will be free to design any complex geometry they desire and RM machines will be able to make them. This will have profound implications on the way designers are accustomed to working as, today, they are normally restricted to designing for a particular manufacturing process (e.g. design for injection moulding).

The project members are working with the designers at the partner companies to get them to free their imagination and arrive at designs that would be unimaginable if conventional manufacturing techniques were used. This is by enabling the fast exploitation of RM advantages.

3.2 Changes to the Design Process

The Design Process is likely to change with the advent of Rapid Manufacturing. Designs are normally “signed off” at the prototype and tooling stages – with RM, no tooling exists and thus this sign-off will not occur. The project will aim to investigate what changes will occur to the overall design process and how this will affect the product development cycle. The impact of Rapid Manufacturing on Design for Manufacture (DFM), Assembly (DFA) and Service (DFS) are being investigated.

3.3 Comprehensive Material Testing

RP machines are rarely used to produce fully functioning end use parts and therefore, there has not been an overriding demand to know the full material properties. However, if designers are to have confidence in specifying the materials that are produced on the RM machines for end-use parts then it is vital that they are fully conversant with the various material properties. Some of this information is already available but there are large gaps in the data set. Therefore a large part of the project is looking into the testing of existing materials to complete the data set.

For automotive applications, designers typically need material properties ranging from –40ºC to +140ºC. Therefore, the project is undertaking extensive material testing program for a range of materials over this temperature range with different humidities and also over extended time-periods (0, 4, 13, 26, & 52 weeks) to consider the ageing of the materials. An extensive range of mechanical properties, such as tensile, flexural and impact properties are being investigated according to ISO standards [5,6,7]. Without this materials data, the designers will be reluctant to ‘design for rapid manufacture’. This will be the most significant data collation for materials being used in RP and RM to date. It is estimated that each material will require around 5700 individual tests that equates to an amortised value of 6 months testing per material. These tests are on going.

In this paper, the discussion will be concentrated on the initial experimental work that is related to the materials properties aspect of the project. The initial work that has been done to investigate some of the mechanical properties of SL 7540 and SL 7560 materials under different conditions of ageing, different wall thickness, different ways of post curing and different surface finish will be discussed in the next sections. The materials to be tested include the latest range of RP materials that are aimed at more of a manufacturing level (i.e. their mechanical properties allow them to be used in more demanding applications). The materials to be tested on the project include:

- Vantico SL7560 – a ABS simulant (Stereolithography)
- RPC Accuflex – a polypropylene simulant (Stereolithography)
- Duraform - (Laser Sintering)

4 Experimental Work & Discussion

The following investigations have so far been carried out:

- i) Isotropy tests of Stereolithography SL 7560 resin (*Tensile*, *Flexure & Impact*).
- ii) Effects on impact strength comparing mechanically notched test specimens with specimens that have the notch built on the SL machine.
- iii) Effects of different wall thickness on the mechanical properties of Stereolithography SL 7540 resin.
- iv) Investigation into the behaviour of SL 7560's mechanical properties during the first two weeks directly after build.

4.1 Isotropy tests of Stereolithography materials

From RP's point of view, the definition of the *Isotropic* behaviour is that the parts produced using the same RP process have the same mechanical properties independent on the building orientation.

In the very early days, stereolithography used to result in Anisotropic parts due to the in-build curing technique that was used in the machines at that time [8]. Since the beginning of the 1990s and after the modifications to improve the performance of the machines, parts produced are considered to be *Isotropic*. In other words they have the same mechanical properties independent of the building orientation. However, this tests have been carried out to confirm this for the new resins.

Due to the additive layer-wise manufacturing techniques that are utilised, it was necessary to evaluate whether the samples produced behave in an isotropic or Anisotropic manner. This has a great relevance to the number of tests that are to be performed as if the parts produced are Anisotropic, then the number of tests performed would have to be increased three-fold to consider the three main build orientations. Some previous work has been done using SL 5170 epoxy resin to investigate the Isotropic behaviour of SL parts, and the results had a variation of a range which is less than 10% [9].

The investigations included tensile, flexure and impact tests at a temperature of 22^{o}C ±1 for samples that have been produced in three different orientations (*Flat*, *Upright*, *and Edge*) as shown in Figure 1 which shows the tensile sample in the three different build orientations. Similar orientations are used for the flexure and impact samples.

