Materials Today: Proceedings 44 (2021) 2080–2086

Contents lists available at ScienceDirect

Materials Today: Proceedings

journal homepage: www.elsevier.com/locate/matpr

Effect of cutting conditions on surface roughness of machined parts in CO_2 laser cutting of pure titanium

M. Boujelbene [a,*], B. El Aoud [a,b], E. Bayraktar [b], I. Elbadawi [a], I. Chaudhry [a], A. Khaliq [a,c], A. Ayyaz [a], Z. Elleuch [d]

[a] University of Ha'il, College of Engineering, Ha'il, Kingdom of Saudi Arabia
[b] Supmeca - Paris, School of Mechanical and Manufacturing Engineering, St-Ouen France
[c] School of Engineering, RMIT University, Australia
[d] University of Ha'il, College of Community, Ha'il, Kingdom of Saudi Arabia

ARTICLE INFO

Article history:
Received 29 November 2020
Accepted 6 December 2020
Available online 23 January 2021

Keywords:
CO_2 laser cutting
Cutting speed
Laser Power
Gas pressure
Surface roughness
Taguchi method

ABSTRACT

Titanium (Ti) and its alloys machining has been a long standing issue in the manufacturing industry. The extraordinary Ti machining costs restrict its used in the specialised applications. To achieve improved surface quality, researchers are working tirelessly to optimize various cutting parameters. In this study, high-power CO_2 laser cutting of the 2 mm thick sheet of pure Ti is investigated. Additionally, effect of the input laser conditions on the machine surface quality is also analysed. The arithmetic roughness *Ra* and total roughness *Rt* of the cut work-pieces, produced by different cutting speed (*V*), laser power (*Pu*) and gas pressure (*p*) are measured by the roughness tester. The machined or cut surfaces were analyzed at several locations along the cutting surface. The Taguchi method was applied to minimize the surface roughness of the cut parts and to optimize the cutting parameters. It was observed that surfaces roughness increases with the evolution of the thermal energy by laser power. However, surface roughness decreases with faster cutting speeds. Finally, the optimum cutting conditions for the arithmetic roughness (*Ra*) was recorded at laser power *Pu* of 2 kW, *V* of 2400 mm/min and *p* of 14 bars. For total roughness (Rt), *Pu*, *V* and *p* were 2 kW, 2400 mm/min and 2 bars respectively.

1. Introduction

Laser cutting is one of the emerging manufacturing technologies in the industrial world. This is due to its excellent performance in several important technical aspects including; cutting speed, low values, good yield and *kerf* machining of difficult to cut materials. Nowadays, the laser cutting of metallic materials particularly advanced composite materials used in many mechanical industries has been adopted. Laser cutting is a non-contact mechanical type machining process based on high thermal energy, which is used extensively and efficiently in mechanical production industry and is applied to several types of materials [1].

The quality of laser cutting can be achieved in terms of high cutting speed, minimal and limited material loss, high precision, high productivity, etc. [2-4]. These unique characteristics related to mechanical production of the laser cutting make it efficient, industrial and adaptable than known conventional methods such as mechanical cutting by Wire Electrical discharge machining WEDM or machining [3]. Laser cutting process is also associated with several other advantages such as; cutting most high hardness metallic materials, regardless of their mechanical strength and low running cost and also, the reduction of the need for fixing during fabrication [5].

Currently, there are several materials used in industry which meet requirements of mechanical systems. Among the materials of high mechanical properties Titanium and its alloys offer superior and profitable properties for a wide range of applications, for examples aeronautical, space, industrial, marine, medical and also civil and military construction industries [6]. This is due to their good combination of mechanical properties; for instance, excellent specific strength, good rigidity, high resistance to all types of corrosion in a sea water environment [7]. Recently, in the mechanical

* Corresponding author.
E-mail addresses: mboujelbene@yahoo.fr (M. Boujelbene), elaoudbouthaina@gmail.com (B. El Aoud).

https://doi.org/10.1016/j.matpr.2020.12.179
2214-7853/

industry, laser cutting has been adopted to cut many shapes of aeronautical and general mechanical parts, also for a wide variety of materials. Significant research has been done on laser cutting of the S285 mild steel, low and high alloy steels, aluminum and its alloys, nickel alloys, and hard materials including nitride boron cubic CBN, which are difficult to machine by any other mechanical or chemical manufacturing processes [8-12].

The output parameters of the system which depend on the input and on the basis of which justifies the application of this technology are: dimensional control, surface roughness, cutting precision, striation frequency, change in micro-hardness, residual stresses, change in the structure of the base material, width of the heat affected zone HAZ, cutting width, cutting angle, system efficiency, etc. [13,14]. The CO_2 power laser is one of the best known types of laser, for the machining of metallic materials used in the mechanical industries. The CO_2 lasers exhibit a dominance of this application because of their good beam quality, output power and high temperature values [14].

