Available online at www.sciencedirect.com
ScienceDirect
Procedia Manufacturing 38 (2019) 1111–1120
Procedia MANUFACTURING
www.elsevier.com/locate/procedia

29th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2019), June 24-27, 2019, Limerick, Ireland

Improving the Cut Surface Quality by Optimizing Parameters in the Fibre Laser Cutting Process

I. Amaral, F. J. G. Silva, G. F. L. Pinto, R. D. S. G. Campilho, R. M. Gouveia

ISEP – School of Engineering, Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 431, 4200-072 Porto, Portugal

Abstract

One of the main problems with laser cutting equipment is related to the wrong setting of cutting parameters. The mismatching of these parameters leads to a loss of cut surface quality, which is hardly re-established. This loss of quality is usually related to a burr problem. Thus, this study is aimed to improve and optimize this process using a fibre laser equipment. Three important laser cutting parameters were studied in order to investigate their importance in the cut surface quality: radiation power, cutting speed and gas pressure. The different values were performed cutting a stainless steel AISI 316L and a cold rolled steel St12. Metallographic and cut surface analysis, burr and roughness measurements were carried out, supported by a Scanning Electron Microscopy and profilometry. Through the Taguchi statistical analysis model, it is possible to indicate the best set of laser cutting parameters. It was verified that the values recommended by the equipment manufacturer can be optimized, being possible to use less radiation power in the laser beam with greater speed of cut, providing a better cut surface quality, improving and optimizing the entire process.

Peer-review under responsibility of the scientific committee of the Flexible Automation and Intelligent Manufacturing 2019 (FAIM 2019)

Keywords: Laser Cutting; Fibre Laser; Parameters Optimization; Cut Surface Quality; Scanning Electron Microscopy; Taguchi Methodology.

1. Introduction

The laser cutting process consists of the focus of radiation on a precise point (focal point or point of maximum energy), to reach high temperatures capable of cutting different materials [1]. The laser beam formation occurs in the laser generator, where the most important elements for the process are, such as the active medium (atoms or molecules of different types) which is disposed between two mirrors and an excitation source (responsible for the

2351-9789
Peer-review under responsibility of the scientific committee of the Flexible Automation and Intelligent Manufacturing 2019 (FAIM 2019)
10.1016/j.promfg.2020.01.199

emission of photons). The active medium is stimulated by the excitation source, which performs a photon incidence, leading to a photon being released each time an electron is positioned in a lower energy-level orbit [2]. That is, when a photon is used to cause the excitation of an electron located in a higher energy-level orbit so that it returns to the ground state, energy is released in the form of a second photon, keeping the same frequency, direction and phase of the incident photon, thus transferring the energy to the transmitted light [3]. Then, the light transformed into a laser is conducted by a mirror system or fibre optical cable (depending on the type of laser) to the focus system where cutting or another type of operation will occur, through a glass lens that must be always clean and which size can be changed according to the focal length [4, 5].

Currently, for the industrial market, two types of laser cutting equipment are the most requested: fibre and CO_2 laser. The CO_2 laser is a type of gaseous state laser, whose main characteristics are the constitution of the active medium (which is a mixture of gases) and the wavelength, being 0.6 µm [6]. The laser beam is guided through a system of mirrors to the focus system, where the raw material will be cut [7]. On the other hand, a fibre laser is a type of solid-state laser, being the main alternative to other types of laser cutting, namely in terms of accuracy, cut surface quality, cutting speed and cost. These types of lasers are distinguished by their laser beam formation, which is generated by the excitation of crystals, no longer needing gas for beam generation. This aspect allows a decrease in equipment cost [8]. Fibre optical lasers are more efficient and faster when cutting raw material with thicknesses below 5 mm, fact due to the wavelength utilized by this technology, which is ten times smaller than CO_2 laser, presenting a value of 1.064 µm [9]. In fibre optic laser, the laser beam generation occurs through the excitation of crystals, where the fibres are composed of silica doped with ions and provided with a second layer that is not doped, allowing the pumped light to be absorbed by the inner layer. The outer layer should be made of glass or polymeric material so that the refractive indexes are the smallest possible [10]. It is also important to note that the laser beam is guided by a typical fibre optical cable, so there is no need for a lot of mirrors to guide the laser beam, like in CO_2 lasers, further decreasing costs [11].