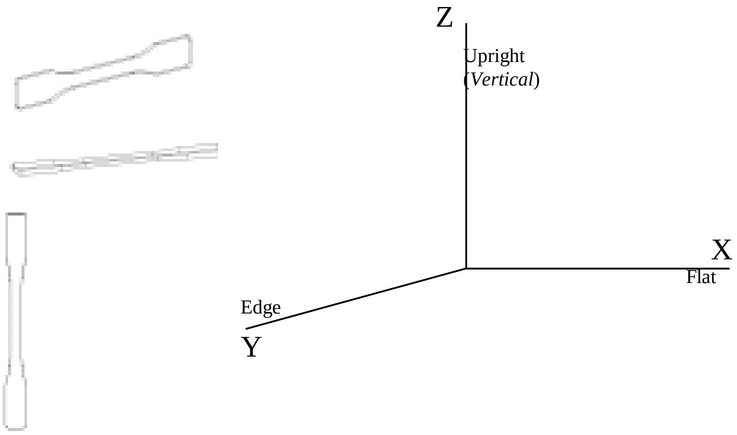

Figure 1: The three orientations that have been used to build the specimens

The samples were produced using an SLA 7000, and were prepared in exactly the same manner. Ten samples of each orientation were been tested for each of the three types of mechanical tests according to ISO standards. The average results of the mechanical tests are given in table 1:

Mechanical Properties	Orientation		
	Flat (X)	Edge (Y)	Upright (Z)
Tensile Strength (MPa)	54.92	56.44	53.77
% Elongation at Break	9.4	8.2	7.6
Young's Modulus (MPa)	2678	2689.3	2755.8
Flexural Strength (MPa)	92.56	96.38	95.31
Flexural Modulus (MPa)	2133.5	2218.1	2178.3
Impact Strength (KJ/m^2)	2.53	2.16	2.44

Table 1: Isotropy test's result

It can be seen from table 1 and figure 2 that, for SL7560, the build orientation has little anisotropic effect on the parts that are produced. Therefore, it can be concluded that the SL parts can be considered isotropic. The same is not expected for LS materials.

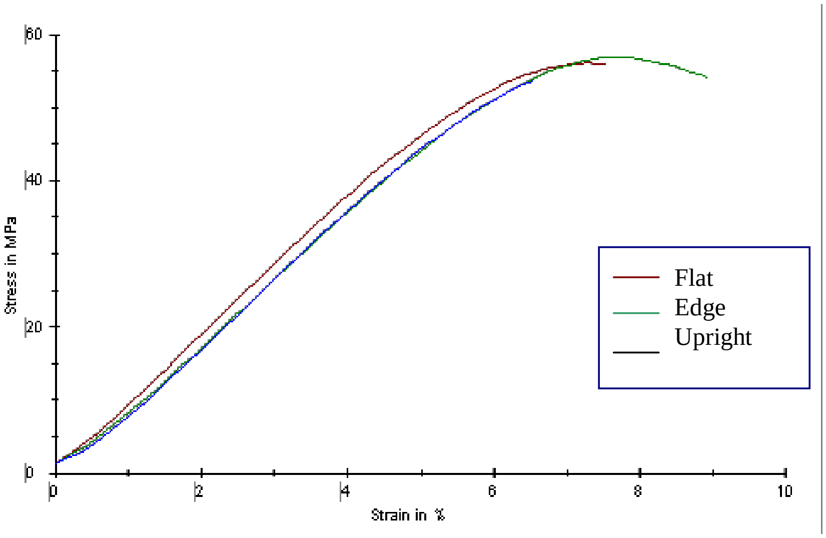

Figure 2: Results of Isotropy Tests for SL7650

For the impact samples that were investigated were produced using SL machine with the requisite notch of the samples being introduced using a conventional notching machine. This lead to another area of investigation, which is; if the samples were produced by the SL machine with the notch included, will the impact strength be affected? This investigation is discussed in the next section.

4.2 Effects of notch creation method on the impact strength of SL 7540

In conventional impact testing, a sample is produced and then a notch is mechanically introduced to the sample by means of a notching machine. However, with RP / RM methods, it is entirely possible to include the notch into the STL file and manufacture this design detail as the part is being built. Figure 3 shows machine-notched and SL-notched samples (respectively) that were build on the SL machine in SL 7540.

For the SL notched sample, the border-scan that has produced the notch profile can clearly be seen. The averaged results for these samples can be seen in table 2.

