Study of input parameters influence on the surface quality at laser processing of Hardox 400 steel

C C Girdu1*, M V Dragoi1, M Mileșan1, L A Mihail1, L Cirtina2 and C Radulescu2

1 Manufacturing Engineering Department, Transilvania University of Brașov, Eroilor nr. 29, 500036 Brasov, Romania
2 University “Constantin Brâncuși” Târgu-Jiu, Str. Republicii, nr. 1, 210135 Târgu-Jiu, Romania

*E-mail: girdu2003@yahoo.com

Abstract. The paper presents the result of the experimental research regarding the influence of the parameters of the laser cutting regime of the HARDOX 400 steel on the roughness of the processed surface. The study was carried on by means of experimental research, based on a plan developed according to the Taguchi method, a fractionated factorial one, applied for three input parameters: assistant gas pressure, laser power, and cutting speed, each having three levels. The statistical processing of the experimental data was performed by ANOM (analysis of means) and S/N indexes (signal to noise), according to Taguchi Method approach, validated by ANOVA (analysis of variation). Particularly, the paper analyses the combined influence of laser power and the pressure of the assistant gas on the roughness. The main conclusion is that among the two parameters, the most significant influence is that of the pressure of assistant gas.

1. Introduction

Roughness is a parameter that characterizes the quality of surfaces. When it comes to laser cutting of metal, the cutting parameters – the laser power, the assistant gas pressure, and the cutting speed - have an important influence on the roughness of the processed surfaces. The scientific literature displays some researches related to cutting parameters at laser processing of metals, and their influence on the output, as follows (selection): Adelmann B and Hellmann R present an optimization algorithm of input parameters (laser power, cutting speed, the distance between nozzle and part, the assistant gas pressure, and their interaction when it comes to laser cutting of Aluminum sheet having the thickness of 1 mm [1]. Lutey A et al. concludes that when cutting steel with part material having thickness of 1…4 mm, the best result in terms of surface quality is obtained when use Oxygen as assistant gas, medium laser power, and low cutting speed [2]. Ivarson A et al. describe a study regarding to the influence of alloying elements in the material on the quality of surface processed by laser [3]. In [4] Bachy B et al. claim the novelty of using Artificial Neuronal Network (ANN) to estimate the roughness of the part processed by laser, based on the values of input cutting parameters: laser power, pulse rate, and cutting speed. Parthiban A claims that the quadratic model is the best in terms of correlation to experimental data and the profile shape (linear or curved) have an important influence on kerf width [5]. Hashemzadeh M et al. presents a study which shows that the width of kerf is directly influenced by the size of laser beam, but it is independent from interaction duration of laser with part material [6]. In [7] Pocorni J et al. analyse the shape of the kerf al laser processing of
stainless steel with CO\textsubscript{2} laser. The conclusion is that there is not a direct relationship between the tilt of strips on the flank of part and the angle of kerf. A different approach on engendering the strips on the flank of laser cut parts has Singh et al. [8]; they affirm that strips are caused of light reflation on the tart surface. The source of the reflection is supposed to be some optical elements locate behind the lens of laser device. Thombansen U et al. say that roughness is influenced by the wavelength of the laser beam, cutting speed, and the position of the focal point [9]. Zhang and Lei affirm in [10] that the perturbations in the flow of melt material cause defects of surface quality, as deep strips and adherent slag. In [11] Madic et al. presents an iterative search algorithm, with six variables to study laser cutting of metal sheets. Pramanik D and collaborators studied the Ti-Al-4V alloy in laser processing, applied to increase the hardness and corrosion resistance, of parts used for medical purposes. The effects of the cutting angle and the melting depth on the Ti alloy were analyzed depending on the power, operating cycle, frequency of pulse, and cutting speed. Inclination of kerf and surface roughness were measured and analysed, as well [12]. Wust et al. presents in [13] an experimental research on laser processing of general usage steel. Their conclusion was that the most relevant influence on the surface quality is that of cutting speed.

Different from the cited studies, the present paper aims to present some aspects concerning with the influence of two of the main cutting parameters on the quality of the surface at processing (cutting) by laser the Hardox 400 steel. This material was selected for study, because it is hard to be processed by chip removing technologies, so laser processing is considered to be more proper. In this context the quality of the surface is expressed by roughness. The experimental research considered the influence of pressure of assistant gas, laser power, and cutting speed. Particularly, this paper discuss only the influence of the first two mentioned parameters. For this study, cutting speed is considered to be constant, that is it does not act as influence factor on the roughness of the processed part. Thickness of the metal sheet was of 10 mm.