In this work, the potentialities of fibre laser equipment were studied, changing three main cutting parameters: radiation power (W), cutting speed (mm/min) and gas pressure (bar). These parameters are commonly changed by operators following the recommended values of each machine's manufacturer [12]. Oftentimes, the parts present lack of quality, because of the high level of burr and roughness on the cutting edge. These are the two main problems caused by the process and can be solved through parameters optimization [13]. Thus, using different parameters recommended by machine manufacturers in samples of stainless steel AISI 316L and cold rolled steel St12, this study has as the main goal to find the best set of parameters that promote low burr and roughness values, using Taguchi's methodology. This work has also the objective to promote the connection between academic knowledge and industry, since it investigated the influence of different values for parameters in a company, to improve quality problems. The tests were made together with operators which allowed to understand the daily problems of quality, as well as create a work methodology to optimize the process.

This paper presents the following structure: section 1 is a brief contextualization about the Fibre Laser Cutting Process; section 2 presents a literature review regarding the most important studies using fibre laser cutting equipment; section 3 presents the methods used in the development of this work; section 4 presents the corresponding results and discussion; section 5 describes the main conclusions extracted from this study.

2. Literature Review

Some studies have been performed by other authors to evaluate the results of the use of different laser cutting parameters on cut surface quality. Using samples of AISI 304, AISI 304L, AISI 316L and AISI 409, and CO_2 and fibre laser types with radiation power of 4000 W, Wandera [14] concluded that fibre laser performs better with thicknesses lower than 3 mm, becoming possible to reach higher cutting speeds. Also, using a CO_2 laser type, Patel *et al.* [15] found that the cutting width presents greater discrepancies when thickness increases, and for larger thicknesses this process is similar to the fibre optical laser, thus it is important to increase focal length to decrease the accumulation of heat in the raw material. Another study performed by Meszlényi *et al.* [16] using a pulsed fibre laser type, focused on the pulse frequency. With a low cutting speed, and also with a low or medium pulse frequency, the cutting width was kept without significant variations.

Studies were also carried out investigating the roughness. In order to establish a relationship between the laser cutting parameters, the cutting width and the quality of the cut surface, Eltawahni *et al.* [17] and Argade *et al.* [18] reported that, at higher cutting speeds, the cutting width tends to be smaller, as well as the average roughness (Ra).

In the same study, the cutting width increased with increasing radiation power. However, an increase in power induced an average roughness (Ra) reduction. The gas pressure also exerts a great influence on the average roughness parameter (Ra). As the gas pressure increases, the roughness also increases. For other materials like Al-Cu alloy, Senthilkumar *et al.* [19] showed that the cutting width has fewer variations with higher radiation power when using a CO_2 laser. Considering the INCONEL 625 alloy, Grepl *et al.* [20] used laser cutting process to obtain 17 samples. The cutting speed was increased, stepwise, by 100 mm/min for each sample cut, the parameters were constant. It was concluded that the sample cut with the intermediate velocity, was the one with the lowest burr level.

The Taguchi Method is usually used in several studies with a view to optimise sets of parameters, promoting different combinations of values to select the best conditions regarding a given process. Initially, the success in obtaining the desired results involves a careful selection of the process parameters, separating them into control variables that can be controlled (examples: cutting speed or radiation power) and noise variables, which are process disturbing (examples: vibrations of equipment or quality of raw material) [21]. Using the Design of Experiments (DOE), available on typical software's, the experiments simulate specific conditions of production under the effect of sources of variation and, analysing the results and identifying the control variables that most affect variability, as well as the levels that they must assume, so that this variation is minimal [22]. The main advantage of this method is that it is able to drastically reduce the number of experiments comparing to the theoretically predicted by traditional methods, resulting in a cost reduction. By selecting the Signal-Noise (S/N) ratio, it is possible to indicate the best levels of the control variables, taking into account the residual value of the noise variables, external to the process. The relationships chosen in this kind of studies should be "the lower the better - the smaller the better". After analyzing the selected set of experiments, Taguchi proposes to analyse the results through Analysis of Variance (ANOVA). The objective is to understand which control variables, at the respective levels, minimise the variability and, consequently, will be the most significant during the process [23].

With the Taguchi Method, some studies of the influence of laser cutting parameters on the cut surface quality were also presented. Sharma *et al.* [24] used this method to achieve the best set of parameters, to obtain the best surface quality, evaluating the average roughness (Ra) parameter, by cutting mild steel samples with Nd:YAG pulsed laser. By analyzing the S/N, ANOVA and statistical values, it was concluded that the cutoff rate and pulse frequency rate are, at different levels, the most important parameters for the quality of the cut surface. It was also concluded that the higher the cutting speed value, the lower the quality of the cut surface is. Tushar [25] also reached a similar conclusion. On the other hand, Madíc *et al.* [26] used a CO_2 laser to cut AISI 304 looking for the the lowest surface roughness. The different results were analysed using graphs and statistical values provided by the analysis of the S/N, cutting speed and radiation power are dominant parameters in order to obtain the lowest roughness on the cut surface.

