Military Technical College
Kobry El-Kobbah,
Cairo, Egypt.

18th International Conference
on Applied Mechanics and
Mechanical Engineering.

AN INVESTIGATION INTO THE EFFECT OF CO_2 LASER CUTTING VARIABLES ON CUTTING EDGE QUALITY OF STAINLESS STEEL 316 SHEETS

A. M. El-Wardany[1], H. A. Sonbol[2] and M. A. Mahdy[3]

ABSTRACT

Laser beam cutting is one of the major applications of lasers in sheet metal working. In this investigation, an experimental study in CO_2 laser cutting process is presented. The aim of this research is to investigate the effect of the laser cutting process variables on the cutting-edge quality parameters. A sheet of stainless steel with a standard grade of 316, 2 mm thickness was chosen as a workpiece material. Several experiments were conducted to investigate the influence of four input variables: laser power (P), traverse speed (v), assist gas pressure (p) and focal plane position (F) on the three most important performance parameters, namely: upper kerf width (UKW), lower kerf width (LKW), and the average surface roughness (R_a). Minitab software was used to determine the main effects of the process variables on the performance parameters. Signal to noise ratio analysis (SN) was used to determine the optimum process variables in their operating rage. This investigation would provide a good demonstration for the most significant input variables on the cutting-edge quality parameters, which will be used for solving related industrial problems.

KEYWORDS

Laser beam cutting, stainless steel 316, Average surface roughness, Upper kerf width, Lower kerf width.

NOMENCLATURE

LBC	Laser beam cutting
UKW	Upper kerf width (mm)
LKW	Lower kerf width (mm)
P	Laser power (kW)
SN	Signal to noise ratio
n	The number of observations in a trial
R_a	Average surface roughness (µm)
v	Traverse speed (mm/min)
p	Assist gas pressure (MP_a)
F	Focal plane position(mm)
y_i	The response value

---

[1] Assist. Lecturer, Modern Academy for Engineering and Tech., Cairo, Egypt.
[2] Professor, Design and Prod. Eng. Dept., Faculty of Engineering, Ain Shams University, Cairo, Egypt.
[3] Professor, Dean of Higher Institute for Engineering and Modern Technology Marg, Egypt.

INTRODUCTION

Laser beam cutting is one of the major applications of lasers in industry [1]. It is a process in which a high intensity focused laser beam is used to melt and vaporize the workpiece material along the traverse contour [2]. The molten material is ejected from the cutting area by a pressurized assist gas jet which coaxially supplied with the laser beam. The laser beam is slitting the workpiece and a small kerf with a certain width is created as a result of the relative motion between the laser beam and the workpiece [1-5].

Many researchers have performed a series of investigations to study the effect of the laser cutting variables on the cutting-edge quality [7, 8]. Madic et al. [3] studied the application of taguchi method for optimization of surface roughness in CO_2 laser cutting of mild steel using oxygen as an assist gas. They reported that the cutting speed and assist gas pressure are the most significant variables affecting the surface roughness, while the influence of the laser power is much smaller, in addition, the interaction effects of the laser cutting parameters are negligible.

Prajapati et al. [4] studied the influence of laser cutting variables on the surface roughness during cutting of mild steel and Hardox-400 using taguchi method. They mentioned that the cutting speed and thickness of plate have a high contribution on surface roughness during laser cutting of both materials, while the laser power had a lesser effect on surface roughness. Moreover, the gas pressure was found to have a higher effect on surface roughness during cutting of mild steel and had a lesser effect on the same parameter during cutting of hardox- 400.

Argade et al. [5] applied taguchi method to find the influence of CO_2 laser cutting variables such as cutting speed, laser power and gas pressure on the machined surface quality of stainless steel SS 409, their results illustrated that the cutting speed and gas pressure were the most significant variables on surface roughness, while the laser power and gas pressure were the most significant ones on kerf width.
Prakash et al. [6], applied taguchi method to find the effect of laser cutting variables such as assist gas pressure, cutting speed, the stand-off distance and laser power on the produced kerf width of the cut edge of stainless steel material. It was concluded that the Kerf width decreases as laser power and stand-off distance increases and when assist gas pressure decreases.

Chen [7] studied the effect of high pressure flow of assistant gas in CO_2 laser cutting on the kerf width, dross, and surface roughness R_a. It was concluded that the cutting quality produced during the use of inert gas in laser cutting can be improved significantly by using high gas pressure up to 10 bar, in addition, high pressure oxygen cutting and high-pressure air laser cutting produces poor quality of the produced cutting edge.

Zhang et al. [8] analyzed and summarized the importance of the laser cutting roughness prediction and develop adaptive neural fuzzy inference system model to predict the laser cutting roughness with cutting speed, assist gas pressure, cutting width and laser power, as the input variables and surface roughness as output variable.

The influencing factors on quality the laser cut edges studied by the previous researches were focused on mild steels as workpiece materials. The quality of the produced edges during laser cutting of stainless steel needs more investigations.

