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Optimization of titanium cutting by factorial analysis of the pulsed Nd: YAG laser parameters

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Abstract

The need to establish the laser processed parts that satisfy all functional requirements of the application as an uniform surface finish, low roughness and the conservation of their metallurgic properties was the main motivation in the accomplishment of this study. Besides the versatility and advantages, as well as the industrial sector global trend, became important factors in the lasers use as machining tools. The scope of present study was to investigate the effects of laser processing on the quality and formation of phases in the cut surface. The cutting process was performed on commercially pure (CP) titanium (grade 2) and alloy Ti–6Al–4V (grade 5) sheets. The obtained samples were analyzed through optical microscopy (OM) in order to determine the edge roughness formations. An increase on the superficial hardness on the cut region and the formation of nitrogen precipitates under a thin layer of a melted zone were verified. A factorial arrangement regarding the several combinations of different processing factors was built and the influence of these specific parameters, which were statistically significant for the process, was evaluated by the analysis of variance statistical test.

Keywords: Laser machining; Nd:YAG laser; Titanium; Analysis of variance

1. Introduction

Every industry inserted in the production chain aims a continuum enhancement on their processes control and also on their products development. The factors such as quality, reliability and costs reduction are important motivations for the operational excellence achievement serving also to generate competitive items in the global scenario.

Consequently, these factors may be the basis of choosing the laser processing [1] replacing the conventional methods. This procedure includes several segments in different areas where the laser is focused by the main industrial applications [2] such as cutting, drilling, welding, thermal treatment and marking.

The applications for the laser material processing involves mechanisms on which it becomes necessary to adequate the type of material and its geometrical shape to the laser type (which is determined by the wavelength and the continuous or pulsed operation mode). From this selection it is also necessary to choose and set the various process parameters that influence on the final result quality, cost and speed, among others factors [3,4].

This technology stimulates major interest due to the fact that it joins various advantages such as: non contact process and no tool wear, possibility of using a controlled atmosphere, high energy density, flexibility on the beam delivering, simplicity in fixation, easy automation, small heat affected zone, high speed, excellent edge quality.

The fabrication of components from titanium alloys [5–7] and commercially pure titanium (Ti-CP) appears associated with the development of machining technology. After the 1950s decade this material aroused a great interest in several engineering applications mainly because its metallurgical and mechanical characteristics such as relatively low density ($4.5\,\mathrm{g\,cm^{-3}}$), medium elasticity module (105 GPa) and high values of the mechanical resistance associated with some alloying elements.

The metallurgical titanium classification [8,9] according to the American Society of Testing Materials (ASTM) is determined by different grades of Ti-CP (also denominated as unalloyed) [10] and its alloys into three categories: alpha, alpha–beta and beta alloys which define the predominance of the phases present in the microstructure.

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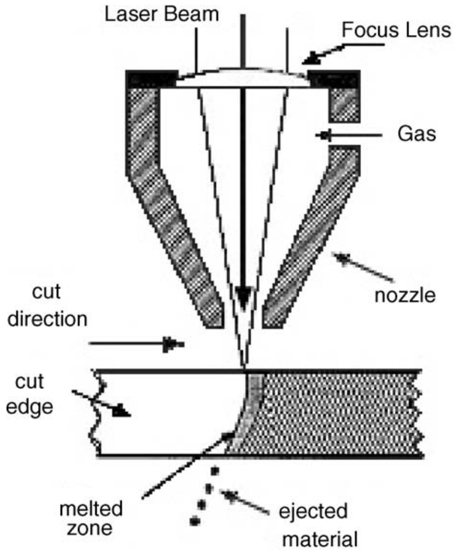

Fig. 1. A schematic of the laser beam interaction with the material (for the cutting process).