3. Methods

The steps taken for methodology of this work were:

- The laser cutting equipment used was a TRUMPF® fibre optical laser. Samples were cut into two types of material, considering the same thickness, with different physical, chemical and mechanical properties (15 mm x 10 mm x 2 mm) – these dimensions were chosen taking into account the analyses necessary to carry out. AISI 316L stainless steel, widely used in many applications, namely in the food area and so on, is characterized by having high corrosion resistance and low carbon content. St12 cold rolled steel is mild steel which is widely used in stamped parts. Eighteen samples of each material were cut;
- The nomenclature of each parameter is mentioned in Table 1. The values were selected regarding the recommendations of the machine's manufacturer and values referred in the literature. Firstly, the samples were cut using the values recommended by the equipment's manufacturer, for each type and dimension of material. For the AISI 316L samples – radiation of power: 4000 W; cutting speed: 20000 mm/min and gas pressure: 15 bar. For the St12 samples - radiation of power: 1000 W; cutting speed 2500 mm/min and gas pressure: 2,8 bar. To understand the changes in the properties of the two materials, the three parameters were changed, respecting the proportional rate between them. Thus, the radiation power is not possible to increase more than the value recommended, the other two values assumed were lower. The cutting speed is possible to increase more than the value recommended, so samples were cut with higher and lower cutting speeds. For gas pressure parameter, only two values

were used, the maximum value allowed that corresponds to the recommended and a lower value, it was not used another lower value because the quality of samples was really bad;

- In the laboratory, Labopol 21® has been used to grind and polish the cut samples. Three types of sandpaper (220, 500 and 1000) and two types of abrasive (3 µm and 1 µm) were used. Still in the laboratory, an Olympus® - model BX52 microscope was used, which is provided with the Analysis® software, allowing the obtention of the microstructures' images;
- Samples were etched with the following reagents: Nital for St12 samples for 15 s; a solution of hydrochloric acid with water for AISI 316L samples for 20 s;
- Furthermore, a FEI®-Quanta SEM (Scanning Electron Microscope) was used to obtain the burr measurements of the samples, as well as the images for the cut surface analysis;
- Regarding the assessment of the average roughness of the cut surface, a Mahr® M2 portable equipment was used. MarSurf® software provided the capture and record of the roughness values regarding the different roughness parameters;
- Finally, using Minitab® software the Taguchi Method was applied to allow the organization of all measured values and the statistical analysis, indicating the best set of parameters.

Table 1. Nomenclature adopted for each parameter

Parameter	Code	Value for AISI 316L	Value for St12
Radiation power (manufacturer recommendation) [W]	Pn	4000	1000
Radiation power reduced [W]	Pr	3500	700
Radiation power doubly reduced [W]	Prr	1500	300
Cut speed (manufacturer recommendation) [mm/min]	Vn	20000	2500
Cut speed higher than the recommended value [mm/min]	Vh	25000	7500
Cut speed lower than the recommended value [mm/min]	Vr	10000	1500
Gas pressure (manufacturer recommendation) [bar]	pn	15	2,8
Gas pressure lower than the recommended value [bar]	pr	7	1,2

4. Results and discussion

After the tests, the samples were ground and polished. Just selected samples were subjected to these procedures:

- Samples with the highest and lowest radiation power (Pn and Prr);
- Samples with seriously damaged surface, with high levels of burr and roughness texture.

