THE INFLUENCE OF SOME INPUT FACTORS IN THE LASER BEAM CUTTING PROCESS ON THE SURFACE ROUGHNESS

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ABSTRACT: Laser beam cutting of metallic workpieces is a frequently used process nowadays, due to the possibilities of cutting according to predetermined contours and the relatively small size of the slit width resulting from cutting. The heights of surface asperities resulting from cutting depend on the values of some input factors in the cutting process. To obtain more information on the influence of some input factors in the laser beam cutting process on the surface roughness achieved by laser beam cutting, experiments were carried out in which the values of the laser beam power, cutting speed, gas pressure, and pulse frequency, respectively, were changed. The experimental results were mathematically processed, being established empirical mathematical models capable of highlighting the direction and intensity of the influence exerted by the input factors considered on the value of the roughness parameter *Ra*, for the two distinct areas of the surface resulting from laser beam cutting. If in the case of the area of penetration of the laser beam into the test sample, the factor with the greatest influence is the power of the laser beam, in the case of the surface through which the beam exits the test sample, the greatest influence is exerted by the frequency of the laser pulses.

KEYWORDS: laser beam cutting, surface roughness, beam power, cutting speed, gas pressure, laser pulse frequency, empirical mathematical model

1. INTRODUCTION

In industrial practice, the problem of separating a part from a workpiece in the form of a plate sometimes arises. In such a situation, contour-cutting procedures can be applied using a punch that makes small diameter holes arranged along the contour of the part, or such holes are made using part a drill. Later, by pressing the part and possibly using a chisel, the part is separated from the workpiece in the form of a plate or sheet. After separation, some additional processing is needed to bring the surface corresponding to the contour to a shape as close as possible to the final part shape. Also, to make the previously mentioned holes, it may be necessary to trace the outline to be obtained for the part. However, there are also some non-conventional processes, such as cutting using plasma, water jet, or laser beam, through which it is possible to significantly reduce the volume of processing after of separating the part from the workpiece in the form of a plate. It turns out to be very convenient, from the point of view of processing material removal rate, of reducing the volume of post-processing operations, but also of the accuracy of the surface achieved by cutting, the use of equipment supplied with numerical control systems.

It is known that using the laser beam to separate a part from a workpiece in the form of a plate provides some advantages, such as the relatively high material removal rate of the process, the reduction of the thermally affected area of the material, the generation of a slit of reduced width, etc. and such advantages lead to the existence, currently, in industrial companies, of some laser beam cutting equipment [1-6].

In some situations, it may be of interest to find by cutting some surfaces characterized by low values of the heights of asperities generated by laser beam cutting. It is known that, by cutting with a laser beam, it is possible to obtain a surface on which it can be observed with relative ease two areas, one in which somewhat parallel grooves are observed, initially rectilinear and ending in a reverse curvature the that of the work movement when cutting and, respectively, an area where also grooves are no longer visible.

The two areas are characterized by different values of the roughness parameters that take into account the heights of the asperities.

The study of roughness parameter values in laser beam cutting has been a concern for different researchers.

Thus, Radovanovic and Dassik highlighted the presence of the two areas characterized by different surface roughness obtained by laser beam cutting [7].

In another work, Radovanović and Dašić present the results of experimental research on the values of the roughness parameters in the case of laser cutting, establishing empirical mathematical models of the power-type function and highlighting the influence exerted on the values of some roughness parameters such are the power of the laser beam, the thickness of the workpiece and the cutting speed [8].

In a review article regarding the quality of surfaces obtained by laser beam cutting, Radovanovic and Madic noted the consideration, by different researchers, of the possibilities of creating surfaces characterized by low values of roughness parameters [9].

By mathematically processing the results of some 15 experimental tests, Noor et al. have established mathematical models of the first-degree polynomial and second-degree polynomial, respectively, to reveal the influence exerted by the power of the laser equipment, by the cutting speed and the tip distance on the roughness parameter *Ra* when cutting acrylic sheets with a laser beam [10].