Table 1
Fixed and variable parameters

Fixed parameters	
Light polarization	Non-polarized
Nozzle design	Simple conical shape, Ø = 0.7 mm
Nozzle-workpiece distance	$w_z = 0.6\,\mathrm{mm}$
Lens focal length	100 mm
Cut geometry	Straight lines
Type of gas	N_2
Transversal mode	Multimode
Variables parameters	
Power density	Controlled by the incident beam diameter relation with the pulse peak power
Laser pulse energy	Given by the system; variation: dozens of millijoules to Joules
Laser pulse length	Scale variation from 0.2 to 10 ms
Process speed	Continuous control by CNC; variation: hundreds of mm/min
Gas flow	Controlled by the injection system valves
Pressure	Controlled by the injection system valves; limit: 14 bar

The allotropic behavior of titanium allows diverse changes in crystalline structures by variations of the temperature. Titanium can exist in the low-temperature a hexagonal close-packed (HCP – alpha phase), or above 890 °C a body-centered cubic (BCC – beta phase). These phases are directly related to the microstructure formation and present different metallurgical and mechanical properties.

Titanium has many desirable properties, most notably its outstanding mechanical strength and high corrosion resistance at room temperature. However, titanium and its alloys suffer from serious disadvantages of poor tribological properties. An attempt to improve such properties surface engineering may cause some difficulties to the conventional machined methods such as: high tool wear, processing time and operational costs. These factors enable the development of titanium laser processing and its alloys as an alternative process.

The present study joins the current laser processing technology to relatively new material, titanium, aiming optimized the process of pulsed laser cutting of thin sheets.

As the processing aims the highest quality excellence, one must obey an optimized combination of parameters [11] as follows: power density; transversal laser beam mode; light polarization; process speed; material characteristics; geometry and diameter; workpiece-focus distance; lens focal length; gas type, pressure, flux and purity; laser pulse energy and temporal length; wavelength; focal point distribution energy distribution among others. Fig. 1 shows the laser cutting procedure and evidences some of the study parameters.

The laser parameters described above lead to a complex interactive relations. Therefore the beginning of the study intends to present the most influent parameters during the cutting procedure and the possible interaction among them. Table 1 shows the fixed parameters and those chosen to be variable.

The parameter classification of Table 1 was elected according to previous acquired knowledge at the laboratories of the Center for Laser and Applications (CLA/IPEN, São Paulo, Brazil, University of São Paulo) and also regarding to easily monitoring process.

The energy per pulse and the pulse overlapping were considered the most significant parameters on the cutting procedure and consequently became the main process variables.

Thus, the minimal energy per pulse was chosen as being capable of accomplish a homogeneous hole on the material. From this, the laser repetition rate can be determined due to the fact that it maintains a constant average power for the laser lamp supply. The importance of keeping it constant is related to its function to determine the thermal lens in the laser medium and by its influence on the laser beam quality (and consequently on the focal diameter). This way, the relation described below (Eq. (1)) was kept constant and with a maximum permitted value by the supply system.

$$P_m = Ef \tag{1}$$

P_m was defined as being the real laser average power output, E as being the energy of each laser pulse and f as the pulse repetition rate (i.e. the number of pulses per second).

An attempt to verify which parameters for the process gives the most adequate machining conditions as well as to establish the best parameters combination the analysis of variance was conducted.

Many experiments involve the analysis of effects of one or more factors in a system being studied. According to Montgomery [12], the method of varying one of the factors at a time and keep the others fixed is not adequate when there is a possibility of the influence of one factor over the other. In this case, the most appropriate is the use of factorial shapes where all the possible combinations of the factors are investigated in a complete run of experiments.

This paper presents an approach to determine the effects of the laser conditions and of the assistant gas on the surface finishing quality, roughness, edges quality, and formation of phases on the cut surface, as well as to establish a set of parameters,

Table 2
Laser parameters

Condition	Pulsing frequency (Hz)	Energy (J)	Hole diameter (mm)	V_{max} (mm min^{-1})
A	89	0.460	0.135	720.90
B	73	0.592	0.167	731.50
C	48	0.925	0.286	823.70

validated by the statistical analysis, in order to optimize the laser process.