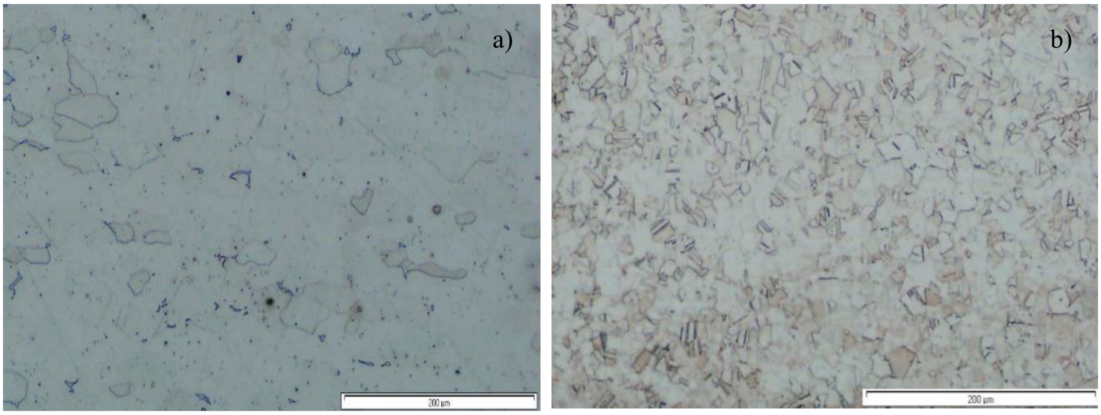

Fig. 1. (a) microstructure of St12 cut samples; (b) microstructure of AISI 316L cut samples

Then, the microstructure of the samples was analysed. In Figure 1 it is possible to observe the microstructure of St12 and AISI 316L samples after laser fibre cutting. Regarding the St12 steel, Figure 1 (a) shows a strong presence of ferrite through the light zones of the image. As can be observed, there is no clear microstructural changes after the cutting operation, comparing with the usual microstructure presented by St12 cold rolled steel, because the radiation power applied is not enough to increase the temperature to values that promote structural changes in this steel. The same analysis was performed on AISI 316L cut samples, which also did not reveal any clear change in terms of microstructure, as can be seen in Figure 1 (b). It is possible to observe the presence of grains in the form of austenite polygons, existence of a small amount of dispersed ferrite (darker areas), and the observed microstructure is typical, regarding that this type of stainless steels belongs to the category of austenitic stainless steels.

After analyzing the microstructures of the different materials, it was concluded that:

- Regardless of the type of material, the maximum power provided by the laser is not sufficient to promote changes in the microstructures;
- The cutting speeds used, together with the radiation power must respect a ratio so that the cutting is performed. In this context, changes in the microstructure must never occur.

The analysis of the samples cut surface and the burr measurements were performed by SEM. The burr is a typical defect occurring in many cut surfaces, independently of the process used. Figure 2 (a) shows a sample with the defect of burr, additional material was created from the bottom up of cut surface. Burr is a residue created during the passage of the laser beam, dragging material that did not melt and which is deposited in the edges of the cut surfaces. Most of the problems related with burr are relative to the incorrect selection of laser cutting parameters, lack of maintenance of the laser source equipment, namely the cleanliness that must be constant on the focus lenses and poor positioning of the focus system (focal length with incorrect value). In this work, the burr was measured by the difference between the average value of the sample thickness and the value of the biggest dimension from the bottom of the cut surface to the top of the burr peak.

The SEM analysis of the burr allowed to extract the following conclusions:

- Burr is a defect created, mainly, due to poor selection of laser cutting parameters;
- With the lowest values of radiation power (Prr), the most extreme cases of burr were observed;
- In Figure 2 (b), the sample with the lowest burr level corresponds to the following parameters: limited radiation power (Pr) and recommended cutting speed (Vn). It is concluded that good cut surface quality is obtained under reduced radiation power and recommend or higher cutting speed;
- Gas pressure is another important parameter in burr control, being responsible for the removal of waste in the area where the laser cut occurs. In Figure 2 (a), the sample presents a higher level of burr because the gas pressure was reduced, so less removal of the undesired particles was performed;

