

**Understanding customer preferences:  
Comparing Additive Manufacturing powders  
(PA2200 & PA2221) in a South African context**

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## 1. Abbreviations

|        |                                                         |
|--------|---------------------------------------------------------|
| AMP    | Advanced Manufacturing Precinct                         |
| CIE    | Commission Internationale de l'Eclairage                |
| CUT,FS | Central University of Technology, Free State            |
| EOS    | Electro Optical Systems GmbH                            |
| FDM    | Fused Deposition Modelling                              |
| FFF    | Fused Filament Fabrication                              |
| LS     | Laser Sintering                                         |
| MJF    | MultiJet Fusion                                         |
| RAL    | Reichsausschuss für Lieferbedingungen und Gütesicherung |
| SLA    | Stereolithography                                       |
| VUT    | Vaal University of Technology                           |

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#### 4. Abstract

This study aims to determine the properties of polymer powders for laser sintering (LS) which are most desirable from a customer perspective. With multiple options of imported material being available, it is possible to directly compare different materials to each other.

Historical usage data is available for two sintering materials, ie. PA2200 and PA2221. This data shows the demand for the different powders over time. Questioners will be used to further analyse the requirements of the VUT's clients. The information gathered will be used to create a foundation for qualifying new and possible locally sourced materials for additive manufacturing operations in South Africa.

Schmid, M. and Wegener, K. (2016) noted that AM is becoming a viable production technique, however there is a significant limitation on applicable materials. They also showed that only 1/200 000<sup>th</sup> of the quantity of polymer material sold globally is produced as LS powder.

The possibility of localising this material has obvious financial and business model implications for South Africa, and will likely increase market penetration in the country by lowering the cost of AM parts. Producing polymer powders for export will also be a possibility if local testing is successful.

## 5. CHAPTER 1 – Introduction

### 1.1 Proposed title

Understanding customer preferences: Comparing Additive Manufacturing powders (PA2200 & PA2221) in a South African context.

### 1.2 Purpose of the study

This study aims to determine the qualities of laser sintered nylon prototypes and parts which are most critical to customers' acceptance thereof. This information will be used to guide the choice of materials for future manufacturing operations, as well as the localisation of powder materials for laser sintering.

### 1.3 Introduction

Commercially available PA12 nylon powder, in this case PA2200 manufactured by Electro Optical Systems GmbH, is used extensively by the VUT Southern Gauteng Science and Technology Park (VUT SGSTP) in its Laser Sintering systems for producing prototypes and other components for research and commercial purposes. The material is favoured by researchers and customers alike for its superior strength, surface finish, and cost effectiveness when manufacturing multiple small to medium-sized components.

The VUT SGSTP's Advanced Manufacturing Precinct (AMP) employs 5 laser sintering systems, all supplied by Electro Optical Systems (EOS GmbH), and constitutes South Africa's largest plastics LS facility. The precinct manufactured more than 20 000 components during the 2018 calendar year, most of which were laser sintered. A large quantity of nylon powder was consumed during this period, with most of the material cost being due to non-reusable material. Due to thermal degradation of the powder after each build, it is necessary to refresh the used powder with virgin material before reusing it in the next build, typically at a ratio of 1/1 in that facility, as recommended by the material supplier (Dotchev, K., & Yusoff, W., 2009).

Only 8% to 12% of the total build volume of an LS machine is typically converted into useable parts (Pande, S., Mauchline, D. & De Beer, D., 2015).

Figure 1 shows how the consumption of polymer powder for LS and Multi Jet Fusion (MJF) used globally has increased from 1.93 million kg in 2014 to 3.9 million kg in 2017. The latter is valued at 291.5 million US Dollars. (4 439 375 344ZAR) (Based on an exchange rate of 15.23ZAR/\$) (Wohlers Associates (2018))

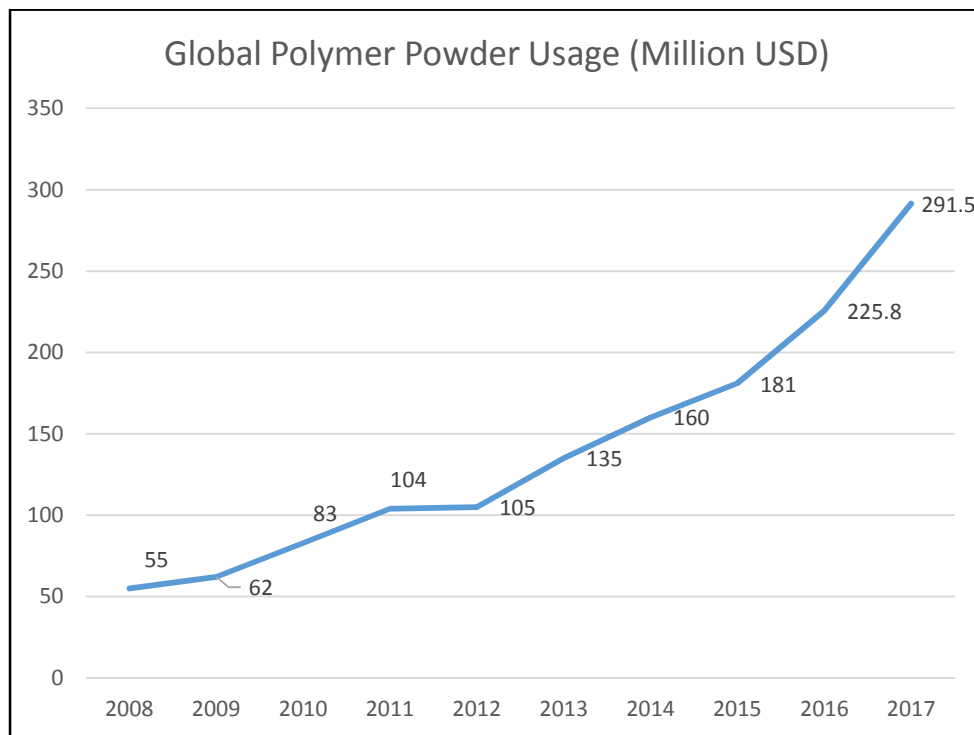


**Figure 1: Global polymer powder usage (cost in millions of USD)**

#### 1.4 Problem Statement

Due to the fact that the LS systems and materials used at the AMP are manufactured in Germany, the cost of operating such technology in South Africa is high. This is caused by several factors:

- High exchange rate between the Euro and the Rand
- High shipping costs for machinery and material
- Lack of local material manufacturers

- High refresh rates needed to maintain material quality
- High cost of maintenance by EOS technicians due to above factors

Short of localising material manufacturing, the only factor under the control of the AMP is the material refresh rate. One method of reducing material refresh rate is using materials designed to withstand thermal degradation better than the standard PA2200.

One such material is PA2221 polyamide (1 088.40ZAR/kg), supplied by EOS GmbH. Refresh rates of 30% are recommended for this material, which compares favourably with the 50% refresh rate currently used for PA2200 within the AMP's LS systems.

PA2200 is based on VESTAMID<sup>®</sup> polyamide, manufactured by Evonik Degussa GmbH, Marl, Germany).

To determine if PA2221 is a suitable replacement for PA2200 as the main material for LS production at the AMP, both materials need to be evaluated and compared.

Within the VUT SGSTP, significant amounts of data are available on the usage of both materials, evaluating the usage trends demonstrated in this data will show the preference for each material within South-African industry.

By comparing the properties of the two materials to the usage trends, it will be possible to establish the most important material properties required by customers. These results will be augmented by questionnaires sent to the AMP's top clients to directly assess their opinions of the different material properties.

## 1.5 Scope of research

This study will focus only on PA12 nylon LS materials. Materials for other AM processes such as Fused Filament Fabrication (FFF) have been successfully localised, and many material and colour options are available.

Other materials are available for EOS sintering platforms, and there are several other manufacturers of LS equipment. However, this study will focus only on the two materials specified, as there is significant experience in their application. Further research into material cost reduction and colouring will be proposed, but not covered in this dissertation.

### **1.6. Objectives**

This study aims to establish an understanding of the aspects affecting the adoption of new laser sintering materials such as PA2221 in South Africa.

#### **Specific objectives are:**

- Quantify the difference in the two materials under consideration
- Evaluate customers' preferences concerning the application of the materials in industry.
- Develop recommendations for future material implementation.

## 6. CHAPTER 2 - Literature review

### 2.1 Additive Manufacturing

Additive Manufacturing (AM) differs from conventional manufacturing in that, instead of removing stock material to create an object, material is progressively added to build up an object from material supplied in a liquid, powder or filament format.

Additive Manufacturing (AM) first became commercially accessible internationally in 1987 (Wohlers, T. & Gornet, T.J., 2018) with the introduction of the SLA 250 stereolithography machine produced by 3D Systems in the USA. This was a vat polymerisation system, creating parts from cross-sections of a computer model reproduced in photo-sensitive resin.

During this period, South Africa was still suffering under economic sanctions as a result of apartheid, meaning that the country's institutions were unable to take full advantage of these new technological developments in Europe and the USA. It took until 1991 for AM to achieve a local foothold.

First to be procured was an SLA 250 machine in 1991. It was imported by Bob Bond, then general manager of 3D Systems (Pty) Ltd, and was used to set up South Africa's first 3D printing service bureau. They offered CAD design using an Integraph system before producing parts on the SLA 250. Their main customers were automotive Original Equipment Manufacturers (OEMs), automotive component suppliers, defence, medical and consumer companies. The company was the most prolific consumer of SLA resin in the world at the time, but eventually lost business to university-based service bureaus, according to Bob Bond.

In 1994, two Stratasys FDM1500 fused deposition modelling machines (as seen in Figure 2) were installed at the Council for Scientific and Industrial Research (CSIR). Both machines were upgraded to FDM 1650 configuration at a later date.

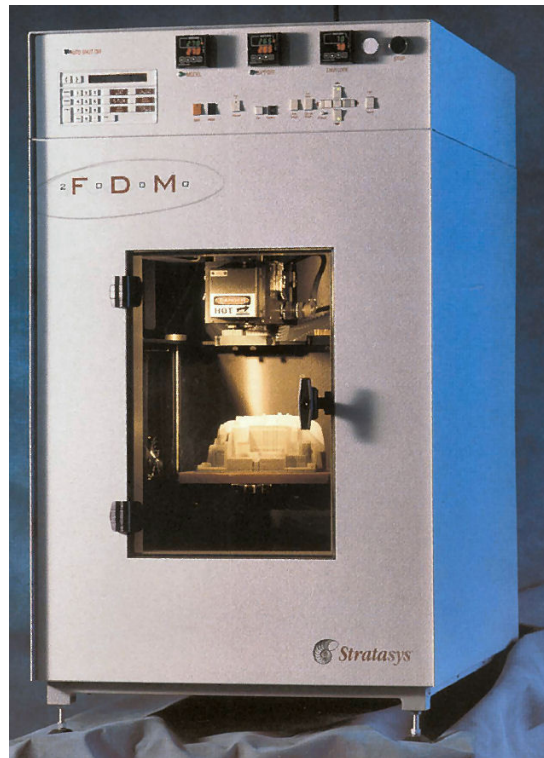


**Figure 2: FDM 1650 machine**

**([httpswiki.london.hackspace.org.ukwimages005FDM\\_1650.JPG](httpswiki.london.hackspace.org.ukwimages005FDM_1650.JPG))**

The first powder bed Laser Sintering (LS) system was released in 1992 by DTM in the USA, and in 1994 the German company Electro Optical Systems (EOS) launched their LS system, the EOSINT.

The first LS machine in SA was the DTM Sinterstation 2000, running Duraform polyamide powder. The machine was acquired by Prof Deon de Beer and installed at the Centre for Rapid Prototyping and Manufacturing (CRPM) at the Technikon Free State, which later became the Central University of Technology, Free State (CUT,FS) (Campbell, R.I. & De Beer, D.J., 2005)

The acquisition of the first EOS laser sintering system in South Africa in 2003 marked the start of true powder bed additive manufacturing capacity in the country. This system, procured by Prof Deon de Beer and installed at the Centre for Rapid Prototyping and Manufacturing (CRPM) at the Central University of Technology, Free State, introduced a new powdered nylon material, EOS PA2200.

The EOS system operates on the same basic principle as the DTM system, however there are process differences between the two systems which affect the properties of the manufactured parts.

## **2.2 Machine differences**

The EOS system produces parts with more uniform shrinkage and less warpage, but exposes the powder bed to high temperatures for longer than the DTM system, due to the fully heated unpacking chamber of the former. The DTM system part cylinder heaters only extend 200mm from the upper powder layer. This results in faster powder degradation on the EOS system.

The acquisition of an EOS P390 laser sintering system and its installation at the Vaal University of Technology (VUT) in 2010 brought commercial and research-centred polymer sintering to Gauteng. By 2015, the VUT's fleet of EOS laser sintering systems had grown to 5, including the dual-laser P760. All 5 systems produced parts using PA2200 polyamide at that stage.

## **2.3 Laser sintering**

Laser sintering is an additive manufacturing technology developed in 1989 by Carl R. Deckard at the University of Texas. (Carl R. Deckard (1989)). It is a means of creating physical objects directly from 3D computer models by selectively sintering successive cross sections of the model into corresponding layers of powdered material (as shown in figure 4). Thus the digital cross sections are reproduced in physical form by the technology.



**Figure 3: Interior of a DTM Sinterstation 2000 (taken from <http://www.me.utexas.edu>)**

Polymer laser sintering systems consist of a build platform, recoater, feed system, scanner, laser and a heating system. The build platform takes the form of a piston which lowers as each consecutive layer is sintered, allowing the model to develop in the layers of powder above the piston. After each lowering of the piston, the recoater applies a fresh layer of powder to the build. The powder is drawn from hoppers on either side of the machine. The recoater can take the form of a metal or elastomeric blade, blade set or roller.

