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Effect of laser cutting parameters on surface quality of low carbon steel (S235)

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ABSTRACT

Purpose: This work analysis surface roughness parameters as a function of Laser power and cutting speed. The surface roughness parameters are determined after statistical analysis (ANOVA) and propose a simple mathematical model.

Design/methodology/approach: Machining were carried out by Laser cutting (CO_2) of sheet metal (low carbon steel, S235) produces different surface quality. The statistical processing of the experimental results enabled development of a mathematical model to calculate the cut surface quality according to the cutting parameters used in the present work.

Findings: The prediction of surface roughness values according to the mathematical model are very precisely analysis and determining of surface roughness values is a very practical tool by the experimental design method. It enables a high quality range in analysing experiments and achieving optimal exact values. A rather small experimental data are required to generate useful information and thus develop the predictive equations for surface roughness values as R_a, R_t and R_z. Depending on the surface roughness data provided by the experimental design, a first-order predicting equation has been developed in this paper.

Practical implications: A simple and practical tool was proposed with the experimental design for predicting the surface roughness values as a function of variables of Laser power and cutting speed for a low carbon steel (S235). This type of analysis gives detailed information on the effect of Laser cutting parameters on the surface roughness.

Originality/value: Experimental data was compared with modelling data to verify the adequacy of the model prediction. As shown in this work, the factor of cutting speed the most important influence on the surface roughness.

Keywords: Surface roughness; Experimental design; Laser (CO_2) cutting; Power

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1. Introduction

Laser machining of the alloy has advantages over the conventional methods and some of these advantages include none-mechanical contact without wearing phenomenon, precision of operation, local treatment, and low cost. The presence of certain alloying elements in the matrix alters the thermal resistance of the materials during laser machining [1-8].

In this case, machining defects, such as sideways burning, “Kerf” width variation, and dross attachment occurs at the cut edges, which is particularly true for small thickness work pieces. For this reason, Laser cutting is well known as the reference among other cutting technologies. It has many advantages over conventional machining techniques such as better quality of cuts, quick and accurate cutting. It's a complex process involving parameters such as laser power and cutting speed.

Extensive research studies were carried out to examine Laser processing of metallic alloys [1-18]. Among them, laser cutting of aluminium silicon alloy composite was carried out by Grabowski et al. [1]. They showed that increasing laser beam scanning speed increases the slope of cutting front. They indicated that the technique in which laser was used provided advantages over the conventional cutting technique. Inert gas cutting of thick-section stainless steel and medium-thickness aluminium using a high power fibre laser gas examined by Wandera et al. [3]. Their findings revealed that low surface roughness was achieved with the focal position inside the work piece, which was associated with the wider Kerf for improved melt ejection in thick-section metal cutting. CO_2 laser cutting quality of light alloys specially for aluminium was investigated by Stournaras et al. [4]. They observed the cut quality through measuring Kerf width, edge roughness, and size of the heat affected zone. The influence of laser processing parameters on cut quality for copper and aluminium sheets was examined by Lee and Mazumder and other researchers in literature [2, 4, 5-7]. They predicted and measured penetration time, penetration depth, and threshold power for laser cutting. Yilbas et al. [6] studied laser cutting of 7050 Aluminium alloy with presence of Al_2O_3 and B_4C in the alloy matrix. They showed that aluminium alloy reinforced with 20% Al_2O_3 resulted in relatively large Kerf width size as compared to that corresponding to 7050 aluminium alloy reinforced with 20% B_4C. Femtosecond laser cutting of alumina tiles were examined by Wang and other researchers. [7, 14-18]. They presented the influence of laser parameters on Kerf width, taper, cleanliness of cut edges and delamination.

In the present study, influence of laser output power was evaluated on the on surface quality of low carbon steel (S235) (roughness, damage such as burning etc.).

For a comparative study, a detail parametric analysis was introduced to predict the R_a, R_t and R_z obtained from the experiment. An optimum combination between cutting speed and the laser power was made in order provide the maximum of quality.