Recently, Boujelbene [15] optimized influence of the CO_2 laser cutting on the parameters and surface topographies of the machined part in low carbon steel. The quadratic mean roughness *Rq* and the effects of the variable laser machining parameters; cutting speed *V* and laser power *P* on the *Rq* were also investigated. In this work author proposed via ANOVA a parametric approach model according to the laser cutting conditions.

The most of the work carried out by the laser process takes into account the physical parameters of the laser cut surface to describe the surface quality of the mechanical parts produced. The most used characteristics are essentially the topographic surface roughness of the parts and width of the HAZ. It can also be argued that the nature and type of assist gas has a relatively small influence on the quality of the cuts of the industrial parts produced. Key factors influencing the laser machining quality of the refractory materials were also studied in the above study. This provided the basis for solving the problem of laser cutting, and their prediction methods [16].

In this study, main laser cutting parameters were investigated to predict the Ti sheet roughness, and then improving the quality level of the process. The maximum cutting speed (*V*) achieved in CO_2 laser cutting with stainless steel sheets of different dimensions was carried out by Stelzer et al. [17]. The experimental results reported by Cekic et al. [13] have shown the decrease in the value of the roughness Ra with an assistance gas N_2 and increased cutting speed of AISI 304 stainless steel. The surface topography is an interesting parameter in the mechanical system, in tribology and in fluid mechanics, due to its great effect on the movement and the separation of the fluid in the micro-fluidic chip. This property was not previously taken into account specifically in systemic studies in general [18-21].

This paper studies and analyzes the process of cutting the 2 mm thick plane sheet of pure Ti via CO_2 laser cutting process. This study will focus on optimising the effect of laser manufacturing parameters that include; laser power (*Pu*), laser cutting speed (*V*) and gas pressure (*p*) on the surface topography of the cut pieces. As an outcome of this study, optimised cutting conditions will be determined.

2. Experimental research

In this study, pure Ti sheet with following dimensions; 12 mm × 8 mm and a thickness of 2 mm were used. The 4000 TLF TURBO CO_2 laser machine was employed to carry out the laser cutting procedures. Mechanical and physical characteristics of pure Ti are given in Table 1.

Table 1
Mechanical and physical properties of Ti.

Fracture strength (MPA)	345
Elastic limit 0,2 (MPA)	275
Elongation %	20
Brinell hardness	160 HB/30
Modulus of elasticity (GPA)	103
Modulus of rigidity (GPA)	40

The laser cutting processing input variables were; *Pu*: 1 to 3 kW, pressure *p*: 2 to 14 bars and *V*: 480 to 2400 mm/min. Table 2 summarise the input variables used in this study.

The cut surfaces of the fabricated part that were taken using the WILD MAKROSKOP M420 with a 12.5 × zoom and camera is shown in Fig. 1. For each pieces produced three areas or places were studies that include;

- Start of entry of the laser beam into the machined material.
- Middle of the cut surface.
- End of the cut part by the laser radiation.

A Somocronic Surfascan measurement system connected to a PC computer was used, in order to obtain the measurements results of the machined surfaces, in the form of 2D profiles and 3D surface topographies. For reliability of the analysis, 3 roughness measurements were taken from each samples produced in this study. This will minimize measurement errors and ensure greater analysis precision. However, the roughness parameters such as *Ra* and *Rt* were critically analysed in this work.

Fig. 2 shows the measurement points taken along the surface of the laser-machined parts

- 0.3 mm below the upper cutting edge (IN)
- Center of the machined surface of the part (MIDDLE)
- 0.3 mm above edge of bottom surface (OUT)

The distances of the elementary surfaces measured were located from the upper machining edge of the part; for 0.3 mm for IN, and 1 mm for MIDDLE and 1.7 mm for OUT as shown in Fig. 2.

3. Results and discussion

The laser cutting operations generate a significant increase in heat, and therefore cut by localized melting of the material and rapid cooling of the cut surface. However, this type of cut generally produces regular patterns called ridges on the machined part surface. The machined surface obtained by the unconventional CO_2 laser process, presents remarkable streaks with significant amplitudes, and therefore have negative effects on the quality expected by the manufacturer and the client. However, the surface roughness obtained is therefore the irregularity of the surface profile and the irregularity of the topography of the manufactured surface. Surface roughness is presented as the unevenness or irregularity of the surface profile. In order to control and analyse the surface quality, the characteristics of the average roughness, or the arithmetic roughness *Ra* and the total roughness *Rt* of the 2D profile of the part surface produced were studied. The average measurement results of the amplitude roughness parameters previously chosen at a value of the laser power of *Pu* = 3 kW and at a gas pressure *p* = 2 bars have been presented in Tables 3 to 5.

