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BEHAVIOUR INVESTIGATION OF PLASTIC PARTS MADE FROM SELECTIVE LASER SINTERING

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Abstract: *One of the most important issues to resolve in parts manufactured from rapid manufacturing (RM) technologies is to know their behavior working under real conditions. Total quality manufacturing (TQM) is only possible if mechanical properties are well known in the design stage depending on the processing pa-rameters. This work is mainly focused on testing of several samples made with different selective laser sin-tering (SLS) parameters and technologies. This procedure is the starting point to establish a basis for de-signing for RM and the standardization of RM testing. The experiments and the analysis of variance (ANOVA) analyzed the effects of several factors on mechanical properties. The SLS technologies were 3DSystem and EOS. The results show which factor has a large effect on the variables and the interaction between them. The conclusions are very useful for developing rules for designing (designing for RM) and creating new standard rules (ISO, AISI, and DIN) for RM materials and parts testing. The ANOVA gives a better knowledge of the effects of these factors and eliminates unimportant parameters.*

Key words: *Selective laser sintering (SLS); analysis of variance (ANOVA); rapid prototyping; addi-tive manufacturing.*

I. INTRODUCTION

Starting in 1950's, new plastic materials and their processing mean one of the most important develop-ments in the industry of products manufacturing. The main challenge is how to replace traditional materials such as metal or wood to plastics. Many years later, the evolution of the equipment for plastic processing, moulds, computer simulation, and knowledge of be-havior under processing and functional conditions, allow to spread polymers application and to respond a key question: How to design for plastics? The rapid manufacturing (RM) technologies in last decade have been somehow becoming a similar issue in relation to what plastics are. Now, the question is: How to design for RM? However, another important challenge for RM is to answer a second question: Are RM technolo-gies suitable to provide total quality of part? Fortu-nately, there are many powerful tools today. Manufac-turers and final users are encouraged to respond the two questions in a positive way and with the hope to reach a successful goal in a short time[1-3]. Moreover, some difficulties and weakness must be resolved if RM claims to be a reliable alternative to traditional manu-facturing processes beyond rapid prototyping.

This paper mainly focuses on laser sintering of plas-tics (selective laser sintering, SLS) as RM application (additive technology layer by layer) to add some addi-tional help for responding the two questions mentioned before. This work is included into a more extensive project, named Trialpro, carried out by members of the Spanish Rapid Manufacturing Association, where RM technologies for plastic and metals are studied and tested.

The work shows a useful vision to designers and manufacturers who want to achieve connecting factors of SLS processing with mechanical and formal proper-ties of the final part. A wide number of samples for testing were made in four SLS machines under differ-ent parameters. Design of experiments was imple-mented as well as an analysis of variance (ANOVA) table, where some conclusions could be the base of some rules for designing and establishing protocol of tests in SLS parts.

1 Experiment

Two well known technologies of SLS in the market were selected to carry out the test: 3DSystem and EOS. Also similar materials of each one were tested: Dura-form PA (3DSystem) and PA 2200 (EOS). Testing proc-ess was implemented in four machines from different companies: two machines model DTM/3DSystems Sin-terstation 2500 plus and two machines model EOSint P380.

1.1 Methodology

The methodology is based on design of experiments[4] (DE) under two different scenarios: (1) considering 3DSystem and EOS technologies separately, (2) ana-lysing the two technologies into DE approach. Statistic calculation with ANOVA table was applied in both cases, showing the effects of different factors on the variables (five factors and five variables). The main aim of this calculation is to establish a hierarchy of factors in terms of their influence over the global SLS process. The factors and their levels were as follows: Technology 1: 3DSystem, Technology 2: EOS; amount of recyclable material, Minimum=50%, Maximum= 66%; layer thickness, Minimum=0.1 mm, Maximum= 0.15 mm; laser power, 10-15 W for 3DSystem and 22-50 W for EOS; location of the sample into the cabin (Fig. 1), the samples placed into the 150 mm×150 mm area are called under the location 1 nomenclature, and the samples outside this area are called location 1.

