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Taguchi optimization of the surface finish obtained by laser ablation on selective laser molten steel parts

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Abstract

Laser ablation consists in laser-material interaction which causes the vaporization of material from the work-piece being machined. It is proper for difficult-to-machine materials, like carbides, ceramics and hardened steels and it is very flexible at micro-fabrication of moulds and other micro-system devices.

The material is ablated by a laser beam through a layer-by-layer mechanism. Some recent studies investigated into the possibility to use this process to improve surface quality of selective laser molten steel parts. The selective laser melting (SLM) process is a layered additive manufacturing technique for the direct fabrication of functional parts by fusing together metal powder particles.

The focus of this study was to perform a Taguchi statistical analysis of laser ablation main process parameters in order to select those which reduce the surface roughness of selective laser molten parts. Taguchi proposed a quadratic loss function as the objective function for optimizing a product or process design.

The laser speed, power, focus and the number of removed layer were studied through a reduced experimental plan. Some significant evidences were found on the sensitiveness of the process to those parameters so optimal strings of laser parameters were selected versus the number of removed layer.

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Keywords: Laser ablation; selective laser molten parts; surface roughness; taguchi optimisation

1. Introduction

Laser ablation is a very flexible process for micro-fabrication of moulds and other micro-system devices. This process is proper for machining difficult-to-machine materials, like carbides, ceramics and hardened steels [1].

The process consists in an ablation operation causing vaporization of material as a result of the interaction between a laser beam and the work piece being machined.

Thus, the material is removed by a laser beam through the layer by layer ablation mechanism. This process has been used for many years for engraving, laser marking and micro machining.

Several studies reported on the optimization of laser ablation parameters in order to improve surface quality of LA parts. Results of these studies showed that laser and process parameters can be adjusted for a number of applications optimization [2-9].

Recent studies began to demonstrate the potential to use this process to improve surface quality of rough steel parts. Steyn et al. [10] studied the possibility on the improvement of surface finish on pre-ablated rough surfaces. They demonstrated that improvement is possible over the conventionally machined surface and a best finish of 0.25 μm Ra was obtained.

Selective laser melting is a layer manufacturing process to fabricate 3D complex and functional parts directly from powder material. During the process, successive layers of powders are completely melted and joined by the energy of a laser beam. The process is able to produce almost fully dense part with mechanical properties comparable to those of bulk material [10-14].

One of the main drawbacks of the selective laser melting technique is the high surface roughness of resulting parts. Since this is a limitation of the process a

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final finishing process is necessary to be valid for operation conditions.

Some studies attempted to use laser technologies in order to improve surface quality of selective laser sintered parts [15-18].

In particular, Yasa et al. found a reduction of roughness of about 60% using laser erosion [19].

The objectives of this study were both to improve the knowledge of laser ablation effect on laser sintered parts and to perform a statistical optimization based on a reduced plan of experiment.

The statistical analysis was performed with the Taguchi method which proposes a quadratic loss function for finding the best levels of the control factors. This technique permits both to use reduced experimental plan and to have robustness against the noise introduced by uncontrolled variables.

This technique has been applied in a number of laser manufacturing investigations [20, 21, 22, 23].

LA	laser ablation
SLM	selective laser melting
P	average power
F_p	pulse frequency
V	scan speed
O	degree of overlap
Ra	surface roughness
d_f	defocus
D	laser spot diameter
N_{rl}	number of removed layers

2. Experimental procedure

2.1. Material preparation

Plates used for LA tests were produced by the SLM technology using a Nd:YAG laser working in the continuous mode.

The powder material had the typical composition of the AISI 316L steel. The used Selective Laser Melting machine consisted (Fig.1) of a control system, a coater, a laser source, a scanning system, a working chamber, a powder chamber and two rooms filled with excess powder. The building chamber could only move downward, while the powder chamber could only move upwards.

The SLM process began with a completely defined 3D CAD model of the object to be made. After having been divided into cross-sections via software operation (slicing operation), the model was then directly introduced in the process.

