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Analysis of shape geometry of Ti6Al4V parts fabricated by nanosecond laser ablation

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Abstract

The process of laser milling, or laser ablation as it is also known, was developed over the last decade. In conventional milling techniques material is physically removed by a milling tool. In laser milling the material is removed by a laser beam through the layer by layer ablation mechanism. Generally, in laser ablation the quality of the processing result is reduced by melt accretions and thermal damage of the workpiece and therefore increases with shorter pulse duration. However, ablation efficiency decreases as well. Thus, laser ablation in the nanosecond range is still offering a good compromise between process quality and efficiency. The aim of this paper was to study the shape geometry and dimensions of Ti6Al4V parts fabricated by laser milling using a nanosecond Nd:YAG laser source. The impact of the laser processing parameters onto the machining outcomes was studied in order to find out optimized processing conditions. Particularly the influence of average power, repetition rate and scan speed was investigated.
The geometry of micro-parts was revealed using a 3D digitizing system Optimet Mini Conoscan 4000, which combines a non-contact, single-point measuring sensor based on conoscopic holography technology. The use of this measurement technology allowed obtaining complete information of the shape geometry and dimensions of built parts.

Keywords: Laser milling, process parameters, 3D Measurement, Conoscopic Holography Main text

1. Introduction

Laser milling (LM) is an emergent process for micro-fabrication, where the material is removed by a laser beam through the layer by layer ablation.

LM shows several advantages compared to the traditional manufacturing processes, such as the capability to work hard to machine materials such as ceramics, graphite, and cemented carbides and the totally absence of tool wear because of the touchless tool, surface finish, aspect ratio, dimensional accuracy, and minimum feature size (Heyl et al., 2001) (Pham et al., 2002) (Pham et al., 2004) (Campanelli et al., 2013).

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Although several work can be found in literature on the effect of laser process parameters on quality of laser ablated parts, few of them focus on the analysis of the shape and of dimensions of parts fabricated by laser milling.

(Chen et al., 2011) analysed the influence of various micro channel structure laser carving features (channel aperture, channel lines, and channel distance) on the efficiency and FF of polycrystalline silicon solar cells.

(Karazi et al., 2009) developed some models for the prediction of the width and depth dimensions of CO2 laser-formed micro-channels in glass. The width and depth dimensions of the micro-channels for each experiment were measured at three different locations along the produced channel. The measurement system used was an in house built laser profilometer that had a 1.95 mm resolution in the x and y directions and a 0.5 mm resolution in the z-direction.

(Schille et al., 2011) studied performance of laser microprocessing of metals in terms of ablation depth, wall-angle, and surface roughness. They used a confocal point sensor CF 4 and a tactile roughness device (DEKTAK 3030) for measurement of parts.

(Campanelli et al., 2015) studied the shape geometry and dimensions of AISI 316L micro-channels fabricated by laser milling, using the 3D digitizing system Optimet Mini Conoscan 4000, based on based on conoscopic holography technology.

Moreover, little knowledge on the use of conoscopic holography technology to measure features in the microscopic scale is available since limited published literature exists on this subject.

Conoscopic holography (CH) is a non-contact interferometric technique used for surface digitization which presents several advantages over other optical techniques such as laser triangulation(Alvarez et al. 2009). Among others, the ability for the reconstruction of high-sloped surfaces stands out, and so does its lower dependence on surface optical properties (Sirat & Psaltis, 1985).

This paper describes the use of the conoscopic holography technology to measure and to analyze the shape of Ti6Al4V parts fabricated by laser milling using a Nd:YAG laser in the nanosecond range.

Since the use of conventional optical microscopes is limited when high slopes walls should be measured, the present work studies the use of a 3D digitizing system OptimetConoscan 4000 measurements to characterize laser milled micro-parts cross-section. The Optimet Conoscan 4000 was employed with a spatial resolution of 12 µm × 12 µm and of 2.5 microns on the z axis.

The impact of the laser processing parameters onto the machining outcomes was studied in order to find out optimized processing conditions. Particularly the influence of average power, repetition rate and scan speed was investigated.

2. Experimental procedure

2.1. Laser machine setup and materials

All experimental tests were carried out on a laser machine equipped with a nanosecond Nd:YAG laser source, pumped by laser diodes, and a scanning head which used deflecting mirrors to turn the laser beam to the scanner head lens. The laser optic converged the laser beam on the material surface. The laser was able to operate both in continuous and in pulse mode, reaching respectively a maximum power of 100W and 20W. The pulse mode was characterized by a laser spot diameter of 70 µm.

Square multilayer samples with dimension of 10 mm x 10 mm were manufactured (Figure 1). A Ti6Al4V plate was used as workpiece material test. The investigation was conducted using a full factorial plan of experiments, characterized by 3 factors (laser power, scanning speed, repetition rate), with 3 levels for scan speed *(v),* 3 levels for laser power *(P)* and 4 levels for Repetition rate *(F_p)* for a total of 36 combinations of the parameters (Table 1). The scanning strategy used to remove the single manufactured layer was characterized by a mix hatching mode consisting in x and z axis parallel scanning vectors and ±45° tilted scanning vectors.