After the deposition of a powder layer, the heating system brings the powder bed to a preset temperature, just below the melting point of the polymer, after which a CO<sub>2</sub> laser, guided by computer-controlled galvanometer mirrors, selectively exposes the top layer, fusing it to previous layers (Pilipovic, A., Valentan, B. and Šercer, M. (2016)). This allows a solid object to be created within the powder bed. The surrounding unsintered powder supports the sintered objects during the manufacturing process.

The laser is focussed and directed through a scanner, containing a set of galvanometer-driven mirrors, which direct the laser beam onto the surface of the powder bed in a pattern corresponding to a cross section of the model being manufactured. To accommodate the

differing focal lengths to the powder bed at different angles, an F-theta lens is used to correct the beam, maintaining consistent focus across the entire build area.

Alternatively, a 3-axis scanner can be used to effect the same result by shifting the focal lenses of the laser system to compensate for varying focal distances.

During the build, the entire build volume is kept at an elevated temperature by the heating system. Certain sintering machines have heaters completely surrounding the build box or cylinder to maintain the temperature of the entire powder volume. Other systems like the DTM Sinterstation 2500 are only heated from above the upper powder layer and the first 200mm of the build (Dotchev, K. and Yusoff, W. (2009)).

When the building process has completed, the heating system is deactivated, allowing the build to gradually cool before the completed objects can be removed. These objects are then bead-blasted to remove excess powder stuck to the sintered objects.

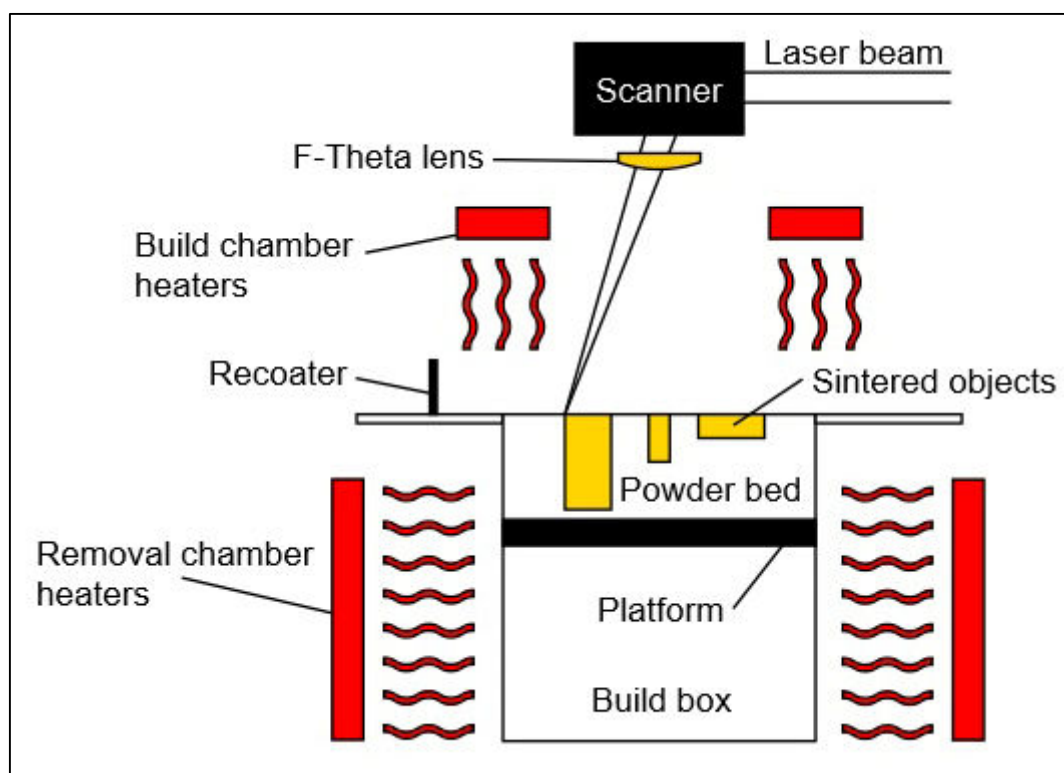


**Figure 4: Layout of a polymer laser sintering system**

When sintering in polymer materials, such as PA12 nylon, there are several aspects to consider:

### **2.3.1 Thermal degradation**

The longer PA12 powder is exposed to high temperatures, the more the material degrades. This is more evident in sintering systems with heated removal chambers, such as the EOS Eosint machines, as the entire build volume remains at a high temperature during the build. Machines such as the DTM Sinterstation do not have fully heated removal chambers, thus the area below the top 200mm of powder remains cooler than the build chamber.

Additionally, powder adjacent to sintered parts degrades faster due to the proximity to high temperature sintered areas (EOS GmbH - Electro Optical Systems (2010)). Powder located towards the centre of the build volume also remains at a high temperature for longer than peripheral powder due to the insulating properties of PA12.

Due to the degradation of PA12 powder during sintering, it is necessary to refresh the used powder with virgin material to maintain the quality of the powder. Refreshment is based on the melt flow rate (MFR) of the used material. If the MFR is too low, surface finish of the final parts will suffer. (Dotchev, K. & Yusoff, W., 2009) and (Pham, D.T., Dotchev, K.D. & Yusoff, W.A.Y.) The powder is refreshed by mixing it thoroughly with fresh powder before allowing the mixture to stand for at least 24 hours to dissipate any accumulated static electricity. Static in the powder causes flowability problems, as cohesion is increased between the powder particles. This in turn causes recoating errors or underfeeding, both detrimental to process stability.

It should be noted that, when mixing powder repeatedly in order to refresh the mixture, some particles in the powder have been through many builds, and have degraded considerably. The mixed powder is therefore far from homogenous in nature. A point is reached where, no matter the refresh ratio, the mixed powder will still yield poor quality surface finishes. It is at this point that the entire batch of mixed powder will need to be discarded in favour of fresh material.

Thermal degradation is the major cost driver in the LS process.

### 2.3.2 Warpage

Warpage manifests in two major ways in laser sintered polymer parts. The first is the upward curling of long, horizontal sections of objects in the powder bed. This is caused by the high temperature top layer shrinking relative to the layer beneath it after each sintering pass. A Mousa (2016) found that the main contributor to this type of warpage is the thickness of the powder layer between the platform and the object being sintered.

The second is buckling of large, flat surfaces in any axis, caused by the non-uniform shrinkage across the flat surfaces due to residual stresses within the part. (Ahmadi Dastjerdi, A., Movahhedy, M. R. and Akbari, J. (2017)). This is exacerbated by insufficient cooling time or uneven cooling of the build volume. Large, flat objects are generally unsuitable for laser sintering without some optimisation for the process, for example the addition of cutouts and ribs. This is illustrated in Figure 5. The lower the MFI of the mixed powder, the greater the chance of both types of warpage.

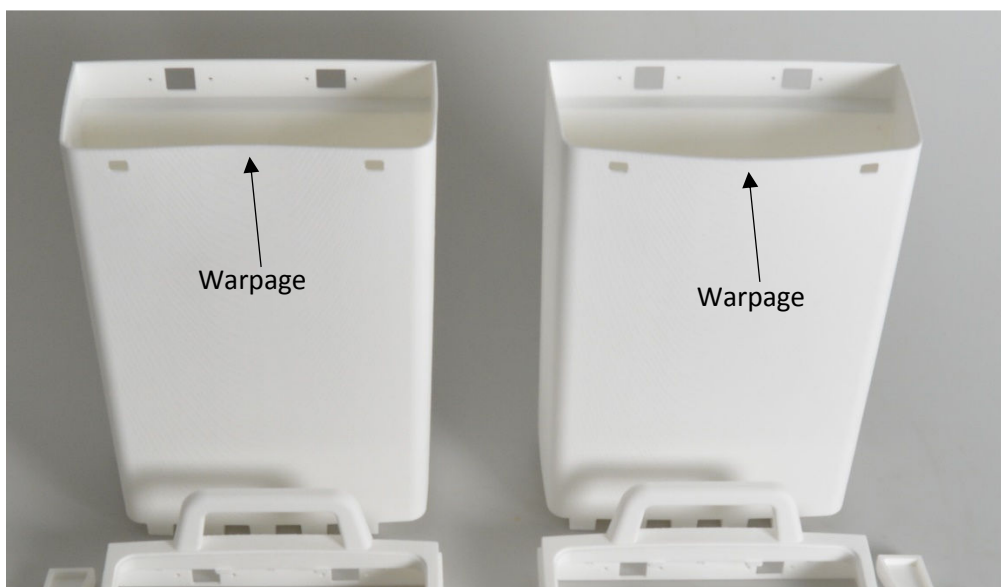


**Figure 5: Warped parts due to uneven contraction**

It is therefore necessary to maintain powder quality in the system to reduce warpage and build failures. Insufficient material refreshment can lead to shortfeeding, severe warpage and build crashes.

## Summary

The AM industry in SA has evolved from being purely prototype-based to a useful manufacturing solution. The large batch sizes handled by LS machinery makes the technology ideally suited to series production. Due to the cost-sensitive nature of the South African market, expansion of LS usage will require more cost-effective materials.

## 7. CHAPTER 3 - Research Methodology

This chapter will outline the theory and methodology used to evaluate the two LS materials, as well as the layout used for questionnaires.

To determine the difference between client perception and physical characteristics of the different materials, it is necessary to scientifically analyse both materials. Samples sintered in both PA2200 and PA2221 powders will be evaluated in terms of the following:

- Tensile strength
- Surface roughness
- Colour
- Cost

### 3.1 Tensile strength

Physical strength is an important factor when using polyamide products, as they are often used in load—bearing environments. Clients have become accustomed to the strength offered by PA2200, therefore it is necessary to quantify the performance of both materials to highlight any differences in performance and therefore, quality.

To achieve this, tensile test samples were prepared according to the ASTM D638-14 standard. (ASTM International (2015) (seen in figure 7)

This standard was chosen as it has been used by other researchers such as Usher, J. S., Gornet, T. J. and Starr, T. L. (2013) to test PA12 samples, and therefore results will be directly comparable.

Type 1 samples were produced on an EOS P100 Formiga laser sintering machine (as seen in Figure 6) at the Vaal University of Technology Southern Gauteng Science and Technology Park. Temperature and scaling parameters used during the sintering process were determined using the standard calibration methods documented in the P100 user manual.

A temperature search build was run, gradually increasing the build chamber temperature until no warpage occurred, revealing the optimal build temperature. A scaling job was run to determine the shrinkage of the sintered parts, as well as the laser beam offset, which are then compensated for to achieve geometrically accurate parts.



**Figure 6: EOS P100 Formiga LS machine**

The samples were aligned to the X axis of the platform. Additional samples in the Y direction were not necessary, as it has been shown by Cooke, W. et al. (2011) that sintered polyamide is isotropic in both horizontal axes. Therefore, comparison of X-axis samples of both materials will effectively show the differences in material properties.

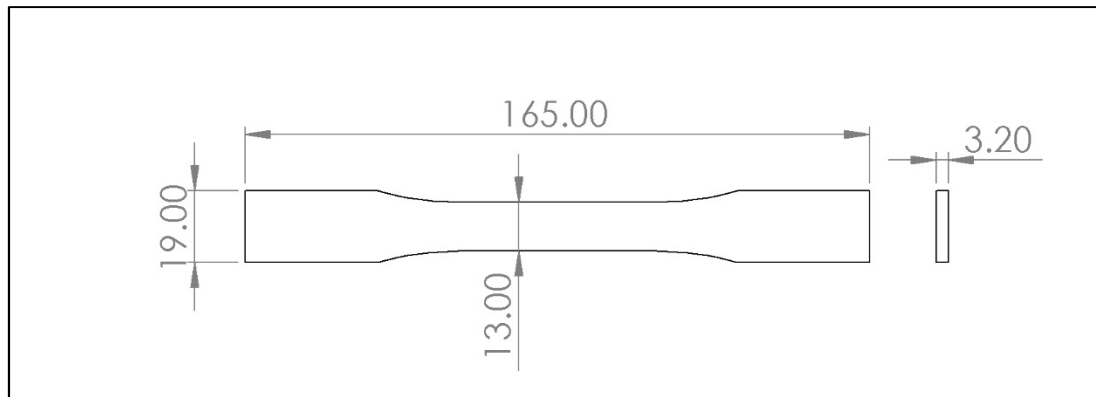


**Figure 7: ASTM 638-14 type 1 sample**

Majewski, C. & Hopkinson, N. noted in 2011 that the measured thickness of the specimens (Z axis) was greater than the thickness of the CAD model. They attributed the difference to scaling factor settings on the P100 Formiga, however, the difference might be due to overburn and cusping.

When calculating stresses within laser sintered parts, the unique geometry generated by the process needs to be considered. The final shape of a sintered part can differ considerably from the original CAD geometry, especially in small components, due to various aspects of the manufacturing process:

### **3.1.1 Overburn.**

When sintering the first layer of a part, the curing zone over-penetrates the plastic powder to create a solid layer thicker than 0.1mm. This overburning also creates a slightly rounded edge on the lower sides of sintered parts. In an attempt to reduce this effect, EOS developed the “Up/Downskin” parameter, which increases the scanning speed on the lower layers of a part, reducing the energy applied to the first few layers. This parameter, however, still leaves roughly 0.12mm of overburn.

Overburn can be mitigated by using Z compensation, a digital corrective process whereby the lower surfaces of a part are translated upwards by an amount equal to the expected overburn. This compensation thereby produces more geometrically accurate parts.

### 3.1.2 Cusping.

While sintering, the density of the powder in the exposed area roughly doubles, creating a depression in the surface of the powder-bed. As the sintered material subsides into this depression, it forms a meniscus. The last layer of a sintered part will also exhibit this meniscus, the edge of which hardens into an upturned cusp.

These factors will result in a sintered part that does not have a perfectly rectangular cross-section, and should be taken into account when measuring the samples for calculation purposes.