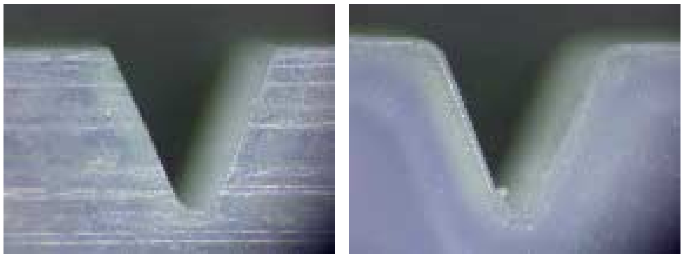

Figure 3: Machine-notched and SL-notched impact test samples

Impact Test Results for SL7540	
Machine Notched Samples (KJ/m^2)	SL notched samples (KJ/m^2)
3.5	9.7

Table 2: Results for machine and SL notched samples

It can be clearly seen that the impact resistance of the SL notched sample is almost a multiple of three higher than that for the machine notched samples. It is clear that the border scan has an influence on the mechanical properties of the produced parts.

This result has clear implications for the design of features such as self-tapping screw threads in that it clearly demonstrates that if the thread is modelled into the CAD model and is therefore produced on the RM machine, then a much greater resistance to failure will be afforded to the product. The effects of manual or machine notching on Laser Sintered parts will also be investigated.

4.3 Effects of the change in wall thickness on the mechanical properties of Stereolithography SL 7540 resin

4.4 This section describes the results that were produced from an investigation into the effects of different wall thickness on the mechanical properties of SL 7540 resin. The tensile and flexural samples were produced at the same time and underwent exactly the same conditions of post curing. Five samples of each thickness (1, 2, 4, 6, 8 & 10mm) have been produced, then tested at temperature of 22°C. The results are shown in table 3.

4.5

Thickness (mm)	Tensile Properties			Flexural Properties	
	Strength (MPa)	% Elongation @ Break	Young's Modulus (GPa)	Strength (MPa)	Modulus (MPa)
1	30.86	16.92	1.4625	-	-
2	35.06	28.77	1.4998	27.33	573.74
4	37.59	21.74	1.7797	49.84	896.25
6	40.55	21.22	1.7793	62.01	1058.28
8	41.68	18.7	1.7796	66.59	917.82
10	41.9	18.09	1.8199	71.48	766.42

Table 3: Different wall thickness samples results (SL 7540)

4.6 Figures 4, 5, 6, 7 & 8 show the change of Ultimate Tensile Strength, % Elongation at break, Young's Modulus, Flexural Strength and Flexural Modulus respectively with the change in the wall thickness.

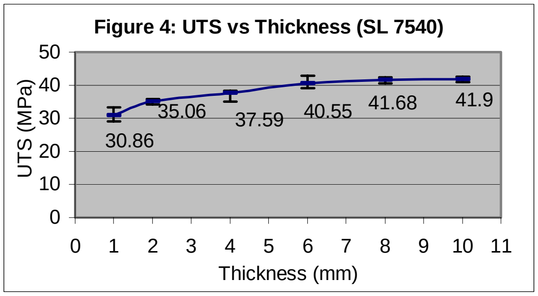
Figure 4: UTS vs Thickness (SL 7540)

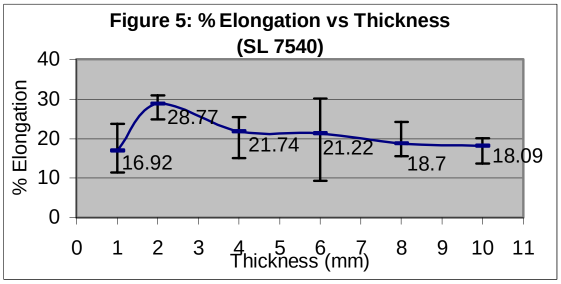
Figure 5: % Elongation vs Thickness (SL 7540)

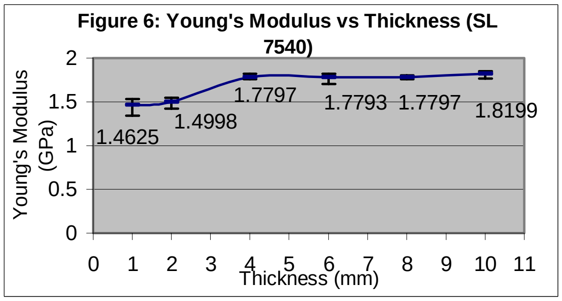
Figure 6: Young's Modulus vs Thickness (SL 7540)

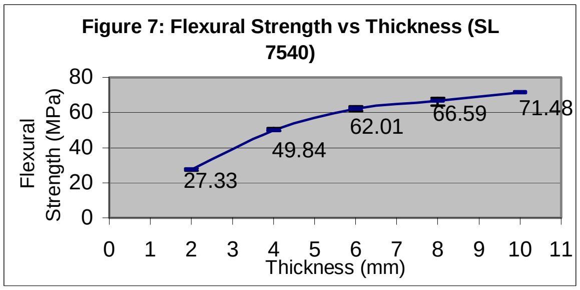
Figure 7: Flexural Strength vs Thickness (SL 7540)