Madic et al. addressed the problem of optimizing the CO_2 laser cutting process from the point of view of the roughness of the cut surface [11]. They considered the use of some quality characteristics expressed with the help of an empirical mathematical model of the second-degree polynomial type, using these characteristics to determine the values of the roughness parameters *Ra* and *Rz*.

The problem addressed in the present paper was that of determining an empirical mathematical model that highlights the intensity of the influence exerted by some input factors in the laser beam cutting process on the value of the roughness parameter *Ra*. For this purpose, an analysis of the laser beam cutting conditions allowed the identification of some factors and groups of factors able to exert influence on the heights of asperities on the surface resulting from the use of the mentioned cutting process. Later, experimental research was carried out for which, by processing the results, it was possible to identify some empirical mathematical models following the objective pursued.

2. INITIAL LASER BEAM CUTTING CONSIDERATIONS

The concept of laser refers to a beam of electromagnetic radiation having a wavelength between certain limits, as well as some particular properties, such as coherence, directivity, and monochromaticity. To be able to carry out some laser beam processing processes, a sufficiently high intensity of the beam is also required. Laser beam processing is based on the thermal and chemical effects that take place in the contact zone between a high-energy laser beam and the surface of the workpiece.

The materialization of a laser beam cutting process (Fig. 1) implies the existence of a relative displacement, according to predetermined trajectories, between the laser beam and the workpiece. Under the action of the heat released in the area of the workpiece affected by the action of the laser beam, there is a rapid increase in temperature, up to values at which the material of the workpiece melts or even evaporates. In the case of laser beam cutting, but also of other laser beam machining processes, which involve the removal of material from the workpiece (for example, in the case of laser beam drilling), it is usually necessary to send, along a direction that coincides with the direction of the beam and coaxial with it, of a assist gas jet. If the gas used is oxygen or atmospheric air, a burning reaction of the workpiece material may develop, which may contribute to an increase in the rate of material removal from the workpiece. The assist gas jet still provides conditions for more efficient removal of the molten and vaporized material and thus contributes significantly to the generation of walls specific to laser beam cutting (Fig. 2). The material of the workpiece affected by the thermal action of the presence of the laser beam will have a modified structure, so there is a thermally affected area.

In an axial section through the laser beam, a normal power distribution can be highlighted (Fig. 3).

In the exit zone of the laser beam from the workpiece, for certain values of the parameters that characterize the cutting conditions, part of the melted material can adhere to the surface of the workpiece, forming a so-called burr. The presence of the burr requires the application of subsequent mechanical processing operations, thus contributing to an increase in the cost of processing.

As previously mentioned, the use of the gas that assists the laser beam cutting process has a determining role in the formation of the surfaces

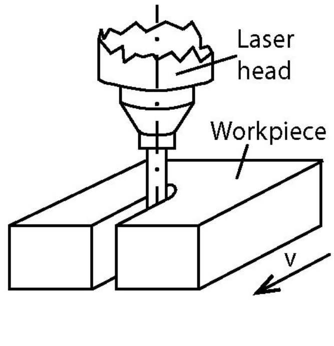

Figure 1. Schematic representation of the laser beam cutting process

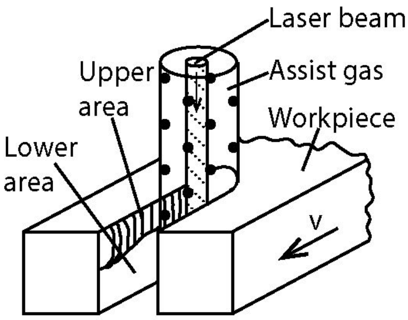

Figure 2. The generation of two areas with different roughness on the surface resulting from laser beam cutting

generated by the cutting. Thus, in the area of penetration of the gas jet into the workpiece (the upper area of the cut), grooves with an initial rectilinear shape and later slightly curvilinear shape can be observed on the surface resulting from the cut (fig. 2). In the case of workpieces with greater thicknesses, the area with a distinct appearance of the surface resulting from laser cutting (the grooved area) continues with an area where particles of molten material that have adhered to the surface of the workpiece can be observed. Obviously, the two areas specific to laser beam cutting of thicker plates will be characterized by distinct values of the surface roughness parameters generated by the cutting process.