2. Materials and methods

Two different types of titanium sheets were chosen: the commercially pure titanium (Ti-CP grade 2) and alloy Ti–6Al–4V (grade 5) that are the most commonly used alloy, compromises more than 60% of the titanium compounds production.

The profiles to be cut were created by CAD/CAM software and transferred to a CNC vertical milling machine combined with an Nd:YAG pulsed solid-state laser. A 10 mm × 15 mm and a 5 mm × 15 mm cut were made in 0.5 and 1.0 mm kerf sheets.

The cutting process mechanism is obtained by focusing the laser beam on the material surface together with a collinear gas jet enabling the material removal by fusion and blow. Aiming for a good quality cut on the superficial finishing surface and according to the studies made by the researchers from the Center for Lasers and Applications a set of parameters was chosen as follows: pulse length (tp), frequency (*f*), pulse energy (*E*), and also the type and pressure of the assistance gas.

On the first phase of this study nitrogen was used as the process gas, as well as focusing lens with focal length of 50 and 100 mm.

A sequence of single shots associated with the lens focal position variation was executed previously in order to determine the focal point position over the titanium surface. The pulse applied on the surface causes a bowl-shaped depression, which under microscope observation, helps to choose the higher intensity spot defining thus the best focal position.

Following this step single shots were used to determine the maximum process speed (V_{max}, mm min^{-1}) by the hole diameter (Ø, mm) and the pulsing frequency (*f*, Hz) according to the Eq. (2):

$$V_{max} = Øf \qquad (2)$$

The maximum speed of the laser beam displacement was determined with this procedure where the pulses cause tangent holes among them. Consequently, a higher speed would become impossible to accomplish the cutting.

The laser pulse length and the lamp supply average power are two important parameters that were kept at 0.6 ms and 5300 W, respectively. Table 2 shows the relation between the hole diameters obtained as a function of laser pulse energy and the frequency. An effort to keep the laser average power constant the frequency was altered for each situation.

A 5% factor of reduction on the maximum speed values was used in order to assure the cutting quality. The pulse overlapping (*S*) was considered as an important factor on the followed experiment. The speed values of the three conditions (A, B, C) were reduced in 80%, 60% and 40% from the initial values as shown in Table 3.

The metallurgical characteristics of the cut edge surfaces, close to the heat-affected zone, were analyzed by Vickers microhardness tests (HV), X-ray diffraction (XRD), optical microscopy (OM) and scanning electron microscopy (SEM).

Table 3
Sample groups their speed values and the pulse overlapping (*S*) for three conditions

Condition	Sample no.	Speed (mm min^{-1})	*S* (%)
A	1	684	5
	2	548	24
	3	410	43
	4	274	62
B	5	700	5
	6	560	24
	7	420	43
	8	280	62
C	9	782	5
	10	626	24
	11	470	43
	12	313	62

The samples were polished and went through a chemical etching procedure for the optical and scanning electron microscopy analysis. The X-ray diffraction was made in the center of the cut surface using a Philips MPD 1880 diffractometer equipped with a copper tube (λ = 1.54 Å). A set of Vickers microhardness measures was obtained using a Wolpert/Werke (M-tester) with 200 g load on the cut surface in three different positions: next to the laser entrance; at the center of the sample; and next to the laser output. Measures on the base material far from the laser-machined surface were also obtained.

The surface roughness and the quantity of irregular edges formation were choosing as the two important indicator of quality for the cut zone. A Mitutoyo Model 211 Surftest Profilometer was used for the roughness determination. The dross that is not fully ejected from the kerf during cutting was captured as digital images format revealing the irregular surface (Fig. 2). Image analysis software allowed amplifying the image of the cutting area and measuring the dross areas as an indicator of variation of each processing parameter.

In a second step, a new group of samples were generated focusing on a relative evaluation of the application of different gases and their influence on the cutting quality. Due to the evidence of nitrogen precipitation, the argon, helium and three mixtures of these gases (in a proportional combination of 75%He–25% air, 25%He–75% air and 50%) were used. This had been used in order to avoid the nitridation phenomenon and probably to reduce the superficial hardening effect.

