Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 132 (2015) 94 – 101

Procedia Engineering

www.elsevier.com/locate/procedia

The Manufacturing Engineering Society International Conference, MESIC 2015

Spectrum Transmission Measurement of a Fiber Laser Beam in Polymethyl Metacrylate for Laser Sintering Processing

K.Monroy[a], Y. Pupo[a], L. Serenó[a], J. Ciurana[a,]*

[a]*Department of Mechanical Engineering and Industrial Construction. Universitat de Girona – Maria Aurèlia Capmany 61, 17071 Girona, Spain.*

Abstract

A novel procedure is applied to evaluate the performance of Polymethyl Metacrylate (PMMA) plates as a pass through window for laser beam transmission, as a part of laser sintering machine construction. The method for laser beam spectrum transmission measurement consists basically in the exposure of a Kapton polyamide film, with the laser in a pulsed mode, in order to obtain variance diameter measurements. Measurements were analyzed in matched paired experiment levels in order to evaluate the effect of the laser beam transmission through the plates.

A negligible effect of the presence of PMMA during the process was found. Selection of this polymer was then validated in performance, besides it owns transparency for purposes of process control and stable properties under harsh environmental conditions. Nevertheless, optical state of the material needs to be preserved in order to ensure consistent results in a long term.

Peer-review under responsibility of the Scientific Committee of MESIC 2015

Keywords: spectrum transmission; polymethyl metacrylate; laser sintering; additive manufacturing.

1. Introduction

A novel procedure for the evaluation of the spectrum transmission of a fiber laser beam in Polymethyl Metacrylate (PMMA) plates for Selective Laser Process application is applied as a part of the building process of a SLM/SLS prototype machine. This machine is based on three essential subsystems: a vertical axis machining center Kondia HS 1000, a fiber laser Rofin FLx50s and a work platform, being the basic idea that the coupling of them can

* Corresponding author. Tel.: +34 972-418-265; fax: +34 972-418-098
E-mail address: quim.ciurana@udg.edu

Peer-review under responsibility of the Scientific Committee of MESIC 2015
doi:10.1016/j.proeng.2015.12.484

be able to perform the typical functions of an additive manufacturing machine that can allow the melting and sintering of a powder material.

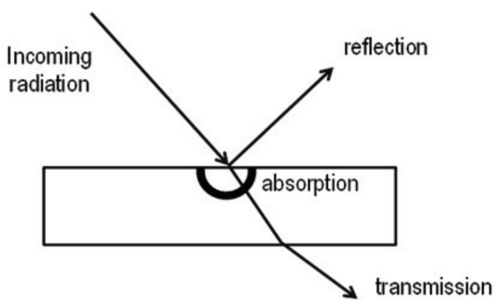
The work platform is the key part of the prototype machine as it is basically where the building of 3D pieces occurs, in contrast to the Kondia which only delivers the movement in x-y-z of the base and laser through its numerical control, and the laser system, providing the radiation for sintering to occur. This platform was designed to comply with compactness (as limited space is available on the CNC), automated control, easiness on installation and removal, and the integration of a controlled protective atmosphere system.

The platform, as stated before, works as a chamber that isolates the building area from the environment ensuring the creation of an adequate atmosphere. Generating a managed atmosphere allows the control of temperature and oxygen, as the temperature variations and oxygen presence during sintering can fuel the surface oxide growth. The amount of oxygen existing during the heating, melting and fusing of the metal powder strongly limits the range of laser energy absorption for successful processing. Therefore, as oxygen levels diminish, powder oxidation reduces, as well as balling and other detrimental surface phenomena [1].

The creation of an appropriate atmosphere is entrusted by an inlet of controlled gas within the sealed working area. As more gas is present inside the chamber, better are the results as in melting and surface quality. Moreover, the presence of this inert gas interacts with the mechanical characteristics of the structural piece consequently improving also the porosity (density) and compression strength. The system operates in both protective nitrogen and argon atmospheres: being the use of protective gas dependent on the material used, as it is necessary to become inert.

