RAPID MANUFACTURING OF POLYMER PARTS BY SELECTIVE LASER SINTERING

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ABSTRACT: Selective Laser Sintering (SLS) is a manufacturing method which has existed since the 1990s. It was initially limited to manufacturing prototypes as it does not require any other tooling than the laser sintering machine to manufacture the part. For several years now, the use of this process has extended to manufacturing of real parts. This article presents an analysis carried out to better understand the advantages and drawbacks of SLS for Rapid Manufacturing. The influence of the various parameters linked with the manufacturing process on the final quality of parts was assessed. We then assisted industrial partners in using this manufacturing method for their own production. The aspects studied are: product design, its qualification and finally support in industrialisation.

KEYWORDS: Rapid Manufacturing, Additive Manufacturing, Selective Laser Sintering, polyamide 12, mechanical properties

1 INTRODUCTION

Cetim (Centre Technique des Industries Mécaniques – Mechanical engineering industries technical centre) is an organisation whose aim is to increase the competitiveness of industrial companies. In order to assist companies in their development it carries out collective interest works.

Spurred on by the "Fédération des Industries Mécaniques" (French Mechanical Industries Federation), Cetim, since 2003, has willingly implemented a limited number of "major federator projects" on some strategic topics for companies in the French mechanical industry. Thus, in the scope of the "Major Powder Project" we studied the technological developments of the Selective Laser Sintering of metals and polymers. This process is primarily used for manufacturing prototypes. This study is aimed at fostering its use for manufacturing industrial parts: Rapid Manufacturing.

The first stage of this work involved determining the mechanical performances of manufactured parts and identifying any weaknesses depending on manufacturing conditions. Design rules where then established which take into account the specific aspects of the material obtained. Finally, we assisted industrial partners in taking advantage of the numerous assets of this manufacturing technique and taking the leap from a traditional manufacturing process to this innovative manufacturing process.

2 ANALYSIS OF THE INFLUENCE OF MANUFACTURING ON MATERIAL PERFORMANCE

2.1 SLS principle

Selective Laser Sintering involves selectively fusing particles of a powder bed using a laser beam which scans the surface and only fuses the powder on a given section. Once the layer is solidified, the construction platform is lowered by approximately one hundred µm and a new layer of powder is applied above the first one. The laser scans the powder surface again to create a new section on top of and joined to the first fused layer. The manufacturing chamber is kept at a temperature slightly lower than the material melting temperature to arrive at the thermal balance of the assembly (powder + part) and reduce distortion of the manufactured part. The entire construction (all the fused layers) is supported by the powder not exposed to the laser. This non-exposed powder may be partially reused for a new production. This principle notably applies to ceramic and metal materials but this study only concerns to SLS polymer polyamide 12 (PA12). The melting temperature of PA12 is 175 °C, the powder is heated to 168 °C and the laser used is a C02 laser.

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3 ANALYSIS OF MACHINE INFLUENCE

3.1 Mechanical characterisation

Standardised tensile specimens were manufactured on 2 types of SLS machines in order to assess performance of the material obtained on each machine. The machines used are: an EOS P300 machine (average capacity machine from a French service provider) and an EOS Formiga machine (small capacity machine from Cetim CERTEC). All test specimens were manufactured with the same PA12 powder reference: PA2200 (supplied by EOS as for SLS machines).
On the whole, the mechanical properties obtained on the Formiga machine are better (higher values and lower dispersions) as shown in Figure 1.