The objective of this work is to study the effect of laser cutting process variables on the kerf widths and the surface roughness of the cut surface of stainless steel 316, and determine the optimum levels of process variables for the selected operating range of experiment to achieve narrow kerf widths and low roughness value of the cut surface. Therefore, it will be beneficial for solving related industrial problems.

EXPERIMENTAL WORK

Experimental Set-Up and Material

A 4.4 kW CO_2 laser cutting machine with nozzle diameter 1.5 mm, focusing lens with focal length of 125 mm, and pressurized nitrogen as an assist gas were used to perform the cut. A sheet plate with dimensions 400 x 600 x 2 mm of stainless steel with standard grade 316 was chosen as workpiece material. Mitutoyo optical microscope with an accuracy of 1µm was used for measurements of the upper and lower kerf widths. TR200 roughness tester was used for surface roughness measurements. Three consistent surface roughness values for each specimen were measured at the center of the produced surface as shown in
Fig. 1, and an average value was calculated for each specimen.

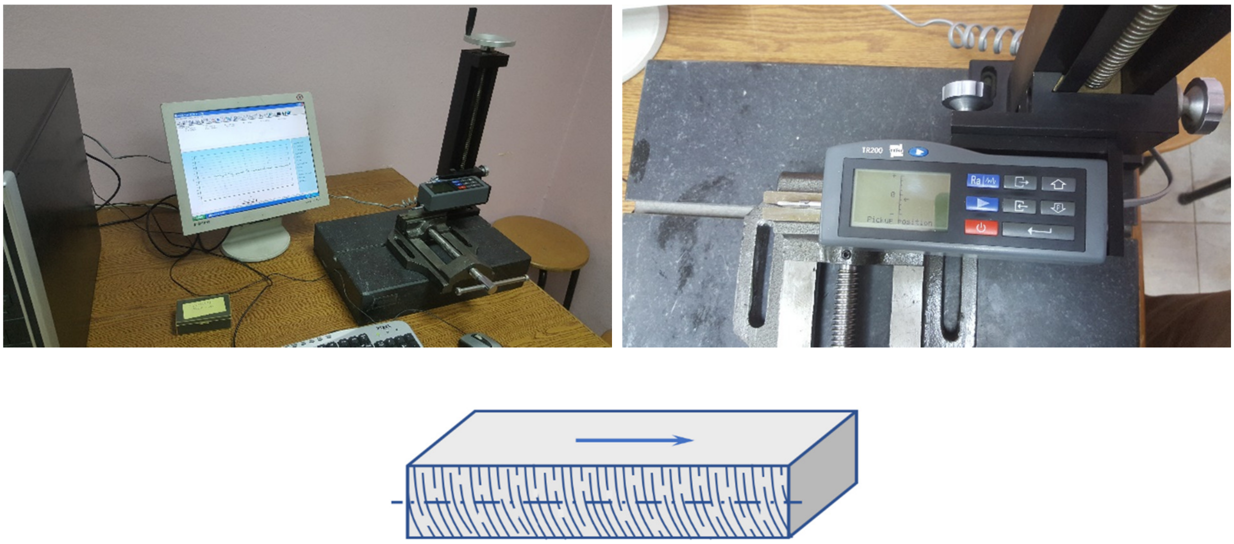

Fig. 1. TR200 surface roughness tester, stylus position, measurement direction.

Controlled Variables and Design of Experiments

In order to have results that can present an impact on laser cutting industry, all specimens were cut using factors levels around the recommended cutting variables provided by the machine manufacturer. Factors, factor levels and factor designations are shown in Table 1. In order to reduce the experimental cost, the experiments were performed according to the design matrix consists of 45 experiments randomly chosen from full factorial design matrix. Moreover, the experiments were performed in a random order to avoid any error**.** Fig. 2 demonstrates the response parameters which generally are studied in CO_2 laser cutting process.

Table 1. Factors, factor levels and factor designations.

Parameters	Unit	Setting values
Laser power, P	kW	1, 1.25, 1.5
Assist gas pressure, p	MP_a	1, 1.25, 1.5
Focal plane position, F	mm	0, -1, -2
Traverse speed, v	mm/min	1000, 2000, 3000