Figure 1 shows the distribution of samples that the cabin of the SLS machine for each combination of nine sample factors were manufactured (three tensile testing, three flexural, and three impact). Therefore, three re-plays were introduced into the DE analysis.

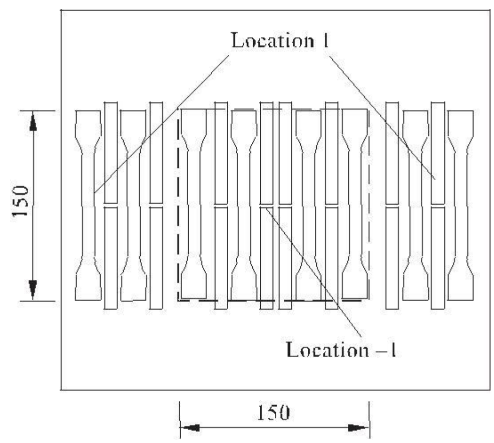

Fig. 1 Samples distribution into the cabin (tensile, impact, and flexural; unit: mm)

The variables for DE were as follows: tensile strength, ultimate (MPa); flexural strength, ultimate (MPa); impact strength (Charpi, unnotched) (kJ/m2); width error (%), percentage of deviation related to the nominal value; thickness error (%). Although only three samples of each category were tested (288 samples), four samples (total 374) were made to prevent deficiency in some of them.

1.2 Equipment and parameters for testing

16 different combinations of factors were implemented in the two technologies (16+16). First of all, it is nec-essary to say that not all the parameters of functioning could be the same in both technologies due to the dif-ferent properties. However, the essential factors could be equated. Hatching mode was alternative X-Y and the hatching speed 5000 mm/s in 3DSystems and 3000-4500 mm/s (depending on layer thickness) in EOS. Other parameters were as follows: beam offset hatching, 0.15 mm (3DSystem), 0.63 mm (EOS); boundary power, 5 W (3DSystem), 5.4-15.1 W (EOS); boundary beam offset, 0.22 mm (3DSystem), 0.33 mm (EOS); exposure mode, sorted; temperature, 173.5 (3DSystem), 175-177 (EOS).

Standard samples for five factors (technology, laser power, layer thickness, % of recyclable material, and location) were tested as follow.

Tensile sample was tested in a machine for dy-namic testing, Microtest, 5000 kN maximum load. Tensile strength, tensile modulus, and elongation were measured. Flexural sample was tested in the same Microtest machine. Flexural strength, tensile value. It is necessary to support the experimenting modulus, and elongation were measured. process with an ANOVA and to study the influence of Impact strength was tested by Charpi un- each factor, or combination between them, on the notched method in a pendulum Ceast Resilim- tested variables. Table 1 shows the intervals of vari- pactor (2.9 m/s2, hammer of 5 J).

Width was measured in X direction of the part and thickness was measured in Z direction (three points body lengthwise). 2 Results A preliminary view of the results shows a significant variability in all the parameters depending on factors ability (maximum and minimum) for each technology and with 66% of recyclable material.

2.1 ANOVA

Global results shown in Table 1 are not enough to un-derstand the effects of all the factors and in conse-quence to the rules to take decisions in the design and processing stages.

Table 1 Variability of parameters into the range of experimented factors

		Tensile strength (MPa)	Tensile modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength (kJ/m^2)	Width error (%)	Thickness error (%)
Duraform PA. 3DSystems	Minimum	29.90	658	40.3	964	13.7	1.0	3.0
	Maximum	47.80	1138	63.3	1498	34.5	3.4	5.7
PA 2200-EOS	Minimum	28.92	532	36.4	851	18.1	1.0	4.2
	Maximum	45.40	943	59.2	1247	49.9	4.8	11.2

ANOVA table divides the variability of the variables (impact, tensile, and flexural) in different segments showing separately each effect. For example, in the case of impact strength (3DSystem technology and two levels of recyclable material amount) three of the effects have p-values below 0.05 (Table 2), remarking they are significantly different to zero in a 95% of re-liability. In other words, if p-value is less than 0.05 the effect of the corresponding factor is significant; if not the effect is negligible. ANOVA table shows both indi-vidual effects and combination between them. For in-stance, in Table 2 effect AB has a p-value below 0.05 and in consequence is significant. The statistic R-square value for impact strength is 97.22%. This value indicates that the adjusted model by ANOVA explains the 97.22% of variability in impact strength.