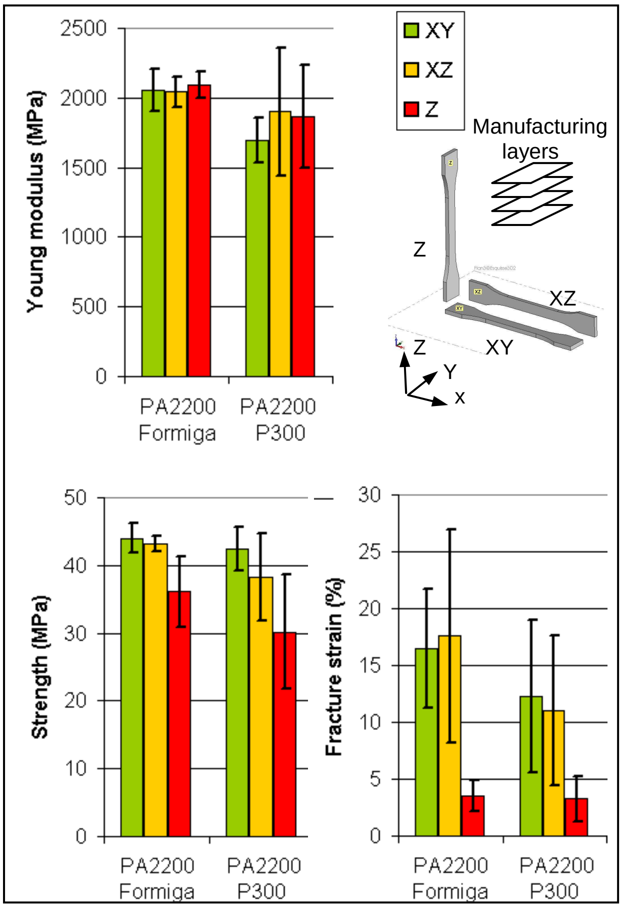
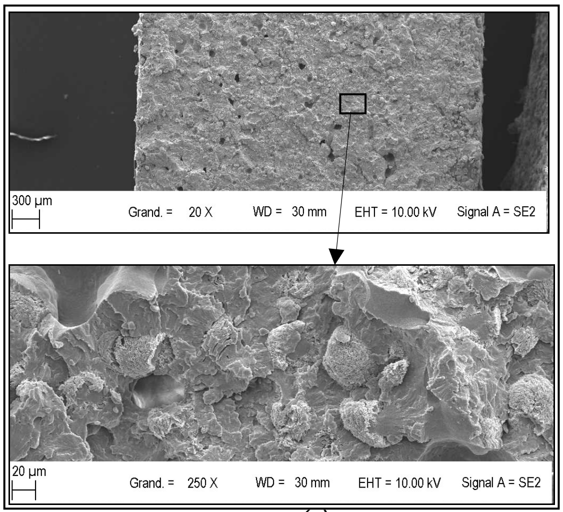


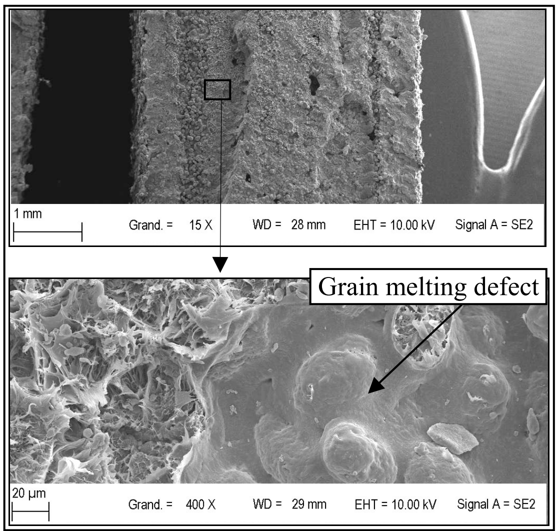
Figure 1: *Mechanical properties*

3.2 Fracture analysis

We performed fractographic analysis of the broken specimens in order to understand the origin of the differences. The fracture surface of specimens manufactured on the P300 machine (Figure 2 (b)) in comparison shows a more significant defect ratio than the specimens manufactured with the Formiga machine (Figure 2 (a)). The defects noted are porosities and areas in which powder grains were visibly not melted enough.



(a)



(b)

Figure 2: *SEM Observation of specimen fractures (a) Formiga manufacturing – (b) P300 manufacturing*

3.3 Weakness of axis Z

The specimens manufactured along axis Z reveal a lower fracture strength and excessively low elongation at break as shown in Figure 1. Observation of fractures reveals that almost all defects are located at the interface between layers melted by the laser. PA12 shows a great density difference between the crystalline phase and the amorphous phase. Changing from the melted state to crystallisation therefore involves shrinkage which is probably the major cause of defects. It is evidently not enough to just heat the product before laser scan in order to avoid the phenomenon.