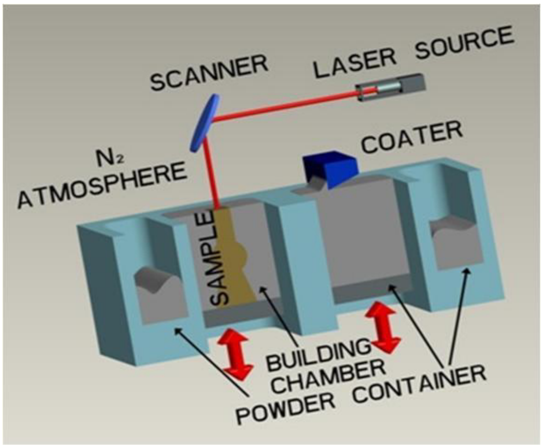


Fig. 1. Schema of the SLM process

Sliced data were transferred to a computer-controlled laser device, which selectively melted successive layers of powder to create a 3D product.

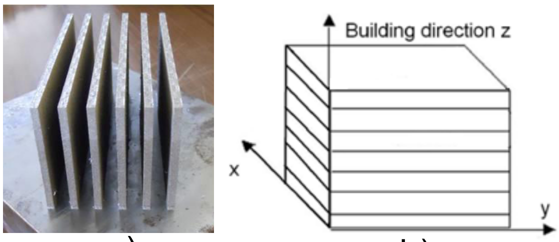
Moreover, the SLM process took place inside a closed chamber, filled with nitrogen to minimize oxidation and degradation of the powdered material.

Parts were produced using a random island scanning strategy, in order to reduce thermal stresses and distortions [24, 25]. The laser power was set to 100 W, the layer thickness was 30 µm and the scanning speed was 200 mm/s.

The resulting relative density was higher than 99%. Fig.2 shows the produced SLM samples, built, layer by layer on a support plate along the vertical direction. The built plates were not post-treated.

Roughness tests were conducted on all samples along the x and z directions, in order to determine its average value on the xz plane.

The Ra index was measured for roughness and values of Ra_x and Ra_z were calculated respectively along the x and z directions. The average roughness Ra_{xz} = 19 µm on the xz plane was then determined as the mean between Ra_x and Ra_z.



a) b)

Fig. 2. a) built SLM plates; b) building direction

2.2. Experimental plane for laser ablation

Many studies reported on the optimization of laser ablation parameters in order to improve surface quality of LA parts.

Results of these studies showed that laser and process parameters can be varied for optimization of surface quality of laser ablated parts.

These include the average power (*P*), repetition rate (F_p), scan speed (*v*), degree of overlap (*O*), laser defocus (d_f). In addition, the number of removed layers (N_{rl}) can be considered.

Table 1. Experimental plane

Levels	P [W]	Scan speed [mm/s]	Pulse Frequency [kHz]	Defocus [mm]
1	10	300	10	-2
2	15	500	20	0
3	20	700	30	2

O is defined as the degree of overlap between two consecutive spot diameters, thus it is a function of F_p, *v* and the spot diameter *D* and it can be calculated by Eq.1.

$$O = \left[1 - \frac{v}{F_p \cdot D}\right] \tag{1}$$

In this study the variation of four parameters were considered: average power, pulse frequency, scan speed and laser defocus.

A full factorial approach would require a total of 3^k experimental runs if there are k investigating factors, each one changed on three different levels. Application of the full factorial approach to the present investigation would require a total of 81 experimental runs.

To reduce the large number of trials required from a full factorial design a Taguchi reduced experimental plan was used. The most appropriate orthogonal array that defined the experiment schedule was chosen on the basis of the degrees of freedom of the experiments.

An L27 orthogonal array was chosen. The four factors varied on three different levels. Four repetitions were done for each combination of the process parameters showed in table 1.

2.3. Laser ablation tests

Laser ablation tests were conducted along the xz plane of SLM plates.

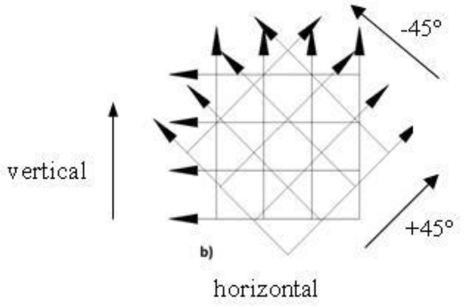


Fig.3. Mix hatching mode for LA: scanning directions.