Fig. 3 and Fig. 4 show the plots of the results of the parts surfaces obtained after the laser cutting operations.

Tables 3, 4 and 5 and Fig. 3 and Fig. 4 present qualitative measurements of the surfaces cut by the laser beam. However, the

Table 2
Process variables and experimental design levels.

Cutting parameters	Symbol	Unit	Level 1	Level 2	Level 3
Laser power	*Pu*	kW	1	2	3
Cutting speed	*V*	mm/min	480	1440	2400
Gas pressure	*p*	bars	2	8	14

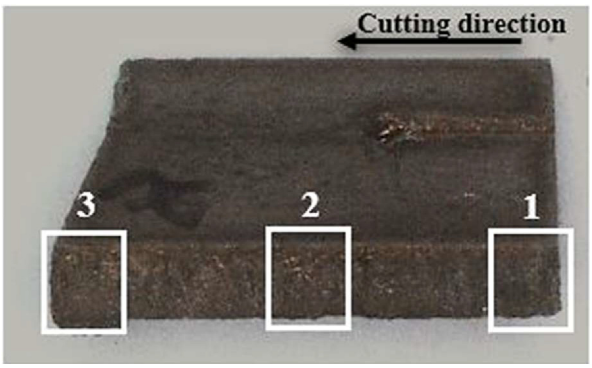


Fig. 1. Three zones of cutting surface for measurement.

Fig. 2. Procedure of roughness measurement.

Table 3
Surface roughness measurement at $V = 480$ mm/min.

Parameters	In	Middle	Out
Ra (μm)	5.755	12.198	15.036
Rt (μm)	47.968	62.324	86.339

Table 4
Surface roughness measurement at $V = 1440$ mm/min.

Parameters	In	Middle	Out
Ra (μm)	4.77	10.252	12.517
Rt (μm)	31.963	51.511	76.805

Table 5
Surface roughness measurement at $V = 2400$ mm/min.

Parameters	In	Middle	Out
Ra (μm)	3.935	9.606	11.017
Rt (μm)	26.761	44.436	72.587

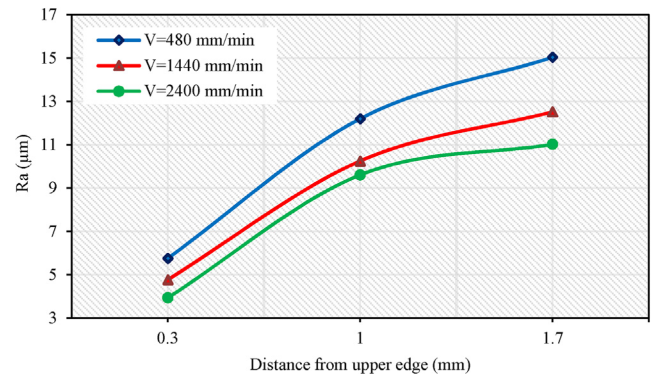


Fig. 3. R_a as a function of distance from upper edge for different cutting speeds at $Pu = 3$ kW and $p = 2$ bars.

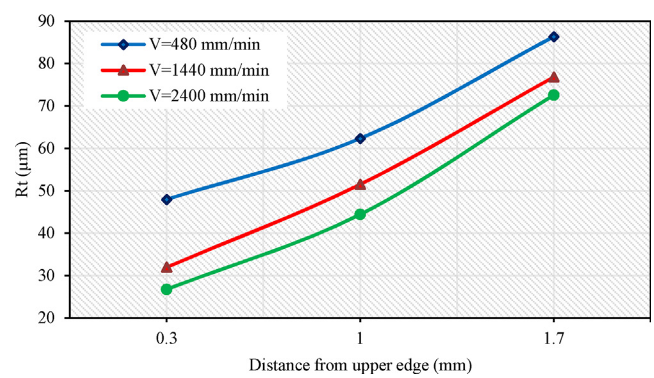


Fig. 4. R_t as a function of distance from upper edge for different cutting speeds at $Pu = 3$ kW and $p = 2$ bars.