The upper closing mechanism of the platform consists in three covering parts: an aluminum sheet where an oxygen sensor is supported and two methacrylate plates. The methacrylate plates are positioned in the center and building side, as it can then allow the laser beam to pass through. The application of plastics, as PMMA, in interaction with lasers depends strongly on their material properties and their compatibility with the laser wavelengths used in the systems. Not all of the currently used thermoplastics absorb (or transmits) laser beams equally well [2]. Laser-material interactions are very complex and only in some simple cases, the laser may be merely seen as a heat source. Absorption, transmission, reflection and the incoming radiation within others are among the intricate aspects of the laser-material interaction, and they all should be taken into account in order to understand in detail the effects of laser processing on the irradiated substrate (Fig. 1).

In this case, PMMA is capable to clear infrared light of up to 2800 nm and blocks longer wavelengths of up to 25000 nm [3]. The fiber laser Rofin x50s, has a wavelength of 1080 nm, therefore, it is within the penetrating infrared band from 700 to 1400 nm, in which a clear 3 mm PMMA cast sheet or extruded sheet can transmit approximately 92% of infrared radiation and reflect about 4% from each of its surfaces – see Fig. 1 [4]. Moreover, its transparency eases the process monitoring and preserves stable properties even in environmental harsh conditions.



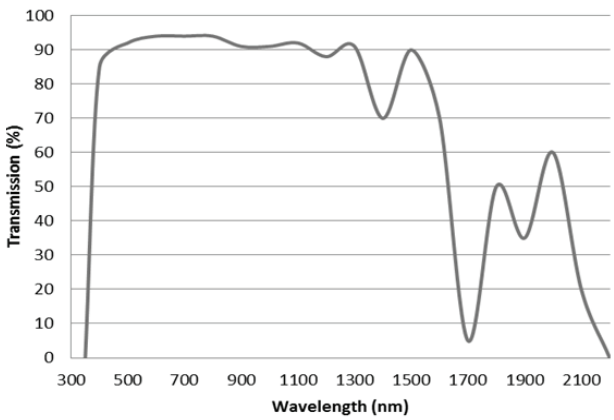


Fig. 1. Laser-material interaction (left) and acrylic transmission according to wavelength in a 3mm thick sample (right)

Based on the latter, the main purpose of this work is the evaluation of the transmission of a fiber laser beam (Rofin, x50s) over the Polymethyl Metacrylate (PMMA) plates. Furthermore of this mere drive, this assessment will help in the validation of the whole SLM prototype system and specifically of the atmosphere control sub-system.

2. Experimental Methodology

The novel method for laser beam spectrum transmission measurement consists basically in the exposure of a film, resistant to high temperatures, with the laser in a pulsed mode, in order to obtain diameter measurements of the perforations as an indication of the transmitted laser beam on the tape [5].

The exposed film used was a Kapton polyimide film HN “2000” of 50 microns of thickness. This film presents a unique combination of electrical, thermal, chemical and mechanical properties that can withstand extreme temperature. Therefore the use of a kind of film as the latter, will led to no overheated affected zones that can skew the measurements in relation to the laser beam interaction with the material. The film fixation during laser exposition was assured by microscope slides, which served as a substrate and aid in probe manipulation. A CNC Kondia HS-1000 was used as the laser head movement control system and laser radiation source from a Rofin FLx50 (ytterbium) fiber laser equipped with an YW30 Precitec head aligned in (Z) to the vertical axis of the Kondia. The fibre laser reaches a maximum power of 500W and operates at a wavelength of 1080 nm. The objective lens has a focal length of 125 mm, and a collimator on 125 mm also. The theoretical minimum beam diameter produced with this configuration is 150 microns.

The experimental procedure starts with the mounting of the kapton film over the substrate, trying to avoid ripples and bubble formation. After the slide is mounted on the CNC table and the laser head is brought to a desired X-Y position (over the slide, and in a Z position corresponding to a standoff working distance which will be varied in between 89-92,5 mm.