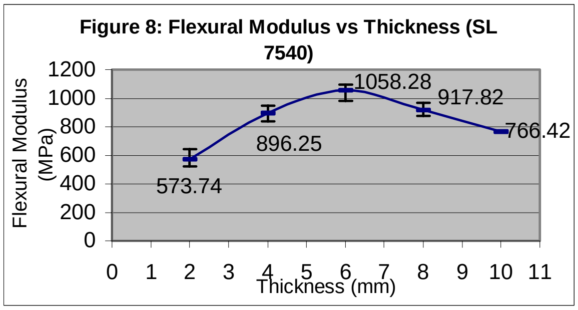
Figure 8: Flexural Modulus vs Thickness (SL 7540)

From these figures, it can be noted that, for SL 7540 resin, as the sample's wall thickness increases, the value of UTS, Young's Modulus and flexural strength increases which is due to the fact that the material becomes stronger. However, it was expected that the mechanical properties would be stronger for thinner parts as the effect of the border scan (presumed to be stronger) would be more pronounced. As these results were surprising, it is suggested that the work to be repeated using other materials. The results of these tests will be reported later.

Percentage Elongation at break in figure 5 can be considered as a constant value starting from 4mm thick and up to 10 mm thickness, which means that the wall thickness does not affect the elongation value of this material.

4.7 Investigation into the behaviour of SL 7560 during the first two weeks

These tests have been carried out to study the stability of the SL 7560 mechanical properties changing the first two weeks. This is to determine of which part the material can be used effectively.

All the required samples for this investigation were produced at the same time and underwent exactly the same procedures of cleaning and post curing. The samples were stored under controlled conditions (20^{o}C & 50% Humidity). The tests were scheduled to take place starting at age of 0 day up to day 13.

The three mechanical tests (tensile, flexure and impact) have been carried out, and 5 samples were being tested for each test type per day.

Table 4 and figures 9 to 14 describe the average tests results for the three mechanical tests.

Day	Tensile Properties			Flexural Properties		Impact
	Strength (MPa)	% Elongation @ Break	Young's Modulus (GPa)	Strength (MPa)	Modulus (MPa)	Impact strength (KJ/m^2)
0	58.67	7.66	2563.1	77.01	1486.4	4.904
1	56.84	6.77	2573.4	87.38	1665.97	4.46
2	59.04	7.38	2684.8	89.26	1753.12	5.264
3	61.71	7.94	2710	91.45	1781.18	5.94
4	64.34	7.79	2776.8	93.23	1831.05	5.72
5	64.15	8.13	2775.8	93.31	1802.1	6.244
6	64.36	7.51	2770.1	93.38	1840.28	5.46
7	65.26	7.91	2830.7	94.34	1854.11	5.69
8	65.35	6.95	2863.4	94.89	1848	6.05
9	66.84	7.9	2883.9	95.85	1764.12	5.64
10	65.39	7.7	2857.7	93.77	1874.25	7.06
11	64.66	8.91	2896.6	96.38	1927.82	6.042
12	66.08	8.57	2921.1	93.98	1812.36	6.174
13	65.61	8.26	2905.9	93.15	1855	6.418

Table 4: Average results for three mechanical tests over a period of two weeks (SL 7560)

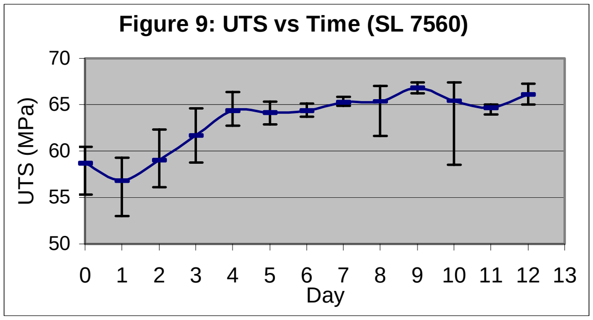
Figure 9: UTS vs Time (SL 7560)

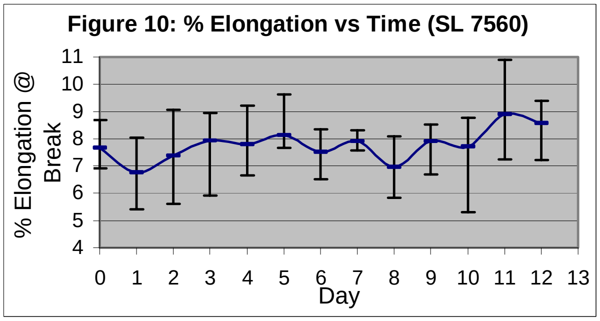
Figure 10: % Elongation vs Time (SL 7560)