2. Experimental conditions

Machining operations for testing requirements are performed on the steel sheets (grade S235 GF (E24-10037)) to take small specimens with the sizes of 30 mm long and 15 mm in width and thickness of 8 mm. Chemical composition of the steel sheets are given in Table 1. For the laser cutting operations, Type AMADA AS 4000 E /CO_2 laser cutting machine was used for the cutting of the specimens (S235). Cutting operations were conducted in the following conditions:

- variable cutting speeds applied: 600, 1200 and 2200 m/min,
- variable of cutting power applied: 3, 4 and 5 KW.

Table 1.
Chemical composition of steel S235 (E 24)

Elements	C	P	S	N
Composition, %	< 0 .18	< 0.05	< 0.05	< 0.009

Two different devices for surface analysis are used for the measurement of the roughness of the specimens after the cutting: A Surface scan 3S-"Somicronic" which gives the surface profile (roughness) in 2D and a 3D-Optical roughness meter work with the an optical sensor without contact. To avoid errors in recovery and for more precision, measurement of the roughness was conducted directly on the machine without disassembly of the specimens. Microhardness test were made on the metallographic specimens (mounted and polished and etched) to evaluate the hardness evolution from the cutting surface to the centre of the specimens. Microstructural evolution near – under the cutting surface were made with an optical microscope and detail analysis in the structure such as White Layer Thickness, surface roughness etc. has been carried out by Scanning Electron Microscope due to heat treatment during cutting operations.

At the end of experimental part, a statistical method (ANOVA) was used to consider what factor has a significant effect on the roughness. This method has a gap that gives estimation value with an error 5%.

3. Results and discussions

3.1. Geometric characteristics of surface roughness by CO_2 laser cutting

Laser cutting (CO_2) of sheet metal is an economically feasible method of production through advances in technology. It works directly with the output of a high-power laser, by computer, at the material to be cut. The material then either melts, burns, vaporizes away, or is blown away by a jet of gas leaving an edge with a high-quality surface finish. Industrial laser cutters are used to cut flat-sheet material as well as structural and piping materials. Laser cutting operations generally produce regular patterns in the cut surface, known as striations. The severity of frequency and amplitude of these striations has a direct impact on surface quality.

To investigate the surface quality, we choose to analyse the mean roughness, or the arithmetical roughness R_a, which is shown as:

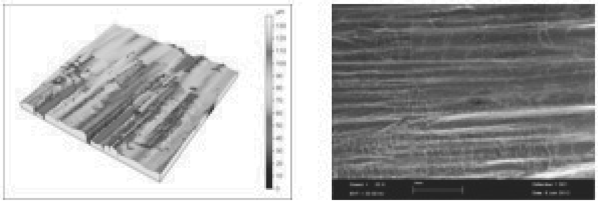
$$Ra = \frac{1}{L}\int_0^L \left|z(x)dx\right| \tag{1}$$

where *Z (x)* is the value of the roughness profile and *L* is the evaluation length.

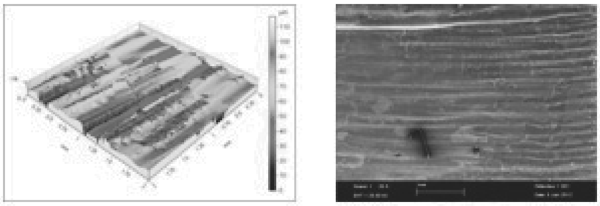
Roughness is defined as minor and periodically repeated disorders on the surface of materials, excluding shape and undulation faults.