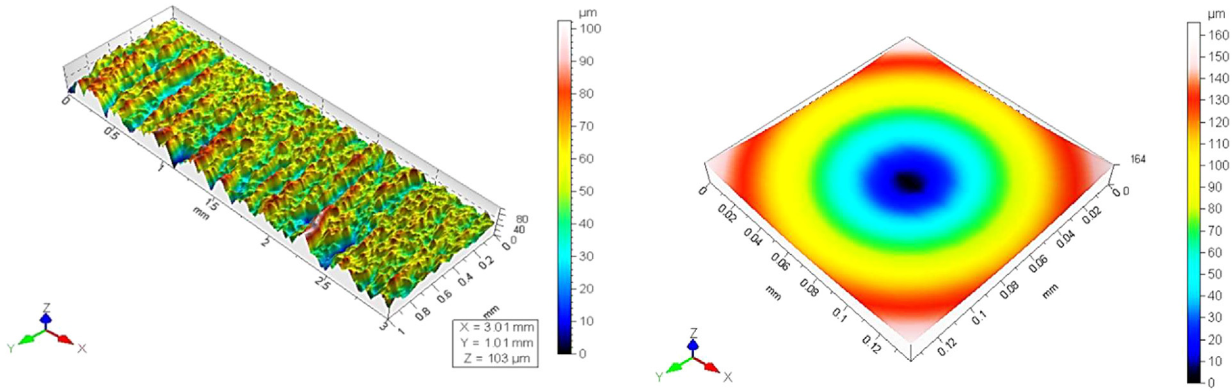
arithmetic mean roughness *Ra* and the total roughness *Rt* increase as a function of the distance from the starting cutting surface (upper cutting edge), and this for all cutting speeds *V* equal to 480; 1440 and 2400 mm/min.

In addition, the cutting surfaces quality of the parts is improved by increasing the cutting speed beyond 2400 mm/min. In fact, one of the key attributes of producing mechanical parts by the laser machining process is cutting speed. If the cutting speed *V* is relatively low, it results in a larger and wider *kerf*, and also greater damage to the cutting precision and the surface quality of the produced parts.

On the other hand, if the cutting speed is increased enormously, the latter may produce insufficient exposure of the part to the laser beam and may cause problems in the machining of the mechanical parts. In general, a compromise must be found between the meterial removal rate, MRR and the quality of the cutting surface for machining materials by the laser process. The work is in agreement with the experience on the cutting of mild steel confirmed that the roughness value decreases marginally with growth or increase with parameter *V* (cutting speed). However, this part also discusses the influence of the principal input of the laser machining parameters process on the precision and geometric quality of machined surface work pieces. A parametric study considers the greater influence of the laser power on surface quality in CO_2 laser cutting process of pure Ti.

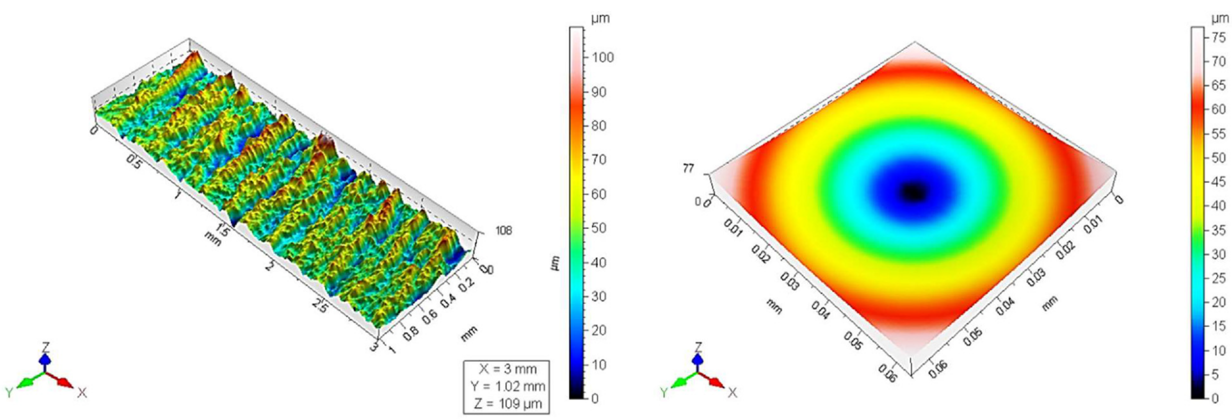
The 3D surface topography of the machined surface is shown in Fig. 5 and Fig. 6. It is interesting to note that laser cutting leads to topographic and micro geometric changes on the cutting surface.

The results of the study show that laser power predominantly influence quality of the surfaces produced. However, to improve the precision and the quality of the surface cut from the part by



(a) (b)

Fig. 5. Machined surface at V = 480 mm/min and p = 2 bar and Pu = 2 kW; (a) 3D surface topography, (b) Contour of elementary filtered surface.