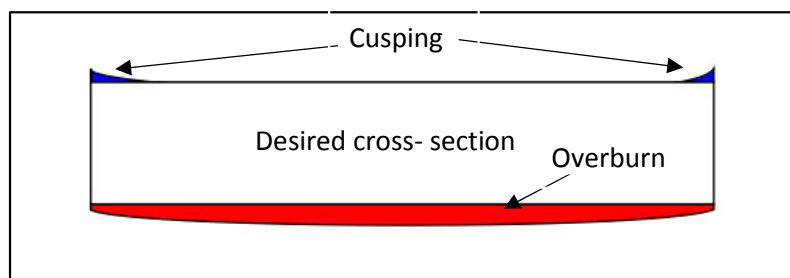


**Figure 8: Overburn and cusping**

These factors cause a slight difference in dimension between sintered samples, so it is necessary to measure each one when calculating stress and strain.

### 3.1.3 Apparatus

Sintered samples of both materials were kept in sealed plastic bags after bead-blasting and dusting, limiting the effect of hydration on the nylon material, which effects the modulus and mass of the sample (Haerst, M. J. *et al.* (2015)). Testing was conducted at the Central University of Technology, Free State using the MTS Criterion Model 43 tensile tester (seen in Figure 9) and MTS TestSuite Elite Software. Ten samples of PA2200 and 8 samples of PA2221 were tested.



**Figure 9: MTS Criterion Model 43**

## 8. 3.2. Colour

### 3.2.1 Theory

Perceived colour is an important aspect of quality perception. It is dependent on many factors such as the individual observer's age, sensitivities, the ambient light conditions, and comparative aspects such as adjacent colours. Perceived colour is defined by Fridell Anter, K. (2000) as "the colour that an observer perceives that an object or a field has in any given light and viewing situation."

The colour of an object can influence perceived quality, particularly in foods. Humanity has developed the association between colour and the ripeness of fruits and the aromas related to different degrees of cooking (Lawless, H.T., and Heymann, H. (1999)). Since colour perception is so closely linked to perceived quality in humans, it is also applicable to other substances and objects, like plastics.

A bright white colour, for instance, will appear to be of higher quality to an off-white or beige colour. This could be due to the fact that plastics age and yellow with exposure to light over time, therefore faded-looking colours are perceived as degenerated and worn, and therefore less desirable than bright ones.

Visually, PA2221 is generally perceived to be slightly darker and browner than PA2200, and this has led to complaints from clients who are used to the purer white colour of PA2200. The reason for this difference in colour is the additives in the PA2221 powder, including thermal stabilisers (EOS GmbH - Electro Optical Systems (2014)) which allow a lower refresh rate than PA2200. These additives change the colour of the material as well as making it slightly more translucent.

### **3.2.2 Measuring colour**

To quantify the difference in colour between the two materials, a spectrophotometer was used to generate spectral reflectance graphs for both materials. Additionally, the colours were mathematically defined using the  $L^*a^*b^*$  colour space as defined by the Commission Internationale de l'Eclairage (CIE) (as seen in Figure 10).

This colour space is a 3-dimensional colour chart incorporating the hue, saturation and brightness of a particular colour.

The 3 aspects of this colour space are:

$L^*$  = difference in lightness and darkness (100 = lighter, 0 = darker)

$a^*$  = difference in red and green (60 = redder, -60 = greener)

$b^*$  = difference in yellow and blue (60 = yellower, -60 = bluer)

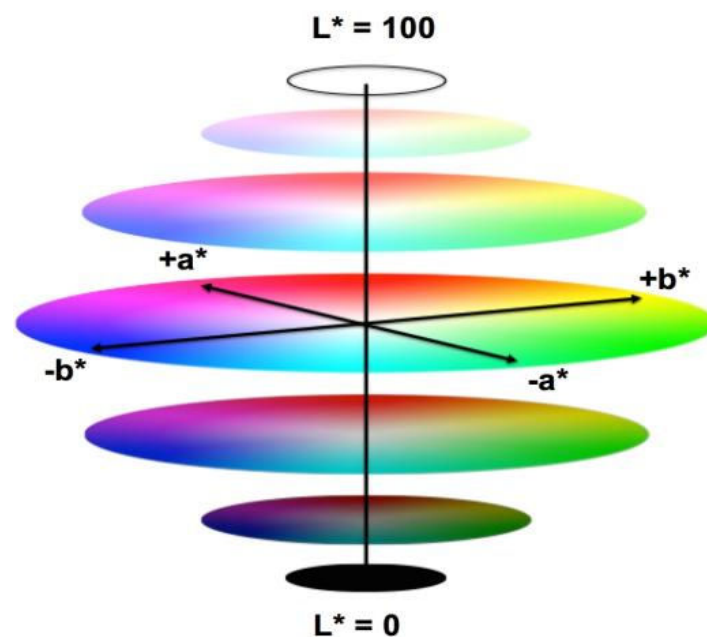


**Figure 10: THE CIE  $L^*a^*b^*$  colour space**

Any colour can therefore be represented by these 3 values.

### 3.2.3 Apparatus

Analysis of the PA2200 and PA2221 samples was conducted using the Konica Minolta CM-5 Spectrophotometer, seen in Figures 11 and 12. This device is able to analyse the colour of a sample and present the results in both a spectral reflectance graph and in CIELab format. The same plastic strips were used for both surface roughness tests and spectral analysis.



**Figure 11: Konica Minolta Spectrophotometer CM-5**



**Figure 12: PA2200 sample loaded for analysis**

All samples were scanned using a D65 Standard illuminant. This represents average daylight, including the ultraviolet region. The correlated colour temperature is 6504K. This illuminant was chosen as it represents full-spectrum daylight, the most likely illumination under which

the powder samples would be compared in prototype form. The spectral profile for Illuminant D65 is shown in Figure 13.

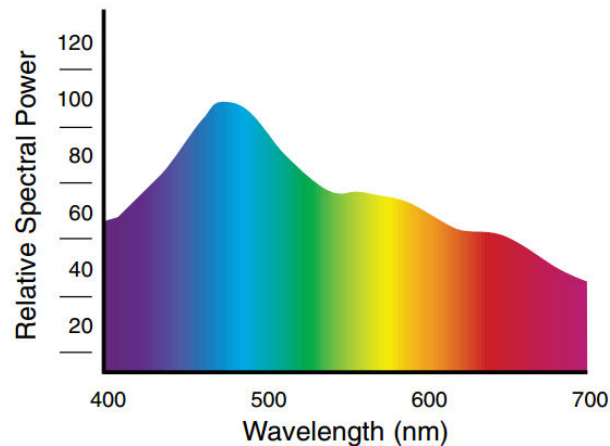


**Figure 13: Daylight (Standard Illuminant D65/10°) (Pantone 2018)**

### 3.2 Surface roughness

An important aspect of the perceived quality of laser-sintered parts is the surface finish (Guo, J. *et al.* (2018)). The inherent roughness introduced by “stair-stepping” or stratification resulting from the additive manufacturing process adds significantly to the surface roughness of manufactured parts. This is however not a function of the material, but rather of the manufacturing process itself, so it will not be included in this study.

Stratification can be reduced by changing the orientation of a part during build preparation, by reducing the layer thickness, by optimising the sintering parameters and by ensuring high powder quality (Pham, D. T., Dotchev, K. D. and Yusoff, W. A. Y.).

The profile roughness parameters are defined in the ISO 4287:1997 standard. Roughness is defined as the deviation from a perfectly flat surface, high surface roughness corresponds to large deviations, while smooth surfaces have smaller deviations. A representation of a roughness profile can be seen in Figure 14.

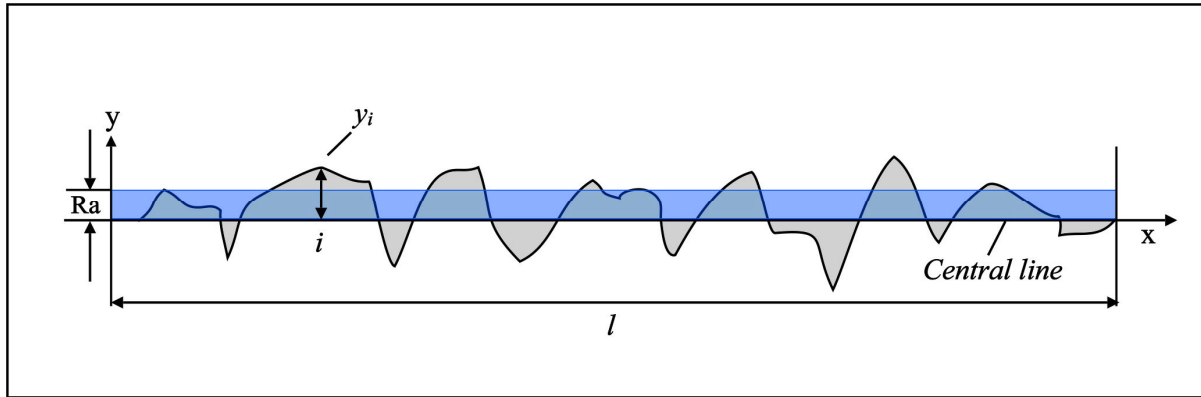


**Figure 14: Roughness profile**

$l$  = length of sample

$n$  = number of equally spaced data points along the sample length

$y_i$  = vertical distance from the profile to the mean line at data point  $i$  (always positive)

$R_p$  = maximum peak height

$R_v$  = maximum valley depth

$R_a$  = Arithmetical mean deviation from the central line

Arithmetical mean deviation is defined as:

$$R_a = \frac{1}{n} \sum_{i=1}^n |y_i|$$

$R_z$  represents the average of the sum of five maximum profile peaks and 5 maximum profile valleys within the sampling length.

$$R_z = \frac{\sum_{i=1}^5 \frac{1}{2} y_i + \sum_{i=1}^5 y_v}{5}$$

$R_q$  is the root-mean-squared (RMS) deviation of the profile within the sample length.

$$Rq = \sqrt{\frac{1}{n} \sum_{i=1}^n \frac{1}{2_i^2}}$$

$R_t$  is the maximum height of the profile.

$$R_t = R_p - R_v$$

### 3.2.4 Apparatus

Three samples each of PA2200 and PA2221 (shown in Figure 15) were tested using a Dobamoni DR-432B Surface roughness tester (Guangzhou Amittari Instruments Co., LTD, Guangzhou, China)(seen in Figure 15). The device draws a diamond-tipped stylus across the test sample surface and measures the resulting profile. The roughness parameters are then calculated by the unit and displayed on the LCD screen.

Measurements were taken on both the upper and lower surfaces of the samples, known as upskin and downskin, respectively, as there are different mechanics at play when these surfaces are created. The downskin receives multiple secondary heating from the upper layers of material, while the upskin is in direct contact with subsequent colder layers of powder. All measurements were taken in the X direction for the sake of uniformity.

An RC filter was applied within the tester before generating the roughness parameters. It is a traditional 2-stage filter with phase difference.



**Figure 15: Dobamoni DR-432B Surface roughness tester**

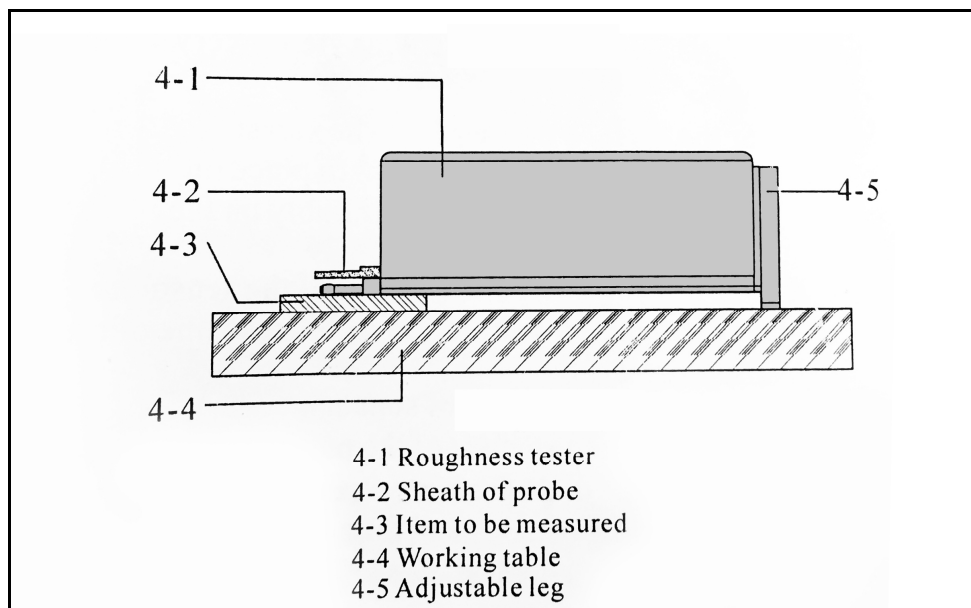


**Figure 16: Setup of the Dobamoni DR-432B Surface roughness tester  
(Guangzhou Amittari Instruments Co., LTD (no date))**



**Figure 15: PA2200 and PA2221 samples used for surface roughness tests**

### 3.3. Cost evaluation

To compare the costs of running the different materials, a test build, shown in Figure 16, was considered. This build consisted of 193 components for a drone accessory company. The height of the build was 242.31mm with a build density of 7.63%.