Table 1. Experimental plane.

Factors	Level 1	Level 2	Level 3	Level 4
Average Laser Power [*W*]	10	15	20	-
Scan speed [*mm/s*]	300	500	700	-
Repetition Rate[*kHz*]	10	20	30	40

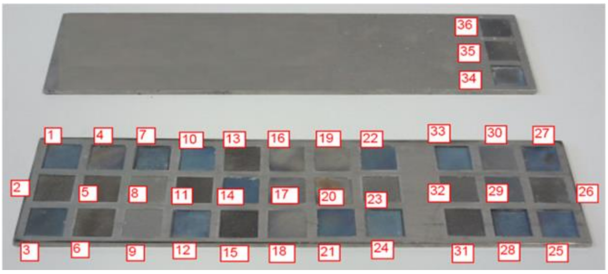

Fig. 1. Built samples

2.2. Dimensional measurements

Dimensional measurements were performed with the 3D digitizing system Optimet Conoscan 4000, which combines a non-contact, single-point measuring sensor (Optimet ConoProbe Mark 3, equipped with a 50HD mm lens, with claimed precision equal to 2.5 microns on the z axis and field of view equal to 2 mm) based on conoscopic holography technology with x-y axes repeatability (3σ) equal to 0.5 microns .

Measurements were obtained setting a laser power approximately equal to 0.71 mW and a charge-coupled device (CCD) frequency power equal to 1000Hz.

The choice of conoscopic holography technology is mainly due to its capability to combine co-linearity with bending optics to measure deep, narrow slots, grooves and blind-holes. It can also be used simultaneously through the same focusing lens of welding and cutting lasers and machine vision cameras. This kind of sensors measures on variable surfaces ranging from highly reflective, partially translucid, diffusive to roughly textured surfaces with no need for painting or resurfacing. The 3D scan results is a dense point cloud with a very high number of information regarding the dimension of the parts, where contact digitizer cannot touch the vertical shape of geometry and conventional optical digitizing systems suffer of problems related to undercuts and non-accessible areas.

Most of the work in literature presents experimental tests in which the dimensions of the part are obtained by cutting the specimens in three or more parts to obtain the cross-sectional profiles and then measuring the depth and the width by digital images processed using optical microscopes. The use of the conoscopic holography technology allows using a not destructive methodology and allows studying every micro dimension of the part. Figure 2 shows an example of benchmark acquisition.

The five geometrical entities considered for each sample are shown in Figure 3 and consist in Top Width *(L_{Top})*, Bottom Width *(L_{Bottom})*, *Depth*, and two wall angles α_1 and α_2.

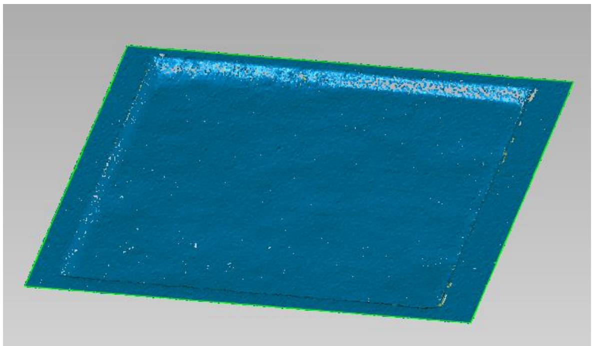

Fig. 2. Benchmark acquisition

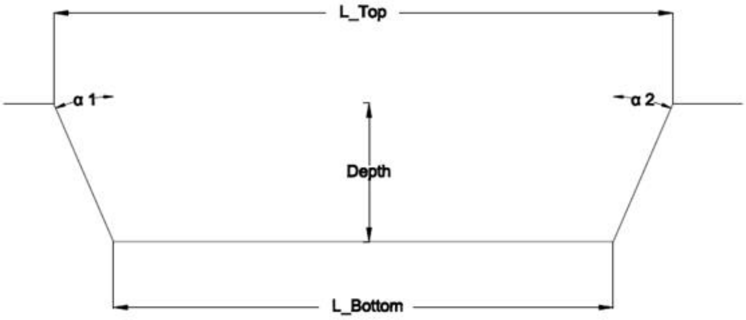

Fig. 3. The five measured geometrical entities

3. Analysis of results and discussion

An error index *(E_R%)* was introduced, according to Eq. 1, in order to compare the single measured dimension *(X_m)* with the single CAD dimension *(X_{CAD})*.

$$E_R\% = \frac{X_m - X_{CAD}}{X_{CAD}} \times 100 \qquad (1)$$

The analysis of results showed that the average error on top width was 0.59%, with maximum values of 2.9%. On the other hand, results for bottom width showed an average error of 3.1%. Results for wall angles α_1 and α_2 revealed an average error of 39.8% and 38.1%. An average value of wall shape angle was also calculated. This error ranges between a minimum value of 13.6% and a maximum value of 78.6%. In this case, the error reaches very high percentages as also confirmed by literature (Schille et al., 2011). In fact, the wall angle forms as the result of the overlap geometry at the start point and the endpoint of the laser ablated geometry.

