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Influence of the CO_2 laser cutting process parameters on the Quadratic Mean Roughness *Rq* of the low carbon steel

M. Boujelbene[a,b,*]

[a]University of Hail, College of Engineering, Hail, Kingdom of Saudi Arabia, KSA
[b]University of Tunis El Manar, Ecole Nationale d'Ingénieurs de Tunis, ENIT, ME, Tunisia

Abstract

High power CO_2 laser cutting of 6 mm thick of the low carbon steel sheets (S235) is investigated with the aim of evaluating the effect of the various laser cutting parameters such as laser power and cutting speed, on the laser cutting quality. In this study, cutting quality was evaluated by measuring the Quadratic mean roughness *Rq* of the machined surface.
A simple and practical model was proposed to predict the Quadratic mean roughness *Rq* as a function of namely parameters; laser power *P*, cutting speed *V* and fixed assistance oxygen flow rate *Q*. The adequacy of the proposed model was tested by Analysis Of Variance (ANOVA). The Experimental data were compared with modeling data to verify the capability of the proposed model. The results indicate that laser power and cutting speed are determinant cutting-parameters on the quadratic mean roughness of the cutting surface. The surface roughness parameter is determined from ANOVA statistical analysis by providing simple analytical model.

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Keywords: Laser cutting, Cutting speed, Laser power, Quadratic mean roughness, ANOVA.

1. Introduction

Laser processing of sheet metals has a wide scope of applications in industry. The high energy focused laser beam provides a fast processing and an excellent precision of the operation. Since the laser processing involves high temperatures gradient depended mainly on laser power, cutting speed, laser beam diameter, pulse frequency and

* Corresponding author. M. Boujelbene
E-mail address: mboujelbene@yahoo.fr

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focus position. This, in turn, causes a generation of thermal stress in the irradiated region. In addition, the high cooling rates contribute to the stress formation in this region. Laser cutting is a thermal cutting process that uses a laser to cut material through the large amount of energy concentrated over a very small surface.

Laser cutting machining has several advantages over conventional methods, in particular in terms of contact without wear, precision, speed, local treatment, reduced thermo-mechanical effects and low cost. It is a complex process that involves several parameters such as laser power, cutting speed and assistance gas flow rate.

Laser beam cutting is an advantageous technology, which allows the reduction of total work times, the increase in production quality added to the simplicity of the operation and a high degree of automation and flexibility. Several investigations have confirmed this process as a very reliable technology. Polypropylene PP, polycarbonate PC, many polymeric, metallic and non-metallic materials are cut by different types of lasers at different operation modes, different gas jet, different powers and of course different laser beam diameter [1-7].

Laser cutting of metallic materials is extensively used as an efficient manufacturing process in industrial applications; automotive, chemical industry, aeronautical and aerospace field. However, internal thermal stresses are developed in the region of the cutting section of the pieces. Depending on the cutting parameters and the substrate material properties, the thermal stress levels can reach very high values and therefore, can influence the microstructure of the cutting surface [8-9]. Due to the heat treatment introduced by the already mentioned high thermal gradient in the substrate material, a very sensitive white layer (WL) on the cutting surface is observed and a heavily changed zone called Heat Affected Zone (HAZ) is occurred just under it [10]. This phenomenon can easily cause damage in that area of the pieces under service conditions.

Alloy laser cutting is more advantageous than conventional methods; we can mention that it's considered as a non-contact cutting-process which means a zero tool wearing, we can also profit from a local treatment coupled with a good precision and a low cost. The presence of certain alloying elements in the matrix alters the thermal resistance of the materials during laser machining [3-6, 11]. Miraoui et al. [9] studied and optimized the effect of CO_2 laser cutting on the cut surface characteristics such as the surface roughness of low carbon steel.

Among them, the surface state of the samples of polypropylene (PP), polycarbonate (PC) and polymathy methacrylate (PMMA) was studied by Choudhury and Shirley [12] who developed a mathematical model of *Ra* reporting firstly, that the effect of the cutting speed and the compressed air pressure is greater than the effect of the laser power on the surface and secondly that the roughness *Ra* decreases with increase the speed, the power and the pressure of the compressed air.

For a comparative study, a detailed parametric analysis was introduced in this work to predict the Quadratic mean roughness *Rq* obtained from the experiment. An optimal combination of the laser power *P*, the cutting speed *V* and the fixed assistance oxygen flow rate *Q* has been made in order to provide the best surface quality.

In the present study, the surface quality which is the Quadratic mean roughness *Rq* developed in the region of the laser cut edges is evaluated and a parametric approach model is used to predict these phenomena due to the variation of the maximum temperature on the surface along the moving direction of the laser heating source with a constant speed along the cut edge. This situation lowers the process quality. Therefore, a comprehensive study becomes essential for the prediction of the *Rq* which is validated through the experimental results.