Table 2 ANOVA for impact strength

Source	Sum of squares	Gl	Average square	F-ratio	p-value
A: Recyclable	866.150 00	1	866.150 00	83.99	0.0000
B: Laser power	2334.590 00	1	2334.590 00	226.39	0.0000
C: Layer thickness	1743.450 00	1	1743.450 00	169.06	0.0000
D: Location	24.829 00	1	24.829 00	2.41	0.1297
AB	840.850 00	1	840.850 00	81.54	0.0000
AC	3.050 21	1	3.050 21	0.30	0.5900
AD	2.566 87	1	2.566 87	0.25	0.6210
BC	5.671 88	1	5.671 88	0.55	0.4633
BD	26.551 90	1	26.551 90	2.57	0.1176
CD	1.576 88	1	1.576 88	0.15	0.6981
Blocks	7.627 92	2	3.813 96	0.37	0.6935
Total error	360.936 00	35	10.312 50		
Total (corr)	7565.650 00				

Pareto graph is a very useful way to see the influ-ence of the effects on the variables. Figure 2 shows Pareto graph for tensile strength. Positive value means increasing of variable if factor increases; negative value means decreasing of variable if factor increases. All the effects in the left of the vertical reference line are negligible in terms of influence.

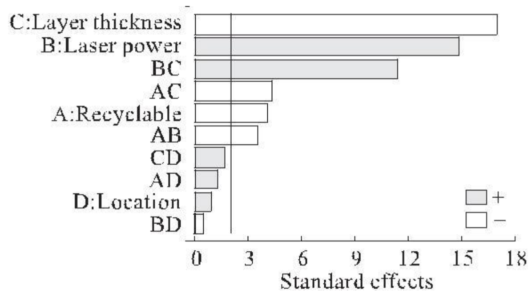

Fig. 2 Pareto graph of tensile strength in 3DSystem

II. SUMMARY OF RESULTS AND DISCUSSION

This study does not aim to compare two technologies and the efficiency of each other but to have a deeper understanding of the parameters behavior in general. The idea is to find points in common in SLS machines for helping to the designer to define the part for SLS technology. The results are commented separately by machine and later under a global view.

Tables 3 and 4 show a brief summary of results in ANOVA table where different levels of influence are defined. The smaller influence level is 9 and the big-gest is 1. N means that the effect is negligible and the positive or negative sign means the trend of the vari-able depending on the factor evolution. For example, in tensile strength testing (3DSystem, Table 3), effect B corresponds to laser power and its value is 2+. Therefore, this factor is in second place in terms of influence level; positive sign presents an increasing value of tensile strength when laser power increases.

Table 3 Summary of effects for Duraform PA. 3DSystems

Factor	Duraform PA. 3DSystems									
	A	B	C	D	AB	AC	AD	BC	BD	CD
Tensile strength	5	2+	1	N	6	4	N	3+	N	N
Flexural strength	4	2+	1	7	5	6	8	3+	N	N
Impact strength	3	1+	2	N	4	N	N	N	N	N
Width error	1	2+	3	5+	4+	6	9+	8+	7	N
Thickness error	1+	N	N	N	2+	N	N	N	N	N

Note: 1, maximum; 10, minimum; N, negligible; A, % recycla-ble; B, laser power; C, layer thickness; D: location