3.4 Conclusion

We cannot directly conclude that the Formiga machine is better insofar as we do not know if all manufacturing parameters (heating temperature, layer thickness, power of the laser, scanning velocity, etc.) were exactly the same as those used by Cetim CERTEC on the Formiga machine. However, it is essential to note that from one manufacturer to the next, mechanical properties may significantly vary (in this case between 10 and 30 %). It is therefore advisable to characterise the material manufactured in the same conditions as future parts and to pay attention to properties along axis z when manufacturing a part.

4 EXPERIMENTAL DESIGN

This involves establishing relations between the parameters of the laser sintering processes and the quality of the parts obtained. The porosity ratio and the mechanical properties are the criteria selected for monitoring quality.
The three factors analysed on the Formiga machine are: the distance between the laser scans in the x, y (E) plane, the scanning velocity (V) and the laser power (P). Experiment No. 0 corresponds to standard parameters. From the three parameters E, V and P, the surface energy density applied on the powder bed can be expressed: Surface energy density (J/mm2) = P/(E.V).
All other factors such as temperature of the manufacturing chamber, thickness of the part per layer, specific boundary parameters, etc. were established for all experiments.

Table 1: PA 2200 experimental design

Exp.	Parameters			Energy density
No.	E (mm)	V (mm/s)	P	P/(ExV)
0	0.25	2,500	21	0.034
1	0.2	2,000	18	0.045
2	0.3	2,000	18	0.030
3	0.2	3,000	18	0.030
4	0.3	3,000	18	0.020
5	0.2	2,000	24	0.060
6	0.3	2,000	24	0.040
7	0.2	3,000	24	0.040
8	0.3	3,000	24	0.027

Five standardised specimens were manufactured for each experiment.

4.1 Results

4.1.1 Porosity ratio measurement

Porosity ratios seem to be representative of the quality. They were measured by 2 methods in order to compare the results.
The first method involves measuring the apparent relative density of the porous material. Measurements were carried out in xylene.
The second method involves performing polished sections and measuring the surface porosity ratio by image analysis. This second method also makes it possible to determine distribution of porosity in the thickness.
The porosity ratio values range between 1.1 % and 3.2 % with the density method and between 2 % and 6.7 % with the optical method. Classification of the results of experimental design experiments is the same for both techniques despite the difference of measurements. The overall porosity ratio measured remains low (less than 5 %).

4.1.2 Mechanical properties

The results of the mechanical characterisations of various experiments do not reveal significant variations. Experiments 6 and 7 seem to offer the best mechanical properties. We observe that the improvements made remain low: 5 % on the maximum strength and 25 % on elongation at break. Young's modulus remains unchanged.

4.2 DISCUSSION

There is no systematic correlation between the porosity ratios and the mechanical properties in the experimental design. We can consider that the porosity ratios are relatively low and that consequently they finally have little impact on the mechanical properties. The improvement brought by the experimental design is limited to the plastic domain. We deduce that fluctuations of the manufacturing process mainly affect the material behaviour in the plastic domain. Therefore, designers who usually take into account only the elastic domain to define the shape of a part can not consider theses fluctuations. However, long term behaviours like fatigue can be affected by defects due to the SLS process.

5 APPLICATION IN THE MEDICAL FIELD

5.1 CONTEXT

The French company Laboratoires NARVAL designs and manufactures ORM devices. It is a medical device which enables apnoea phenomena to be avoided during sleep. The devices are manufactured by dental technicians through thermoforming from patient's dental prints sent by dentists or stomatologists. In addition to inaccuracy due to thermoforming manufacturing, the artisanal nature of production considerably limits development possibilities. Previously, a dental technician was not able to create more than three devices per day whereas the demand was constantly on the rise: a few hundred devices in 2006 to more than 1,000 in 2007. With these findings in mind, Laboratoires Narval would like to improve the situation with an innovative manufacturing method.