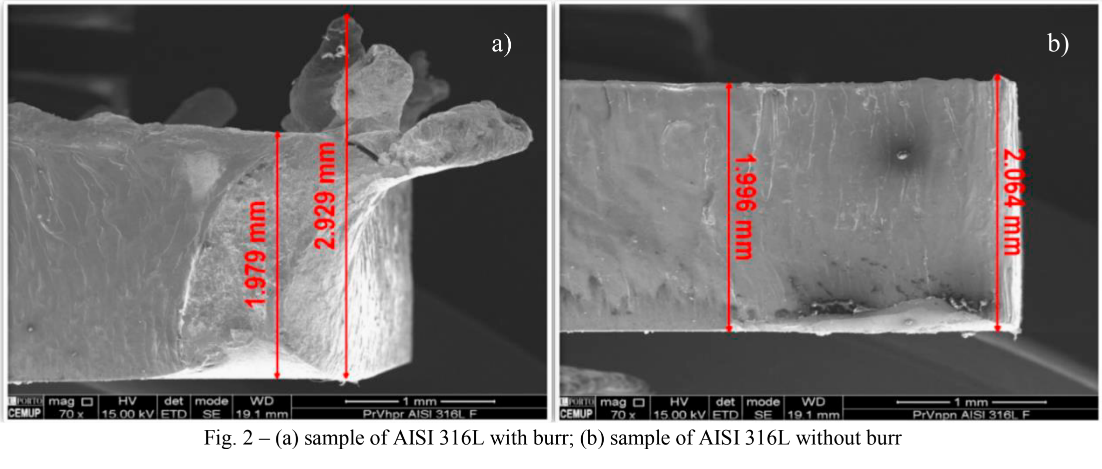

Fig. 2 – (a) sample of AISI 316L with burr; (b) sample of AISI 316L without burr

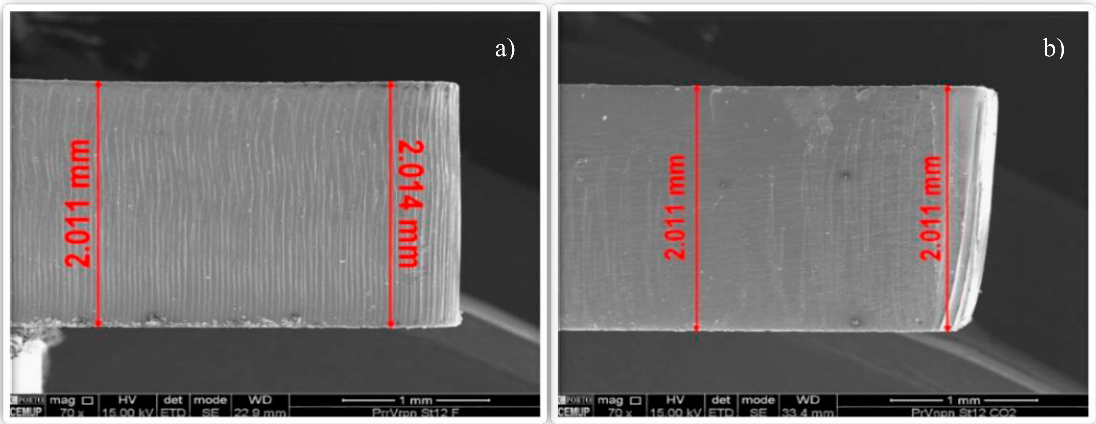

Fig. 3. (a) rough cut surface of the St12 samples; (b) flat cut surface of the St12 samples

The roughness analyses were also performed using SEM, allowing to conclude that:

- The samples of St12 material present the most intense roughness level. This can be explained by the softness of the St12 compared to AISI 316L;
- Figure 3 (a) shows defects such as striations, which contribute to the degradation of the roughness parameters;
- Higher values of cutting speed and radiation power give rise to a lesser roughness.

The average roughness parameter (Ra) is not sufficient for a complete roughness analysis of a surface. Therefore, it was decided to complement the analysis with other parameters, such as the average maximum height of the profile (Rz) and the maximum roughness depth (Rmax). The Mahrsurf® software plots the graphs of the R profile for each sample, as well as provides values for the above-mentioned parameters (Ra, Rz and Rmax). In Figure 4, it is possible to observe the R profile of the sample presented in Figure 3 (a), which gives an idea about the peaks and valleys variations, showing higher peaks due to the striations presented by the cut surface. Eighteen samples of each material were measured, means and deviations are presented in Table 2.

In Table 3, it is possible to view the measured roughness values, corresponding to the sample presented in Figure 3 (a). The values are higher compared to the average, so it indicates that the presence of a high number of striations promotes an increase in roughness. The sample of Figure 3 (a) was cut using parameters below the values recommended by the Laser machine’s manufacturer, i.e., reduced radiation power (Prr) and the reduced cut speed (Vr), promoting a roughness increase.