2. Experimental Procedure

Laser cutting operations for the purpose of the experiment are carried out on structural steel sheet (grade S235 LAC (E24-10037)) in order to produce, with the AMADA FANUC AF 2000C machine, 27 small samples, with dimensions of 30 mm in length, 10 mm in width and 6 mm in thickness. The chemical composition and the basic mechanical proprieties of the low carbon steel S235 samples are given in Tables 1 and 2.

Table 1. Chemical composition of the low carbon steel S235.

Element	(%)
Fe	97
C	< 0.18
P	< 0.05
S	< 0.05
N	< 0.009

Table 2. Mechanical properties of the low carbon steel S235.

Parameter	Value
Ultimate tensile Strength UTS (MPa)	340
Yield strength σ_y (MPa)	235
Elongation A (%)	11
Poisson's ratio	0.3
Modulus of Elasticity E (Gpa)	205

The cutting operations were carried out under the following conditions (Table 3).

Table 3. Main process parameters and their levels.

Factor	Parameters	Unit	Experimental Levels		
			Level 1	Level 2	Level 3
A	Power *P*	(kW)	1	2	3
B	Cutting speed *V*	(mm/min)	600	1400	2200

A Hommel T1000 Mechanical Sensor Roughness tester was used to measure the surface roughness parameter, the quadratic mean roughness *Rq* by indicating that several periodic calibrations were performed to ensure measurement accuracy.

At the end of the experimental part, a statistical analysis method (ANOVA) was used to consider the factor which has a significant effect on roughness. This method presents an uncertainty of 5% in the estimation of the values.

3. Results & discussions

The quadratic mean roughness is the result of the micro-geometric modification of a surface caused by the intensive bombardment of this surface by projectiles while giving roughness as called peaks and cavities called hollows. The roughness of a surface explains adhesion, slippage, rolling, or the sensitivity to wear or corrosion. Quadratic mean roughness or quadratic mean deviation of the profile *Rq*; This is the mean of the absolute values of the deviations, between the peaks and the troughs. It measures the distance between this average and the centre line. It corresponds to the quadratic mean of all the values of the roughness profile *R* calculated over the evaluation length l_m (Fig. 1) and Eq. (1).

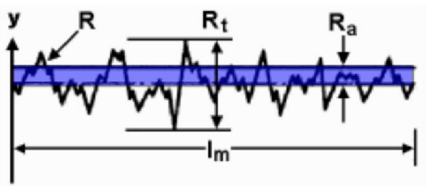

Fig. 1. Roughness profile *R* for the measurement of *Rt*, *Ra* and *Rq*.

$$Rq = \sqrt{\frac{1}{l_m}\int_{x=0}^{x=l_m} y^2(x)dx} \quad (1)$$

3.1. *Effect of cutting parameters on the quadratic mean roughness Rq*

The experimental results obtained by the mechanical probe roughness tester are given in Table 4 which presents the values of the quadratic mean roughness *Rq* as a function of the laser power *P*, and of the cutting speed *V* and with an assist oxygen flow *Q* fixed.

Table 4. The values of the *Rq* as a function of the power *P* and cutting speed *V*.

N°	*V* (mm/min)	*P* (kW)	*Q* (m^3/h)	*Rq* (µm)
1	600	1	0.5	16.65
2	600	2	0.5	15.39
3	600	3	0.5	13.87
4	1400	1	0.5	13.42
5	1400	2	0.5	12.53
6	1400	3	0.5	12.01
7	2200	1	0.5	8.17
8	2200	2	0.5	7.72
9	2200	3	0.5	7.49

The evolutions of the *Rq* values are shown in Fig. 2 as a function of the laser power for three different cutting speeds.

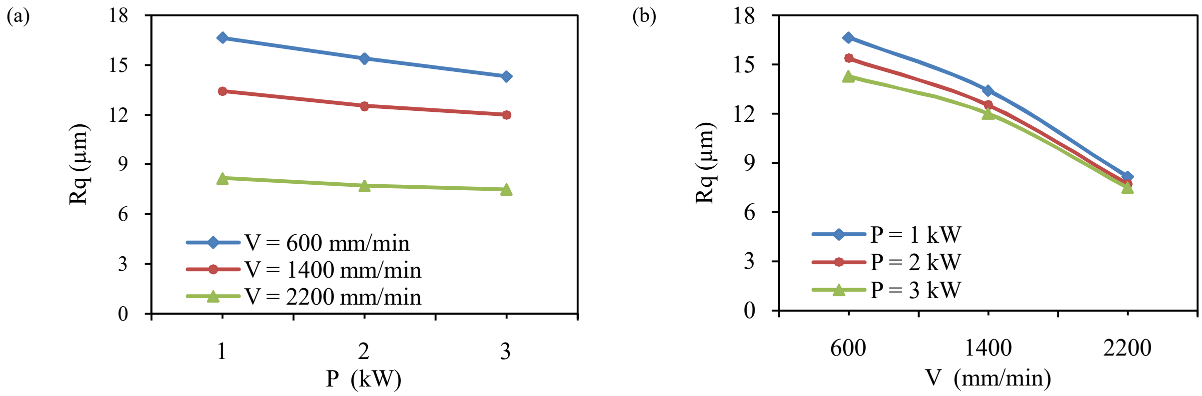

Fig. 2. Evolution of *Rq* values as a function of *P* and *V*; (a) *Rq* = f(*P*), (b) *Rq* = f(*V*).