Table 4 Summary of effects for PA 2200-EOS

Factor	PA 2200- EOS					
	A	B	C	AB	AC	BC
Tensile strength	1	2+	3	N	N	N
Flexural strength	1	2+	3	N	N	4+
Impact strength	1	2+	N	4+	N	3-
Width error	2	1+	5	6	4+	3
Thickness error	4	2	N	1+	5+	3

Note: 1, Maximum; 10, Minimum; N, Negligible; A, layer thickness; B, laser power; C, location

In Table 3, the factor of recyclable material amount is introduced with other three factors: laser power, layer thickness, and location of the sample into the cabin. Table 4 is only referable to EOS technology.
Tables 3 and 4 are quite useful because they give quick view of the process and the effects on the pa-rameters needed to control under optimal values.

The main conclusions from these tables are as follows.

Layer thickness is almost the most important factor in terms of mechanical properties (tensile strength, flexural strength, and impact strength). The mechanical properties are improved in all cases when the layer thickness is small. This trend is similar in both technologies. This is because of a better compaction and uniformity of the layers when the thickness of each one is small.
Laser power has big influence on mechanical properties but mainly on dimensional precision: width error grows with laser power. When laser power gets bigger the area of influence affects nearby places from the point of incidence. In all cases mechanical properties are better with laser power.
Amount of recyclable material is not as impor-tant on mechanical properties as layer thickness or laser power is (lightly more important in impact strength) but is essential in the part pre-cision. However, the effect on the width error is inverse to the thickness error: width error im-proves with amount of recyclable material.
There is no clear explanation but probably the characteristics of recycled material (thermal conductivity, thermal expansion coefficient, and melt index) are favorable to the quality contrary to what laser power effect is. Figure 3 shows strong effect of recyclable material on width error, quite far from the laser power ef-fect.

Location of the samples into the cabin (inside or outside place) in general is a very poor fac-tor and its influence or effect is negligible in many factors of both technologies. Only two mechanical properties (tensile and flexural) are slightly influenced by this factor.

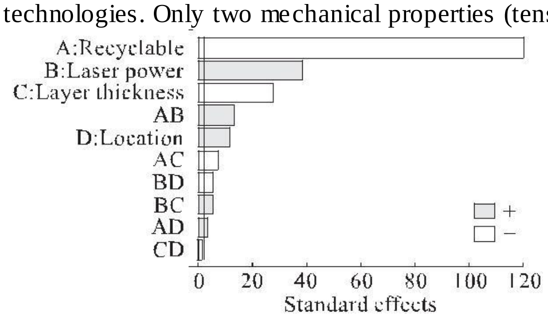

Fig. 3 Pareto graph of width error in 3DSystem

According to statistic calculation in the implemented DE, theoretical optimum values of variables can be achieved if factors are adjusted into specific levels (Tables 5 and 6). This statistic calculation is conditioned by the maximum and minimum interval of factors in the testing process. It is clear in the tables that optimum values for mechanical properties are corresponding to the smaller layer thickness (0.1 mm) and the biggest laser power (15 W in 3DSystem and 50 W in EOS). However, in 3DSystem the amount of re-cyclable material needs to be a value around 58%-59% if mechanical properties must be maximized (tested interval was 50%-66% of recyclable material). This trend of recyclable material % is similar in terms of part precision as observed in Table 5. Thickness error is minimized in the same direction as mechanical properties are, i.e., the directions of maximum laser power and minimum layer thickness. However, width error is minimized with intermediate values of them. Otherwise due to the weak effect of location only op-timum width error is lightly affected by it. Neverthe-less, optimum values are not always suitable to be vi-able in the corresponding technology because of op-erative and collateral problems in the materials. In any case this calculation is an useful reference for design-ers and users[5].