The characteristic morphology of a surface that has undergone laser cutting is due to the enormous amount of heat generated by the discharges, which causes melting and vaporisation of the material, followed by rapid cooling. In general way, the surface topography-profile reveals that the arithmetical roughness R_a rises up when the Laser energy increases. In the frame of this paper, R_a, R_t and R_z values will be evaluated depending on two test conditions; power and cutting test

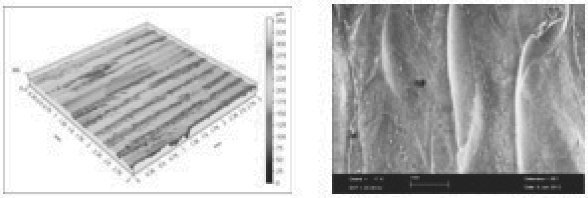
At the first stage, direct measurements of surface roughness parameters are determined as shown in Figure 1. This picture clearly indicated by the three-dimensional roughness profile, where the peaks appear as striations depending on the two basic test parameters, power and cutting speed considered here in the present work.



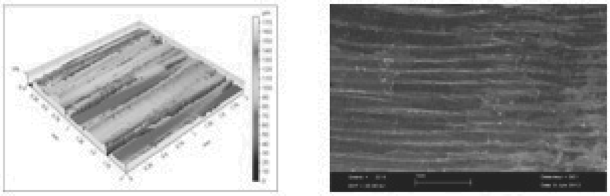
P=3; V=600



P=3; V=1200



P=4 ; V=600



P=4 ; V=1200

Fig. 1. Variation of Surface roughness as a function cutting parameters (power and cutting speed): 3D roughness meter and Scanning Electron Microscopy, SEM

3.2. Effect of cutting parameters on the surface roughness values: R_a, R_z and R_t

Experimental results obtained by optical 3D roughness meter are given in Table 2 for mean roughness, or the arithmetical roughness (R_a) values depending on the laser power used in this paper. All of the values are classified as a function of the cutting speed.

Table 2.
Surface roughness values (R_a) depending on power

		V=600, mm/min	V=1200, mm/min	V=2200, mm/min
Specimen, N°	Power, KW	R_a, µm	R_a, µm	R_a, µm
1	3	86.88	12	11.47
10	4	72.89	17.82	14.34
19	5	67.62	13.19	46.11

Evolution of R_a values are shown in Figure 2 as a function of the laser power for three different cutting speeds. Most considerable evolution of R_a values occurred with the low cutting speed (600 mm/min). A very keen decrease in R_a values are observed in high power applications in this cut speed.

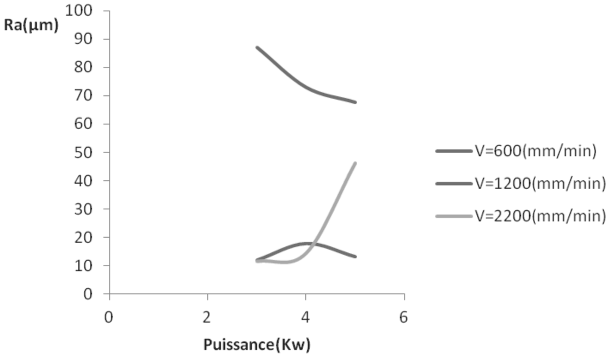


Fig. 2. Evolution of R_a values depending on Laser power for three cutting speed

However, in the highest cutting speed (2200 mm/min) of R_a values increases very fast depending on the power. For the cutting speed for 1200 mm/min, R_a values are quasi constant with variable of the power.

Experimental results obtained by optical 3D roughness meter are given in Table 3 for R_z values depending on the laser powers. All of the values are classified as a function of the three different cutting speeds.

Evolution of R_z values are shown in Figure 3 as a function of the laser power for three different cutting speeds. Similar evolutions are observed for R_z values as observed in case of mean roughness values. Most considerable evolution of R_z values occurred with the low cutting speed (600 mm/min). A very keen decrease in R_z values are observed in high power applications in this cut speed but after a power value of 4 KW, R_z value is constant.