3. Results and discussion

The laser processing dynamics suffers the influence of a complex interaction among the fixed and variable parameters. However, some of them may seem to influence definitively on the quality of the processed surface.

The effective power of the equipment is initially a limiting factor on the material selection directly linked the maximum thickness, because thicker materials need more energy density for the interaction between the laser beam and the material surface.

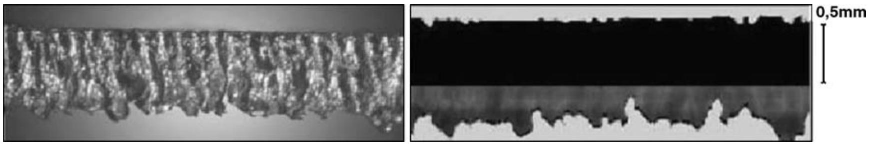

Fig. 2. Digital image of the cut edge (left) and graphically treated photo image (right). Note the thickness of titanium thin sheet is overlaid with light black box and the gray area highlighting the dross.

Table 4
Measured dross area (mm^2) for three energy values and four different overlapping rates

Overlapping rate	Energy								
	E_2 – 0.460			E_3 – 0.592			E_5 – 0.925		
S_1 – 5%	0.23	0.25	0.30	0.29	0.22	0.20	0.28	0.27	0.25
S_2 – 24%	0.38	0.48	0.44	0.43	0.48	0.46	0.32	0.33	0.34
S_3 – 43%	0.32	0.36	0.41	0.69	0.59	0.65	0.50	0.55	0.48
S_4 – 62%	0.56	0.47	0.54	0.68	0.67	0.71	0.45	0.49	0.47

Note: The group of the 12 values showed above, divided in three columns, is the reference of the dross area obtained on the samples.

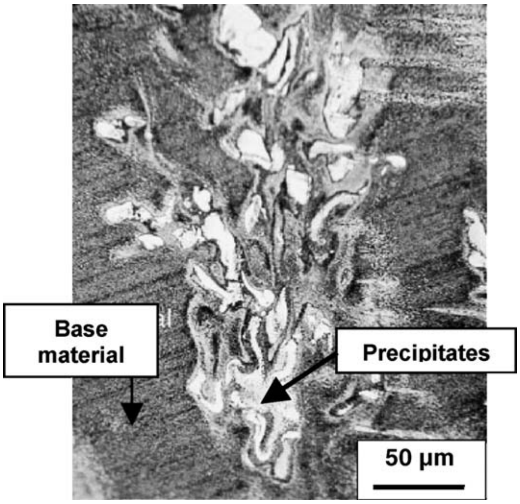

Fig. 3. Optical micrograph of the cutting surface (after polishing and etching) shows the base material (Ti) and some precipitates.

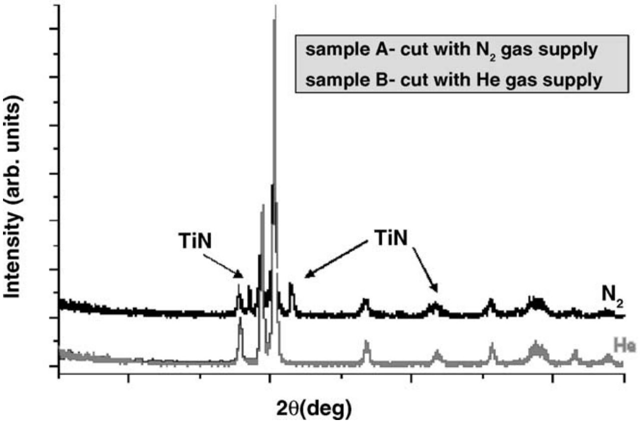

Fig. 4. X-ray diffraction spectra: N_2 and He surface cuts where the peaks correspond to the TiN phase.