To characterize the roughness of a surface, in the field of machine manufacturing, parameters which are used that are grouped into 5 categories:

1. Amplitude parameters, which take into account aspects related to the prominence and valley corresponding to the profile obtained in a section perpendicular to the analyzed surface;

2. Amplitude parameters, which take into account the average values of the profile ordinates;

3. Step parameters;

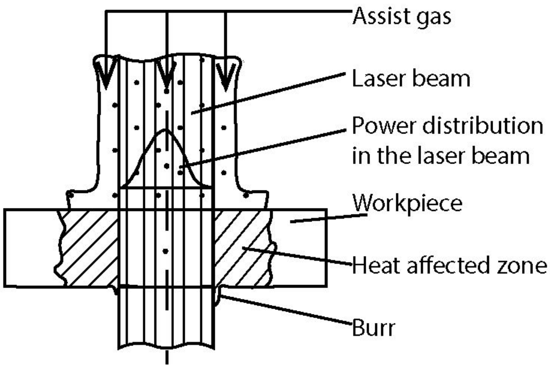

Figure 3. Contribution of the assist gas jet to the removal of the material and the appearance of the burr when laser beam cutting

4. Hybrid parameters;

5. Parameters associated with certain categories of curves.

Currently, the most common parameter and for which values are prescribed on the mechanical drawing of a part is a parameter from the second group, namely the *average arithmetic deviation Ra* of the assessed profile. The value of this parameter is calculated as an arithmetic mean of the values corresponding to the ordinates of the points that make up the profile, within the limits of a so-called *base length*.

Several factors and groups of factors can influence the value of the roughness parameter *Ra* corresponding to a surface generated by laser beam cutting;

1. The nature and some thermal properties of the semi-finished material;

2. The thickness of the workpiece;

3. Some characteristics of the laser beam (beam power, wavelength, beam divergence angle, pulse frequency in the case of a pulsed laser, laser spot shape, etc.);

4. The nature and some characteristics of the gas jet sent along the laser beam (the shape of the jet in a cross-section, the gas flow rate, etc.);

5. Parameters characterizing the laser beam cutting conditions (the distance between the front surface of the nozzle through which the laser beam exits into the atmosphere and the surface of the workpiece, the angle of inclination of the surface through which the laser beam penetrates the material of the workpiece, cutting speed, etc.).

As *output parameters* of the laser beam cutting process (parameters of technological interest), it can mention the maximum cutting speed at which an acceptable quality of the surfaces resulting from cutting is ensured, the values of some surface roughness parameters, the thickness of the heat affected zone, the heights of the burrs generated when the laser beam exits the workpiece, etc.

It should be noted that laser beam cutting generates several adverse effects from the point of view of environmental protection, and it is necessary to take appropriate measures to minimize these effects.

3. EXPERIMENTAL CONDITIONS AND RESULTS

It was aimed to determine some empirical mathematical models that would provide information regarding the direction and intensity of the influence exerted by some input factors in the laser beam cutting process on the heights of asperities on the surface generated by cutting. The experimental tests were performed on C15 steel test samples.

A Tianqi Nd: YAG laser, model 3015 (manufactured by the Chinese company Wuhan Tianqi Laser Equipment Manufacturing Co., Ltd.) was used for cutting. As the active medium, this equipment uses a bar of neodymium-doped yttrium garnet. The wavelength of the radiation emitted by the active medium is 1064 nm. The equipment provides an adjustable beam power, with values between 520 and 580 W, a cutting speed with values of 2-10 mm/s, a frequency of laser pulses of 110-180 Hz, and a gas pressure of 30 000-50 000 Pa. The thickness of the workpiece that can be cut with a laser beam has values of 0.2-8 mm. It can therefore be noted that the equipment allows the use of different values of the parameters characterizing the cutting conditions.