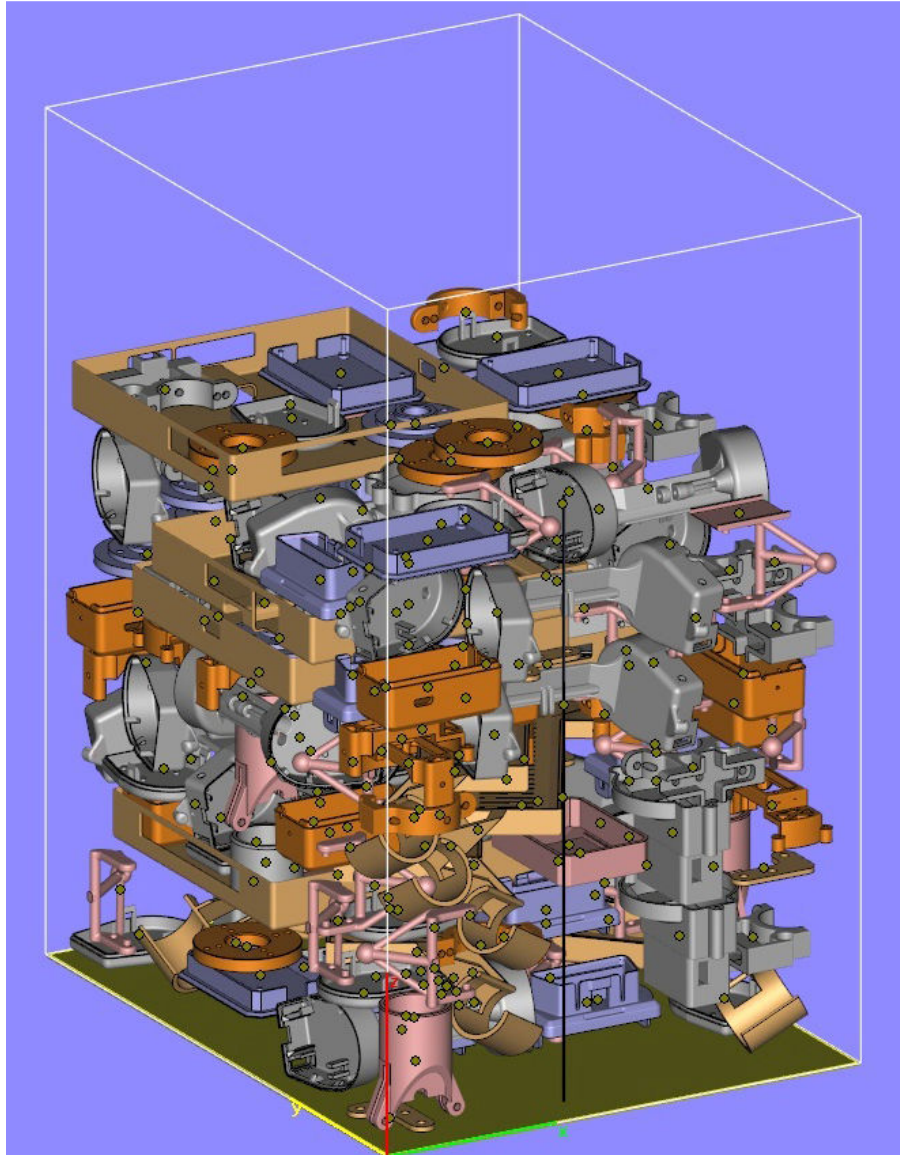


**Figure 16: P100 test build**

### **3.4. Questionnaires**

A survey was conducted to evaluate the opinions of the clients who purchased the most components manufactured in PA2221. Of primary interest was the application of the sintered parts within the clients' businesses: whether or not the parts were used without additional finishing, and whether clients received comments on part quality from third parties.

### 3.4.1 Selection of clients

To select suitable clients to participate in the survey, historical sales data, shown in Figure 17, was evaluated to select the most prolific users of PA2221. The Figure shows the percentage of total income per client.

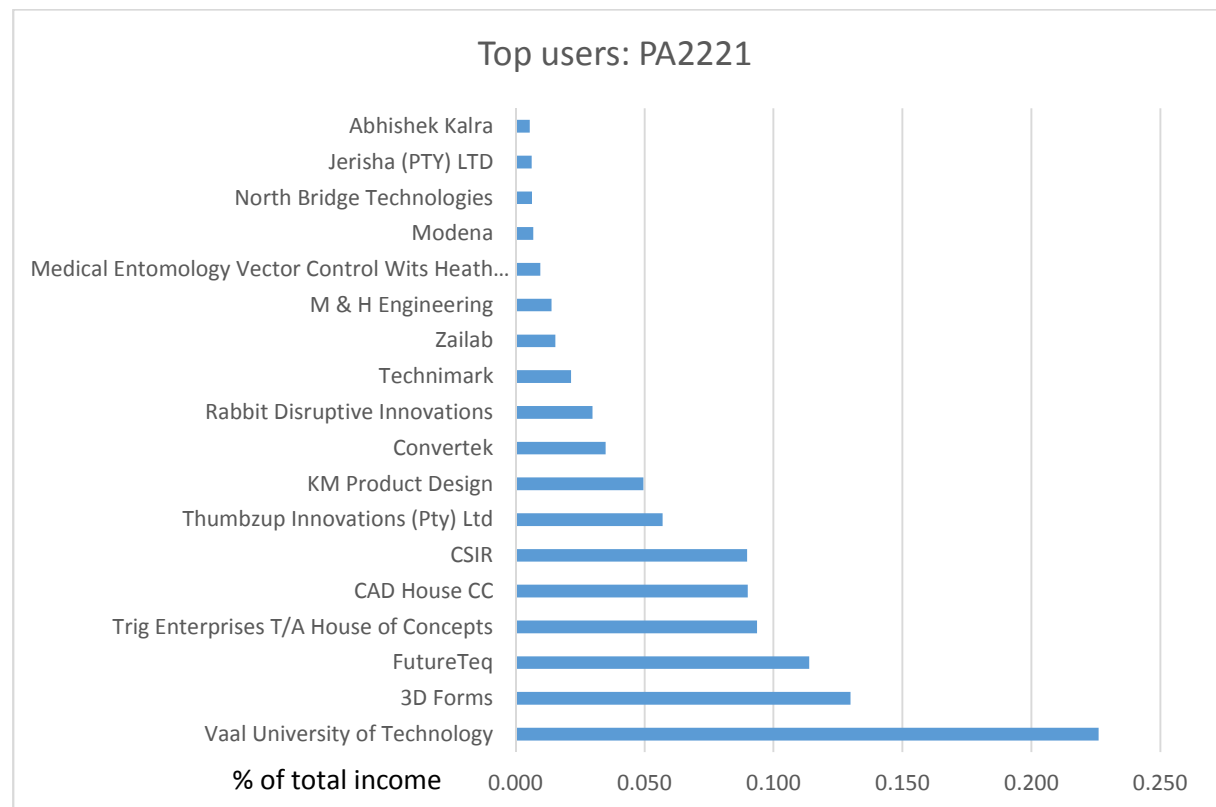


**Figure 17: Top users of PA2221**

### 3.4.2 Question selection

Questions were developed to evaluate the opinions of the PA2221 users. All of these users have also purchased components in PA2200, and will therefore be able to compare the two materials.

1. What did you use the sintered parts for? (prototyping, production etc.)
2. When considering sintered parts, how important do you consider the following:

(1 – unimportant, 5 – very important)

- 2.1. Surface finish
  - 2.2. Mechanical strength
  - 2.3. Cost
  - 2.4. Colour
3. Did you apply any finishing procedures to the sintered PA2221 parts?
  4. Which 3D printing technology do you make the most use of?  
  
(Fused Filament Fabrication, Laser Sintering, Binder Jetting, MultiJet Fusion, StereoLithography, Direct Metal Laser Sintering, Material Jetting)
  5. If a more cost effective powder material were available, say 23% cheaper (based on the test build costing calculations), and available in black, would you consider using laser sintering more often?

### Summary

It is possible to compare the mechanical and optical properties of PA2200 and PA2221 using well established testing procedures. The aspect of cost is also easily illustrated by making use of real-world build data. Questionnaires were kept simple, highlighting customer perceptions.

## 9. CHAPTER 4 – Results

This chapter contains the results of tests conducted on the two powders, as well as feedback from interviewed customers. Preliminary conclusions are also included.

### 4.1. Tensile Test results

Results obtained from the tensile tester were plotted on two-dimensional graphs depicting the applied load versus the extension of the sample. From these graphs, values such as the elastic modulus, yield stress and strain were extracted. The results for PA2200 are shown in Figure 18:

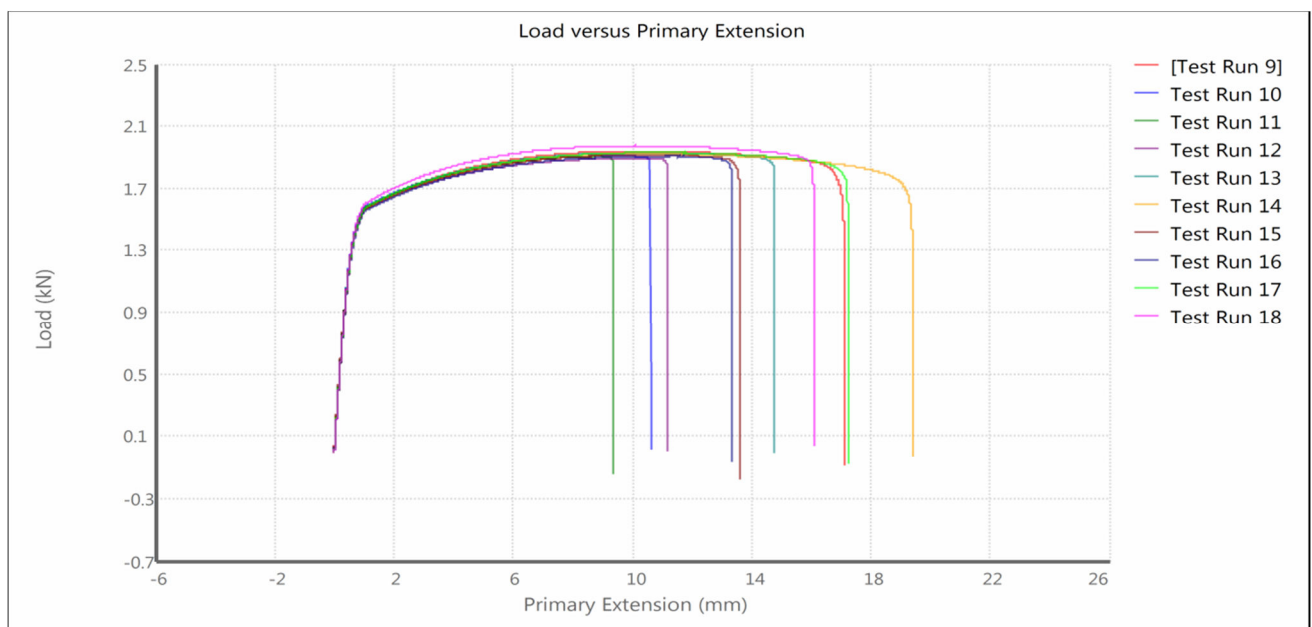


**Figure 18: Force - extension graphs for PA2200**

**Table 1: Tensile test results for PA2200**

| Name        | Specimen Label | Comments | Width (mm) | Thickness (mm) | Modulus (MPa) | Chord Modulus Strain 1 - 2 (MPa) | Stress at Offset Yield (MPa) | Stress at Yield (MPa) |
|-------------|----------------|----------|------------|----------------|---------------|----------------------------------|------------------------------|-----------------------|
| Test Run 9  | 1.1            |          | 12.950     | 3.300          | 1639.160      | 1549.046                         | 24.716                       | 45.349                |
| Test Run 10 | 1.2            |          | 12.850     | 3.320          | 1721.936      | 1590.673                         | 24.344                       | 44.710                |
| Test Run 11 | 1.3            |          | 12.800     | 3.320          | 1715.494      | 1584.952                         | 24.137                       | 44.845                |
| Test Run 12 | 1.4            |          | 12.860     | 3.350          | 1612.479      | 1532.744                         | 24.843                       | 43.898                |
| Test Run 13 | 1.5            |          | 12.860     | 3.340          | 1708.666      | 1580.718                         | 24.054                       | 44.850                |
| Test Run 14 | 1.6            |          | 12.860     | 3.330          | 1624.370      | 1537.098                         | 24.760                       | 44.860                |
| Test Run 15 | 1.7            |          | 12.840     | 3.360          | 1701.892      | 1560.163                         | 23.284                       | 44.344                |
| Test Run 16 | 1.8            |          | 12.870     | 3.330          | 1599.733      | 1523.883                         | 24.665                       | 44.468                |
| Test Run 17 | 1.9            |          | 12.840     | 3.320          | 1707.469      | 1566.299                         | 23.561                       | 45.255                |
| Test Run 18 | 1.10           |          | 12.950     | 3.330          | 1660.371      | 1567.109                         | 24.962                       | 45.739                |
| Mean        |                |          | 12.868     | 3.330          | 1669.157      | 1559.269                         | 24.333                       | 44.832                |
| Standard D  |                |          | 0.047      | 0.017          | 47.197        | 23.020                           | 0.568                        | 0.530                 |

**Table 2: Tensile test results for PA2200**

| Name        | Elongation In Percent | Strain at Break (%) | Peak Load (kN) | UTS (MPa) | Final Length (mm) | Initial Length (mm) | Area (mm <sup>2</sup> ) |
|-------------|-----------------------|---------------------|----------------|-----------|-------------------|---------------------|-------------------------|
| Test Run 9  | 17.786                | 16.372              | 1.938          | 45.3      | 57.680            | 48.970              | 42.7350                 |
| Test Run 10 | 6.851                 | 11.611              | 1.908          | 44.7      | 52.250            | 48.900              | 42.6620                 |
| Test Run 11 | 5.595                 | 11.127              | 1.906          | 44.8      | 48.880            | 46.290              | 42.4960                 |
| Test Run 12 | 6.769                 | 12.378              | 1.891          | 43.9      | 50.630            | 47.420              | 43.0810                 |
| Test Run 13 | 10.357                | 14.223              | 1.926          | 44.8      | 51.360            | 46.540              | 42.9524                 |
| Test Run 14 | 21.267                | 18.449              | 1.921          | 44.9      | 58.560            | 48.290              | 42.8238                 |
| Test Run 15 | 10.270                | 13.158              | 1.913          | 44.3      | 52.290            | 47.420              | 43.1424                 |
| Test Run 16 | 9.021                 | 13.402              | 1.906          | 44.5      | 52.330            | 48.000              | 42.8571                 |
| Test Run 17 | 17.906                | 16.454              | 1.929          | 45.3      | 52.150            | 44.230              | 42.6288                 |
| Test Run 18 | 13.440                | 15.437              | 1.972          | 45.7      | 56.550            | 49.850              | 43.1235                 |
| Mean        | 11.926                | 14.261              | 1.921          | 44.8      | 53.268            | 47.591              | 42.8502                 |
| Standard D  | 5.434                 | 2.370               | 0.023          | 0.5       | 3.201             | 1.617               | 0.2230                  |

The results for PA2221 are shown in Figure 19 and Table 3.