Another interfering parameter on the quality of the cut is the gas supply. The titanium presents high chemical reactivity with some gases, restricting the oxygen use on the process due to its pyrophoric reactions. The nitrogen was used on the initial phase of this study as the assistant gas on the laser process. According to the optical micrograph of the laser processed surface presented in Fig. 3 and the X-ray diffraction results, the use of this gas on the machined surface caused the formation of nitride precipitates under a thin layer of the melted zone.

These nitrides were formed due to the interaction of the overheated liquid metal with the gas flow that blows the melt pool from the kerf during cutting.

The cutting region was compared with the base material using a Vickers microhardness tester, which demonstrated an increase on the hardness of the fusion zone. An increase of about two times in microhardness to the commercially pure titanium melted surface and a three times higher value for the melted surface on the alloy Ti–6Al–4V was verified.

The samples originated from the use of He and Ar gases and their mixture resulted in a reduction of irregular edges and also in the elimination of nitride precipitates. The results obtained through the X-ray diffraction in Fig. 4 shows that only the cut with the nitrogen gas induces the TiN phase on the cutting edges. The peaks related to this phase are not observed on the cuts made with Ar and mixtures of Ar and He gases.

Thirty-six samples were cut according with the parameters listed in Table 4 for the verification of the influence of the laser pulse energy and overlapping rate on the cutting quality. It was possible to observe cuts with all the possible combinations for three different pulse energy values and four different overlapping rate values of these pulses. The roughness and dross quantity of irregular edges were measured for each sample and Tables 4 and 5 show the obtained results.

The analysis of variance thorough the ANOVA statistical test allows concluding that these two parameters (laser pulse

Table 5
Roughness (µm) measured for three energy values and four different superposing rates

Overlapping rate	Energy								
	E_2 – 0.460			E_3 – 0.592			E_5 – 0.925		
S_1 – 5%	4.72	5.73	8.67	7.21	6.98	7.29	19.15	18.57	16.70
S_2 – 24%	6.13	4.34	3.71	7.07	5.91	8.62	12.09	17.28	16.38
S_3 – 43%	3.07	5.13	4.25	9.51	6.37	8.11	7.79	5.32	8.75
S_4 – 62%	2.67	4.58	5.62	2.69	3.92	3.95	7.08	5.29	9.00

Note: The group of the 12 values showed above, divided in three columns, is the reference of the roughness values.

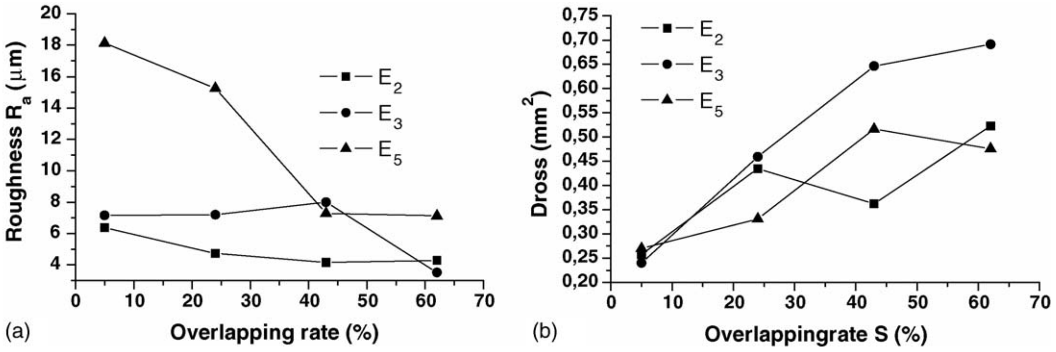

Fig. 5. (a) Roughness × overlapping rate variation. (b) Dross × overlapping rate variation.