(b) (b)

Fig. 6. Machined surface at V = 480 mm/min and p = 2 bar and Pu = 4 kW; (a) 3D surface topography, (b) Contour of elementary filtered surface.

laser beam, it is recommended to optimise laser power and cutting speed simultaneously.

4. Optimization using Taguchi's method

Laser cutting is similar to other machining and mechanical manufacturing processes in general which require several inputs and results in outputs. However, the answers must be optimized according to the requirements of manufacturers in the laser or mechanical industry. The objective of this research study is to control the topography and the desired values of the surface to obtain optimal values for the inputs of the cutting parameters by the laser cutting process. While keeping the gas pressure p fixed; Fig. 7 and Fig. 8 show a remarkable influence of the laser beam power Pu and the cutting speed V on the output responses, topography and surface quality Ra and Rt.

The plots shown in Fig. 7 and Fig. 8 indicate that the arithmetic surface roughness and total surface roughness are significantly affected by both the V and Pu. In order to obtain a good optimization of the output or the surface quality in this case, it is incumbent to identify the input variables of the system or the cutting conditions by the power laser machining process. All parameters and cutting conditions and their interactions were applied for the initial analysis with Root Mean Square, RMS. Equations (1) and (2) represent the final quadratic models of the response with real factors.

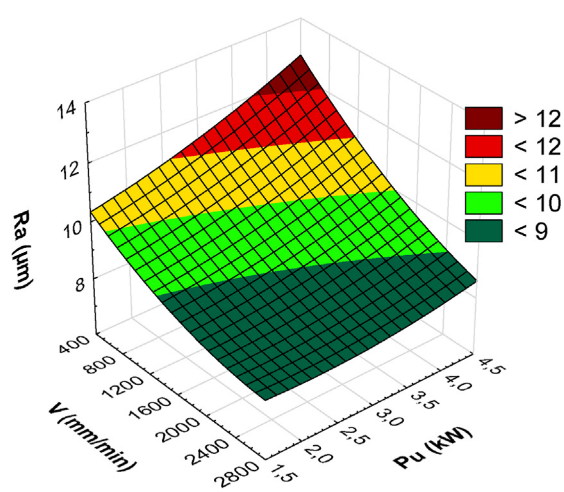


Fig. 7. Effect of V and Pu on Ra.

$$Ra = 9.73 + 0.773Pu - 0.000977V - 0.082p - 0.000186Pu.V + 0.0163Pu.p + 0.000038V.p - 0.000009Pu.V.p \quad (1)$$

$$Rt = 62.50 + 3.17Pu - 0.00977V - 0.60p - 0.00012Pu.V + 0.213Pu.p + 0.000366V.p - 0.000110Pu.V.p \quad (2)$$

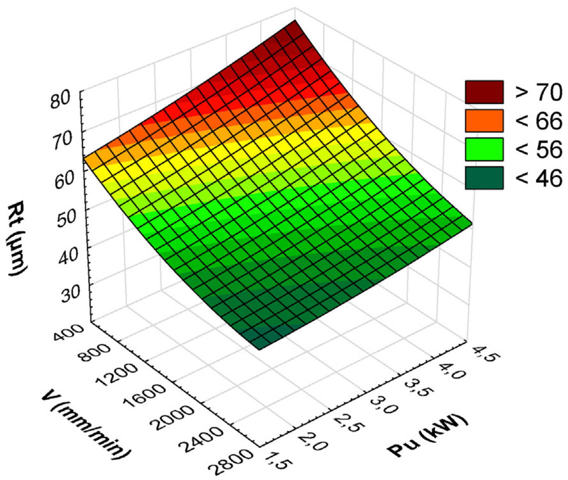


Fig. 8. Effect of *V* and *Pu* on *Rt*.

where the Average roughness *Ra* in (µm), the total roughness *Rt* in (µm), the cutting speed *V* in (mm/min), the laser power *Pu* in (kW) and the gas pressure *p* in (bar).

Among the experimental design techniques, the Taguchi method which allows minimizing and reducing the number of experiments and trials by using orthogonal tables was used. In addition, attempts were made to minimize the influence of factors out of control. However, among the advantages of the Taguchi method are to minimize and to reduce the time allocated for the experiments, also to reduce the cost and to determine the most significant factors of the system in an efficient way.

From Equation (3), the calculations of the levels values and the S/N ratios were performed correctly of using the Minitab 17 program, while specifying "the smaller is the better"

$$\frac{S}{N} = -10\log\frac{1}{n}\left(\sum y^2\right) \quad (3)$$

where *y* is the average of the observed data, *n* the number of observations, Σy^2 the variation of *y*, and *y* the observed data or each type of the characteristics.