By considering the technological possibilities of the equipment, the power N developed by the laser beam, the relative speed v between the beam and the workpiece, the pressure p of the assist gas and, respectively, the frequency f of the laser pulses were taken into account as input factors. Three values of each of the previously mentioned input factors were used. These values are listed in columns 2-5 of Table 1. The value of the roughness parameter *Ra* was the output parameter considered. The measurements were performed using a Mitutoyo SJ-201P roughness meter.

Three measurements of the roughness parameter *Ra* were performed both in the upper area of the surface resulting from cutting and in the lower area of that surface. For the determination of the empirical mathematical models, averages of the values determined for each surface resulting from the use of certain values of the parameters characterizing the cutting conditions were taken into account.

4. MATHEMATICAL PROCESSING OF EXPERIMENTAL RESULTS

The experimental results included in Table 1 were mathematically processed using specialized software based on the least squares method [13]. The software provides conditions for selecting the most appropriate empirical mathematical model from five types of such models (first-degree polynomial, second-degree polynomial, power type function, exponential function, hyperbolic function). The selection of the most appropriate empirical mathematical model takes place by considering the value of the so-called *Gauss criterion* [13-15]. This value is determined as a ratio in which the numerator is calculated as a sum of the squares of the differences between the values determined by using a certain empirical mathematical model and the ordinate values corresponding to the experimental results. The denominator of the ratio corresponds to a difference between the number of experimental tests and the number of constants in the proposed empirical mathematical model.

The lower the value of Gauss's criterion, the more it is appreciated that the proposed empirical mathematical model is more appropriate for the obtained experimental results.

In the case of the experimental results in Table 1, their mathematical processing led to the conclusion that the most appropriate mathematical models are:

- For the upper area of the surface resulting from laser beam cutting:

$$\boldsymbol{Ra = 13.657 - 0.00686N + 0.0000161N^2 - 0.389v + 0.0209v^2 - 0.000173p + 0.00000000182p^2 - 0.115f + 0.000598f^2}, \quad (1)$$

the value of Gauss' criterion being, in this case, S_G=2.085729·10^{-7};

- For the lower area of the surface:

Table 1. Experimental conditions and results

Exp. no.	**Input factors**				**Output parameter: roughness parameter Ra, µm**							
					In the upper area				In the lower area			
	Power *N*, W	Cutting speed, *v*, mm/s	Gas pressure, *p*, Pa	Pulse frequency, *f*, Hz	*Ra*1	*Ra*2	*Ra*3	Average value *Ras*	*Ra*4	*Ra*5	*Ra*6	Average value, *Rai*
1	520	4	30000	120	2.95	3.26	3.25	3.15	3.27	4.24	3.69	3.73
2	520	6	40000	140	3.12	3.04	1.87	2.67	6.99	7.52	7.24	7.25
3	520	8	50000	160	3.16	2.76	3.47	3.13	5.93	6.20	6.77	6.3
4	550	4	40000	160	4.27	4.12	3.88	4.09	8.02	6.44	6.77	7.07
5	550	6	50000	120	2.92	2.65	2.09	2.55	4.26	4.82	4.32	4.46
6	550	8	30000	140	3.74	3.34	2.67	3.25	7.51	6.97	5.05	6.51
7	580	4	50000	140	3.78	3.65	3.34	3.59	6.18	5.81	5.22	5.73
8	580	6	30000	160	4.16	4.77	4.68	4.53	6.70	5.73	6.97	6.46

$$Ra = -65.492 + 0.0140N - 0.00000538N^2 + 0.465v - 0.0183v^2 + 0.00114p - 0.0000000142p^2 + 0.558f - 0.00184f^2, \quad (2)$$

in this case, the value of Gauss's criterion being S_G=1.08513·10-5.