***Figure 3**: ORM device manufactured by thermoforming*

5.2 Adopting SLS

The choice of the material which determines the direct manufacturing process must also comply with the standards related to this type of medical device. All the manufacturing processes must also be defined in order to

make use of the file generated in STL format by CAD software. This requires defining rules for designing the device through machine configuration in order to ensure precision of the finished product dimensions and definition of part finishing operations.
The SLS technology enables devices to be directly manufactured from a CAD 3D file obtained through digitizing a plaster mould and from CAD software dedicated to this application.

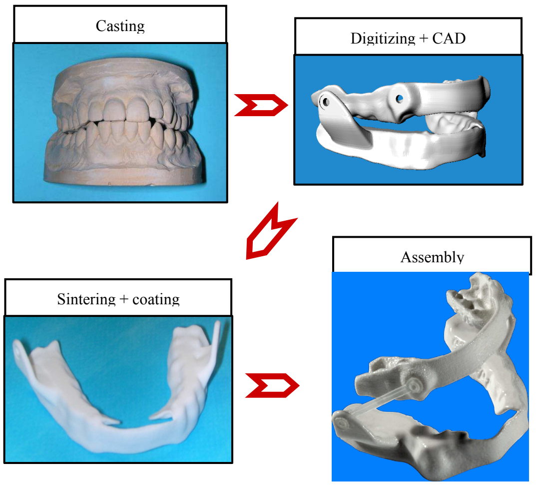


***Figure 4**: Device manufacturing stages*

5.3 Qualification

Accelerated ageing and mechanical fatigue tests were carried out on the first devices manufactured. Devices were also successfully tested with around fifty patients of partner dentists located all over France.

5.4 Redesign

Using the SLS process, the design itself of the device was improved by incorporating in its body parts which up to now were produced separately and assembled manually. The original drawing of the device included 22 different parts which had to be assembled and adjusted to the patient's mouth. Further to redesign, the device now only counts 4 parts whose assembly and lifetime are in fact greatly improved.
A coating was applied in order to further improve their product and oral comfort. The best suited bio-compatible product had to be selected and its manufacturing conditions defined.
This new coating has two advantages: it improves oral comfort and again increases the device's lifetime.

5.5 Conclusion

These improvements very rapidly led to a large increase in orders. Laboratoires Narval has decided to equip itself with a laser sintering machine in order to keep all production, inspections and know-how in-house.
Laboratoires Narval is already considering other developments and a new approach in the device manufacturing method for remote customers in France or abroad.
To date, ORM devices have been manufactured by dental technicians trained by Laboratoires Narval. Using Rapid Manufacturing and CAD/CAM, dentists or dental technicians equipped with a scanner will be able to digitise the casting of their customer's teeth and send the STL file via safe networks. Laboratoires Narval thus keep all production which was carried out in France or abroad as well as quality control and make possible to ensure that products commercialized correspond to quality and performance criteria. In fact, the company markets its products in France, in Canada and in Great Britain and has now established contacts in Germany, Italy, Sweden and Spain.

6 CONCLUSIONS

The analysis carried out makes it possible to understand the differences in mechanical behaviour of material produced with SLS Formiga or P300 machines. The analysis reveals the differences in mechanical properties between the machines and shows that the material is not isotropic. These factors are to be taken into account for part design. We carried out an experimental design aimed at optimising manufacturing parameters so as to try to optimise the quality of the material manufactured from powder. The best results obtained enabled elongation at break to be improved by 25 %, however in the elastic range, we can consider that standard conditions are already optimised.
We also observed that even in optimised manufacturing conditions, fracture strain along axis z remains three times lower than along other axes. This problem doesn't exist in injection molding. Manufacturing layers have to be oriented so as to foster maximum strength in the required direction.
Full knowledge of mechanical properties and their dispersion enables industrial parts to be safely dimensioned. In spite of its many assets, very few designers currently think of this process for their new products: the total freedom of shape which makes it possible to largely reduce the number of complex assembly parts and incorporate several functions, the possibility to easily customise or modify each manufactured part and time saving between the design and initial productions. This process proves to be quite competitive for small and medium part series despite a high part unit cost. Industrial partners just have to be convinced that this process historically only dedicated to prototyping, is now mature enough for manufacturing industrial parts: Rapid Manufacturing.
This is even truer as in the years to come, SLS will be able to be carried out on a larger number of polymers such as PA11 or even PEEK.