Table 6 shows the results of S/N ratios while using Equation (3). The result of the present study shows that the optimal values of the S/N ratio are: −18.04 for *Ra* and –32.94 for *Rt*. In order to obtain the mixed responses of the arithmetic roughness *Ra* and total roughness *Rt*, we find the following optimal parameters; *V* equal to 2400 mm/min, *Pu* equal to 2 kW and *p* equal to 2 bars.

Using the Taguchi design, Tables 6 and 7 represent the found values of the levels factors for *Ra*. Also, the Fig. 9 shows the graphic of mean of S/N ratios versus factor levels *Ra*.

In order to determine the most significant parameters on the responses of the machining system, we worked on the scientific Taguchi method. However, the result of the study shows that the cutting speed *V* has the most important difference 2.45 between values, and also we found a great variation of the S/N ratio values, this specifies that there is a significant influence on roughness Ra.

Table 6 represent the results of experiments and S/N ratios values of the surface roughness *Ra* and *Rt* as function of the three parameters. However, at the end of this study, we recorded the following optimal cutting parameters; *Pu* equal to 2 kW, *V* equal to 2400 mm/min and gas pressure *p* equal to 14 bars.

Consequently, the optimum cutting conditions determined under the same conditions for the experiments will be: laser power (*Pu*): 2 kW, cutting speed (*V*): 2400 mm/min and gas pressure (*p*): 14 bars. The Taguchi design was conducted to obtain *Rt* values. The Table 8 clearly shows the values of the levels which were obtained using the MINITAB 17 software, and also according to the Taguchi method.

Fig. 10 and Table 8 show the following optimum values; *V* corresponds to the third level (2400 mm/min), *Pu* corresponds to the first level (2 kW), and *p* corresponds to the first level (2 bars).

The critical analysis of this study showed that the optimal values of the cutting parameters are as follows: Laser beam power *Pu*: 2 kW, the cutting speed *V*: 2400 mm/min and finally the pressure of gas *p*: 2 bars.

Table 6
The results of experiments and S/N ratios values.

Experimental number	*Pu* (kW)	*V* (mm/min)	*p* (bar)	R_a (µm)	R_a *for S/Nratios*	R_t (µm)	R_t *for S/Nratios*
1	2	480	2	10.56	−20.47	63.21	−36.02
2	2	480	8	10.61	−20.51	67.53	−36.59
3	2	480	14	10.06	−20.05	61.17	−35.73
4	2	1440	2	9.14	−19.21	50.46	−34.06
5	2	1440	8	9.47	−19.52	58.62	−35.36
6	2	1440	14	8.76	−18.84	53.02	−34.49
7	2	2400	2	7.98	−18.04	44.37	-32.94
8	2	2400	8	8.41	−18.49	49.74	-33.93
9	2	2400	14	7.94	−17.99	45.38	-33.14
10	3	480	2	11.00	−20.82	65.54	-36.33
11	3	480	8	11.53	−21.23	71.96	-37.14
12	3	480	14	10.74	−20.62	64.95	-36.25
13	3	1440	2	9.18	−19.25	53.43	-34.56
14	3	1440	8	9.93	−19.94	60.81	-35.68
15	3	1440	14	9.24	−19.31	55.81	-34.93
16	3	2400	2	8.19	−18.26	47.93	-33.61
17	3	2400	8	8.68	−18.76	52.09	-34.33
18	3	2400	14	8.25	−18.33	48.85	-33.78
19	4	480	2	11.80	−21.44	69.52	-36.84
20	4	480	8	12.97	-22.26	77.68	-37.81
21	4	480	14	11.51	−21.21	73.48	-37.32
22	4	1440	2	9.84	−19.85	57.61	-35.21
23	4	1440	8	10.25	−20.21	63.18	-36.01
24	4	1440	14	9.72	−19.75	57.22	-35.15
25	4	2400	2	8.72	−18.81	49.22	-33.84
26	4	2400	8	9.22	−19.29	56.38	-35.02
27	4	2400	14	8.47	−18.55	51.16	−34.18

Table 7
S/N response table for R_a factor.