In the field of machining in the manufacturing of machines, however, mathematical models of the power function type are frequently used, since such models directly provide information on the direction and intensity of the influence exerted by the input factors on the size of the output parameters of the investigated process. It is worth noting, however, that when such models are not the ones that lead to a minimum value of Gauss's criterion, they can also lead to less adequate information, since power-type functions are monotonic functions, so functions that cannot highlight the existence of maxima or minima of the dependent variable (of the output parameter) to the values of the independent variables (of the input factors) corresponding to the investigated process.

In the case of laser beam cutting, the power functions were as follows:

- For the upper area of the surface resulting from cutting:

$$Ra = 0.0000236N^{1.623}v^{-0.245}p^{-0.322}f^{1.10}, \quad (3)$$

in which case Gauss's criterion has the value S_G=0.0260434;

- For the lower area of the surface:

$$Ra = 0.000708N^{0.132}v^{0.135}p^{0.0407}f^{1.517}, \quad (4)$$

the Gauss criterion having, in this case, the value S_G= SG=0.9125687.

By considering equations (1) and (3), the graphical representations included in Figures 4, 5, and 6 were developed. The analysis of these graphical representations and the empirical mathematical models determined allowed the following observations to be formulated.

The analysis of power-type function mathematical models and graphical representations allows us to state that in the case of the upper area of the surface resulting from laser beam cutting, the strongest influence is exerted by the power *N* of the laser beam, followed by the frequency *f* of the laser pulses. In the determined power-type function mathematical models, these factors were assigned the largest exponent values. Increasing the mentioned input factors increases the value of the roughness parameter *Ra*. In the case of the lower area of the surface resulting from laser beam cutting, it is found that the greatest influence is exerted by the frequency *f* of the laser pulses, followed by the cutting speed *v* and the power *N* of the laser.

The increase in the value of the roughness parameter *Ra* when the power *N* of the laser beam increases can be explained by a more intense action of melting the material of the workpiece when the power *N* of the laser beam increases. The statement is especially valid in the upper area of the surface resulting from laser beam cutting. For the range used to change the frequency *f* of the laser beam, it can be considered that an increase in the frequency results in a more intense transfer of energy to the material of the workpiece, which could also lead to an increase in the value of the roughness parameter *Ra*.

It can still be observed that in the lower area of the surface resulting from laser cutting, i.e., where the assist gas jet pressure *p* could exert less influence, the value of the exponent attached to this factor is very low, compared to the value of the exponent attached to the same factor in the power-type function

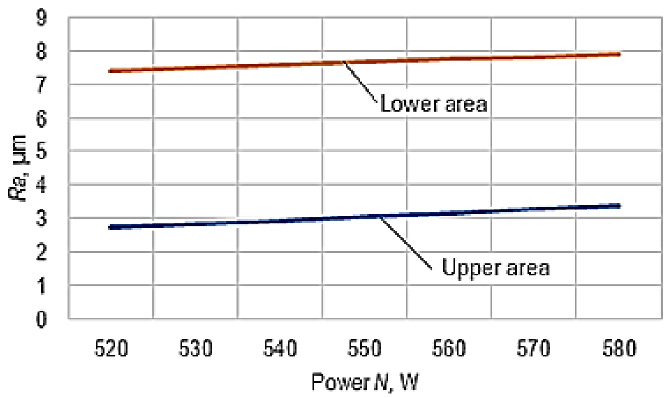

Figure 4. Influence of the laser beam power *N* on the surface roughness parameter *Ra*, in the two areas of the resulting surface, according to the mathematical model of the second-degree polynomial type (v=6 mm/s, p=40000 Pa, f=140 Hz)