Finally, In order to evaluate the influence of the considered process parameters on the error index calculated for single considered geometrical entities, the Analysis of Variance (ANOVA) was performed (Montgomery et. Al, 2003). The evaluated response results were *Error* L_{Top}, *Error* L_{Bottom}, *Error* α_{Medium} and *Depth*.

The General Linear Model was used to perform ANOVA. Factors for this model are discrete variables, therefore the ANOVA examines whether the variance of the factor is zero. The p-value tells whether the effect for that term is significant. If the effect of a discrete factor is significant, then the variance of the factor is not zero.

The probability value α represents the factor coefficient, the smaller the value the more significant it represents the factor. In the present analysis, the threshold value was chosen at 0.05. If the p-value is greater than the chosen level, the null hypothesis is accepted and the coefficient is judged not to be significant. Analysis of variance results are summarized in Table 2. The Symbol (S) refers to the influence of each part parameter on the measured geometrical entities. $(E_R\%)_\alpha$ and Depth result to be affected by the variation of all the considered process parameters, while $(E_R\%L_{Top})$ is influenced only by (R_p) and $(E_R\%_{Lbottom})$ by both (v) and (R_p).

Table 2. Significance of factors vs. geometrical entities

Geometrical entities	Average laser power [W]	Scan speed [mm/s]	Repetition Rate [kHz]
Error L_{Top} $(E_R\%L_{Top})$	NS	NS	S
Error L_{Bottom} $(E_R\%L_{bottom})$	NS	S	S
Error α_{Medium} $(E_R\%)_\alpha$	S	S	S
Depth	S	S	S

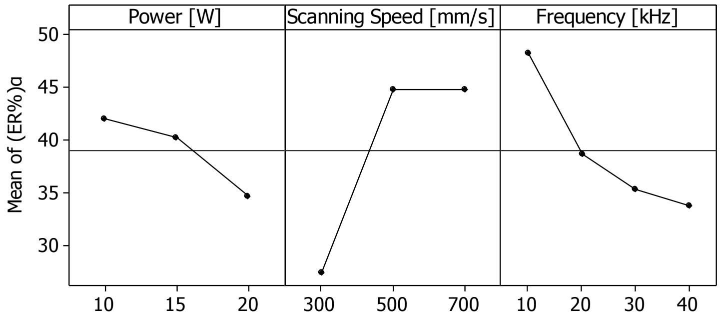

Fig. 4. Main Effects Plot for (ER%)α

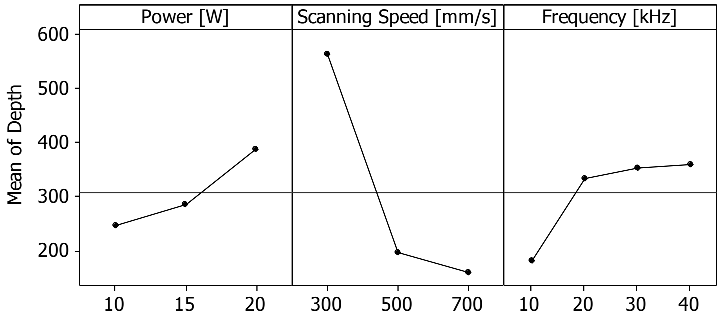

Fig. 5. Main Effects Plot for Depth

Figures 4 and 5 show respectively main effects plots for *(E_R%)$_\alpha$* and Depth versus *(P)*, *(v)* and *(F_p)*. It is interesting to observe that values of process parameters which maximize the ablation Depth (*P* = 20 W, *v* = 300 mm/s, F_p = 40 kHz) are the same which minimize the average error on wall angle *(E_R%)$_\alpha$*.

4. Conclusions

In this paper an experimental work to investigate the shape and the dimensions of Ti6Al4V micro-parts fabricated by nanosecond laser milling was performed. Dimensional measurements were performed with the 3D digitizing system Optimet MiniConoscan 4000, based on conoscopic holography technology with claimed precision equal to 2.5 microns on the z axis, field of view equal to 2 mm. The effect of three main process parameters (average laser power, scanning speed and repetition rate) on the error index calculated for the single considered geometrical entities was studied. Results showed an average error on top width and bottom width respectively of 0.59% and 3.1%. On the other and, results for wall angles revealed average errors considerably higher (about 39%). Analysis of Variance confirmed the effect of the variation of the considered process parameters on quality results of built parts.

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