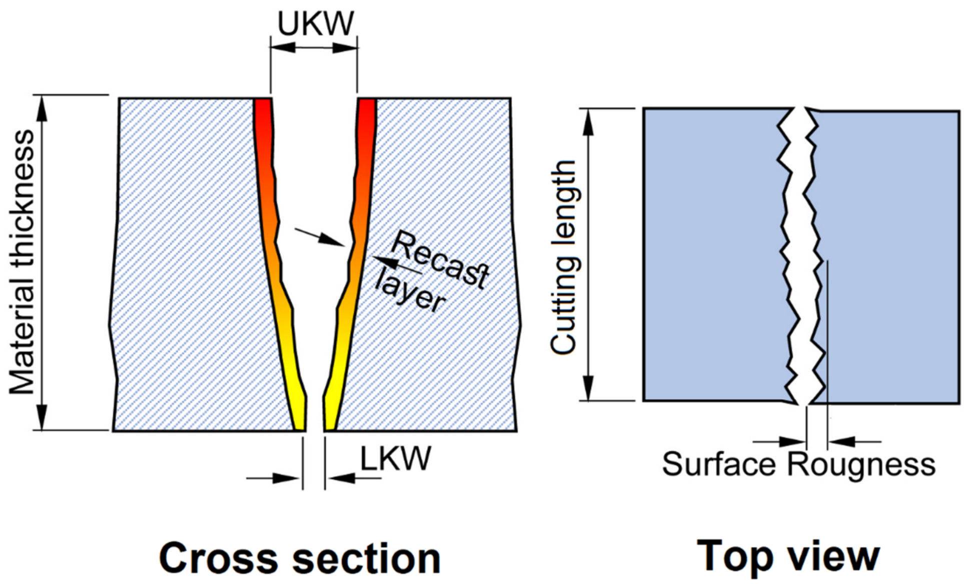

Fig. 2. General response parameters in CO2 laser cutting process.

RESULTS AND DISCUSSION

Signal to Noise Ratio Analysis (SNR)

As a smaller values of surface roughness R_a, upper kerf width and lower kerf width are desired, signal-to-noise ratio analysis (SNR) is used to detect the optimal condition. The common practice in SN ratio analysis procedure is to calculate the η for each treatment combination and to consider the one which presents the largest η as the optimal condition. The kind of problem which matches UKW, LKW, and R_a in SN ratio analysis is "the smaller-the better" static problem. For such type of problems signal-to-noise ratio (SN) is calculated as follows:

$$\eta = -10Log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right)$$

In which: η is the signal to noise ratio, y_i is the response value and (n) is the number of observations in a trial. The rationale behind SN ratio analysis is to find a setting of parameters in which signals are predominant. This rationale eventually leads to a situation in which the system is least sensitive to noises. It is focused on each factor level rather than treatment combination. Each factor level SN ratio (η) is the average of the treatment combinations SN ratios of the corresponding factor level. The largest value of η indicates the optimal condition [9].

Effect of Laser Cutting Variables on the Average Surface Roughness (R_a)

Surface roughness is an effective and commonly adopted parameter representing quality of a machined surface in general engineering practice. It gives a good general description of the height variations in the surface. Fig. **3** illustrates the effect of different laser cutting variables on the average surface roughness R_a of the cut edges.

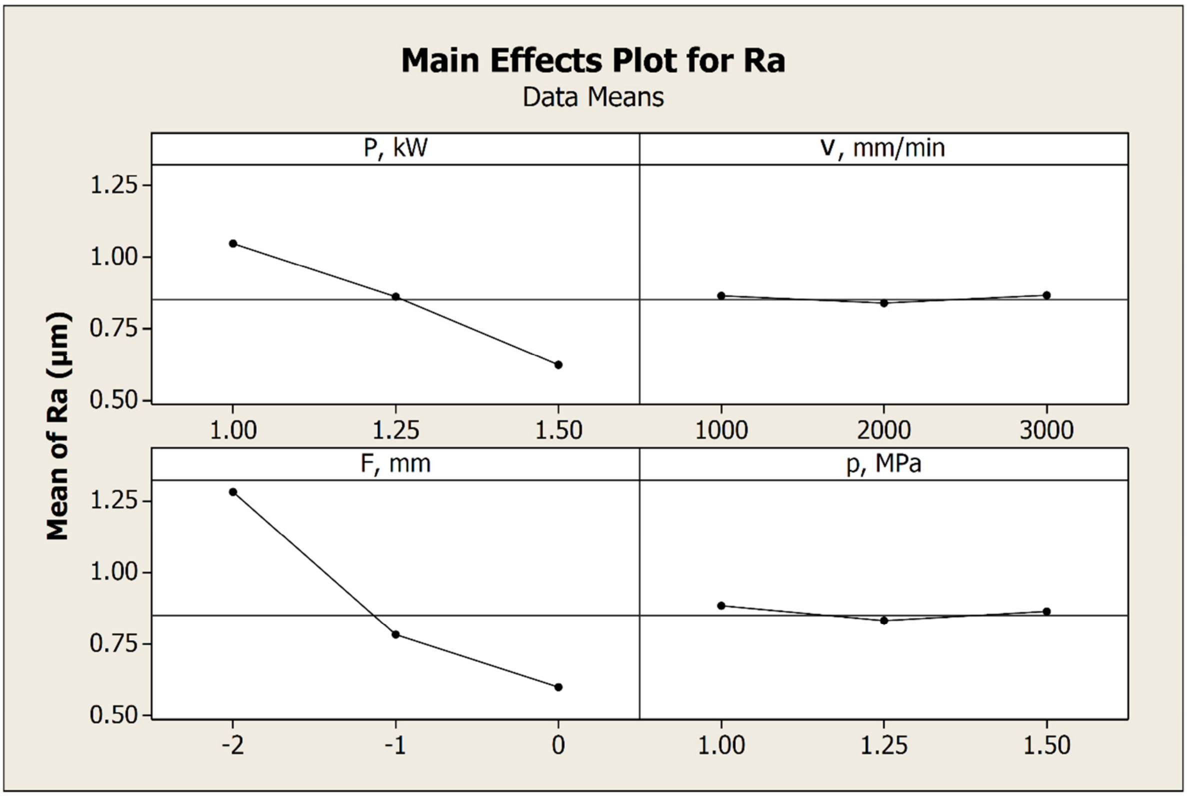

Fig. 3. Plot of the effect of the different parameters on the surface roughness R_a, (The mean value = 0.802, Standard Deviation = 0.354).