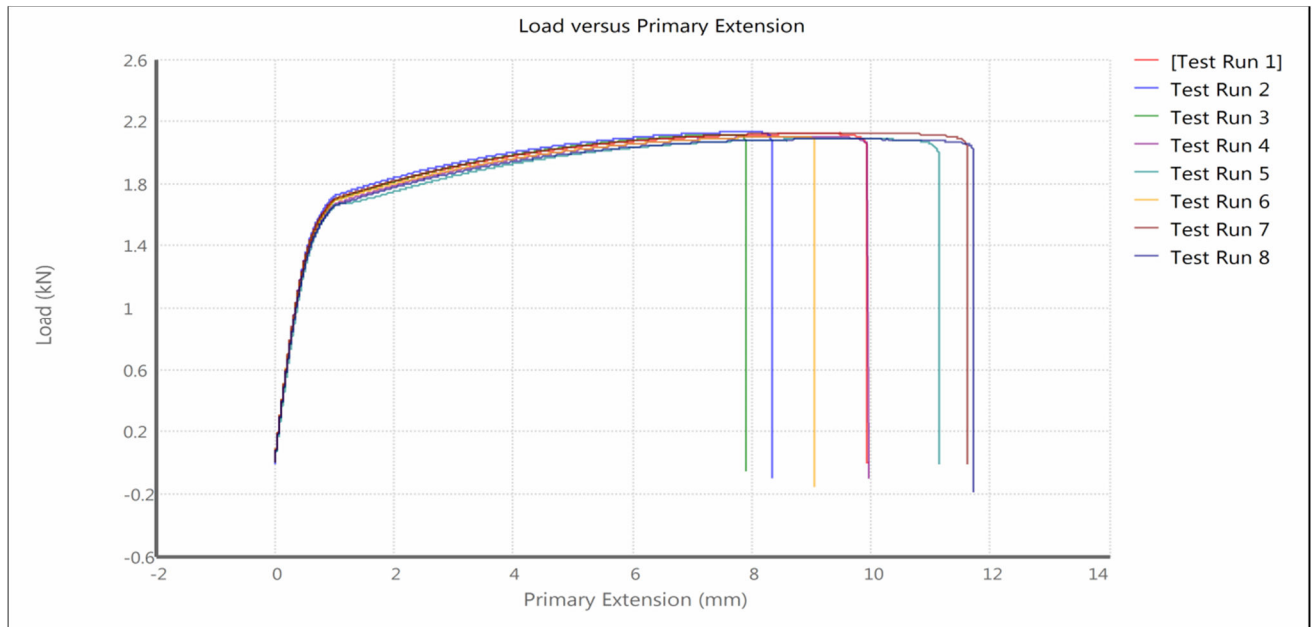


**Figure 19: Force - extension graphs for PA2221**

**Table 3: Tensile test results for PA2221**

| Name       | Specimen Label | Comments | Width (mm) | Thickness (mm) | Modulus (MPa) | Chord Modulus Strain 1 - 2 (MPa) | Stress at Offset Yield (MPa) | Stress at Yield (MPa) |
|------------|----------------|----------|------------|----------------|---------------|----------------------------------|------------------------------|-----------------------|
| Test Run 1 | #1             |          | 12.970     | 3.400          | 1720.840      | 1640.262                         | 26.467                       | 48.068                |
| Test Run 2 | #2             |          | 12.930     | 3.460          | 1787.699      | 1654.722                         | 25.283                       | 47.667                |
| Test Run 3 | #3             |          | 12.900     | 3.440          | 1713.580      | 1634.225                         | 26.187                       | 47.686                |
| Test Run 4 | #4             |          | 12.940     | 3.410          | 1776.181      | 1633.801                         | 24.325                       | 47.666                |
| Test Run 5 | #5             |          | 12.990     | 3.470          | 1604.739      | 1547.802                         | 25.571                       | 46.313                |
| Test Run 6 | #6             |          | 12.910     | 3.460          | 1792.454      | 1636.528                         | 24.192                       | 47.066                |
| Test Run 7 | #7             |          | 12.890     | 3.420          | 1793.374      | 1673.925                         | 25.606                       | 48.239                |
| Test Run 8 | #8             |          | 13.020     | 3.440          | 1725.900      | 1588.761                         | 23.761                       | 46.576                |
| Mean       |                |          | 12.944     | 3.438          | 1739.346      | 1626.253                         | 25.174                       | 47.410                |
| Standard D |                |          | 0.046      | 0.025          | 64.076        | 39.759                           | 0.981                        | 0.691                 |

**Table 4: Tensile test results for PA2221**

| Name       | Elongation_In_Percent (%) | Strain at Break (%) | Peak Load (kN) | UTS (MPa) | Final_Length (mm) | Initial_Length (mm) | Area (mm <sup>2</sup> ) |
|------------|---------------------------|---------------------|----------------|-----------|-------------------|---------------------|-------------------------|
| Test Run 1 | 6.014                     | 11.268              | 2.120          | 48.1      | 52.710            | 49.720              | 44.0980                 |
| Test Run 2 | 5.177                     | 10.228              | 2.133          | 47.7      | 50.180            | 47.710              | 44.7378                 |
| Test Run 3 | 4.391                     | 10.096              | 2.116          | 47.7      | 51.350            | 49.190              | 44.3760                 |
| Test Run 4 | 6.183                     | 11.220              | 2.103          | 47.7      | 52.550            | 49.490              | 44.1254                 |
| Test Run 5 | 8.058                     | 11.752              | 2.088          | 46.3      | 53.640            | 49.640              | 45.0753                 |
| Test Run 6 | 5.530                     | 11.009              | 2.102          | 47.1      | 50.190            | 47.560              | 44.6686                 |
| Test Run 7 | 8.144                     | 11.668              | 2.127          | 48.2      | 53.380            | 49.360              | 44.0838                 |
| Test Run 8 | 7.890                     | 11.909              | 2.086          | 46.6      | 52.780            | 48.920              | 44.7888                 |
| Mean       | 6.423                     | 11.144              | 2.109          | 47.4      | 52.098            | 48.949              | 44.4942                 |
| Standard D | 1.439                     | 0.677               | 0.017          | 0.7       | 1.360             | 0.850               | 0.3760                  |

#### 4.1.1 Discussion

Differences in thickness and width are due to the inherent variability of the LS process, caused by lens distortion of the laser beam, uneven contraction and overburn. It has been shown that variation in section thickness does not affect the tensile strength or modulus of the samples (Majewski, C. and Hopkinson, N. (2011))

The results of the tensile testing show slight differences to those listed in EOS's datasheets. This is likely due to storage of the samples in a non-desiccating environment.

#### For PA2200:

The modulus is listed as 1650 MPa, while the mean value of the tests is 1669.157 MPa, a 1.16% deviation.

The tensile strength in the X direction is listed as 48MPa, while the mean value of the tests is 44.8 MPa, a 7.14% deviation.

#### For PA2221:

The modulus is listed as 1650 MPa, while the mean value of the tests is 1739.346MPa, a 5.41% deviation.

The tensile strength in the X direction is listed as 48MPa, while the mean value of the tests is 47.4MPa, a 1.27% deviation.

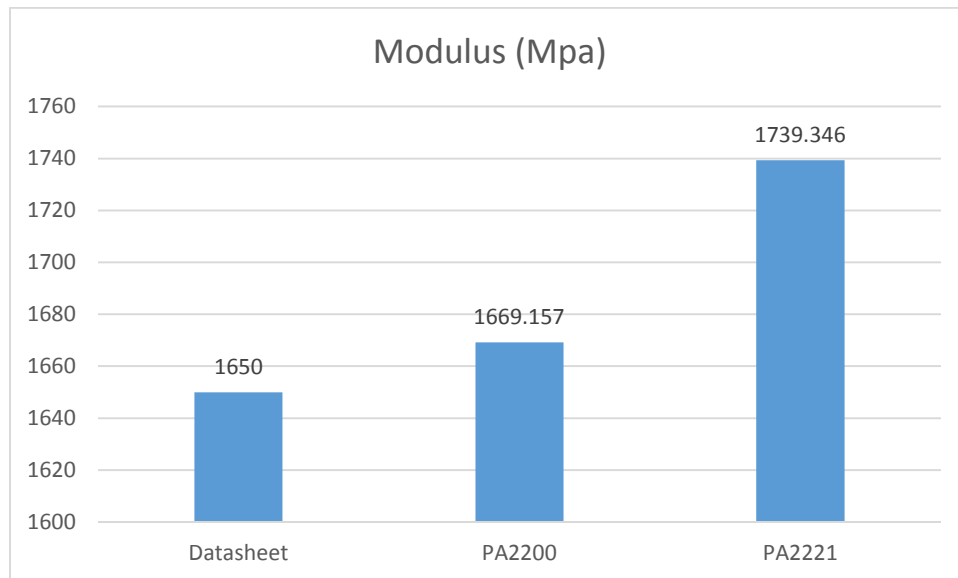


**Figure 20: Tensile test results: modulus**

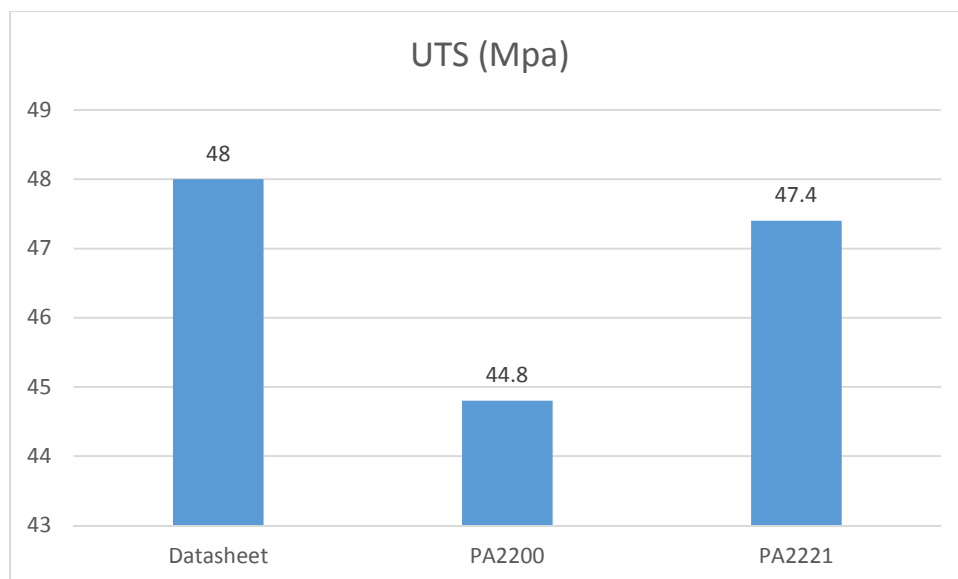


**Figure 21: Tensile test results: Ultimate tensile strength**

#### 4.1.2. Conclusion.

Therefore, PA2221 is 4.21% more rigid than PA2200, and 5.8% stronger in tension. These results show that, even with a lower refresh rate, PA2221 is able to exceed the strength and rigidity requirements defined by PA2200.

#### 4.2 Spectrophotometry results

Figure 22 shows the results obtained from the comparison of several PA2200 samples to a PA2221 sample. The aim was to compare the deviation among the PA2200 samples to establish specular similarity between samples of the same material, then to compare PA2221 to these readings. The difference in values between the two materials will determine how noticeable the colour difference is.