Level	*V* (mm/min)	*Pu* (kW)	*p* (bars)
1	−20.96	−19.24	−19.58
2	−19.55	−19.62	−20.03
3	−18.51	−20.16	−19.41
Delta	2.45	0.92	0.62

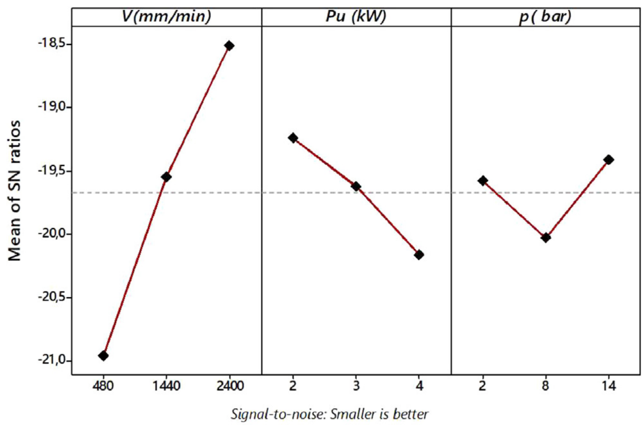


Fig. 9. The graphic of mean of S/N ratios versus factor levels *Ra*.

Table 8
S/N response table for R_t factor.

Level	*V* (mm/min)	*Pu* (kW)	*p* (bars)
1	−36.67	−34.70	−34.82
2	−35.05	−35.18	−35.76
3	−33.86	−35.71	−35.00
Delta	2.81	1.01	0.94

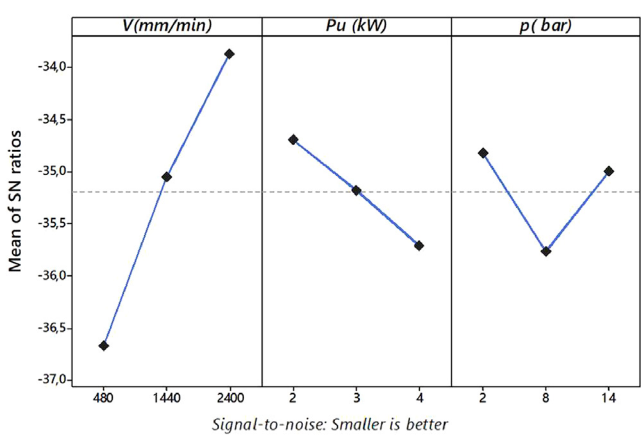


Fig. 10. The graphic of mean of S/N ratios versus factor levels *Rt*.

5. Conclusion

The laser cutting process has been used in several engineering applications. This research focused on the CO_2 laser cutting of pure grade 2 Ti sheet. Results show significant influence of cutting speed (*V*), laser power beam (*Pu*), and the gas pressure (*p*) on the surface quality of machined parts. Following conclusions could be drawn from this study:

- The quality and the surface topography of the cut pieces were influenced by the main input parameters such as the power of the laser beam and the speed of movement of the nozzle.
- Cutting speed has a dominant effect on surface quality and topography. However, several macro-irregularities for example; the presence of slag, molten and burnt material were observed.
- A cutting speed of 2400 mm/min resulted in high quality surfaces after cutting process. The values of roughness parameters grow with the increase in distance from upper cut edge.

The Taguchi experimental design was used to obtain optimum cutting parameters on CO_2 Laser cutting. At the end of this research work, we iterate the following additional outcomes;

- *Ra* and *Rt*'s S/N ratios were found as a result of experiments conducted according to the *L27* orthogonal array.
- The S/N ratio equation with "the smaller-the better" to find maximum values was adopted. The maximum S/N ratio allowed us to find optimal machining parameters.
- For the smallest value of the arithmetic roughness *Ra*, a maximum value of the S/N ratio is −18.04. The optimal values of the parameters are; *V*: 2400 mm/min, *Pu*: 2 kW and the gas pressure *p*: 14 bars.
- For the smallest value of the total roughness *Rt*, a maximum value of the S/N ratio is –32.94. However, the optimal values of the parameters are; *Pu*: 2 kW, *V*: 2400 mm/min and the gas pressure *p*: 2 bars.

CRediT authorship contribution statement

M. Boujelbene: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **B. El Aoud:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **E. Bayraktar:** Formal analysis, Investigation, Writing - original draft. **I. Elbadawi:** Writing - review & editing. **I. Chaudhry:** Writing - review & editing. **M. Abdul Khaliq:** Writing - review & editing. **A. Ayyaz:** Supervision. **Z. Elleuch:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research has been funded by Scientific Research Deanship at University of Ha'il – Saudi Arabia through project number RG-191281.