After the desired standoff distance is reached, several pulses are shot until a visible and circular mark in the Kapton film is captured. The pulse shooting is done in a parameter combination, as in Table 1, through PMMA plates and without plate, in order to analyze the difference. The shooting is performed with variable laser powers (between 200 and 500 watts), along with a fixed setting of 25% in duty cycle, a frequency of 24 Hz, a pulse scale in ‘Fix mode’ and a pulse duration of 25 ms. For each level of experiment 6 perforations are made on the film. During the shooting, compressed air flow is delivered in order to shield the protective glass of the laser head from possible smoke formation.

Table 1. Experimental Parameters for Laser Beam Transmission Measurement

Power [W]	Standoff distance (SD) [mm]	Duration (d) [ms]	Duty cycle (DC) [%]	Frequency (f) [Hz]	Pulse scaling
400	89	250	25	24	Fix
450	89	250	25	24	Fix
500	89	250	25	24	Fix
300	90	250	25	24	Fix
350	90	250	25	24	Fix
300	90,5	250	25	24	Fix
200	91	250	25	24	Fix
200	91,5	250	25	24	Fix
250	92	250	25	24	Fix
250	92,5	250	25	24	Fix

Once the set of experiments is fully completed, the perforations are labeled; the slides are removed and micrographs taken. A Nikon SMZ 745T digital camera with a CT3 is used for microscopic imaging. Images were treated with ProgRes software for perforation radius measurement as an indicator of the transmitted laser beam on the tape. Since all the images usually present a fine burnt edge, measurements of the outer edge radius are neglected.

Data is finally analyzed statistically by a paired t-test and ANOVA. Statistical interpretation will indicate if spectrum transmission of the laser beam through the PMMA plates is within adequate levels.

3. Results

The micrographs obtained by the Nikon SMZ-745T equipment can be seen in Fig. 2. The output of the mean radius measurements and its comparison in between 'with' and 'without PMMA' are shown in Fig. 3.