Table 3.
Surface roughness values (R_z) depending on power

		V=600, mm/min	V=1200, mm/min	V=2200, mm/min
Specimen, N°	Power, KW	R_z, μm	R_z, μm	R_z, μm
1	3	140.242	35.38133	35.306
10	4	69.296	45.938666	41.583
19	5	62.128	34.991666	52.476

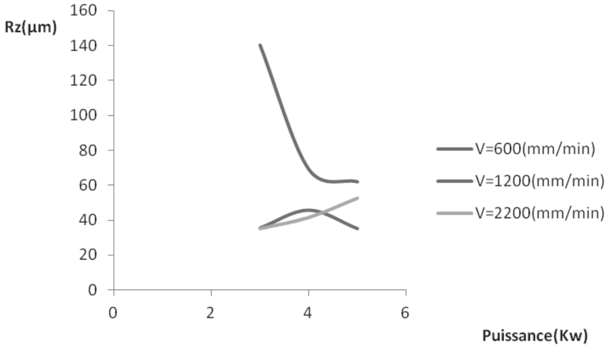


Fig. 3. Evolution of R_z values depending on Laser power for three cutting speed

However, in the highest cutting speed (2200 mm/min) of R_z values increase weakly depending on the power. Again, for the cutting speed for 1200 mm/min, R_z values are quasi constant with variable of the power.

Experimental results obtained by optical 3D roughness meter are given in Table 4 for R_t values depending on the Laser powers. All of the values are classified as a function of the three different cutting speeds.

Table 4.
Surface roughness values (R_t) depending on power

		V=600, mm/min	V=1200, mm/min	V=2200, mm/min
Specimen N°	Power, KW	R_t, μm	R_t, μm	R_t, μm
1	3	387.72	58.84	60.33
10	4	382.38	103.96	67.749
19	5	350.37	82.38	235.67

Also, evolution of R_t values are shown in Figure 4 as a function of the Laser power for three different cutting speeds. Evolutions of R_t values in the highest cutting speed (2200 mm/min) are very similar as observed in case of the R_a measured roughness values (Figure 2). A very fast increment in R_a values is observed with increasing of applied power. Variations of R_t values occurred with the low and medium cutting speeds (600 mm/min and 1200 mm/min respectively) are not so significant.

To predict these values according the experimental values very simply and practical applications, it will be useful for an application of statistical (ANOVA) method as will be considered in the next section.

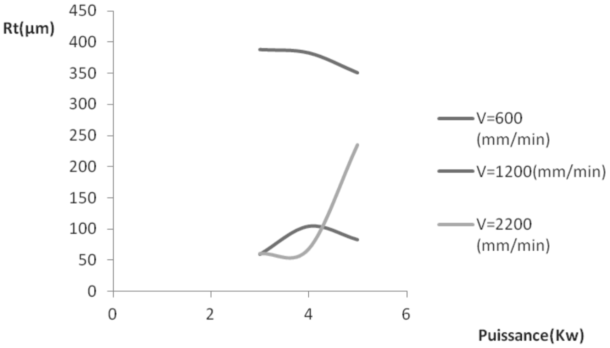


Fig. 4. Evolution of R_t values depending on Laser power for three cutting speed

Similar analysis of the experimental measurements obtained for R_a, R_z and R_t values are made this time as function of the cutting speed for three different Laser powers.

First evaluation was made for R_a values (Table 5). Considerable variations are observed at the highest power (5 KW) applications. It decreases very fast and shows a minimum at 1200 mm/min. However, in case of lower and medium power levels (3 and 4 KW), variations of R_a values show the same evolutions (Figure 5); they decrease up to the level of 1200 mm/min after that they do not change the slope (they are quasi constant).

Table 5.
Surface roughness values (R_a) depending on cut speed

		P=3 Kw	P=4 Kw	P=5 KW
Specimen, N°	Cutting speed, mm/min	R_a, μm	R_a, μm	R_a, μm
1	600	27.32	49.46	67.62
10	1200	12	17.82	13.81
19	2200	8.29	14.34	46.11