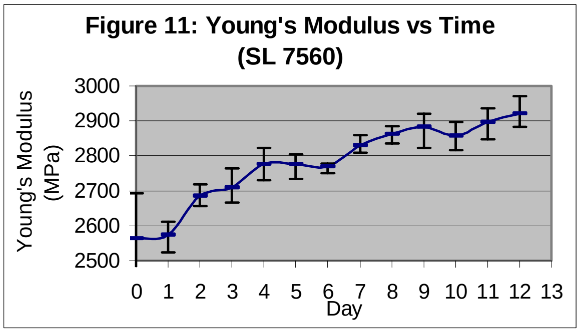
Figure 11: Young's Modulus vs Time (SL 7560)

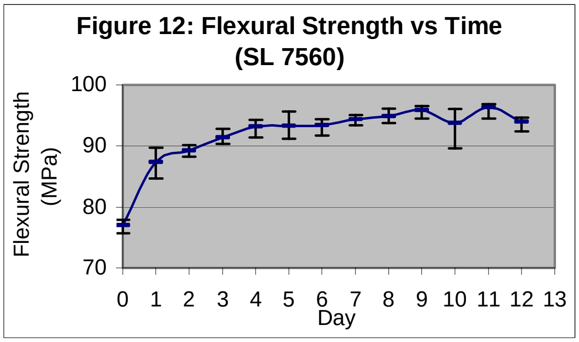
Figure 12: Flexural Strength vs Time (SL 7560)

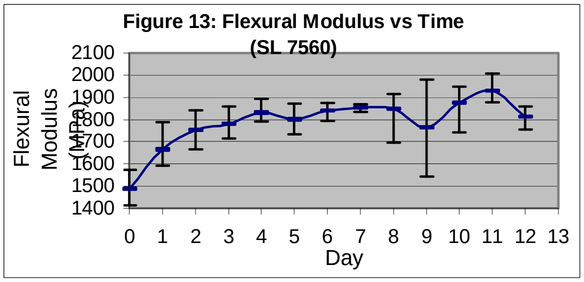
Figure 13: Flexural Modulus vs Time (SL 7560)

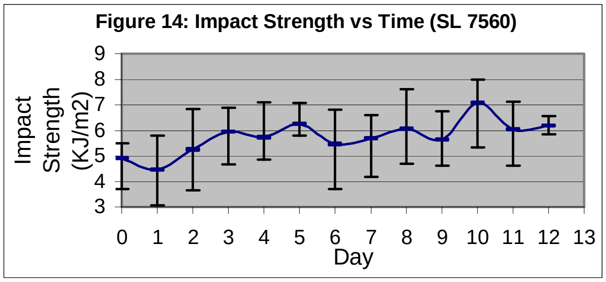
Figure 14: Impact Strength vs Time (SL 7560)

From the illustrated results, it can be seen that the SL 7560 mechanical properties are changeable during the first few days after manufacturing, and they improve and stabilize with ageing.

It is the aim of the project to ascertain the material properties over a one-year period. For the SL 7560 material, because of the one-week “settling” time of the material, the tests will be performed at intervals of 1, 4, 13, 26 & 52 weeks, rather than starting on day zero.

5 Conclusions

i) The isotropy tests have confirmed that the parts that produced by the SLA are isotropic.
ii) The Izod impact samples that were produced by the SL machine with the notch have higher impact resistance. This has implications for designing with SL materials.
iii) Most of the mechanical properties of SL 7540 have been improved with the increase in the wall thickness, which was not expected. This needs more investigation using other materials.

iv) SL 7560 mechanical properties can be found to be changeable, generally increasing during the first week directly after build.

6 Future work

As mentioned previously, there is a plan of work that includes three different mechanical tests (tensile, flexure, and impact) that will be applied for three different types of materials (2 SL & 1 LS) at a wide range of temperature (-40 to 140^{o}C at 10^{o}C interval) and different three levels of humidity (wet, dry and controlled) at different ages, this is to complete the available materials data for the designers to become confident about the materials so as to employ them in the correct application.

The same initial mechanical tests that are described throughout this paper will be applied for the other two materials to determine their plan of testing.

The research will also include an investigation into the methods to control the effects of humidity and ageing for SL 7560 resin with coatings.

7 Acknowledgment

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9 References

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