The result of the study of the surface state shows:

- A slight decrease in the quadratic mean roughness *Rq* with the increase of the laser power. This is due to the heating of the microstructure which becomes more flexible by ensuring a fine cutting and therefore a more rigorous cut surface. These results are in agreement with the results found by Rajaram et al. [13] which show that for the cutting of steel 4130, an increase in power leads to a slight decrease in the surface roughness.
- A remarkable reduction in the quadratic mean roughness *Rq* with the increase in cutting speed, which is in full agreement with the literature of laser cutting CO_2 [14]. This is due to the fact that more than the laser beam passes the surface to be cut out less than it will impact the surface state.
- A slight increase in the quadratic roughness *Rq* with the increase the assistance oxygen flow rate. This is due to the fact that the low carbon steel S235, so it does not require a large oxygen flow, the rest of which tends to damage the cut surface state.

3.2. Experimental design: statistical analysis method ANOVA

The experimental design is a powerful analytical tool for the study and modeling of the influence of process variables, especially a specific variable which is an unknown function of these process variables. In general, the parameters of the roughness will depend mainly on the machining conditions mentioned above. Thus, the complete modeling of the roughness parameters must take into account all the above factors.

In this work, a statistical analysis ANOVA (ANalysis Of VAriance) was carried out for the prediction of the set of roughness assessments that were discussed from the experimental results in the previous sections. According to the ANOVA analysis, a mathematical model was determined for each parameter of the quadratic mean roughness *Rq*.

3.3. Effect of cutting parameters on quadratic mean roughness values Rq

As a first step in the ANOVA analysis, two parameters (the laser power P and the cutting speed V) are chosen as extreme conditions for determining the level matrix. These two parameters are named by following respectively A and B as indicated in Table 5.

Table 5. Level matrix.

Parameters		Min (-1)	Max (+1)
Laser power P (kW)	A	1	3
Cutting speed V (mm/min)	B	600	2200

The effect of the assistance oxygen flow rate Q has been neglected, the introduction of which improves the accuracy of the analytical models, which is already very satisfactory without it, but also tends to complicate the calculations. In the second step, the ANOVA results, which are the coefficients (*df*, *SS* and *MS*) and the calculated and measured Fisher values (F_{test} and $F_{theoretical}$), are shown for the values of Rq in Table 6.

Table 6. Results of ANOVA for the Rq level.

Source of variation	d_f	SS	MS	F_{test}		F_{theo}
A	1	234.872	234.872	1372.850	>	7.71
B	1	566.445	566.445	3674.640	>	7.71
AB	1	0.796	0.796	4.413	<	7.71
Error	4	0.562	0.141			
Total	7	802.675				

The ANOVA method is in agreement with the experimental results of this study since it shows that the effect of the cutting speed V on the roughness is stronger than that of the laser beam power P:
$F_{test}(A) < F_{test}(B)$.

3.4. Analytical model of the roughness Rq as a function of the cutting parameters

To model the quadratic mean roughness values Rq, the Taguchi method is used. The mathematical model depend only on two parameters (A and B) since their interactions were neglected because they are not significant (less than the F_{theo}) and their effects are negligible with respect to A and B.
Thus, the model to be determined can be in the following form Eq. (2):

$$Y = b_0 + \sum b_i X_i \tag{2}$$

In the final step, the determined model can be written as the following Eq. (3):

$$Y = \alpha . A^a . B^b \tag{3}$$

According to the experimental results and the variation of the Rq values as a function of the cutting speed V and the laser power P, the mathematical model of Rq can be determined in the final form as follows Eq. (4):

$$R_q = 435.7\, V^{-0.5111}\ P^{-0.1227} \tag{4}$$

This analysis is a very simple and useful tool for industrial application in order to predict the operational parameters of laser machining and to optimize these values in a short period of time using the analytical equation (4).

4. Conclusions

In present work analyses the quadratic mean roughness characteristic after the laser cutting operations in different test conditions and proposes a parametric approach model via ANOVA. This model to predict the Quadratic mean roughness *Rq* depending on the different experimental test conditions by the means of a simple mathematical model considered as a practical tool.

Confirmatory tests were carried out to verify the adequacy of the model developed for this purpose. The predicted and measured values were compared by verifying the variation in error percentage of the roughness values which was estimated to be around 5%.

It can be concluded that the models are validated and can be used to predict laser CO_2 machining responses within the experimental region of S235 steel.

This work provides detailed information on the effect of the laser cutting parameters (laser power *P*, cutting speed *V*) on the quadratic mean roughness while ensuring the prediction of the different values of *Rq* through simple mathematical model as being a very useful and practical tool for the Laser industry in order to focus first and foremost on the laser cutting process as a function of the quality of the desired surface state of low carbon steel S235.

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