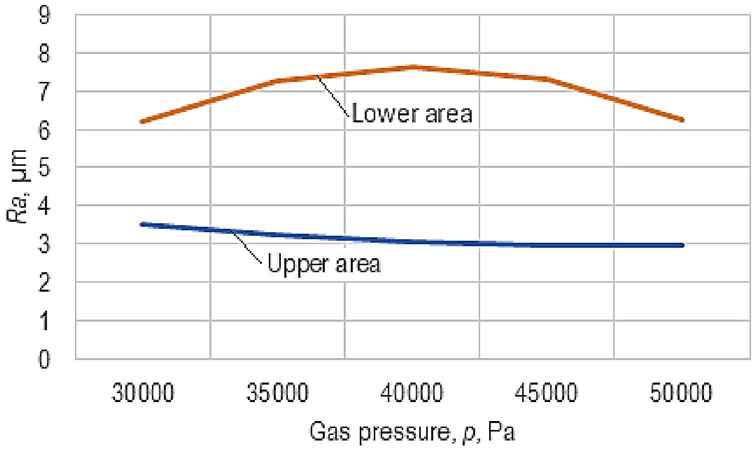

Figure 5. Influence of the assist gas pressure *p* on the surface roughness parameter Ra (*N*=550 W, *v*=6 mm/s, *f*=140 Hz)

empirical mathematical model valid for the upper area of the resulting surface.

An influence characterized by different effects is exerted by the cutting speed *v*. Thus, in the upper area of the resulting surface, increasing the cutting speed *v* leads to a decrease in the value of the roughness parameter *Ra*, an aspect highlighted by the negative value of the exponent attached to this factor. An inverse effect seems to characterize the influence of the cutting speed *v* in the lower area of the surface, when increasing the cutting speed *v* results in an increase in the value of the roughness parameter *Ra*.

5. CONCLUSIONS

Laser beam cutting is used to separate parts or workpieces including complex contours from a plate-type workpiece. The reduction of the volume of subsequent processing of the surfaces resulting from cutting is dependent on the roughness of the respective surfaces. Through the experimental research whose results are presented in the article, the aim was to determine empirical mathematical models that would provide information on the direction of action and the intensity of the influence exerted by different factors on the magnitude of the roughness parameter *Ra*, for the two distinct areas of the surface resulting from laser beam cutting. The analysis of the empirical mathematical models highlighted the fact that for the upper area of the surface, the strongest influence is exerted by the laser power, followed by the frequency of the laser pulses. In the case of the lower area, a strong influence is exerted by the frequency of the laser pulses, followed by the cutting speed and the laser power. Increasing the values of laser power and pulse frequency leads to an increase in the value of the roughness parameter *Ra*. In the future, it is intended to continue research on the influence of the nature of the workpiece material and other input factors in the cutting process on the value of some roughness parameters of the resulting surface.

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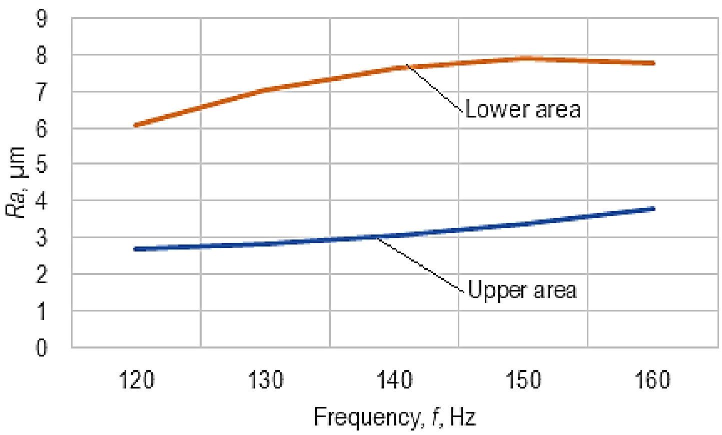

Figure 6. Influence of the laser pulse frequency *f* on the surface roughness parameter *Ra* (N=550 W, *v*=6 mm/s, *p*=40000 Pa)

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