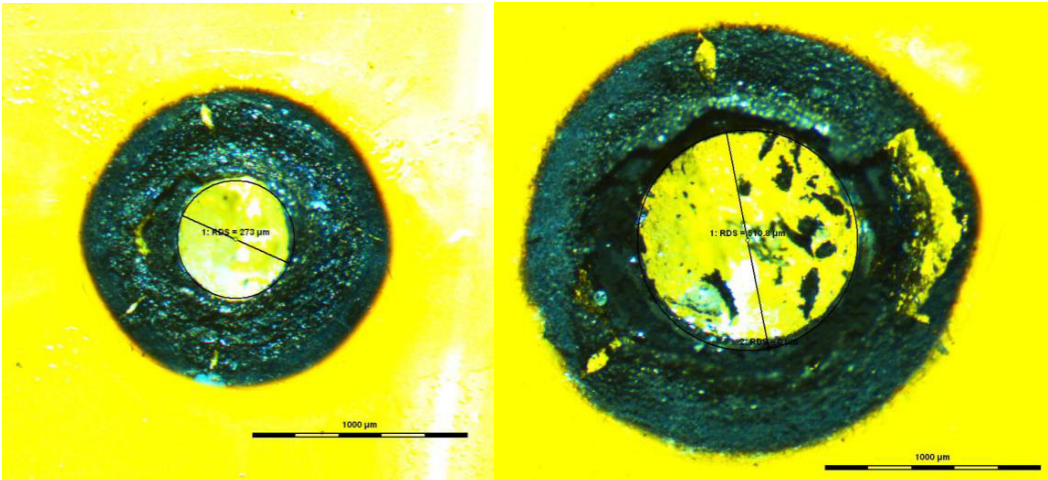


Fig. 2. Micrographs from laser beam perforations

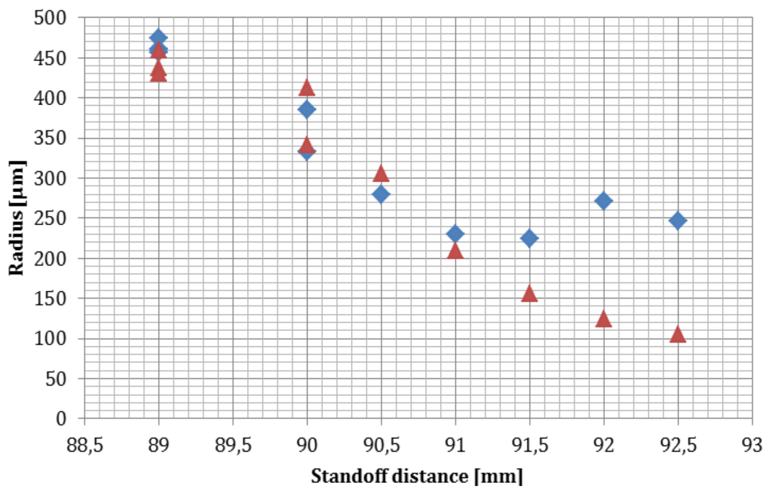


Fig. 3. Comparison between the measured radius with PMMA (red) and without PMMA (blue) for different power levels.

The data was statistically analyzed by a hypothesis test of difference between means with a 95% confidence level and a null hypothesis of 'not equal'. Statistical interpretation of the output will indicate the adequate spectrum transmission of the laser beam through the PMMA plates, meaning by this, if the PMMA is interfering with the radiation transmission and/or if its use causes losses that can be neglected. The analysis was made on Minitab software by a linear general model of ANOVA using only the variable factors of: Power [W] and the presence of PMMA plate which had to be codified by binary values. Including a process variable in addition to PMMA presence, will permit to know if the changes come from the other variable rather than of the usage of PMMA. Graphs from main and interaction effects are included to support ANOVA results visually. A paired t-test was also conducted in order to analyze the data as matched set, and to see the effect before and after the use of PMMA.

The statistical analysis results show a statistic R2, at ~84% indicating that the test parameters used explain a very high proportion of the changes in the results and only 16% is due to errors and noisy parameters of the process used, validating the coherence of the measurements. As the results are validated, the F-statistic and p-value can be then interpreted. A p-value at 0,001 in the power factor, which is less than significance level of α= 0.05 and a very low F and high p-value in PMMA presence, indicates the approval of the null hypothesis, meaning that there is lack of evidence of an statistical difference in the results by the presence or absence of PMMA. Certainly power level affects the laser beam transmission and these results can be graphically seen in the main effect and interaction plot, which clearly indicates that all changes in the measurements are due to the power level changes (Fig. 4). Finally, the t-paired test supports the latter results with a p-value=0,089 (greater than α= 0.05), which indicates that the mean difference between the paired observations is not significantly different from 0; this outcome can also be seen visually in the boxplot (Fig. 5).

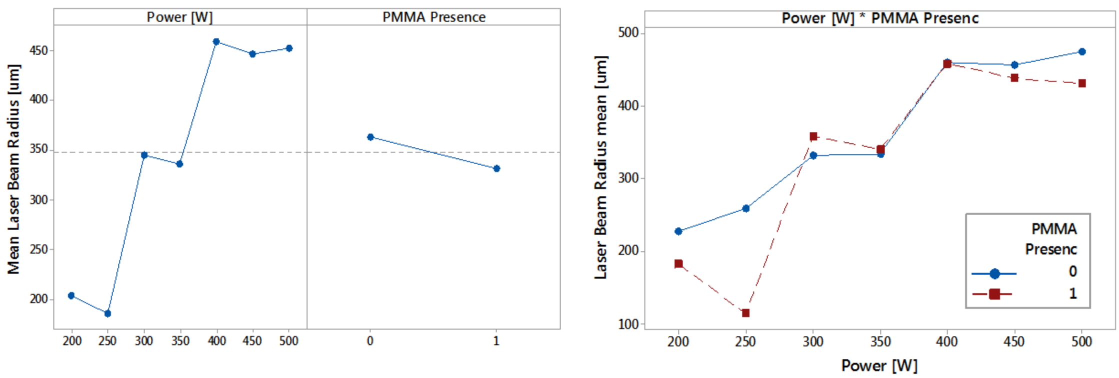


Fig. 4. Main Effects (left) and Interaction Plot (right) for Laser Beam Radius, being 0 "without PMMA" and 1 "with PMMA"