References

[1] A.K. Dubey, V. Yadava, Laser beam machining - A review, Int. J. Mach. Tools Manuf. 48 (6) (2008) 609–628.
[2] B. El Aoud, M. Boujelbene, E. Bayraktar, S. Ben Salem, Optimization of *Kerf* quality during CO_2 laser cutting of titanium alloy sheet Ti-6Al-4V and pure titanium Ti, Mech. Compos. Hybrid Multifunct. Mater. 5 (2019) 213–219, https://doi.org/10.1007/978-3-319-95510-0_26.
[3] M. Boujelbene, A.-S. Alghamdi, I. Miraoui, E. Bayraktar, M. Gazbar, Effects of the laser cutting parameters on the micro-hardness and on the heat affected zone HAZ of the mi-hardened steel, Int. J. Adv. Appl. Sci. 4/(5) (2017) 19–25.
[4] I. Miraoui, M. Boujelbene, E. Bayraktar, Analysis of cut surface quality of sheet metals obtained by Laser machining: Thermal effects, J. Adv. Mater. Process. Technol. 1 (3-4) (2015) 633–642.
[5] W.M. Steen, J. Mazumder, Laser Material Processing, Springer, New York, 2010.
[6] N. Poondla, T.S. Srivatsan, A. Patnaik, M. Petraroli, A study of the microstructure and hardness of two titanium alloys: Commercially pure and Ti–6Al–4V, J. Alloy. Compd. 486 (1-2) (2009) 162–167.
[7] J.A. Jacobs, T.F. Kilduff, Engineering Materials Technology, 5th edition., 2004, p. 886.

[8] I. Miraoui, E. Elimi, M. Boujelbene, E. Bayraktar, Analysis of roughness and microstructure for high-power laser cutting of stainless steel, Adv. Sci. Lett. 19 (2) (2013) 483–486.
[9] B. El Aoud, M. Boujelbene, E. Bayraktar, S. Ben Salem, I. Miskioglu, Studying effect of CO_2 laser cutting parameters of titanium alloy on heat affected zone and *Kerf* width using the taguchi method, Mech. Compos. Multi-funct. Mater. 6 (2018) 143–150.
[10] A. Hascalik, M. Ay, CO_2 laser cut quality of Inconel 718 nickel – based superalloy, Opt. Laser Technol. 48 (2013) 554–564.
[11] C. Mao, X. Sun, H. Huang, C. Kang, M. Zhang, Y. Wu, Characteristics and removal mechanism in laser cutting of cBN–WC–10 Co composites, J. Mater. Process. Technol. 230 (2016) 42–49.
[12] I. Miraoui, M. Boujelbene, E. Bayraktar, Analysis of roughness and heat affected zone of steel plates obtained by laser cutting, Adv. Mater. Res. 974 (2014) 169–173.
[13] A. Cekic, D. Begic-Hajdarevic, M. Kulenovic, A. Omerspahic, CO_2 laser cutting of alloy steels using N_2 assist gas, Procedia Eng. 69 (2014) 310–315.
[14] A. Riveiro, F. Quintero, F. Lusquiños, R. Comesaña, J. Pou, Parametric investigation of CO_2 laser cutting of 2024–T3 alloy, J. Mater. Process. Technol. 210 (9) (2010) 1138–1152.
[15] M. Boujelbene, Influence of the CO_2 laser cutting process parameters on the Quadratic Mean Roughness *Rq* of the low carbon steel, Procedia Manuf. 20 (2018) 259–264.
[16] B.T. Rao, R. Kaul, P. Tiwari, A.K. Nath, Inert gas cutting of titanium sheet with pulsed mode CO_2 laser, Opt. Lasers Eng. 43 (12) (2005) 1330–1348.
[17] S. Stelzer, A. Mahrle, A. Wetzig, E. Beyer, Experimental investigations on fusion cutting stainless steel with fiber and CO_2 laser beams, Physics Procedia 41 (2013) 399–404.
[18] J. Powell, S.O. Al-Mashikhi, A.F.H. Kaplan, K.T. Voisey, Fibre laser cutting of thin section mild steel: An explanation of the 'striation free' effect, Opt. Lasers Eng. 49 (8) (2011) 1069–1075.
[19] B. El Aoud, M. Boujelbene, E. Bayraktar, S. Ben Salem, A. Boudjemline, Experimental comparison of the microstructure and surface roughness in CO_2 laser cutting of the titanium alloy Ti–6Al–4V and the pure titanium Ti, Mech. Compos. Hybrid Multifunct. Mater. 5 (2019) 249–255.
[20] M. Bahrami, M.M. Yovanovich, J.R. Culham, Pressure drop of fully developed, laminar flow in microchannels of arbitrary cross-section, J. Fluids Eng. 128 (2006) 1036–1044.
[21] Y.-L. Zhang, J.-H. Lei, Prediction of laser cutting roughness in intelligent manufacturing mode based on ANFIS, Procedia Eng. 174 (2017) 82–89.