The results clearly indicate that the increase of laser power to 1.5 kW and setting focal plane position at the top plane of the cut surface significantly decrease the average surface roughness R_a from 1.04 to 0.623 µm. However, the increase in the laser beam power causes an increase of the cut surface temperature which leads to an increase of the area of the fusion zone (the beam-metal interaction zone). During the cooling, recast layer is formed and affects the surface roughness [10,11,12].

These results also demonstrate that, the traverse speed has no effect on the surface roughness R_a, while the assist gas pressure has a little significance on the average surface roughness R_a. At high gas pressure (1 to 1.5 MP_a), and varying the cutting speed from 1000 to 3000 mm/min, the roughness of the cut surface is of approximately the same value.

The roughness of the cut surface was decreased, from about 0.884 to 0.861 µm, when the gas pressure was varied from 1 to 1.5 MP_a. Indeed, the use of pressurized assist gas in laser cutting has two major effects, it ejects molten material from the cut as well as cools the melt by forced induction. However, a high-pressure gas with a greater drag force can remove the molten material more effectively, making the cut surface smoother. In contrast, the remaining thick molten layer in low-pressure cutting will deposit on both sides of the cut surface and, therefore, make the cut surface more irregular [1,2,7,12,13].

Figure 4 and Table 2 illustrates factor level SN ratios (η) for the surface roughness R_a. The optimum levels of process variables for minimum surface roughness R_a are obtained from Table 2 and summarized in Table 3.

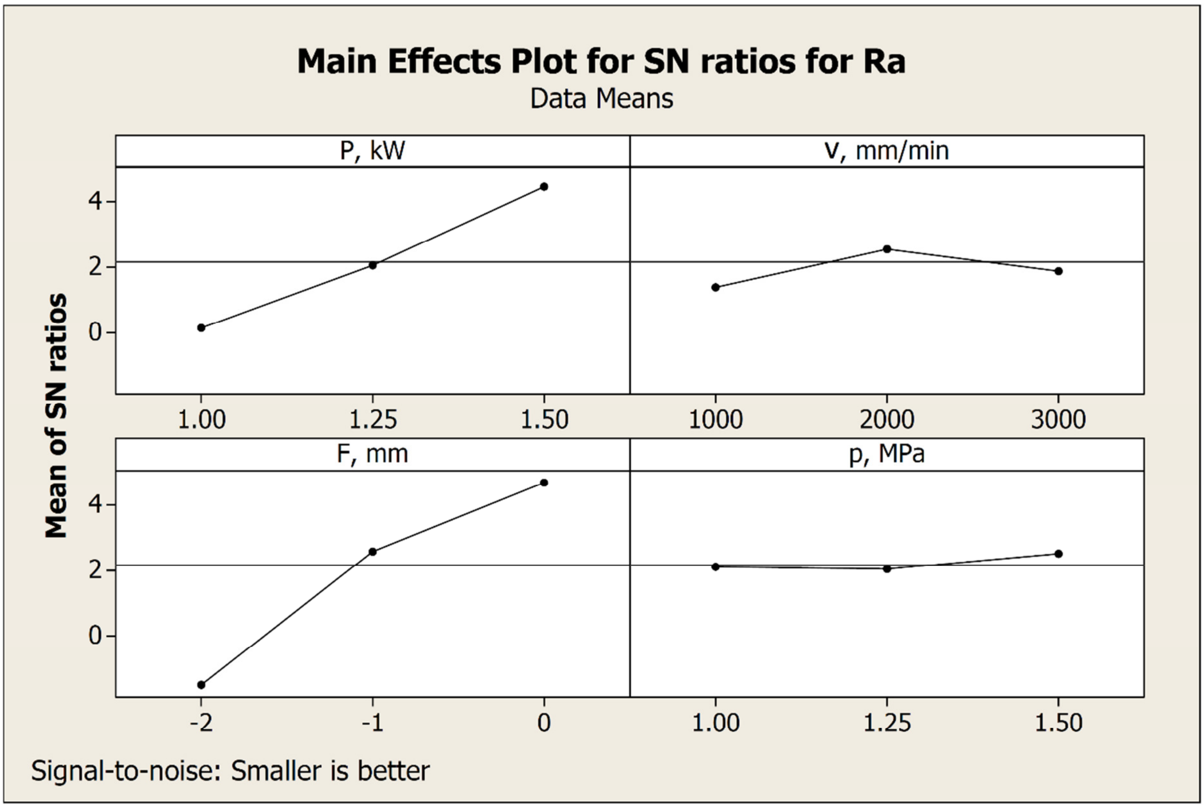

Fig. 4. Plot of the SN ratio for surface roughness R_a.