Table 5 Theoretical optimum values in Duraform PA. 3DSystem

Factor	Optimum value	Recyclable material (%)	Layer thickness (mm)	Laser power (W)	Location (1: inside; 1: outside)
Tensile strength (MPa)	47.4	58.7	0.10	15.0	1
Flexural strength (MPa)	62.9	59.0	0.10	15.0	1
Impact strength (kJ/m^2)	44.3	57.7	0.10	15.0	1
Width error (%)	0	56.5	0.12	13.6	0.2
Thickness error (%)	2.11	55.0	0.10	15.0	0.4

Table 6 Theoretical optimum values in PA 2200-EOS

Factor	Optimum value	Layer thickness (mm)	Laser power (W)	Location (1: inside; 1: outside)
Tensile strength (MPa)	55.7	0.1	50.0	1
Flexural strength (MPa)	68.8	0.1	50.0	0.4
Impact strength (kJ/m^2)	68.4	0.1	50.0	0.2
Width error (%)	0	0.1	40.5	0.2
Thickness error (%)	0	0.1	49.9	0

A regression model predicting all the experimented variables is developed. For instance, the equation cor-responding to width error (3DSystem) is

Width error = 14.3156 0.239 063×Recyclable – 0.411 25×Laser power 0.625×Layer thickness + 0.240 625×Location + 0.008 125×Recyclable×Laser power 0.4375×Recyclable×Layer thickness + 0.004 687 5×Recyclable×Location + 1.0×Laser power×Layer thickness 0.025×Laser power×Location 0.5×Layer thickness×Location.

If the ANOVA table is calculated simultaneously for two technologies (Technology 1: 3DSystem, Technol-ogy 2: EOS) and "technology" is an additional factor, the conclusions are not too much different from the study before (Figs. 4 and 5). As expected the technol-ogy effect has significant influence on variables but it is placed in third position from behind the layer thick-ness and laser power. This is a useful conclusion to comment in the following paragraph because it means the option for designers to work about materials and not with technologies (3DSystem or EOS) if necessary.

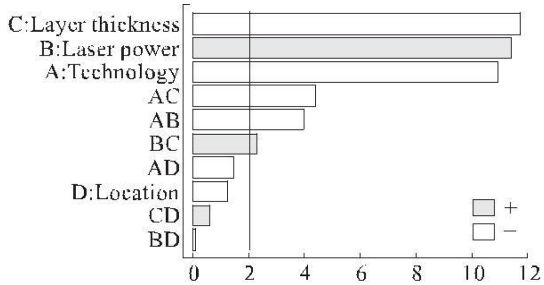

Fig. 4 Pareto graph of tensile strength in EOS-3DSystem

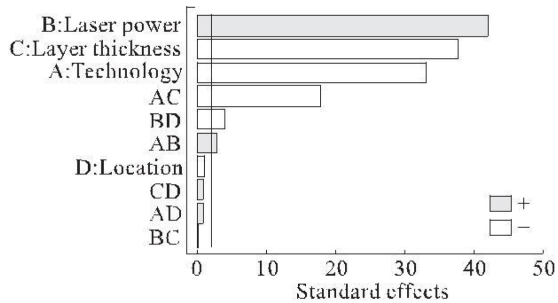

Fig. 5 Pareto graph of width error in EOS-3DSystem

III. DESIGNING FOR RAPID MANUFACTUR-ING AND STANDARDIZATION

Although the experimented process has not considered all the factors in the SLS process, it is clear the uncer-tainty concerning the accuracy and mechanical proper-ties after processing. Furthermore, some references[6,7] stated that the mechanical properties and accuracy of SLS parts are influenced by the geometry. Research by Kruf et al.[8] has concentrated on three main questions.

What is the best method to introduce and carry through loads in SLS parts? A large series of stress situations were investigated.

How to construct SLS parts to get good shape accuracy of the end-use product? Accuracy de-pends strongly on shrinkage[9] during process-ing. Otherwise shrinkage is not uniform be-cause of thermal variations in the powder. Warpage depends on thermal properties of material, shape of part, and position.

How to deal with tolerances?