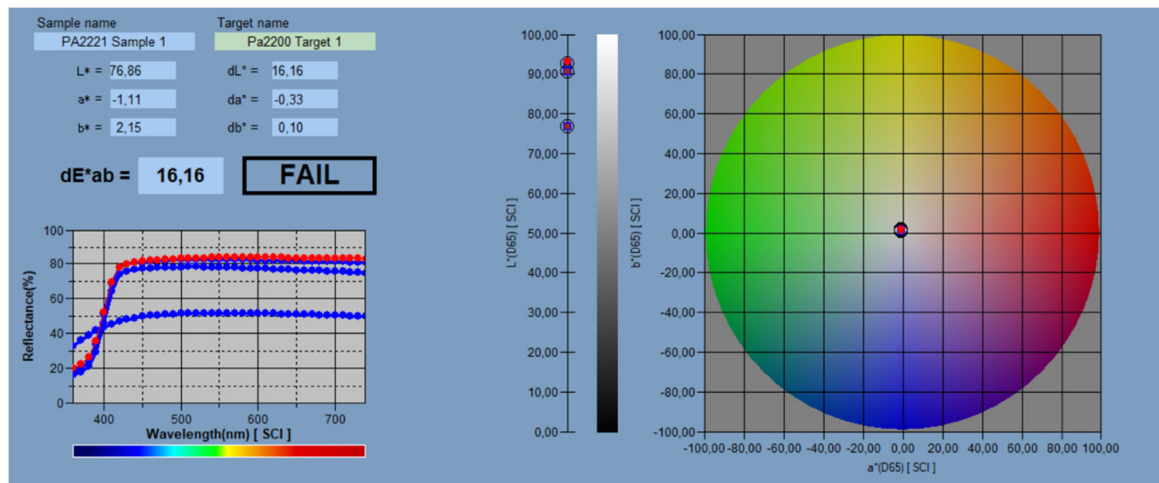


Figure 22: Results from the CM-5 Spectrophotometer

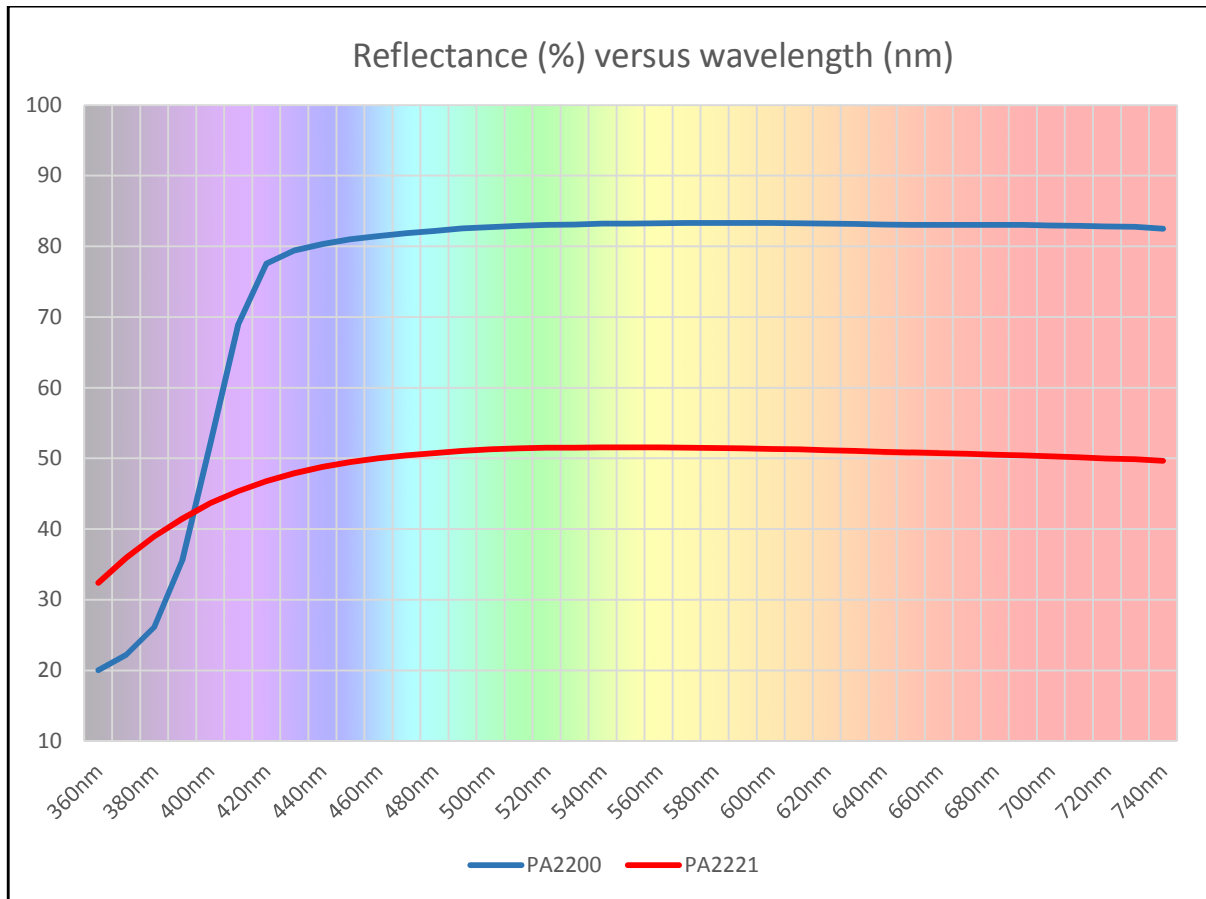


**Figure 23: Spectral reflectance graphs for PA2200 and PA2221**

Figure 23 shows the difference in reflectance across the colour spectrum for both materials. The higher the reflectance, the brighter the colour in a particular frequency. A relatively flat graph indicates a shade of grey, as all colours reflect similarly.

It is evident in the figure that PA2200 is much brighter than PA2221, around 30% on average, meaning that PA2221 will appear duller than PA2200, except in the near ultraviolet region, where the graphs cross.

#### 4.2.1 Colour difference

The results yielded by the spectrophotometer for both materials are:

**Table 5: Lab values for both materials**

| For PA2200: | For PA2221: |
|-------------|-------------|
| L*=93.02    | L*=76.86    |
| a*=-0.78    | a*=-1.11    |
| b*=2.05     | b*=2.15     |

The difference between the corresponding values are:

**Table 6: Difference in L\*a\*b\* values**

|   | PA2221 | PA2200 |        |          |
|---|--------|--------|--------|----------|
| L | 76.86  | 93.02  | -16.16 | darker   |
| a | -1.11  | -0.78  | -0.33  | greener  |
| b | 2.15   | 2.05   | 0.1    | yellower |

This means that PA2221 is 16.16 points darker, 0.33 points greener and 0.1 points yellower than PA2200

In the L\*a\*b\* colour space, colour difference can be expressed as a single numerical value:  $\Delta E^*_{ab}$ . This value expresses the magnitude of the difference between colours, but not in which way the colours are different (Konica Minolta Inc. (2007 - 2013)).

$\Delta E^*_{ab}$  is defined as:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

$$\Delta E^*_{ab} = \sqrt{(93.02 - 76.86)^2 + (-0.78 - -1.11)^2 + (2.05 - 2.15)^2}$$

$$\Delta E^*_{ab} = 16.163$$

A value of 1.0 is referred to as the “Just Noticeable Difference” and any difference value below 1.0 is indiscernible. (Konica Minolta Inc. (2007 - 2013))

#### 4.2.2 Conclusion

Just Noticeable Difference can also be expressed as one noticeable shade, so PA2221 is 16.163 shades different than PA2200.

#### 4.3 Surface roughness test results

**Table 7: Surface roughness results**

| sample        | 1     | 2     | 3     | 4     | 5     | Sum    | Average |
|---------------|-------|-------|-------|-------|-------|--------|---------|
| PA2200 upskin |       |       |       |       |       |        |         |
| Ra            | 9.193 | 20.96 | 10.69 | 12.15 | 14.74 | 67.733 | 13.5466 |
| Rz            | 25.99 | 59.29 | 30.23 | 34.35 | 41.69 | 191.55 | 38.31   |
| Rq            | 9.396 | 19.68 | 10.85 | 12.39 | 15.06 | 67.376 | 13.4752 |
| Rt            | 26.25 | 63.83 | 30.53 | 34.7  | 42.1  | 197.41 | 39.482  |

|                 |       |       |       |       |       |        |         |
|-----------------|-------|-------|-------|-------|-------|--------|---------|
| PA2200 downskin |       |       |       |       |       |        |         |
| Ra              | 15.92 | 7.006 | 10.04 | 10.36 | 10.77 | 54.096 | 10.8192 |
| Rz              | 45.04 | 19.81 | 28.4  | 29.32 | 30.46 | 153.03 | 30.606  |
| Rq              | 15.47 | 7.29  | 10.77 | 10.61 | 11.09 | 55.23  | 11.046  |
| Rt              | 46.65 | 20.01 | 28.68 | 29.61 | 30.76 | 155.71 | 31.142  |

|               |       |       |       |       |       |        |        |
|---------------|-------|-------|-------|-------|-------|--------|--------|
| PA2221 upskin |       |       |       |       |       |        |        |
| Ra            | 5.873 | 7.654 | 6.52  | 6.034 | 9.153 | 35.234 | 7.0468 |
| Rz            | 16.6  | 21.64 | 18.44 | 17.06 | 25.88 | 99.62  | 19.924 |
| Rq            | 5.953 | 7.816 | 6.602 | 6.075 | 9.436 | 35.882 | 7.1764 |
| Rt            | 16.77 | 21.85 | 18.62 | 17.23 | 26.13 | 100.6  | 20.12  |

|                 |       |       |       |       |       |        |        |
|-----------------|-------|-------|-------|-------|-------|--------|--------|
| PA2221 downskin |       |       |       |       |       |        |        |
| Ra              | 8.424 | 7.088 | 7.654 | 6.966 | 7.614 | 37.746 | 7.5492 |
| Rz              | 23.82 | 20.04 | 21.64 | 19.69 | 21.53 | 106.72 | 21.344 |
| Rq              | 8.991 | 7.411 | 7.978 | 7.411 | 7.857 | 39.648 | 7.9296 |
| Rt              | 24.05 | 20.24 | 21.85 | 19.89 | 21.74 | 107.77 | 21.554 |

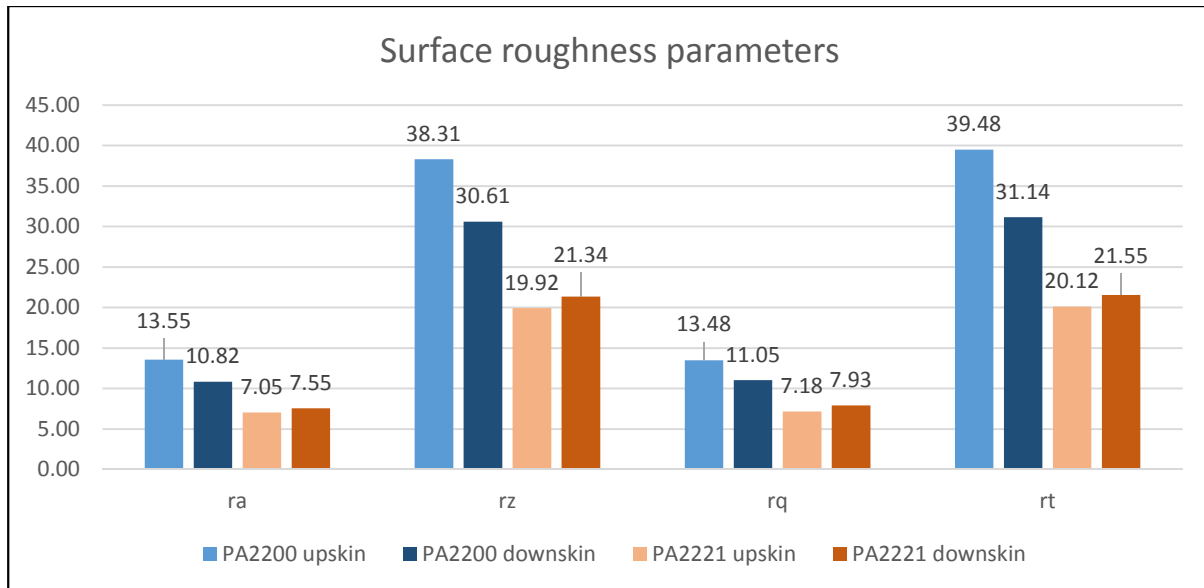


**Figure 24: Surface roughness results**

#### 4.3.1 Discussion

Figure 24 shows the different roughness readings obtained. These readings show that:

1. PA2221 is smoother on both downskin and upskin, as indicated by the Ra (arithmetic mean) and Rq (RMS) values for PA2221 being lower than for PA2200.
2. The PA2221 sample has shallower peaks and valleys on both downskin and upskin than PA2200, as indicated by the Rz and Rt values.

The additives in the PA2221 powder have caused the material to behave differently to PA2200 when sintered, resulting in a smoother surface finish. This will likely be more desirable than the rougher PA2200, as less filling, sanding and polishing will be needed to produce an acceptable finish.

#### 4.4 Cost calculation results

The machine used was the EOS P100 Formiga, which has a build platform area of 61909mm<sup>2</sup>.

To calculate the volume of virgin material used, the total height of the build (including the 16mm thick upper and lower layers of powder) is multiplied with the platform area and the refresh rate of the particular material.

For PA2200

$$(242.31 + 16) \times 61909 \times 0.5 = 7995856.895\text{mm}^3$$

For PA2221:

$$(242.31 + 16) \times 61909 \times 0.3 = 4797514.137 \text{ mm}^3$$

Both materials have a cost of R0.00094/mm<sup>3</sup>, Material costs come to R 4509.66 for PA2221 and R 7516.11 for PA2200.

This makes PA2221 R3006.44 cheaper than PA2200.

When taking into account the machine running cost, markup and tax, using PA2221 costs R4010.59 less than using PA2200 for the test build in question. This equates to a saving of 23.66%

## 4.5 Response to questionnaires

### Interviewee 1:

Jared de Waal,

Business development manager, Solid Edge Technologies.

[jdewaal@setech.co.za](mailto:jdewaal@setech.co.za)

Solid Edge Technology is a service provider for AM components, recently obtaining an HP multijet fusion system producing thermally sintered parts in nylon 12. Prior to this, they made use of the VUT AMP to supply parts in PA 12.

1. What did you use the sintered parts for? (Prototyping, production etc.)

Middleman, service provider, supplying clients who used parts for prototyping

2. When considering sintered parts, how important do you consider the following:

2.1. Surface finish: 3

2.2. Mechanical strength: 5

2.3. Cost: 5

2.4. Colour: 1

3. Did you apply any finishing procedures to the sintered parts? no

Which 3D printing technology do you make the most use of? Laser Sintering

4. If a more cost effective powder material were available, say 23% cheaper, and available in black, would you consider using laser sintering more often?

Yes. Cost is the most important factor to our clients. Our clients haven't requested any white LS parts since the adoption of HP multijet fusion technology – they are happy with grey and black

## Interviewee 2

(Redacted)

Owner: 3D Forms

[info@3dforms.co.za](mailto:info@3dforms.co.za)

3D Forms is the largest external user of PA2221 parts. The company offers AM fabricated parts to a range of industries in the Johannesburg and Cape Town areas.