Effect of Laser Cutting Variables on the Upper Kerf Width (UKW)

Figure 5 illustrates the effect of different laser cutting variables on the upper kerf width (UKW) of the cut surface. As shown in the figure, the transverse speed has the most significant effect on the UKW, whilst, laser power, focal plane position and assist gas pressure have a moderate significance.

Table 2. SN ratios for factor levels for surface roughness R_a

Level	P kW	V mm/min	F mm	P MPa
1	0.1470	1.3892	-1.4898	2.1136
2	2.0596	2.5520	2.5806	2.0505
3	4.4603	1.8817	4.6831	2.5184
Delta	4.3134	1.1628	6.1729	0.4679
Rank	2	3	1	4

Table 3. Optimal factor levels for surface roughness R_a

Parameter	Optimal level	Optimal value
P, kW	3	1.5
V, mm/min	2	2000
F, mm	3	0
p, MPa	3	1.5

The UKW increases as laser power increases because the increase of laser beam power increases the volume of molten metal, which can increase the kerf width [14]. These results also demonstrate that the upper kerf width decreases with increasing the laser cutting speed. Indeed, increasing cutting speed reduces the rate of laser power available at the cutting section, i.e. the time when laser power is available at the cutting section becomes short as the cutting speed increases. This in turn reduces the rate of energy transfer from the laser source to the workpiece material. Consequently, the rate of temperature rise and the diffusional energy transport in the radial direction become less, resulting in small kerf width [15].

The UKW tends to increase as the focal plane position is increased, this is primarily because the beam is often focused deep into the material and therefore presents a larger diameter beam at the kerf entrance [16]. These results also illustrate that the upper kerf width increases with the increase of assist gas pressure. The high gas pressure provides an extra mechanical force to blow out the molten material from the cut kerf. The increase of the UKW of the cut surface by increasing the assist gas pressure may be the result of the greater drag forces [17].

Figure 6 and Table 4 illustrates factor level SN ratios (η) for the upper kerf width (UKW). The optimum levels of process variables for minimum upper kerf width are obtained from Table 4 and summarized in Table 5.

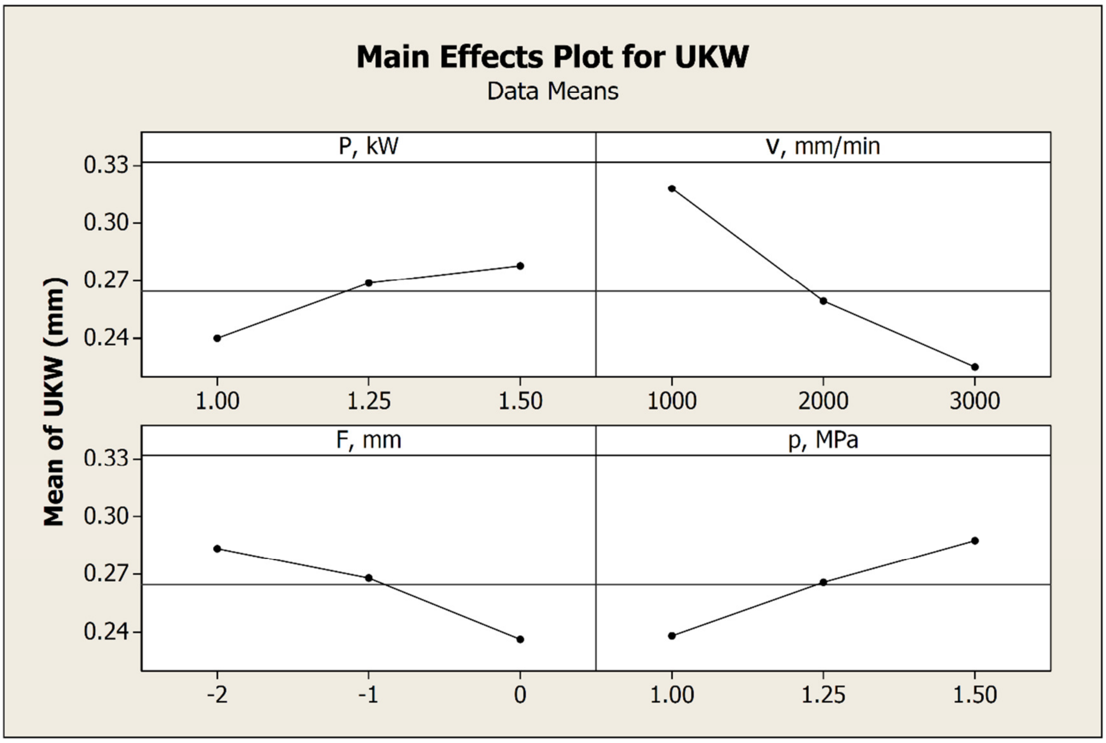

Fig. 5. Plot of the effect of the different parameters on the upper kerf width (UKW), (mean value = 0.2686, standard deviation = 0.042).