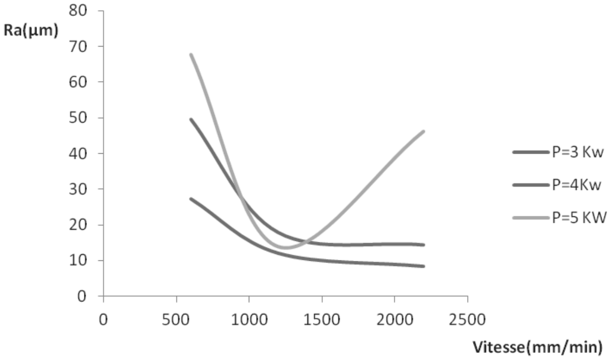


Fig. 5. Evolution of R_a values depending on cutting speed for three different laser powers

Second evaluation was made for the R_t values (Table 6). Very similar evolution as R_a values for all of the power levels. Evidently, the level of R_t values are always higher than that of R_a values.

Table 6.
Surface roughness values (R_t) depending on cut speed

		P=3 KW	P=4 KW	P=5 KW
Specimen, N°	Cutting speed, mm/min	R_t, µm	R_t, µm	R_t, µm
1	600	105	245.27	350.13
10	1200	58.84	103.96	82.38
19	2200	50.52	67.74	235.67

In the same way, these values are indicated in Figure 6 that can give the same slopes for all the power levels as shown for R_a values in Figure 5 just above here.

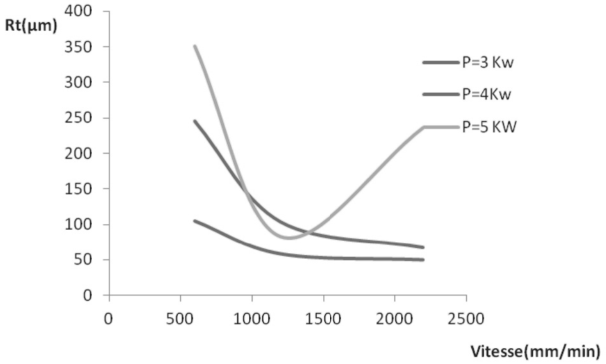


Fig. 6. Evolution of R_t values depending on cutting speed for three different laser powers

Table 7.
Surface roughness values (R_z) depending on cut speed

		P=3 KW	P=4 KW	P=5 KW
Specimen N°	Cutting speed, mm/min	R_z, µm	R_z, µm	R_z, µm
1	600	73.26	87.44	350.13
10	1200	35.38	45.93	82.38
19	2200	30.63	41.58	235.67

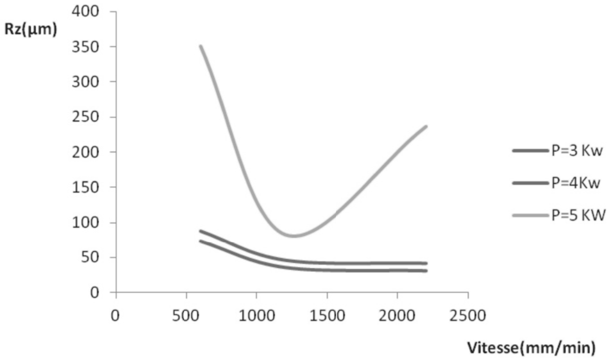


Fig. 7. Evolution of R_z values depending on cutting speed for three different laser powers

Last evaluation was made for the measured R_z values and the results were given in Table 7 and evolution of the R_z values as a function of cutting speed are indicated in Figure 7 for the three different power levels.

Only two power levels (3 and 4 KW) have shown very close evolutions; they decrease with a weak slope. Again, the highest power level (5 KW) has given a considerable variation: it decreases very fast and shows a minimum at 1200 mm/min.

All of the roughness measurements have shown that R_a values are always smaller than that of two other roughness values (R_t, and R_z) again for all measurements, R_t values show always the highest values for the different power and cutting speed conditions.

4. Experimental design: statistical analysis (ANOVA method)

Experimental design is a powerful analysis tool for modelling and analysing the influence of process variables on a specific variable, which is an unknown function of these process variables [10-15]. In general, the roughness parameters will mainly depend on the manufacturing conditions mentioned above. Thus, complete modelling of these roughness parameters should take into account all the previous factors.