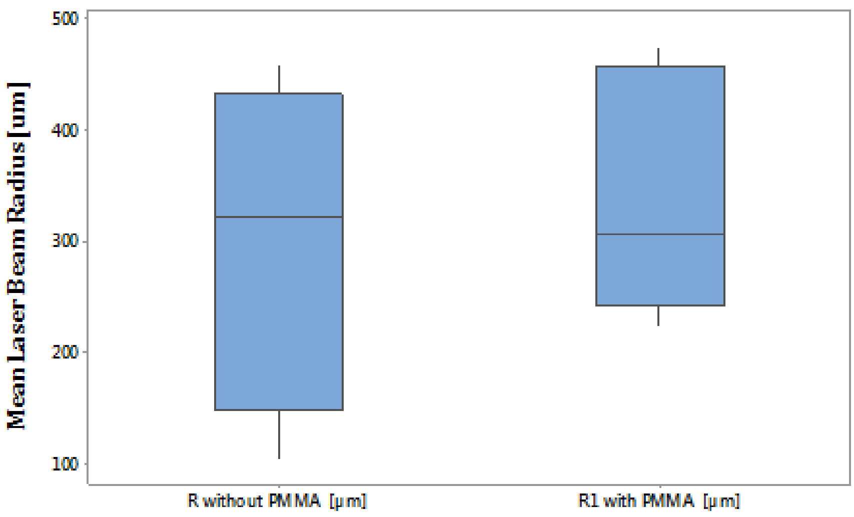


Fig. 5. Boxplot of PMMA effect on Laser Beam Radius Measurements

As it can be appreciated on the interaction plot (Fig. 4b), the lowest divergence in between the use or absence of PMMA stands on the power level of 350 W. Therefore, further experimentation was made by fixing the power at this level (350W), but keeping the previous values of frequency, duty cycle, duration and pulse scaling; changing simply the SD from 89 to 92,5 mm. Same statistical studies are applied to the second analysis at constant power. Fig. 6 displays the comparison of the measured radius 'with' and 'without PMMA' by SD and Table 2 shows the measured radius versus each factor level used.

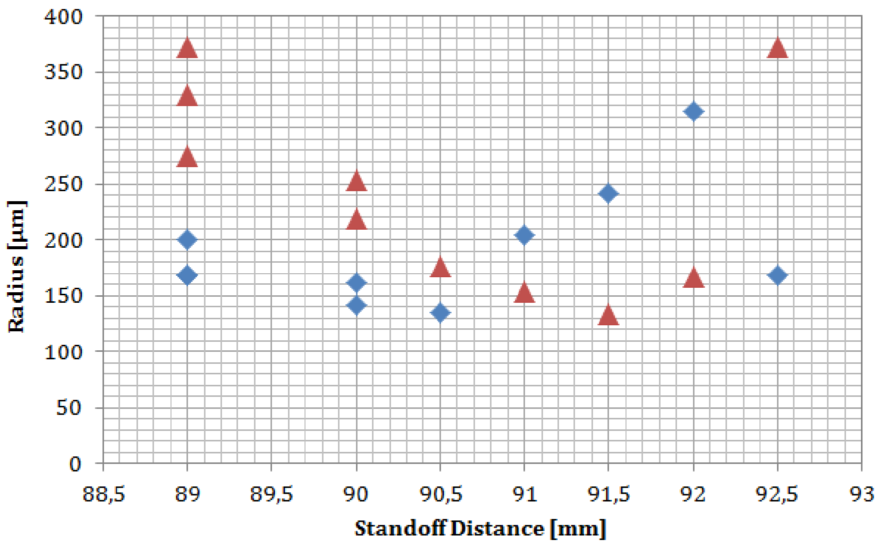


Fig. 6. Comparison between measured radius without PMMA (blue) and with PMMA (red) for a fixed power level.