2. The experimental research methodology
The study is based on an experimental research, conducted according to a plan developed through Taguchi method, a fractionated factorial one. The plan is applied for three of the important cutting parameters: assistant gas pressure, laser power, and cutting speed, each having three levels. Processing of the experimental data was performed by ANOM (analysis of means) and S/N indexes (signal to noise), according to Taguchi Method approach, validated by ANOVA (analysis of variation). A series of nine combinations of input data level was selected. The input data are presented in table 1. The set of processings was repeated five times.

Table 1. Input/output data (input data set was replicated four timed).

| Part # | Laser power [w] | Gas pressure [bar] | Cutting speed [mm/min] | Roughness [µm] |
|-------|----------------|-------------------|------------------------|----------------|
| 1     | 4100           | 0.35              | 1200                   | 3.48           |
| 2     | 4100           | 0.45              | 1400                   | 3.00           |
| 3     | 4100           | 0.55              | 1600                   | 4.40           |
| 4     | 4200           | 0.35              | 1400                   | 2.32           |
| 5     | 4200           | 0.45              | 1600                   | 1.70           |
| 6     | 4200           | 0.55              | 1200                   | 4.19           |
| 7     | 4300           | 0.35              | 1600                   | 2.94           |
| 8     | 4300           | 0.45              | 1200                   | 3.74           |
| 9     | 4300           | 0.55              | 1400                   | 3.52           |

Material used was Hardox400, having the chemical composition presented in table 2.
Table 2. Chemical composition of Hardox400 steel [%].

|                | C   | Si  | Mn  | Cr  |
|----------------|-----|-----|-----|-----|
| Hardox 400    | 0.19| 0.50| 1.25| 0.70|

The thickness of 10 mm is a commonly used one in industry to produce parts that are subject of hard mechanical abrasion and wear. This thickness is sufficient to allow measuring in appropriate conditions the hardness and roughness. By means of screening trials have been determined the limit values of input parameters. These values were chosen such that even the extreme combinations of parameters (min, min, min, and max, max, max) to ensure appropriate conditions for processing. The values of input parameter assistant gas pressure were varied within the ranges of 0.35...0.55 bar, which means low pressures. The first conclusion was that bigger values of pressure lead to worse output in terms of surface quality. The melt material is eliminated from the kerf being blown by the assistant gas. The normal piercing and cut is done with a laser power ranged 4100...4300 W. When interacting with the processed material, the laser beam produces an intense flow of incandescent drops that cause strips and craters occurrence on part surface. The cut is facilitated by the low level of light reflection of the steel. The low thermal conductivity of the steel makes more difficult heat dissipation; this helps melting material in the cutting area. The burnt material caused of presence of O₂ can affect negatively the surface quality.

The type of experimental plan, a fractionated factorial one, was selected such that to fit best to production conditions, which impose to make correct decision by means of a low time consuming experiment. The working parameters used in the research are presented in table 3.

Table 3. Working parameters used in processing.

| Parameter                           | Value    |
|-------------------------------------|----------|
| Focal lens length                   | 190.5 mm |
| Focal position above the part surface | -0.5 mm |
| Diameter of nozzle                  | 1.5 mm   |
| Stand-off distance                  | 0.8 mm   |
| Assistant gas                       | O₂       |
| Pulse regime                        | Continuous |

The experimental processing was performed by means of a Bystronic Bysprint Format 3015 machine, presented in figure 1.

Figure 1. Bystronic Bysprint Format 3015 machine. (a) general view; detail of working space.
3. The experimental research
The roughness was measured on the side flanks of the laser processed parts. The side flanks follow both straight and curved contour. Roughness measurements were performed using, a roughness meter Mitutoyo SJ 301 (figure 2).

![Figure 2. The roughness meter Mitutoyo SJ 301](image)

(a) general view  
(b) detail of working space.

In figure 3 some processed parts are presented.

![Figure 3. Processed parts](image)

The values of the measured roughness were ranged in the domain of 2.32...4.40 µm. Measurements have been performed on a planar flank of the part. For each part have been determined three parameters: Rₐ – the average deviation of roughness, Rₛ – the mean value of roughness measured in 10 points, and Rₜ – the quadratic mean deviation of roughness. In the next sections all the refering will point to Rₐ.

4. Data processing
In order to evaluate laser processing of Hardox400 steel, and to find out the mathematical relationship between the output and input parameters an analysis with Statistica 7.0 was performed. In the experimental research three input variable parameters were considered: laser power, assistant gas pressure, and cutting speed. In Statistica, cutting speed was considered constant. Analysis is based on statistical models. Two different models were used to emphasize the dependence of roughness on laser power and assistant gas pressure: the quadratic and the linear ones. From this point, for easyness of reading purpose, laser power will be named shortly power, and assistant gas pressure, shortly, as well pressure.