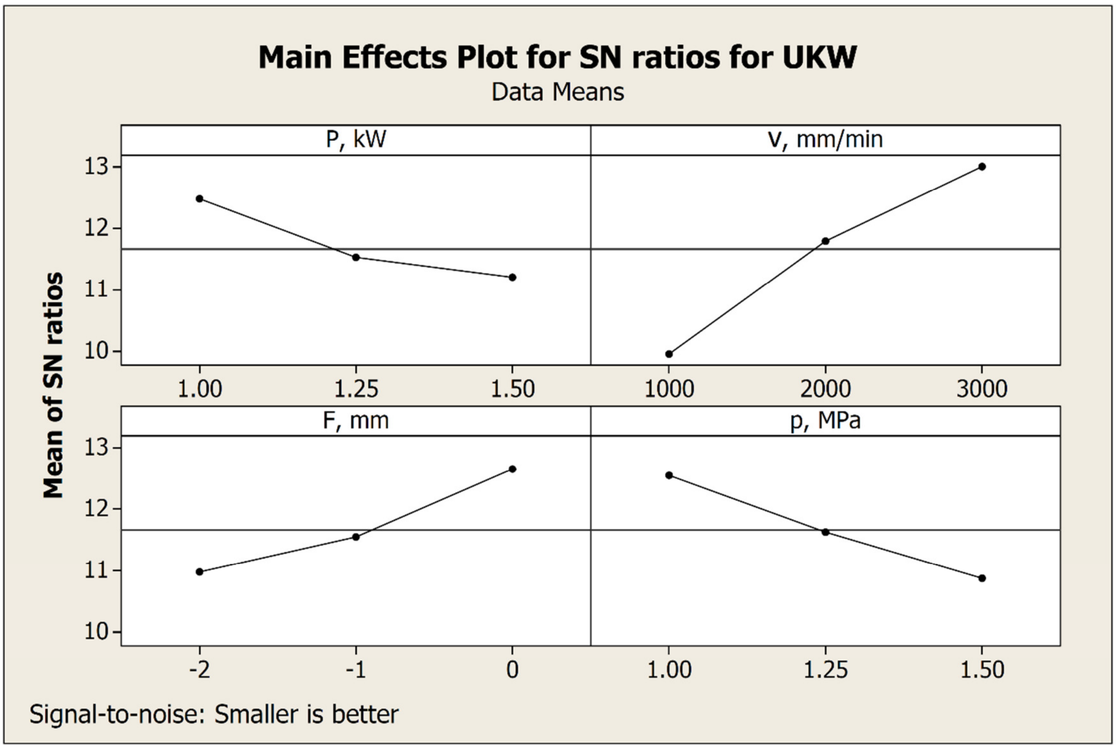

Fig. 6. Plot of the SN ratio for the upper kerf width (UKW)

Table 4. SN ratios for factor levels for the upper kerf width (UKW)

Level	P kW	V mm/min	F mm	P MPa
1	12.479	9.959	10.977	12.548
2	11.529	11.794	11.549	11.626
3	11.205	13.007	12.653	10.873
Delta	1.274	3.048	1.676	1.675
Rank	4	1	2	3

Table 5. Optimal factor levels for the upper kerf width (UKW).

Parameter	Optimal level	Optimal value
P, kW	1	1.0
V, mm/min	3	3000
F, mm	3	0
P, MPa	1	1.0

Effect of Laser Cutting Variables on the Lower Kerf Width (LKW)

Fig. 7 illustrates the effect of different laser cutting variables on the lower kerf width (LKW) of the cut surface. As shown in the figure, the transverse speed and laser power have the most significant effect on LKW, whilst the focal plane position and assist gas pressure have a moderate significance on the LKW.

The results clearly illustrate that, the increase of laser power significantly increase the LKW, while the increase of the traverse speed significantly decreases the LKW. However, the temperature of the cut zone rises as the laser power increases and the cutting speeds decreases, whilst, the higher intensity of the beam can contribute to the melting process which reflecting the kerf widths. [15-17].

The results also demonstrate that using a moderate value of the gas pressure and setting the focal plane position to the center of the workpiece thickness are beneficial for LKW. However, If the focal plane is positioned too high relative to the workpiece surface or too far below the surface, the kerf width and recast layer thickness increase to a point at which the power density falls below that required for cutting [17]. The increase of the LKW of the cut surface by increasing the assist gas pressure can be understood from the increased drag force and velocity of the flow in the molten material [7,18].

Fig. 8 and Table 6 illustrate factor level SN ratios (η) for the lower kerf width (LKW). The optimum levels of process variables for minimum lower kerf width are obtained from Table 6 and summarized in Table 7.