1. What did you use the sintered parts for? (Prototyping, production etc.)

Clients use parts for Engineering, architectural and industrial design prototypes

2. When considering sintered parts, how important do you consider the following:

(1 – unimportant, 5 – very important)

2.1. Surface finish: architecture: 5 engineering: 2 industrial design: 4

2.2. Mechanical strength: engineering: 5 industrial design: 4

2.3. Cost: 3

2.4. Colour: 1

3. Did you apply any finishing procedures to the sintered PA2221 parts?

Yes, Sanding, drilling, dying

4. Which 3D printing technology do you make the most use of?

Evenly distributed, LS SLA FFF

5. If a more cost effective powder material were available, say 23% cheaper, and available in black, would you consider using laser sintering more often?

Yes, as finishing is generally applied.

### Interviewee 3

Michael Serapelo

michaels@vut.ac.za

Design Manager: VUT Southern Gauteng Science and Technology Park

The design department is the largest consumer of PA2221 components sintered by the AMP. The department offers design and product development for companies and private entrepreneurs, and accesses funding from the Technology Innovation Agency (TIA) when appropriate.

1. What did you use the sintered parts for? (Prototyping, production etc.)

Final prototypes for clients

2. When considering sintered parts, how important do you consider the following:

(1 – unimportant, 5 – very important)

2.1. Surface finish: 4

2.2. Mechanical strength: 5

2.3. Cost: TIA funded projects: 2 Privately funded projects: 5

2.4. Colour: 1

3. Did you apply any finishing procedures to the sintered PA2221 parts?

Sanding, painting

4. Which 3D printing technology do you make the most use of?

(Development: FFF, mainly LS for final prototypes

5. If a more cost effective powder material were available, say 23% cheaper, and available in black, would you consider using laser sintering more often?

Yes, particularly privately funded projects, as cost is critical for these clients.

#### **4.4.1 Conclusion**

The individuals interviewed revealed that when LS parts are used for prototyping applications, colour is of relatively low importance, as finishing techniques are typically applied. Additionally, it was clear that cost is more important to clients who are funding their projects privately, as opposed to using government funding.

Mechanical strength was shown to be important, as the prototypes will need to stand up to the rigors of use indicative of their mass –produced application.

The excellent strength of LS parts makes the process more suitable for final prototypes, while FFF or FDM technologies were preferred for developmental work.

#### 4.6 Historical data

Since the installation of the first Eosint P390 at the VUT in 2010, PA2200 was used as the primary manufacturing material. An aluminium – nylon mixture, Alumide<sup>®</sup>, was also offered and used predominantly for injection-moulding inserts for research purposes.

With the acquisition of the EOS Formiga P100 sintering system, an increase in quality became evident due to the finer laser beam diameter and thinner layers (0.1mm) of the new machine. Parts produced by the P100 machine became the state of the art for laser sintered components in South Africa.

This quality was only matched by the 3 new machines acquired by the VUT in 2012, namely the P110, P395 and P760, all of which are capable of producing 0.1mm layers. The increase in number of machines available at the VUT led to country-wide adoption of sintered components of high quality, with the older P390 being mothballed in the process.

Due to pressure from several AMP clients, it was decided to seek a more cost-effective material for the VUT's laser sintering machines. A newly-released material, EOS PA2221 was available, which allowed cost savings by reducing the refresh rate of used material from 50% to 30%.

PA2221 was implemented in May 2016 as the main manufacturing material at the AMP, running on all LS platforms. The small amount of PA2200 that was left was used up on existing orders, and by June 2016, all laser sintering was conducted using PA2221.

By September, however, clients had begun to request PA2200 instead of the more cost effective PA2221, citing quality problems as their reason for doing so. The VUT AMP then began offering both materials, with the large-scale Eosint P760 running PA2221 and the other 3 smaller machines running PA2200. Questions about the quality, especially colour, of the PA2221 parts increased, and by the end of 2017, demand for PA2221 had disappeared completely. These changes over time can be seen in figures 26 and 27.

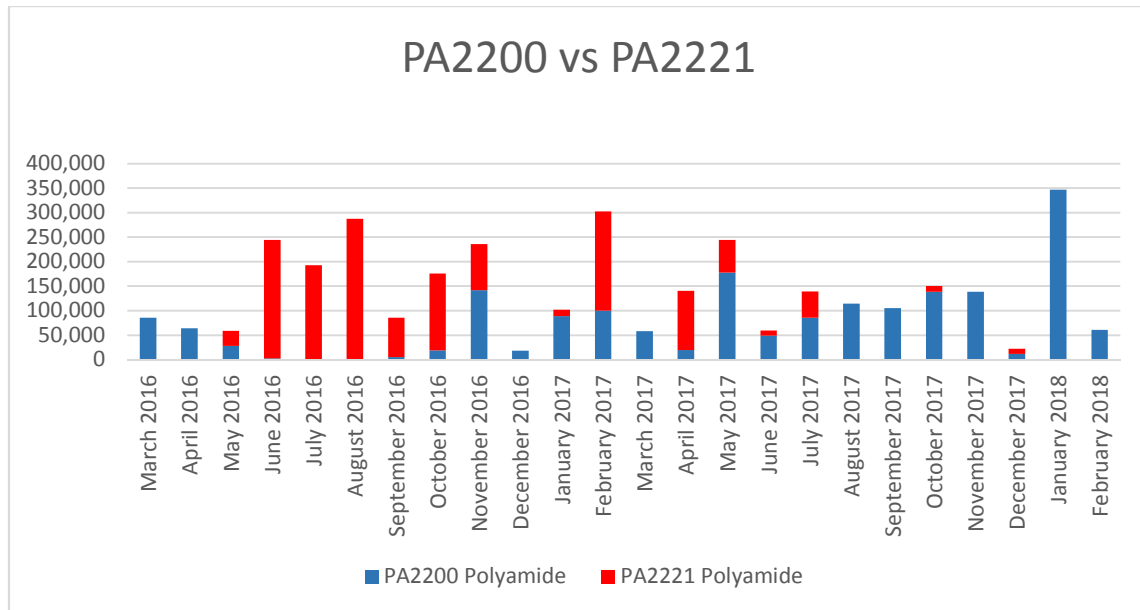


**Figure 25: Income: PA2200 vs PA2221**

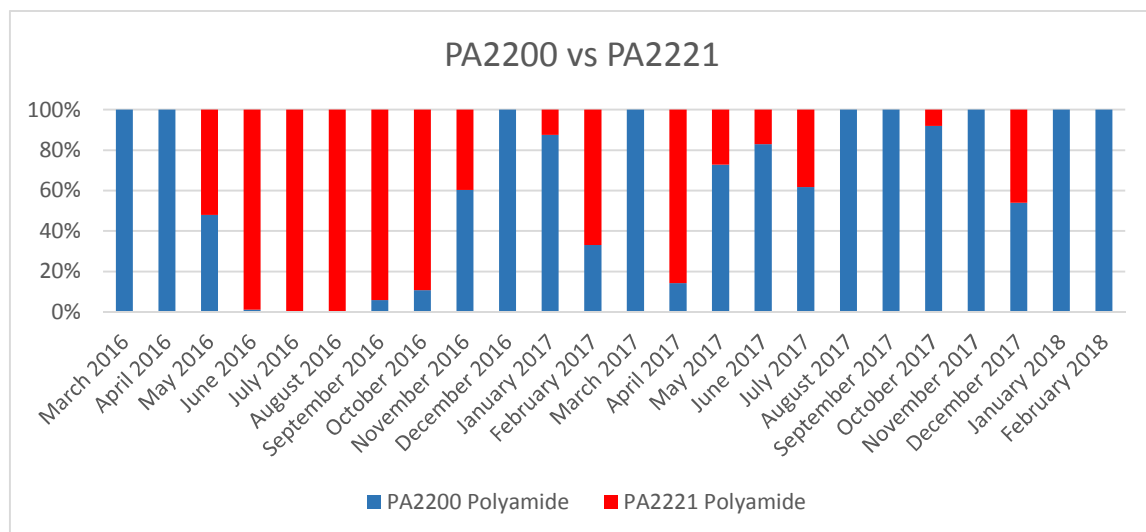


**Figure 26: % Income: PA2200 vs PA2221**

## Summary

Test and interview results are clear, and indicate a significant change in opinion from that demonstrated in the historical data. There is a definite shift in priorities concerning material characteristics.

## 6. CHAPTER 5 - Conclusion

The results obtained from tests conducted are summarised as follows:

### 6.1. Tensile strength:

PA2221 is 4.21% more rigid than PA2200, and 5.8% stronger in tension. These results show that, even with a lower refresh rate, PA2221 is able to exceed the strength and rigidity requirements defined by PA2200.

### 6.2. Colour:

Just Noticeable Difference can also be expressed as one noticeable shade, so PA2221 is 16.163 shades different than PA2200. Reflectance graphs show that PA2200 is much brighter than PA2221, around 30% on average, meaning that PA2221 will appear duller than PA2200, except in the near ultraviolet region, where the graphs cross.

### 6.3. Surface roughness:

1. PA2221 is smoother on both downskin and upskin, as indicated by the Ra (arithmetic mean) and Rq (RMS) values for PA2221 being lower than for PA2200.
2. The PA2221 sample has shallower peaks and valleys on both downskin and upskin than PA2200, as indicated by the Rz and Rt values.

The additives in the PA2221 powder have caused the material to behave differently to PA2200 when sintered, resulting in a smoother surface finish. This will likely be more desirable than the rougher PA2200, as less filling, sanding and polishing will be needed to produce an acceptable finish.

### 6.4. Cost:

When taking into account the machine running cost, markup and tax, using PA2221 costs R4010.59 less than using PA2200 for the test build in question. This equates to a saving of 23.66%

It is evident from the historical data that the VUT and CUT have created certain expectations of quality concerning laser sintered PA12 parts. Customers have become accustomed to

bright white parts with fine layer thicknesses and excellent detail. Deviations from the expected colour were quickly noticed, and this proved to be undesirable, even at a lower cost.

Changes to the local AM industry in the last year have added material options that were not previously feasible.

## 7. Recommendations

- With the increasing range of post-processing options becoming available each year, the colour of the raw material used in LS production is becoming less important than they were in 2016. With this paradigm shift, it will likely become easier to produce material locally, with the option of using recycled plastic feedstock becoming possible.
- The use of lower-cost materials will depend on the implementation of effective post-processing technology, such as colouring and surface treatment.
- Customers must be exposed to proposed materials and finishing techniques before large scale adoption, as this will align material choices to customer preferences.

## 7. Further research

As colour has proven to be significantly important, colour modification techniques should be considered as a way to change the perception of off-white materials. Several new technologies, such as the blue-laser based Sintratec system and the multijet fusion Hewlett Packard systems produce grey pigmented components is PA12 nylon.

These are typically dyed black to hide surface colour variations. Customers of the VUT AMP have also requested black dyes components in the past, however, a suitable dye has only recently been discovered. Previous attempts using acid-based polyamide clothing dye yielded mediocre results, especially with black dye. Dyes manufactured by French company Techniques Chimiques Nouvelles have been successfully tested at the VUT, and produce durable colour finishes on PA2200. Dying of PA2200 in black has become a standard service offered at the VUT AMP since the beginning of 2019, with several clients choosing this finish.

Dymansion is a recently established company offering surface finishing and colouring machines specifically designed for sintered PA12 components. The technology offers precise and repeatable colouring consistent with the RAL (Reichsausschuss für Lieferbedingungen und Gütesicherung) palette (See Figure 27). The RAL palette is internationally used as a standard for defining the colour of paint and other surface finishes, and is thus highly desirable when pursuing the integration of sintered polymer parts into developed industries.

With the available finishing options available today, it is finally feasible to investigate lower-cost materials, as they can be processed to the same quality as currently available materials.



**Figure 27: A selection of shades available from Dyemansion**

Other methods of colouring white PA2200 powder include mixing with pigmented powders or the use of pre-coloured nylon powder.

Research done at the VUT AMP (see appendix C) showed that mixing white PA2200 with activated carbon resulted in dark grey sintered parts when used in the Sintratec system. The Sintratec typically uses pre-coloured grey PA12 powder to allow compatibility with its blue laser diode. White powder reflects blue laser radiation, while the carbon additive allowed the absorption and transmission of the laser energy. Substituting carbon black pigment for the activated carbon used in the experiment should allow even deeper shades of grey to be achieved.

It is likely that PA2221 will combine equally well with pigmented powders, and be sinterable on infra-red laser-based LS systems such as the EOS P100. If possible, pigment mixing or dying PA2221 may remove the only negative characteristic of the material, making it a plausible, more cost-effective alternative to PA2200.

In mid-2019, Hewlett Packard (HP) commissioned their first multijet-fusion machine in South Africa. Local clients have embraced the new technology which offers parts comparable to laser sintering in quality at roughly 50% of the cost of LS parts. These HP components are available in mottled grey, but mostly dyed black.

This trend shows that colouring of nylon sintered components could allow the widespread acceptance of PA2200 alternatives. Research into this approach will begin in 2020 at the VUT AMP.

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9. Appendix A: Correspondence with Bob Bond, former General Manager of 3D Systems SA.

**Email to Bob Bond, 17 May 2019 (bondrj@tut.ac.za)**

Good day, referring to our telephonic chat, I would be grateful if you could assist me with some information:

I understand that you were the pioneer of AM in South Africa, yet I have not been able to find much info on your activities in the 90's - I would like to change that.

I'm writing a dissertation on Laser sintering materials, and part of it is on the history of AM in SA.

Prof de Beer mentioned you imported the first SLA 250 machine in 1991 while you were GM of 3D Systems SA:

1. Was your company acting as a local distributor as well as a service bureau?
2. Where was your company based?
3. Who were your main clients in those early days, was it mostly academic or commercial?
4. Why did you decide to set up 3D Systems in SA? - was there existing local demand for the technology?
5. Did economic sanctions cause any difficulty in importing equipment from the USA in 1991?
6. Did you offer 3D printing services during your time at Rapid Design Technologies?