4.1. The quadric model
For the interpretation of data the Response Surface Model – RSM was used. Based on the experimental data a chart was built; it is shown in figure 4. Analyzing this chart, one can observe:

- The lowest values of roughness occur at low values of power and pressure;
• The increase of the roughness determined by the increase of the pressure, at low values of the power, is a linear one;

![Figure 4](image)

**Figure 4.** The predictive quadratic model of the combined influence of power and pressure on roughness, when cutting speed is constant.

• At high values of power, roughness varies in a quadratic way under the influence of gas pressure. In these conditions, roughness has the minimum value corresponding to medium values of gas pressure, and increases at higher values of gas pressure;

• Acceptable values of roughness are obtained for medium values of power and pressure (the yellow area on the chart);

• Bad values of roughness are obtained when extrem values of power and pressure are combined \((p_{\text{max}}, p_{\text{min}})\) and \((p_{\text{min}}, p_{\text{max}})\);

• On the chart, the plane surface, corresponding to roughness of 1.5 µm is the plane projection of quadric surface. This shows clearly the zone where the best values of roughness are obtained, that is the zone of the lowest power and pressure;

![Figure 5](image)

**Figure 5.** The linear mathematical model of dependence of roughness on pressure and power.
Based on the remarks above, some conclusions can be drawn, as follows:

- A more intense gas flow stimulates burning of material, that causes suplimentary and non uniform heating of the surface, that is oxidation is a reason of increasing roughness;
- Prediction shows that the best conditions to get a good roughness are low values of pressure and power, if cutting speed is kept constant.

\[ R_u = -4.2673 + 0.0016P + 2.0433p \]  
(1)

where \( B_0 = -4.273 \) is the constant of the model, \( B_1=0.0016 \) and \( B_2 = 2.0433 \) are the coefficients of the two variables, power, and pressure, respectively.

4.2. ANOVA linear model
The linear model for computing the value of roughness using ANOVA variations reveals that the most influent factor is pressure of assistant gas, since it has the biggest coefficient. The tilt of planar surface confirms the dependence of roughness on the input parameters - pressure and power. It is a direct dependence, increasing the value of any input parameter causes an increasing of roughness. Combining the influence of both input parameters emphasizes the negative effect of each independent factor. The flow of the melted material on the flank of the part influences negatively the roughness.

4.3. ANOVA quadratic model
Using specific means, i.e. quadratic regression, a relationship of form (2) is determined. The function is explicited in equation (3).

\[
R_a=B_0+B_1*X +B_2*Y + C + B_{11}*X^2+ B_{12}*X*Y + B_{22}*Y^2
\]  
(2)

\[
R_a= -71.275+ 0.0322X + 13.9533Y + 3.1667*10^{-6}X^2- 0.0088*X*Y + 27.8333*Y^2
\]  
(3)

In (2) and (3) were marked down power with X, and pressure with Y. In equation (3) the magnitude of coefficients \( B_2 \) and \( B_{22} \), which expres the quadratic and respectively linear interaction of pressure, reveals that this input parameter has the most significant influence on the roughness. The coefficient of interaction of power and pressure is the smallest; that shows that the input parameters potentiate each other in a small measure.

**Figure 6.** The quadratic model of influence of power and pressure on the surface roughness, obtained by ANOVA.
The 3D graph (figure 6) allows drawing some conclusions concerning with the way the roughness is influenced by the input parameters:

- Roughness increases exponentially with the pressure at high values of power;
- Roughness increases linearly with power when pressure has low values;
- At low values of power, the best values of roughness migrate slightly to the middle of pressure range compared to graph in figure 4, where clearly, the best roughness corresponds to the lowest levels of both power and pressure;
- While values of power increase the values of roughness are distributed closer to its mean value;
- Values of roughness are symmetrically distributed around the mean value.

5. Results and discussion

The prediction of the roughness indicates in the case of the linear model that the low Ra roughness is obtained at low values of pressure and power. Roughness bigger than 2.5 µm occur at values of pressure ranged in 0.35…0.40 bar, respectively of power ranged in 4100…4150 bar. As the pressure and power increase, roughness values equal to 3 µm are reached. This trend remains constant at average pressure values and close to the average for laser power. For values of pressure higher than 0.50 bar and power above 4200 W, the roughness exceeds 3.5 µm. The increase of roughness follows the Gaussian curve from the minimum to medium values of pressure and power. The roughness graph is flattened at low values of pressure and power, and the average roughness is placed around 3 µm. Above these values the roughness deteriorates with increasing laser pressure and power. Roughness also gets values to the maximum in the situation of high pressure and low power, respectively low pressure and high power. The average value of roughness for the 45 parts is Ra = 3.0440 µm. In the power range 4150…4200 W, the roughness values fall within the confidence limits. In the power range 4250…4300 W, roughness values obtained are outside the 95% range. The good prediction of the roughness as a function of pressure to obtain the average value Ra = 3.0440 µm is in the range 0.40…0.45 bar. Between 0.45…0.55 bar the roughness prediction as a function of pressure displays a quadratic increase.