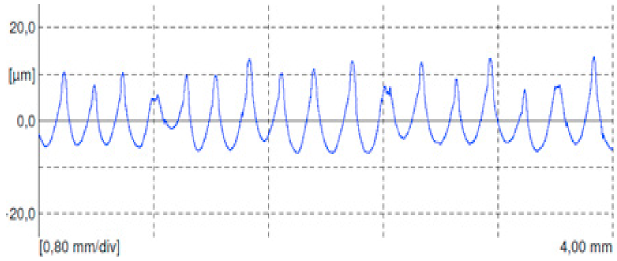

Fig. 4. R profile of a sample with a lot of striations

Table 2. Means and deviations for roughness parameters

Parameter	Mean for Ra (μm)	Standard deviation for Ra (μm)	Mean for Rz (μm)	Standard deviation for Rz (μm)	Mean for Rmax (μm)	Standard deviation for Rmax (μm)
AISI 316L	2,12	±0,35	11,3	±1,83	14,6	±2,56
St12	1,41	±0,36	7,89	±1,78	8,56	±2,08

Table 3. Roughness parameters of the sample presented in Figure 3 (a)

Parameter of roughness	Value (μm)	Average
Ra	3,18 ± 0.28	2,38
Rz	16, 9 ± 2.48	12,7
Rmax	18,4 ± 2.37	15,1

After the levels of burr and roughness have been measured, the corresponding data was explored using Minitab® software in order to use Taguchi methodology allowing the obtention of the best set of laser cutting parameters. Through DOE (Design of Experiments), the values of the burr measurements (μm) and the roughness parameters Ra (μm), Rz (μm) and Rmax (μm) were combined with the values of the laser cutting parameters. The orthogonal table chosen was the L18, which correspond to the eighteen tests performed for each type of material. The S/N ratio provided by Taguchi's analysis (DOE), allows an analysis of the results variation, indicating the best set of parameters, taking into account that the goal is to obtain the best cut surface quality, in this case meaning the lowest burr possible. This ratio reduced noise factors, i.e., uncontrolled factors such as the manufacturing process of the raw material or its inherent imperfections. As in this case the intention it to perform a quality assessment, it is indicated that the category of the S/N ratio must be "the lower, the best", referring to the value of the defect that must be minimized. Unlike the category chosen, the highest value of the S/N ratio is what characterizes the best conditions, because it is the value that less varied, with respect to the expected result, therefore the most appropriate.

In Figure 5, it is possible to see through S/N graph the best set of values for the parameters tested. Thus, like the Taguchi method points out, the highest values in the graph correspond to the parameters which lead to a better quality of the cut surface, taking into account mainly the burr generated and measured, are: 15 bar gas pressure, 10000 mm/min cutting speed and 3500 W radiation power. The same work was done with roughness evaluation.

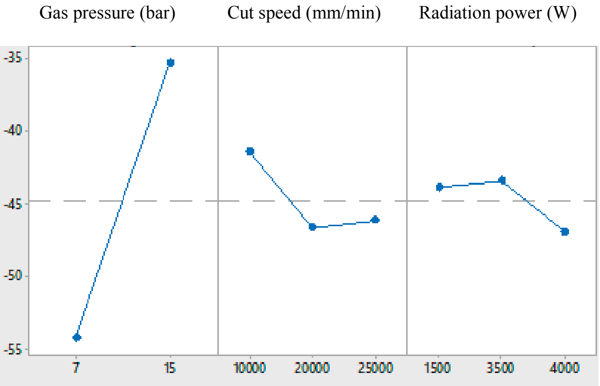

Fig. 5. S/N ratio graph of the best set of parameters for burr measurements

Minitab® software also allowed obtaining an analysis of variance regarding the results obtained. This analysis is important because permits to understand the importance of each parameter in the results obtained for the burr and the roughness, allowing as well to analyse result dispersion. The ANOVA indicates the contribution in percentage of each parameter through the p-value, or probability of significance. If the p-value is farther away to 0.05, the impact of that parameter is stronger relatively to the others. It is still possible to analyse if the test model is appropriate, through the trend line with the correlation coefficient (R^2). The value is between 0% and 100% and the closer it is to 100%, the more reliable the model is. Thus, Table 4 shows that the gas pressure and cut speed are the parameters with the greatest impact on burr and roughness levels, respectively. The models can be considered as reliables because the (R^2) values are very high.