Many thanks in advance, I look forward to your reply

**Reply from Bob Bond, May 27 2019**

Indeed our company pioneered Rapid Prototyping from 1990, only 4 years after introduction in USA, invented by Chuck Hull of 3D Systems Inc. John Bond, my brother identified the technology from 1986 based on his laser business and links with Omnichrome where Chuck Hull sourced the first lasers. I have extensive editorial of all the projects since inception.

In answer to your questions:

1. Sole Distributor in SA, and Service Bureau. At the time few companies had capability for solid modelling, mainly in the domain of mainframe systems of Applicon, Computer Vision, Catia and Integraph. The first PC systems became available 1993 typical of Cad Key, Autocad and Bentley Microstation. We operated an Integraph EMS system where we did 99% of the modelling before prototyping.
2. Randburg per attached
3. Only commercial, all 7 Automotive OEMS, Automotive component suppliers, Defence, Medical and Consumer companies. Delta Motor Corporation our biggest client, we did the full design of the Astra Grille.
4. At the time we thought there would be major demand which was not the case. Also the worst possible time to start a company pre 1994. I personally travelled all over the country making direct contact with potential clients. We invested R4 million of our own money, equivalent to R30 million today
5. Yes, at the time it was a major effort to get the Distributor Agreement in place as the State of California had SA on the denials list which we had to resolve. Also the software ran on Silicon Graphics who refused to sell us a workstation so we made other arrangements to get the workstation other means.
6. We formed RDT in 1994 when it became apparent that a company was required to take responsibility for the full product development cycle from Industrial Design to Tool Manufacture and Testing.
7. In 1991 we won first prize from 3D Systems Inc for the most complex part built worldwide as judged by Chuck Hull at the International Sales Meeting in Oxnard California. Our SLA was also the highest resin consumer worldwide based on our 24 hour operation 7 days a week.

## 8. We sold 6 SLA's and Thermojet Units by 1998

In the 14 years I was active I was probably the most well-known person locally and internationally based on our client base. Our business was eroded when universities acquired systems funded by government grants hence undercutting the market as they had no overheads like a commercial company.

On the brochure I sent you will see a photo of the emergency light bar of Hazard Electronics. You still today see this product on police vehicles.

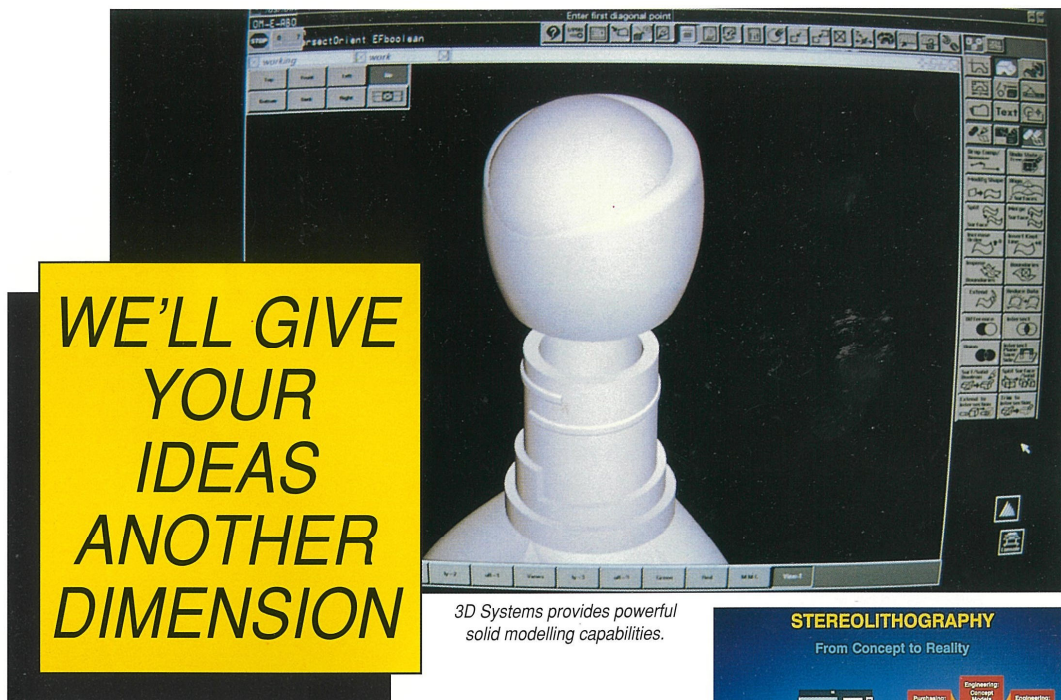
In 1991 we were commissioned by Acjohn Plastics (Colin Hasty) to produce a prototype as they were late in producing an off-tool sample and the client was considering cancelling the contract.

We modelled this design on our Intergraph EMS system and built the prototype in sections on our SLA 250 system with early generation acrylate resin. These were problematic to work with pre epoxy resins.

You will note the scale of the prototype, exhibited on John Newbury's Nissan ZX200 (He was CEO of Nissan) which he lent us for the day. I am on the extreme right of the photo, Colin Hasty middle and Brian Steinhobel left.

This was the first day factor project to be completed in SA, to the amazement of 3D Systems Inc about our capabilities and the projects we undertook.

## 10. Appendix B: 3D Systems SA pamphlet



## BRINGING YOUR PRODUCT TO MARKET SOONER

3D Systems (Pty) Ltd pioneered the introduction of stereolithography (SLA) in South Africa with the sole distribution rights for this exciting technology.

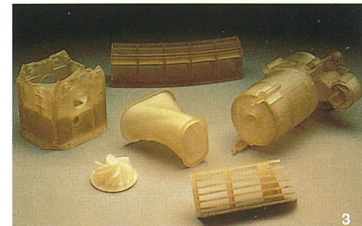
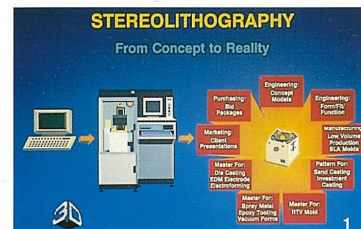
Stereolithography uses data from virtually any CAD system to build complex three-dimensional models. This is achieved by successively laser forming cross-sections of liquid resin into solid form.

3D Systems operates from the base of a strategic alliance of companies qualified to assist in all aspects of product development.

Services include:

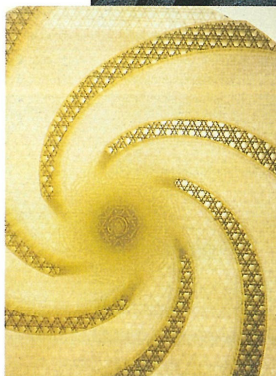
- **SYSTEMS SALES:** sales and support of a wide range of stereolithography apparatus for in-house prototyping requirements.
- **STEREOLITHOGRAPHY BUREAU:** provides accurate prototype parts, overnight if required.
- **CAD MODELLING BUREAU:** using our Intergraph CAD systems and highly skilled designers.
- **INDUSTRIAL DESIGN:** total product development from concept to full production using state-of-the-art CAD/CAM technology. Clients include major international concerns.
- **SOFT TOOLING:** provides low-cost tooling for short production runs for injection moulding and Resin Injection Moulding (RIM) technology.
- **TOOL DESIGN:** tool design capability for most manufacturing technologies. Full tooling manufacture, directly from CAD NC data, is facilitated.

Talk to our sales representatives and let us demonstrate how we can dramatically slash your product development cycle, resulting in reduced time-to-market and improved product quality.



1. Product development cycle using stereolithography.
2. New emergency light bar developed for the South African market using 3D Systems' stereolithography technology.
3. Prototype models of components grown using stereolithography.
4. Example of tooling capability produced by a part grown using stereolithography.

Printed by Dando &amp; Van Wyk



All of these parts, shown here in aluminium, steel, titanium and beryllium copper, were cast directly from SLA patterns such as the one shown in the top of the photo, using the shell casting technique. (Part design complements of Boeing.)

QuickCast combines open hatching, inter-connected passages and special attention to construction of the part "skin" to achieve a unique build style which allows investment casting directly from the SLA part.

- **QUICKCAST:** Rapid tooling has arrived with 3D Systems' development of its cutting edge technology called QuickCast. Investment casting is set to enter a new era marked by reduced tooling costs and cycle time. QuickCast reduces costs, speeds time-to-market and improves productivity. This is achieved by using a special resin with an open hatch interior structure, covered with a thin skin when producing the part using stereolithography. This allows the structure to collapse on itself without damaging the ceramic shell when it is baked.

**"GROWING YOUR IDEAS AT THE SPEED OF LIGHT"**

### 3D Systems (Pty) Ltd

Allrand Place, 372 Kent Avenue  
Ferndale, Randburg  
P.O. Box 3373, Randburg 2125  
Tel: (011) 886-3816. Fax: (011) 787-9615

## 11. Appendix C: PA12 colour modification

### Modifying PA2200 powder for use in blue-laser LS systems

David Mauchline

Vaal University of Technology

#### Aim:

To explore alternative materials for use in the Sintratec platform

#### Background:

The Sintratec kit is a desktop laser sintering machine capable of processing grey PA12 powder to create parts. The material is sourced from the machine supplier. It is of interest to investigate the compatibility of other polymer powders with the Sintratec hardware.

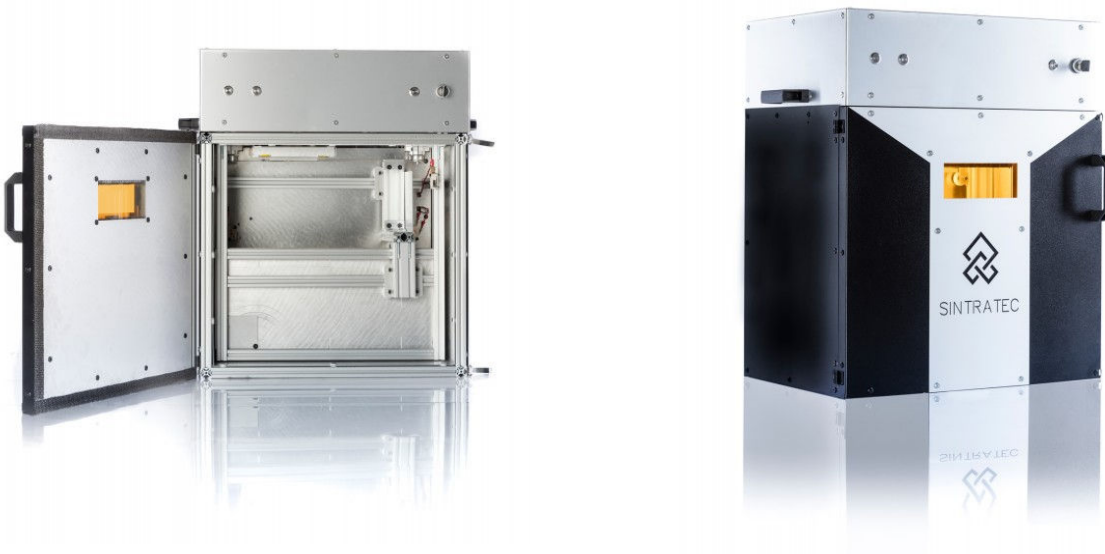


Fig.1. The Sintratec kit

#### Methodology:

As the VUT already uses white PA12 nylon powder, it was decided to test this material in the Sintratec machine. After running a build with white nylon, it was observed that the Sintratec's blue laser did not affect the powder at all. No sintering took place and no parts were produced.

It was theorised that the powder was simply not absorbing the particular wavelength of laser light used. To counter this effect, fine activated charcoal powder was added to the white nylon and mixed thoroughly. The addition of 5 – 10% charcoal to powder was sufficient to give the mixed powder a dark grey colour.

The experiment was repeated using the mixed powder, and it was observed that sintering took place. After the initial test, a larger batch of mixed powder was made up, and various artefacts were sintered.

Initial tests show the mixed powder to yield similar characteristics to the grey nylon powder, particularly in bending.

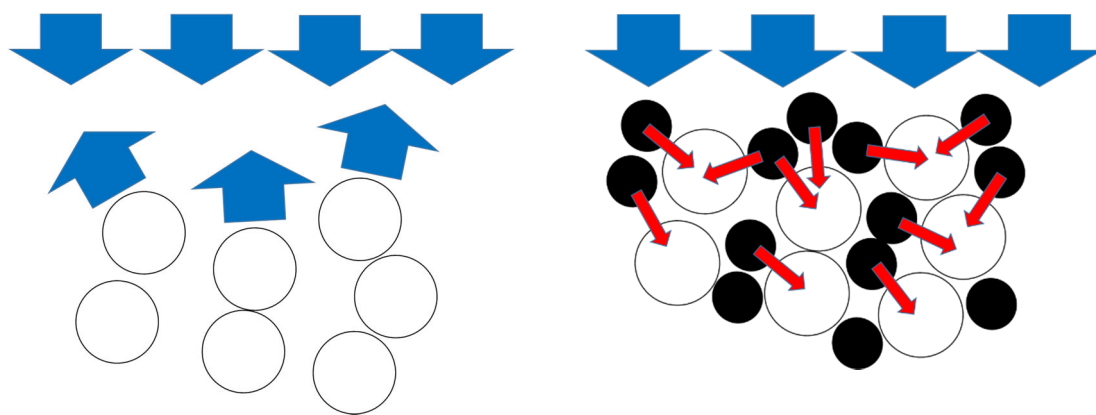


Fig.2. Heat transmission in mixed powder

### Conclusion:

It is likely that the black charcoal particles absorb the laser light and subsequently heat up the adjacent nylon particles, facilitating sintering. The powder turns black when sintered, showing that the charcoal particles are wetted by the molten nylon, thus indicating a good bond between nylon and charcoal.



Fig.3. Artefacts sintered in mixed powder

#### **Future research:**

The next step is to investigate the usefulness of used PA12 powder for mixing and sintering: this will allow the re-use of waste material to create parts. Additionally, a sample of chitosan was acquired to allow investigation into sintering this material in the Sintratec. This will create new possibilities in the manufacturing of bioplastics.