Comparing the linear graph for prediction with those for the calculation the roughness by analysing ANOVA variations results in a good compatibility, with similar results. The best values of roughness are at low values of pressure and power, but they are high at high values of influencing factors.

However, comparing the results obtained by the two methods, some differences can be observed. The differences of performance between prediction and regression are caused by the modelling techniques that take into account supplementary criteria. The regression equations are more accurate because they establish a relationship between the dependent value (roughness), and input parameters, pressure and power, while prediction takes into account the performance, concordance, and tuning, described by RSM model. Some small differences might be induced by the fact that cutting speed was considered to be constant in modelling, despite that it was slightly varied in the experiment.

6. Concluding remarks

It is important to emphasize again, that these conclusions are based on an experimental plan developed according to the Taguchi method, a fractionated factorial one, applied for three input parameters, each having three levels. This is the method that allows an experiment with as less as possible number of tests, which still to provide with confident results. This type of plan was selected because of it fits the best to production conditions, when experimental research must be not a long time consuming process.

Analyzing the results of the experimental research on the influence of input parameters on roughness of parts made of Hardox400 steel by laser cutting process, some conclusions can be drawn. The main of them are as follows:

- The experimental research allowed to find the range of assistant gas pressure and laser power that provide a proper processing of Hardox400 steel in sheets having a thickness of 10 mm; these are 0.35…0.55 bar, and 4100…4300 W, respectively;
The best results in terms of roughness are obtained when both pressure and power are at low levels;
Pressure has a more significant influence on roughness than power has;
Prediction and regression produce slightly different results. The difference are explicable
The recommendation for a proper laser cutting process of Hardox400 steel (10 mm thickness) is the combination of assistant gas pressure of 0.35 bar and the laser power of 4100 W; according to regression results, the best combination should be 0.40 bar and 4100 W.

Acknowledgments
The present paper was supported by SC BYSTRONIC SA Brasov, which made possible the experimental research of Hardox400 steel laser processing.

References
[1] Adelmann B and Hellmann R 2011 Fast Laser Cutting Optimization Algorithm Physics Procedia 12 591
[2] Lutey A H A, Ascari A, Fortunato A and Romoli L 2018 Long-pulse quasi-CW laser cutting of metals Int. J. Adv. Manuf. Technol. 94 155
[3] Ivarson A, Powell J and Siltanen J 2015 Influence of alloying elements on the laser cutting process Physics Procedia 78 84
[4] Bachy B and Al-Dunainawi Y 2020 Influence of the effective parameters on the quality of laser micro-cutting process: Experimental analysis, modeling and optimization J. Laser Appl. 32
[5] Parthiban A, Sathish S, Chandrasekaran M and Ravikumar R Optimization of CO\textsubscript{2} laser cutting parameters on Austenitic type Stainless steel sheet IOP Publishing materials Science and Engineering 183
[6] Hashemzadeh M, Suder W, Williams S, Powell J, Kaplan A F H and Voisey K T 2014 The application of specific point energy analysis to laser cutting with 1 μm laser radiation Physics Procedia 56 909
[7] Pocorni J, Powell J, Frostevarg J and Kaplan A 2018 Dynamic laser piercing of thick section metals Optics And Lasers In Engineering 100 82
[8] Singh S S, Baruah P K, Khare A and Joshi S N 2018 Effect of laser beam conditioning on fabrication of clean micro-channel on stainless steel 316L using second harmonic of Q switched Nd: YAG laser Optics AndLasers In Engineering 99 107
[9] Thombansen U, Hermanns T and Stoyanov S 2014 Setup and Maintenance of Manufacturing Quality in CO\textsubscript{2} Laser Cutting Procedia CIRP 20 98
[10] Zhang YL and Lei J H 2017 Prediction of Laser Cutting Roughness in Intelligent Manufacturing Mode Based on ANFIS Procedia engineering 174 82
[11] Madic M, Mladenovic S, Gostimirovic M, Radovanovic M and Jankovic P 2020 Laser cutting optimization model with constraints: Maximization of material removal rate in CO2 laser cutting of mild steel Journal Of Engineering Manufacture 234
[12] Pramanik D, Kuar AS, Sarkar S and Mitra S 2020 Enhancement of sawing strategy of multiple surface quality characteristics in low power fiber laser micro cutting process on titanium alloy sheet Optics And Lasers In Engineering 122
[13] Wust P, Edelmann A and Hellmann R 2020 Areal Surface Roughness Optimization of Maraging Steel Parts Produced by Hybrid Additive Manufacturing Materials 13