In the frame of the present work, a statistical analysis (ANOVA) has been carried out for the prediction of all of the roughness evaluations discussed the experimental results in the former sections. According to ANOVA analysis a mathematical model was determined for each roughness value.

4.1. Effect of cutting parameters on the surface roughness values: R_a, R_t and R_z

At the first stage of the ANOVA analysis, two parameters (power and cutting speed) were chosen as two extreme conditions to determine the size of matrix established. These two parameters are called here after A and B respectively as shown in Table 8.

Table 8.
Size (level) of Matrix

Parameters		Min (-1)	Max (+1)
Cutting speed, mm/min	A	600	2200
Power, W	B	3000	5000

At the second stage, ANOVA results are indicated for R_a value in Table 9; all of the coefficients and F values obtained by measurement and calculation are also given in the same table (last two columns).

The same evaluations were also made for R_z and R_t values and ANOVA results are summarized in Tables 10 and 11 respectively.

Table 9.
ANOVA results for the size of R_a

Variables	d_f	SS	MS	F_{test}	$F_{theoretical}$
A	1	135.41	135.41	6770.57	7.71
B	1	8290.25	8290.25	414512.54	7.71
AB	1	243.44	243.44	12172	7.71
Error	4	0.08	0.02		
TOTAL	7	8669.18			

Table 10.
ANOVA results for the size of R_z

Variables	d_f	SS	MS	F_{test}	$F_{theoretical}$
A	1	2622.30	2622.30	131115.2	7.71
B	1	7946.02	7946.02	397301.2	7.71
AB	1	3511.91	3511.91	175595.92	7.71
Error	4	0.08	0.02		
TOTAL	7	14080.32			

Table 11.
ANOVA results for the size of R_t

Variables	d_f	SS	MS	F_{test}	$F_{theoretical}$
A	1	165.82	165.82	8291.0768	7.71
B	1	178692.14	178692.14	8934607.3	7.71
AB	1	1622.20	1622.20	81110.27	7.71
Error	4	0.08	0.02		
TOTAL	7	180480.25			

4.2. Determination of mathematical model for R_a, R_z and R_t values

The functional relationship between response (surface roughness) of the cutting operation and the investigated independent variables can be represented by the following way:
For modelling the surface roughness values (R_a, R_z and R_t), the Taguchi method has been used.

One may note that to determine the mathematical models, only two parameters (A and B) and their interactions were neglected because they are non significant and also their effects are negligible regarding to A and B.

Thus the model that will be determined can be form as the following;

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

X_i value can be replaced by their values as a function of x_i.

In final stage, the determined model can be written as the following form;

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

According to the experimental results, the variation of R_a values depending on the cutting speed and power, Mathematical model can be determined in final shape as the following:

$$R_a = 6.8783.10^6 .\ V^{-0.0312} . P^{-1.37752} \tag{4}$$

In the same way, mathematical models for the values of R_z and R_t can be determined respectively in the final shape as the following:

$$R_z = 1.725.10^{27} . V^{-6.5071} . P^{-0.6907} \tag{5}$$

$$R_t = 3.29632.10^5 . V^{-0.1726} . P^{-1.2851} \tag{6}$$

This type of analysis is very simple and useful tool for industrial application to predict the operational parameters and optimise these values in a short time with these analytic equations.

5. Conclusions

The present work analyses the surface quality (roughness) after the laser cutting operations in different test conditions and also predicts the surface roughness values with a simple mathematical model as a practical tool.

The experimental results can be used in industry to select the most suitable parameter combination for obtaining required surface roughness values for products. One may consider that the cutting parameters used here play an important role on surface roughness values, R_a, R_z and R_t.

Confirmation runs were performed to check the adequacy of the developed model. The predicted and measured values from confirmation runs were compared by checking the variation in the percentage error. The variation in percentage errors for the roughness values were estimated around 5%. It can be concluded that the models are valid and can be used to predict the machining responses within the experimental region.

Acknowledgements

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