Table 2. Experimental Parameters for Laser Beam Transmission Measurement

Power [W]	Standoff distance (SD) [mm]	Duration (d) [ms]	Duty cycle (DC) [%]	Frequency (f) [Hz]	Pulse scaling	R1 without PMMA [µm]	R1 with PMMA [µm]
350	89	250	25	24	Fix	168	372
350	89	250	25	24	Fix	200	329
350	89	250	25	24	Fix	168	275
350	90	250	25	24	Fix	162	253
350	90	250	25	24	Fix	141	219
350	90,5	250	25	24	Fix	135	176
350	91	250	25	24	Fix	204	153
350	91,5	250	25	24	Fix	242	133
350	92	250	25	24	Fix	315	167
350	92,5	250	25	24	Fix	168	372

After fixing constant the power level at 350W and varying the standoff distance for radius measurement, the same trends where presented as before. The p-value of 0,177 indicated once more a negligible effect of its presence in the radius; merely the standoff distance presented a barely lower value than the confidence level showing that there is a statistical evidence of influence in the radius, though this is totally obvious and normal (Table 3). The evident influence can be seen in the main effect and interaction plots in Fig. 7. The t-paired test with a p-value=0,191, once again showed that mean difference between the paired observations is not significantly different from 0, null difference that can be seen in the boxplot (Fig. 8 and Table 3).

GENERAL FACTORIAL REGRESSION

Factor	DF	F-value	P-value
Model	13	8,02	0,009
Linear	7	4,28	0,048
SD	6	4,6	0,043
PMMA Presence	1	2,34	0,177
2-way interactions	6	10,37	0,006
SD * PMMA Presence	6	10,37	0,006
Error	6		
Total	19		

T-PAIRED TEST FOR RADIUS WITHOUT AND WITH PMMA PRESENCE

	N	Mean	Std Dev	Mean Std Error
Radius without PMMA	10	190,3	54,0	17,1
Radius with PMMA	10	244,9	89,9	28,4
Difference	10	-54,6	122,0	38,6

CI of 95% for the mean difference: (-141,9; 32,7)

t-Test for the mean difference = 0 (vs. ≠ 0): T-Value= 1,42 P-Value = 0,191

Fig. 7. Statistical Results for General Factorial Regression and T-Paired test

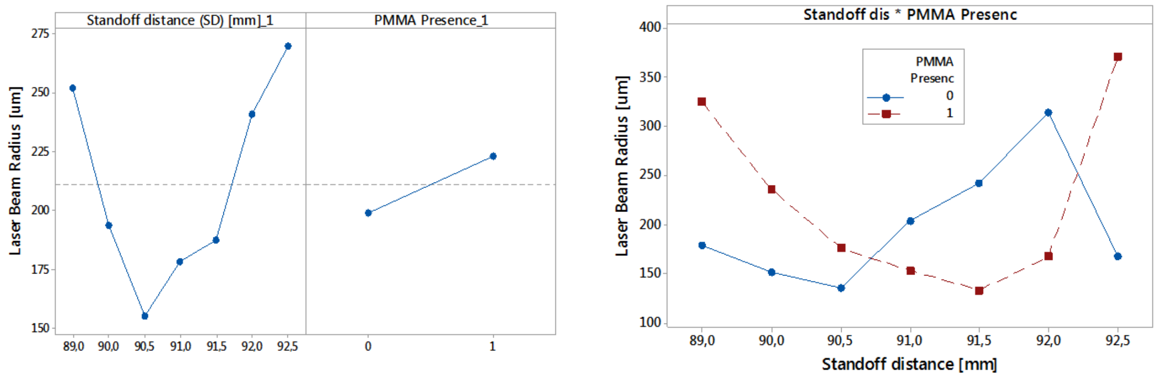


Fig. 8. Main Effects (left) and Interaction Plot (right) for Laser Beam Radius at a fixed power level, being 0 "without PMMA" and 1 "with PMMA"