Establishing universal rules for RM designing is not an easy issue if no isotropic materials such as in SLS are worked. Designers need to provide to manufactur-ers the maximum level of definition in the part speci-fications: shape for functional, mechanical require-ments, and manufacturing tolerances. For instance, good designers of injected plastic parts know some rules for designing to avoid excessive shrinkage or ineligible warpage, improve the mechanical behavior with ribs, and reduce weight. Also, they know about injection moulding process and its limitations about plastic materials. However, even today there is some level of uncertainty in injected plastic parts design where in some cases only the final manufacturing of part supplies real behavior. Therefore, why should not SLS plastic parts follow such a similar process with different features, parameters, process, and materials?

Obviously designers do not need to be experts in SLS or RM technologies but there are some informa-tion about the process they need to know and also some basic rules for SLS parts designing. First of all, it is necessary to say that the rules for RM designing are not absolutely universal: the main disadvantage of RM related to injection processing is the variability of technologies and their nature. The rules for injection moulding are not dependable of the equipment and the material is quite standard. Even in SLS of plastic parts, is the same designing for 3DSystem alike as EOS? If experiment results mentioned before are considered, the answer could be in a negative way. Must the de-signer design for each SLS technology? In order to find an operative procedure in terms of designing and manufacturing integration and take into account the results of the research, the designer should work with the following basic parameter at least:

Layer thickness depending on the location into the part (a part can have several different layer (thicknesses);
Orientation of the part into the machine ac-cording to axes of it; Laser beam direction if necessary;
An interval of mechanical and thermal re-quirements must be supplied;
Formal and dimensional tolerances must be supplied being compatible to RM processing specifications.

With this basic information the SLS parameters of functioning should be decided by the SLS operator under certain level of feedback with design engi-neers[10]. In other words, supplying only a STL file is not enough if mistakes need to be avoided. Is today viable an integration of geometric STL and the basic technical information into a new standard format? Meanwhile, a simple approach is shown in the draw (Fig. 6), where additional information is added such as layer thickness (i.e., 0.12 mm and others), laser beam direction (i.e., 30 mm×120 mm and others), direction of growing (triangle with parallel lines), and orienta-tion of part related to axis. For the time being this pro-posal is not yet under standard rules. However, this standardization is not only crucial for drawing but also for testing RM parts if total quality is aimed by manu-facturers. Focusing this issue on SLS plastic parts, there is no standard testing from ASTM, ISO, etc. For instance, ISO 527 (or ASTM D638), for tensile strength testing, is only defined for conventional plastic parts, isotropic and orthotropic fibre-reinforced plastic composite. But plastic parts with similar characteristics to SLS parts are not included. Manu-facturers of SLS equipment and powders are charac-terizing their materials under existing normative but it

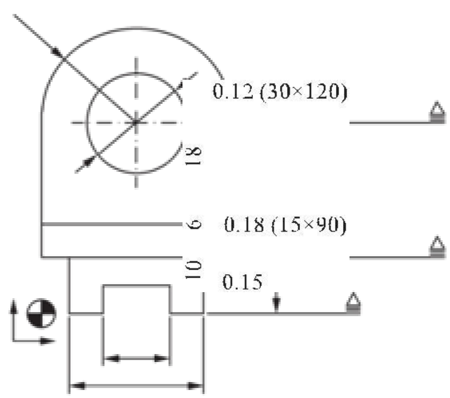

Fig. 6 Proposal of standard draw in RM (unit: mm)

is imperative new standard tests adapted to specific problems and properties of SLS parts. Something similar should be done with powder characterization for SLS. Are the standard tests for powders suitable to be applied? Is, for example, the common use of recy-clable material taken into account by testing rules of powders?

IV. CONCLUSIONS

The work is mainly focused on applying DE methodology to study behavior and predictability of plastic parts made from SLS. The effects of several factors have been ordered in terms of influence on mechanical and dimensional properties of final parts. Layer thick-ness, laser power, and SLS technology are the most significant factors but amount of recyclable material is the most important in terms of part precision. Results are useful for establishing rules for designing and standard test development.

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