Table 4. ANOVA analysis for the burr and roughness measurements

Parameter	p-value	R^2 (%)
Burr		
Gas pressure	0,001	
Cut speed	0,350	78,57
Radiation power	0,605	
Roughness		
Gas pressure	0,049	
Cut speed	0,002	72,49
Radiation power	0,093	

Table 5 shows the best sets of parameters regarding each variable considered for the quality of the cut surface, as well as the parameter that most impacts each quality factor. Thus, it can be concluded that:

- For AISI 316L and St12, the gas pressure is the parameter with the greatest impact on burr results. This is due to the operating method of the gas pressure, which removes undesired particles created during the laser cutting process, thus reducing the probability of burr creation;
- Cutting speed is the parameter with the greatest impact on roughness results. Lower values of cutting speed produce many grooves, thus higher roughness;
- Analysing both burr and roughness, the radiation power can be reduced (Pr) to the recommended value. Thus, the laser cutting process will be optimized and cheaper, with better cut surface quality;
- Regarding roughness, the cutting speed value must be higher than the recommended value. Regarding the burr, the cutting speed must be slightly reduced (Vr) relatively to the recommended value, but only for the St12 material. However, the recommended (Vn) value should be used for AISI 316L;
- The gas pressure value (pn) recommended by the machine's manufacturer suits perfectly with the goals of this work, allowing very high cut surface quality.

Table 5. Best set of parameters for cutting the two materials

Parameter	Best value for burr	Parameter with the greatest impact on burr	Best value for roughness	Parameter with the greatest impact on roughness
AISI 316L				
Gas pressure	15 (pn)		15 (pn)	
Cut speed	10000 (Vn)	Gas pressure	25000 (Vh)	Cut speed
Radiation power	3500 (Pr)		3500 (Pr)	
St12				
Gas pressure	2,8 (pn)		1,2 (pr)	
Cut speed	2500 (Vr)	Gas pressure	7500 (Vh)	Cut speed
Radiation power	300 (Prr)		700 (Pr)	

5. Conclusions

The main objective of this work was to test and choose the best laser cutting parameters in order to obtain the best quality of the cut surface, optimizing the process. Radiation power, cut speed and gas pressure are the parameters that are most frequently adjusted in order to increase productivity and/or quality. It was confirmed during the tests that engineering can change the values of these parameters and improve the cut surface quality. The tests were made on a recent optical fibre laser equipment, cutting samples of AISI 316L and St12 under different sets of parameters. It was concluded that, at the microstructural level, there are no changes worthy of notating, leading to the conclusion that the temperatures reached during the cutting process were not high enough to promote changes. Using the Taguchi's method, for both burr and roughness assessments, radiation power must be lower than the value recommended by the machine's manufacturer. In general, it was concluded that the cutting speed must be higher. Gas pressure is the only parameter that needs to follow the values recommended by the machine's manufacturer to obtain the best cut surface quality. Thus, it was concluded that the values recommended by the machine's manufacturer are not the optimum to get the best quality because, with less radiation power and higher cutting speed values, the laser cutting process will be optimized, allowing as well the reduction of power consumption and increase in productivity. Therefore, the scientific contribution of this work shows that the values usually indicated as optimal by equipment manufacturers do not always correspond to those that allow to obtain higher quality parts. In addition, it is possible to increase quality and simultaneously improve productivity and sustainability of a process by simply mapping out experiences and analyzing the results accordingly.

References

[1] L. Schaeffer, V. Martins, L. Folle, A. S. Marques, P. R. Böesch, C. Ambrosi, CAD / CAE / CAM programs to reduce losses in sheet, 1st International Conference on Sheet Forming, Brazil October 5-7, 2011. [Online]. http://www.ufrgs.br/ldtm/publicacoes/2012/programas%20cad.pdf. Retrieved on16th of December 2017.

[2] J. Meijer, Laser beam machining (LBM), state of the art and new opportunities, Journal of Materials Processing Technology 149 (1-3) (2004) 2-17.

[3] J. Almeida, Conversion of a manual welding process in automatic welding, Master's Thesis, Department of Mechanical Engineering of University of Oporto, Oporto, Portugal, 2018.

[4] B. Yilbas, Parametric study to improve laser hole drilling process, Journal of Materials Processing Technology 70 (1-3) (1997) 264-273.

[5] C. Karatas, O. Keles, I. Uslan, Y. Usta, Laser cutting of steel sheets: Influence of workpiece thickness and beam waist position on kerf size and stria formation, Journal of Materials Processing Technology 172 (1) (2006) 22-29.

[6] M. Silveira, Effects of copper vapor laser radiation on dentin wall of root canals: in vitro study using scanning electron microscopy and stereoscopic microscope, Master's Dissertation, Faculty of Dentistry, University of São Paulo, São Paulo, Brazil, 2001.

[7] J. DeMaria, V. Hennessey, CO2 Laser, SPIE, 2010. [Online]. Available: https://spie.org/membership/spie-professional-magazine/spie-professional-archives-and-special-content/jan2010-spie-professional/co2-laser?SSO=1. Retrieved on 20th of December 2017.