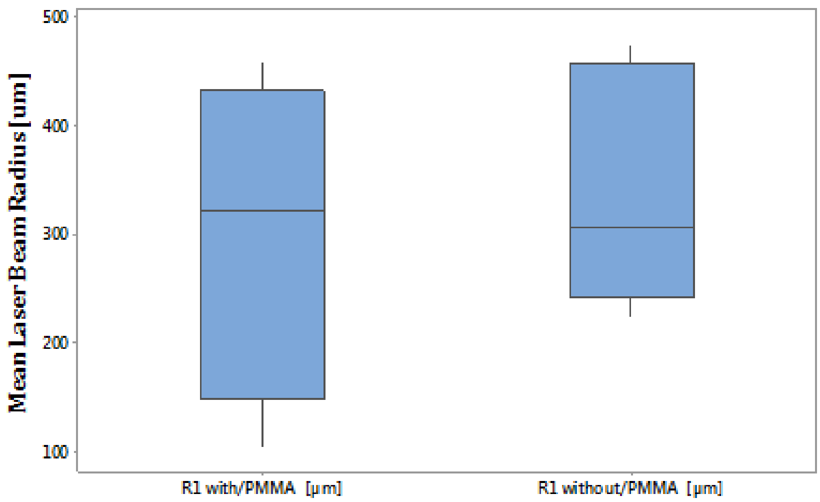


Fig. 9. Boxplot for PMMA effect on Laser Beam Radius Measurements at fixed power level (P=350W)

4. Results

A negligible effect of the presence of PMMA during the SLM process was found. The magnitude of its effect did not affect the measurements in a statistical significant approach by using the PMMA plate as a through transmission plate during selective laser melting process.

In their natural state PMMA polymers are not strong absorbers of infrared radiation, so they could be used as a through transmission window theoretically, but this was also proved experimentally. Selection of this polymer was then validated in performance, as in costs it is also advantageous as it is a cheaper material than other high spectrum transmission materials. Nevertheless, optical state of the material needs to be preserved in order to ensure consistent results in a long term, as superficial quality of the plates can highly affect in the way the beam enters and goes through the polymer permitting the radiation to be more diffused instead of focused. Therefore, preservation can be obtained by PMMA sheets with scratch resistance and anti-reflective coating which improves the transmission, lowers the reflection and offers a better impact strength.

Furthermore, optical properties of transmittance and reflectance change at different thicknesses. Transmission intensity decreases with the increasing of the thickness, as in thicker films more atoms are present, and more states will be available for photons to be absorbed. When the thickness increases the scattering of light also increase. The absorption coefficient of the PMMA in research is calculated using the ratio of optical density and thickness, so thickness is a factor that highly affects the transmittance in PMMA.

Therefore, coating for superficial preservation and a thinner plate are recommended.

Acknowledgements

The authors gratefully appreciate the financial supports from the National Council of Science and Technology (CONACYT) and the Secretary of Public Education (SEP) in Mexico that leaded to these research results. Additionally, this investigation has been partially supported by the Project DPI2013-45201-P of the Spanish Ministry of Economy and Competitiveness.

References

[1] C. Hauser, T.H.C. Childs, K.W. Dalgarno, R.B. Eane, Atmospheric Control during Direct Selective Laser Sintering of Stainless Steel 314S powder, Proceedings of SFF. Austin, Texas, 1999.

[2] R. Göring, Performance Polymers: Laser Application Center. Evonik Industries (2011) 6

[3] V. Sood, An Experimental Study on Thermal Bonding Effects of PMMA Based Micro-devices Using Hot Embossing, ProQUEST (2007) 118.

[4] ACRYLITE, Light Transmission and Reflectance, Evonik Cyro LLC (2014) 9

[5] R.W. Fuerschbach, J.T. Norris, R.C. Dykhuizen, and A.R. Mahoney, Development and Evaluation of an In-Situ Beam Measurement for Spot Welding Lasers, Welding Journal 83(2004) 154-159.