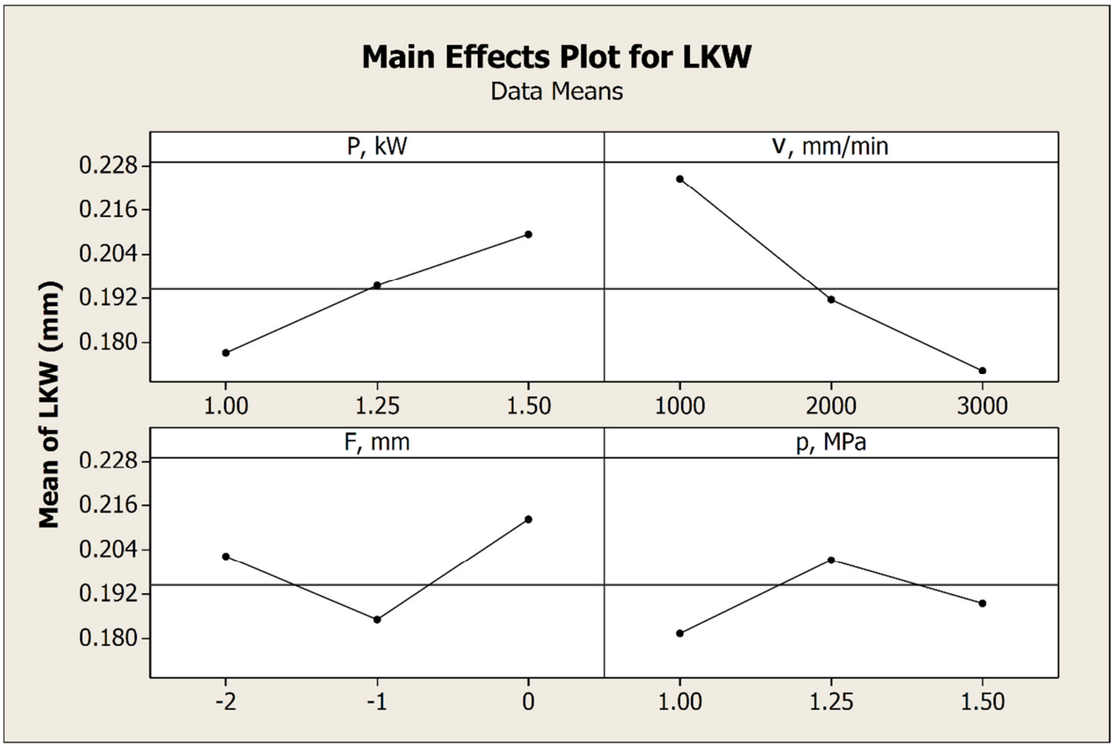

Fig. 7. Plot of the effect of the different parameters on the lower kerf width (LKW), (mean value = 0.191, standard deviation = 0.028).

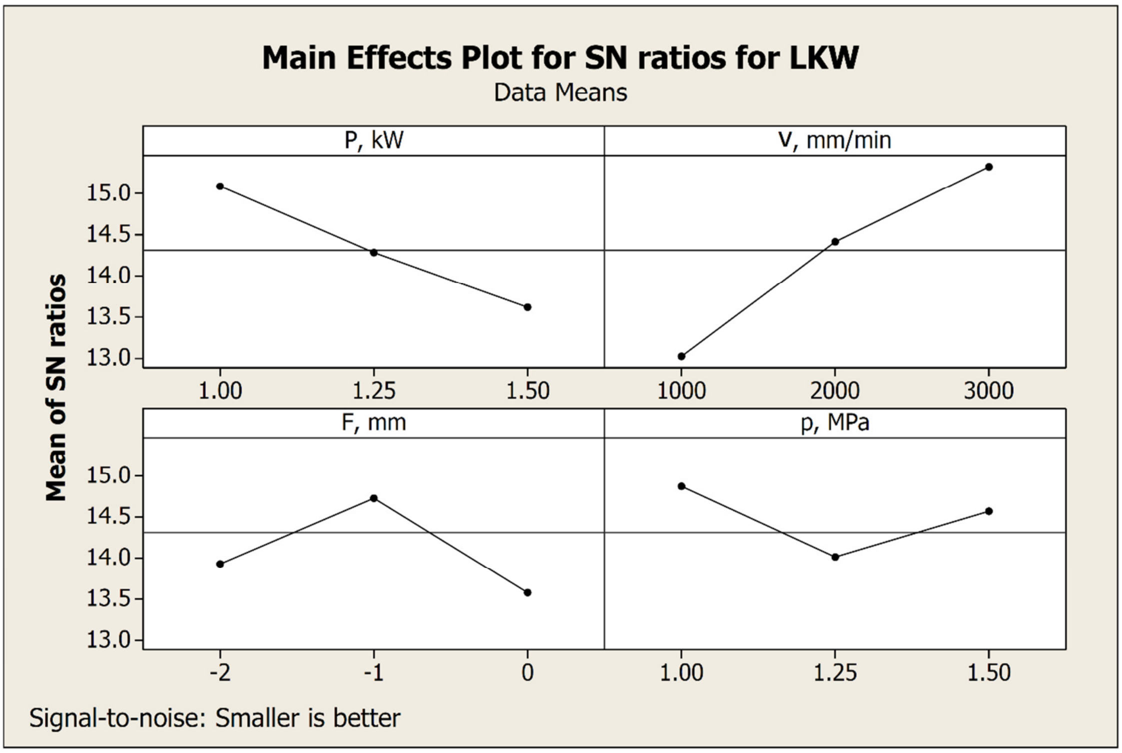

Fig. 8. Plot of the SN ratio for lower kerf width (LKW).