The laser used for experiments was a pulsed Nd:YAG laser with maximum average power of 20 W, repetition rate variable between 0 and 65 kHz, pulse duration in the nanosecond range, laser spot diameter of 70µm and wavelength of 1064 nm.

The scanning strategy used to remove layers consisted in a mix hatching mode (Fig. 3), characterized by x and z axis parallel scanning vectors and ±45° tilted scanning vectors.

2.4 Roughness tests and analysis of measurements

Roughness test were performed on all ablated samples. The Ra index was measured and values of Ra_5, Ra_{10}, Ra_{15}, Ra_{20}, Ra_{30} were collected for N_{rl} equal to 5, 10, 15, 20 and 30.

Fig. 4 shows the tendency of R_a with the degree of overlap for all considered numbers of removed layers.

It is evident that R_a has the tendency to decrease with the increase of the number of removed layers.

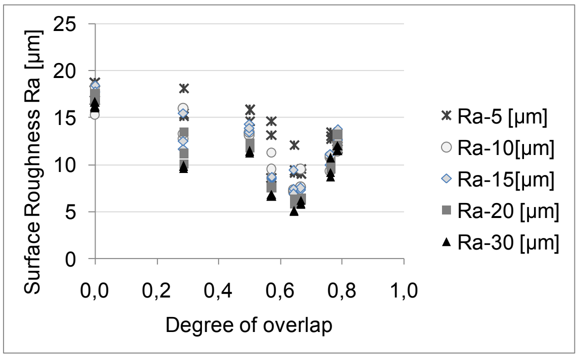


Fig. 4. Roughness Ra versus degree of overlap.

3. Taguchi optimization methodology

In order to evaluate the influence of the studied factors on the roughness results the analysis of variance (ANOVA) was performed.

The ANOVA showed that most of the considered parameters have a significant effect on roughness regardless to the number of removed layer. Two evidences were outlined:

1) for N_{rl} = 5 the variation of the scan speed is not influent on Ra; v has a significance for the other values of Nrl;
2) for N_{rl} = 15, 20 and 30 the variation of the defocus of the laser beam is not influent on Ra; d_f affects R_a for lower values of removed layers (N_{rl} = 5, 10).

The level of significance set to 0.05 permits to select the parameters whose effect is not negligible from a statistical point of view [26].

They are those having a p-value smaller than the level of significance; p-values were reported in table 2.

Table 2. Results of ANOVA

Factors	N_{rl}	p-value
P	5	0.000
v		0.207
F_p		0.000
d_f		0.025
P	10	0.000
v		0.000
F_p		0.000
d_f		0.003
P	15	0.000
v		0.000
F_p		0.000
d_f		0.294
P	20	0.000
v		0.000
F_p		0.000
d_f		0.459
P	30	0.000
v		0.000
F_p		0.000
d_f		0.236

The optimization procedure was performed by means of the method of Taguchi [27].

A loss function is defined which measures the deviation of the quality characteristic from a desired value.

In order to assess the influence of each factor on the roughness, were calculated the means and Signal-to-Noise ratios (S/N) for each control factor.

The signals are indicators of the effect on the average responses and the noises are measures of the influence on the deviations from the average responses, which accounts for the sensitiveness of the experiment output to noise factors.

The appropriate S/N ratio must be chosen using previous knowledge, expertise, and understanding of the process. There are three categories of the quality characteristic in the analysis of the S/N ratio, i.e. the lower-the-better, the larger-the-better, and the nominal-the-better.

In this study the goals were to identify the parameters which minimized the roughness and which were robust to noises.

Therefore in this study, the S/N ratio was chosen according to the criterion the-smaller-the-better.