[8] F. Henrique, Difference between Fiber Laser Cut and CO_2 Laser, Indústria Hoje, 2013. [Online]. Available: https://www.industriahoje.com.br/diferenca-entre-corte-laser-de-fibra-e-laser-de-co2. Retrieved on 22th of December, 2017.

[9] B. Weston, Technology considerations for laser welding tubes and pipes, The fabricator, 2014. [Online]. Available: https://www.thefabricator.com/article/laserwelding/technology-considerations-for-laser-welding-tubes-and-pipes. [Online]. Retrieved on 7th of December 2017.

[10] T. Faro, Study and optimization of the laser cutting of high speed in thin sheet metal, Master's Thesis, Faculty of Engineering of the University of Oporto, Oporto, Portugal, 2006.

[11] G. Costa Rodrigues, H. Vanhove, J. R. Duflou, Direct diode lasers for industrial laser cutting: a performance comparison with conventional fiber and CO_2 technologies, Physics Procedia 56 (2014) 901-908.

[12] J. F. Santos, L. Quintino, R. M. Miranda, Processing of materials by electron beam, laser and water jet, Institute of Welding and Quality, Lisbon, Portugal, 1991.

[13] H. Golnabi, M. Bahar, Investigation of optimum condition in oxygen gas-assisted laser cutting, Optics & Laser Technology 41 (4) (2009) 454-460.

[14] C. Wandera, Research work - Laser cutting os austenitic stainless steel with a high quality laser beam, Master's Thesis, Lappeenranta University of Technology, Lappeenranta, Finnland, 2006.

[15] U. Patel, S. Sanghavi, Parametric Analysis of Process Parameters of Laser Cutting Machine (Mazak Hyper Gear 510) By Using Anova Method On SS 304, Saffrony Institute of Technology, Gujarat, India, 2014.

[16] G. Meszlényi, J. Dobránszky, L. Dévényi, Laser cutting of stainless steel thin sheets with pulsed Nd:YAG laser. Master's Thesis, Budapest University of Technology and Economics, Budapest, Hungary, 2008.

[17] H. Eltawahni, M. Hagino, K. Benyounis, T. Inoue, A. Olabi, Effect of CO_2 laser cutting process parameters on edge quality and operating cost of AISI316L, Optics & Laser Technology 44 (4) (2012) 1068-1082.

[18] P. V. Argade, R. Arakerimath, Parametric Investigations on CO_2 Laser Cutting of AISI 409 to Optimize Process Parameters by Taguchi method, International Journal of Engineering Trends and Technology 37 (6) (2016) 311-316.

[19] V. Senthilkumar, M. Bharath, K. Dhanapal, M. Kumaran, R. Gobinath, Analysis and Optimization of Laser Machining Parameters, International Journal of Innovative Research in Science, Engineering and Technology 5 (2016) 33-40.

[20] M. Grepl, J. Petru, R. Cep, L. Petrkovska, T. Zlamal, The effect of process parameters on result quality of cut during laser cutting of material, 23rd International DAAAM Symposium Croatia October 24-27, 2012. [Online]. http://www.daaam.info/Downloads/Pdfs/proceedings/proceedings_2012/1035_Greplatal.pdf. Retrieved on 10th of December 2017.

[21] V. M. Santos, What is the Six Sigma Taguchi Method (Robust Design)?, FM2S 2017. [Online]. Available: https://www.fm2s.com.br/taguchi-design-robusto-seis-sigma/. Retrieved on 10th of June 2018.

[22] M. Alam, ECE 695A Lecture 35: Design of Experiments, Nano Hub, 2013. [Online]. Available: https://nanohub.org/resources/17671. Retrieved on 10th of June 2018.

[23] P. M. Castro, Academic Work - Taguchi Method: quality control with non-conventional resource to the statistical design of experiences (DOE), Portuguese Institute of Marketing Administration, Lisbon, Portugal, 2015.

[24] V. Sharma, S. Chattopadhyaya, S. Hloch, Surface Quality Finish in Laser Cutting using Taguchi Design. Tehnički vjesnik 24 (1) (2017), 15-19.

[25] J. Tushar, Parameters Optimization of Laser Beam Machine, International Journal of Advance Research, Ideas and Innovations in Technology 3 (2017) 801-809.

[26] M. Madíc, M. Radovanovíc, M. Gostimirovíc, Selection of near optimal laser cutting parameters in CO_2 laser cutting by the Taguchi method, Technical University of Ostrava 59 (2013) 99-107.