Table 6. SN ratios for factor levels for the lower kerf width (LKW).

Level	P kW	V mm/min	F mm	P MPa
1	15.09	13.03	13.93	14.87
2	14.29	14.42	14.73	14.02
3	13.62	15.33	13.58	14.57
Delta	1.47	2.30	1.15	0.86
Rank	2	1	3	4

Table 7. Optimal factor levels for the lower kerf width (LKW)

Parameter	Optimal level	Optimal value
P, kW	1	1.0
V, mm/min	3	3000
F, mm	2	-1.0
P, MPa	1	1.0

CONCLUSIONS

From the experimentally acquired data of CO_2 laser cutting on stainless steel 316, varying laser power, traverse speed, assist gas pressure, and focal plane position gives following conclusion.

- Laser power and focal plane position have high contribution on surface roughness R_a.
- At high gas pressure (1 to 1.5 MP_a), and varying the cutting speed from 1000 to 3000 mm/min, the roughness of the cut surface is of approximately the same value.
- The assist gas pressure has little effect on the surface roughness.
- The traverse speed and assist gas pressure had high significance on upper kerf width.
- The traverse speed has high significance for UKW, while the other parameters have moderate significance.
- The laser power and traverse speed have high significance for LKW, while the focal plane position and assist gas pressure have moderate significance.
- The SN ratio suggests the optimum parameter setting for selected operating rage of experiment.

REFERENCES

[1] J. F. Ready, Industrial Applications of Lasers. 1997.
[2] Hassan Abdel Gawad El-Hofy, Advanced Machining Processes; Non Traditional and Hybrid Machining Processes. 2005.

[3] I. Management, “Surface Roughness Optimization in Co_2 Laser Cutting By Using Taguchi Method,” vol. 75, 2013.
[4] B. D. Prajapati, R. J. Patel, and B. C. Khatri, “Parametric Investigation of CO_2 Laser Cutting of Mild Steel and Hardox - 400 Material .,” vol. 3, no. 4, pp. 204–208, 2013.
[5] P. V Argade and R. R. Arakerimath, “Parametric Investigations on CO_2 Laser Cutting of AISI 409 to Optimize Process Parameters by Taguchi method,” vol. 37, no. 6, pp. 311–316, 2016.
[6] S. Prakash, L. Naresh, V. H. Prakash, M. A. M. Riyaz, and K. P. Selvam, “Experimental analysis of laser cutting process parameters of stainless steel,” vol. 1, no. 1, pp. 2–5, 2016.
[7] S. Chen, “The effects of high-pressure assistant-gas flow on high-power CO_2 laser cutting,” vol. 88, pp. 57–66, 1999.
[8] Y. Zhang and J. Lei, “Prediction of Laser Cutting Roughness in Intelligent Manufacturing Mode Based on ANFIS,” Procedia Eng., vol. 174, pp. 82–89, 2017.
[9] Madhav S.Padke, “Quality Engineering Using Robust Design,” AT & T Bell Laboratories. 1989.
[10] M. Madić and M. Radovanović, “Application of RCGA-ANN approach for modeling kerf width and surface roughness in CO_2 laser cutting of mild steel,” J. Brazilian Soc. Mech. Sci. Eng., vol. 35, no. 2, pp. 103–110, Mar. 2013.
[11] A. A. Hendriks, Iris E , Olabi, “Challenges in CO_2 laser cutting of composite materials,” dublin city university, 2011.
[12] M. Thakkar, K. Viradia, M. Patel, and A. Jadhav, “Effect of Co_2 Laser Machining for Surface Roughness of Thick Stainless Steel,” no. June, pp. 764–770, 2017.
[13] Save and Svetog, “Defining new processing parameters in laser cutting Ph . D . Snežana Radonji ć , f ull professor,” 16th Int. Res. Conf. ”Trends Dev. Mach. Assoc. Technol., no. September, pp. 1510–1516, 2012.
[14] B. S. Yilbas, “Effect of process parameters on the kerf width during the laser cutting process,” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 215, no. 10, pp. 1357–1365, 2001.
[15] I. Uslan, “CO_2 laser cutting: Kerf width variation during cutting,” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 219, no. 8, pp. 571–577, 2005.
[16] D. Petring and J. Powell, “The Effect of Laser Type and Power on the Efficiency of Industrial Cutting of Mild and Stainless Steels,” pp. 1–6, 2016.
[17] S. Wadekar and S. U. Deokar, “Effect of Process Parameters on Laser Cutting Process: A Review,” Imp. J. Interdiscip. Res., vol. 2, no. 7, 2016.
[18] A. Riveiro et al., “Experimental study on the CO_2 laser cutting of carbon fiber reinforced plastic composite,” Compos. Part A Appl. Sci. Manuf., vol. 43, no. 8, pp. 1400–1409, Aug. 2012.
[19] B. S. Yilbas, “Effect of process parameters on the kerf width during the laser cutting process,” vol. 215, pp. 1357–1365, 2001.