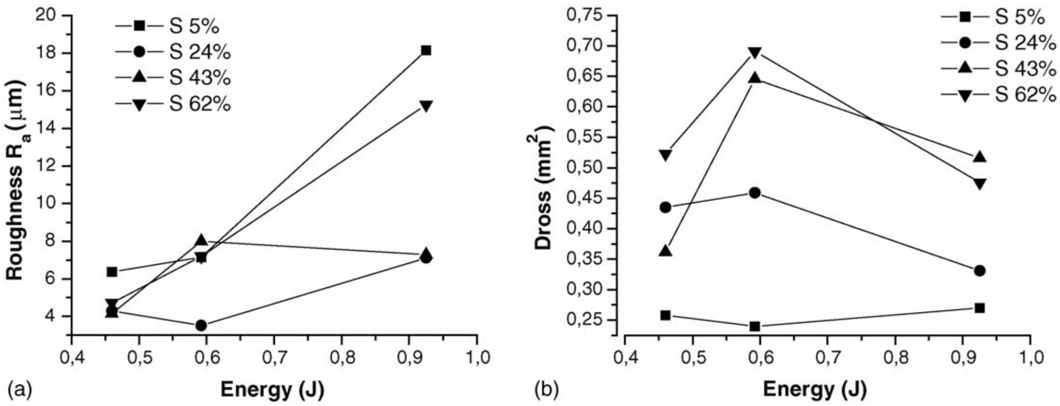

Fig. 6. (a) Roughness × energy variation. (b) Dross × energy variation.

energy and overlapping rate) are important for the chosen factors (roughness and dross quantity), as shown in Table 6. Besides that they strongly influence on the roughness and irregular edges formation on the cutting surfaces. According to Table 6, the analysis also shows that there is a significant interaction between these two parameters (*P*-values called the significance level).

The roughness variation and dross area as a function of overlapping rate and energy are shown in Figs. 5 and 6.

Table 6
The analysis of variance table for surface finishing of the titanium processed samples

Source	DF	SS	MS	Fo	*P*-value
Analysis of variance for dross quantity					
Overlapping	3	0.490	0.163	119.74	0.000
Pulse energy	2	0.101	0.051	37.12	0.000
Interaction	6	0.126	0.021	15.43	0.000
Error	24	0.032	0.001		
Total	35	0.751			
Analysis of variance for roughness					
Overlapping	3	170.09	56.69	22.78	0.000
Pulse energy	2	329.85	164.92	66.27	0.000
Interaction	6	158.18	26.36	10.59	0.000
Error	24	59.73	2.48		
Total	35	717.86			

Note: The abbreviations (DF), (SS), (MS), (Fo) stand for degrees of freedom, sum of squares, mean square and ratios of mean squares, respectively.

In general increasing the overlapping rate, i.e. closer pulses and lower speed values on the process, decreases the roughness and increases the dross quantity as well. This quality enhancement must be connected to a high laser-material energy transfer, which increases the amount of expelled liquid and enables a wider titanium smooth area. The roughness values were not significantly increased for the two lower pulse energy, however it significantly increases for the higher energy value. On the other hand, the amount of dross caused by the laser pulse energy is not very perceivable suggesting an intermediate energy value, which leads to an increase of irregular edges.

4. Conclusions

The X-ray diffraction results for the cutting with nitrogen clearly show the formation of TiN precipitates on the observed surfaces. The microhardness tests also show that the hardness was considerably increased in this region. Probably due to the TiN precipitates formation. The cuts which were made with the He, Ar and their mixtures did not presented the formation of nitrides and probably do not present an accentuated change on the hardness of cut surfaces.

Titanium reputation for being difficult to machine is well known, but selecting the proper laser processing approach in conjunction with the gas supply should satisfy all manufacturing needs including edge quality and finishing.

Regarding the factors chosen for the experiment design, the energy per pulse and overlapping rate were highly influential to the process. The particular application must be evaluated for the best parameters choice since the enhancement of one of the cut characteristics (dross or roughness) leads probably to failure of the other characteristic.

Obviously, this present study explored some among all the possible parameters of influence for the laser machining. Only after the evaluation of all these several parameters (ongoing future studies) it will be possible to have a clear scenario of the real importance of each one of them and this way to establish an "optimized" set that will enable to have a cut characterized by less irregular edges, low roughness and almost oxide-free under the laser optimum conditions for the titanium cut with the pulsed Nd:YAG laser.

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