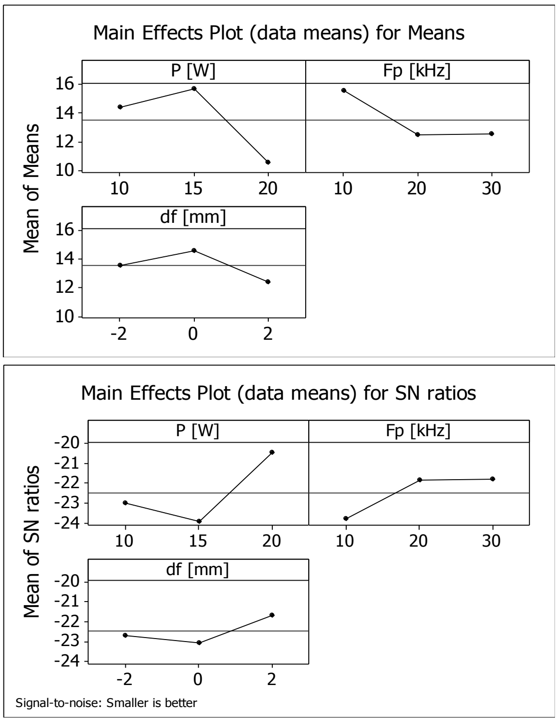


Fig. 5. Main effect on means and S/N ratios for 5 removed layers.

The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the quality characteristic, a larger S/N ratio corresponds to a better quality characteristic.

Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. The optimal combination of the process parameters can then be predicted.

Specifically, table 3 reports values of parameter levels which minimize roughness, which correspond to the highest S/N ratios.

Table 3. Levels of process parameters optimizing roughness

	N_{rl}	P	v	F_p	d_f
Levels	5	3	-	3	3
	10	3	2	3	3
	15	3	1	3	-
	20	3	1	3	-
	30	3	1	3	-

Figs. 5 and 6 show main effect plot for means and for S/N ratios, respectively for $N_{rl} = 5$ and for $N_{rl} = 30$.

The following considerations can be made:

The minimum roughness, for all N_{rl}, is obtained for average power and repetition rate set to the maximum value, respectively 20 W and 30 kHz and for lower values of scan speed.

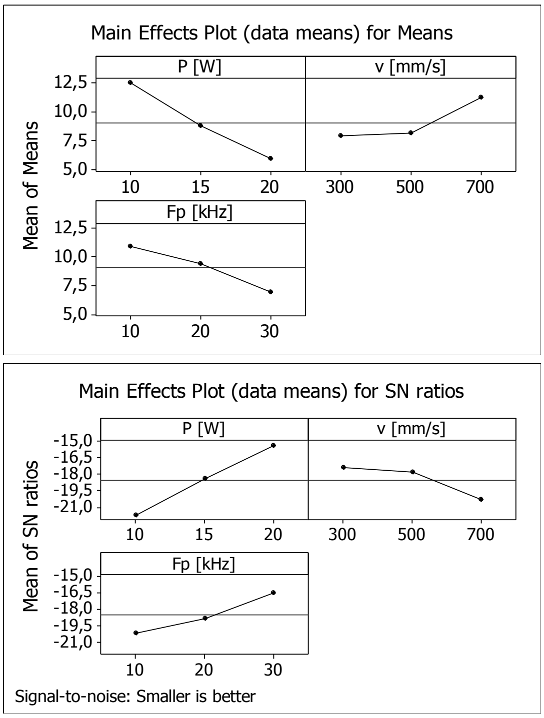


Fig. 6. Main effect plot for means and for S/N ratios for 30 removed layers

Laser defocus affects Ra only for lower values of N_{rl}. Thus, for a number of removed layers of 5 and 10 it has to be considered and its optimal value corresponds to a laser defocus of 2 mm. This means that when LA is used to remove a limited number of layers, the laser beam should be defocused to obtain a further improvement in surface finishing of SLM parts.

The analysis of main effect plot for $N_{rl} = 5$ and $N_{rl} = 30$ confirms, as observed in section 2.4, that roughness decreases considerably with the increasing number of layers.

4. Conclusion

The present work investigated the use of LA ablation for improving surface roughness of selective laser molten steel parts.

A statistical analysis was performed and the Taguchi optimization methodology was used to find out the optimal process parameters reducing surface roughness. The following list sums up the results that were obtained.

- Surface roughness of SLM parts decreased significantly with the number of the removed layers.
- In the considered range the higher scan speeds affected the surface finish only for the larger number of the removed layers.
- The lower scan speeds did not influence the roughness.
- The laser power and the repetition rate had to be set to the maximum value for all N_{rl} in order to optimize roughness.
- Laser defocus affected roughness only for the lower values of removed layers. This means that when LA is used to remove a limited number of layers, the laser beam should be defocused to obtain a further improvement in surface finishing of SLM parts.

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