Chapter 26
Optimization of Kerf Quality During CO_2 Laser Cutting of Titanium Alloy Sheet Ti-6Al-4V and Pure Titanium Ti

B. El Aoud, M. Boujelbene, E. Bayraktar, and S. Ben Salem

Abstract CO_2 laser cutting is an advanced processing technology, which can, according to the computer-aided design graphics, cut a variety of shapes in the surfaces of many metallic sheets. Laser cutting of various materials including the Titanium alloy Ti-6Al-4V and pure Titanium Ti is carried out to assess the kerf width size variation along the cut section. This work aims to analyze the effect of laser power, cutting speed, and gas pressure on the kerf quality of Ti-6Al-4V alloy and Ti with CO_2 laser cutting process. The kerf width size is formulated and predicted using the lump parameter analysis and it is measured from the experiments. The influence of laser output power Pu and laser cutting speed V and pressure nitrogen assisting gas p on the kerf width size variation is analyzed using the analytical tools including scanning electron and optical microscopes. The quality of laser cut kerf mainly depends on appropriate selection of process parameters. Uniform kerf with minimum kerf width is always demand. It has been found that the kerf width during CO_2 laser process is not uniform along the length of cut. A considerable improvement in kerf quality has been achieved.

Keywords CO_2 laser cutting · Kerf quality · Titanium alloys Ti-6Al-4V · Pure titanium Ti · And optimization

26.1 Introduction

Sheet-metal cutting is the single largest, in terms of sales, global industrial laser application. CO_2 lasers dominate this application due to their good-quality beam combined to high output power. It is estimated that more than 40,000 cutting machines using CO_2 lasers have been installed worldwide. However, aluminum alloys, typical engineering materials in different industries such as automotive or aerospace industry, are not extensively cut by lasers [1]. Laser cutting involves with high temperature processing of materials including solid phase heating, melting, and evaporation. In the case of metallic materials processing, assisting gas is used to reduce the oxidation reactions in the cutting section. Since the oxidation reactions gives rise to excessive heating in the cutting section via high temperature exothermic reactions, the resulting section suffers from cutting asperities such as sideways burning, dross attachments, and thermal erosion [2]. The proper controlling of the laser cutting process through appropriate selection of the cutting parameters minimizes the defect sites along the cut sections. However, further investigations are needed for net shaping of the materials, which involve with high thermal conductivities and low fracture toughness such as titanium alloys and alumina [3]. Laser cutting of thick sections offers considerable advantages over the conventional techniques due to precision of operation, short processing time, and low cost. The physical processes involved in laser cutting of thick sections are complicated and significantly influences the end product quality. Laser parameters, in particular laser output power, focus on setting of focusing lens, cutting speed, assisting gas, and its pressure influence the physical processes in the cutting section. In this case, controlling the affecting parameters results in improved cutting quality. Consequently, investigation into affecting parameters in laser cutting process is necessary to improve the end product quality [4–6]. Laser cutting widely used in metallic and non-metallic materials such as polymer, composites or ceramics [7–9]. Most authors were focusing on the power intensity and cutting speed.

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Table 26.1 Chemical composition of Ti-6Al-4 V (%)

Ti	Al	V	Fe	C	N	H	O
Base	6	4	0.3	0.08	0.05	0.01	0.2

Table 26.2 Mechanical and physical properties of pure Titanium Ti

Mechanical break (MPA)	345
Elasticity limit 0,2 (MPA)	275
Elongation %	20
Hardness	160 HB/30
Normal modulus of elasticity (GPA)	103
Tangential modulus of elasticity (GPA)	40

Laser cutting of advance ultra-high strength steel 22MnB5 by Abdul Fattah et al. [10] resulted in combined effect of laser power and cutting speed on kerf width formation. Most study show that Increment of cutting speed reduced kerf width formation and HAZ region, whereas the higher laser power produced inverse results [11, 12]. Laser cutting process and the assessment of cutting parameters on kerf size and geometry are important aspects of the quality evaluation of the end product. Optimization studies on laser cutting offers improved process control and securing of the end product quality. Modelling and optimization study for the assessment of the cut quality of a thin aluminum-alloy was carried out by Sharma and Yadava [13]. They introduced the entropy measurement methodology for the calculation of weight corresponding to each quality characteristic. Ghany and Newishy [14] have observed the variation of kerf width with cutting speed, laser power, and type of gas and pressure as above during experimental study of Nd: YAG laser cutting of 1.2 mm-thick austenitic stainless steel sheet. During his experimental investigation, found that kerf width increases with increasing laser power and decreasing the cutting speed. He also observed that oxygen or air gives wider kerf while use of inert gas gives the narrow kerf. They have also found that on increasing pulse frequency the kerf width decreases. A CO_2 laser cutting of 3 mm thick of Titanium alloy sheet grade 5 Ti-6Al-4V is investigated by B. El AOUD et al. [15]. Results indicate that the thickness of the Heat affected Zone increases with the evolution of laser power and decreases with the increase of cutting speed, and the optimum cutting condition was found to be 1 kW for the laser power, 2400 mm/min for the cutting speed and 2 bars for gas pressure. Also, it is underlined that the kerf width is mainly influenced by laser power and cutting speed.

In the present study, laser cutting of composites consisting of Titanium alloy (Ti-6Al-4V) and pure Titanium (Ti) are carried out. The kerf width variation due to the laser output power parameters is examined. The study is extended firstly to investigate the kerf width variation along the cut edges with the cutting parameters such as laser power, cutting speed and gas pressure and secondly to introduce the use of Taguchi method to optimize kerf variation. The resulting cut sections are examined using the scanning electron microscope (SEM) and optical microscope.

26.2 Experimental Work

The CO_2 laser from laser machine type 4000 TLF TURBO is used to irradiate the workpiece surface. Nitrogen emerging from a conical nozzle and co-axially with the laser beam is utilized. The workpieces accommodated are Ti-6Al-4V and pure Ti with their elemental composition are given in Tables 26.1 and 26.2 respectively. The sheet dimensions were 20 mm × 15 mm with thickness of 3 mm for Titanium alloy Ti Ti-6Al-4V and 12 mm × 8 mm with thickness of 3 mm for pure Titanium Ti.

26.3 Design of Experiment

The experiment was designed based on a three levels of parameters. Laser power ($Pu = 1$–4 kW), cutting speed ($V = 480$–2400 mm/min) and gas pressure ($p = 2$–14 bars). In order to achieve best cutting quality, Taguchi's experimental design, an efficient plan, was used for conducting experiments. According to Table 26.3, L_{18} orthogonal array are used to reduce number of the experiments.

Table 26.3 Experimental multi-performance results

EXP. No	*Pu (kW)*	*V (mm/min)*	*p (bar)*	*Kw [Ti6Al4V] (μm)*	*Kw [Ti] (μm)*
1	2	480	2	623.10	574.78
2	2	480	8	586.20	517.20
3	2	480	14	607.42	562.02
4	2	1440	2	582.01	542.53
5	2	1440	8	534.71	483.65
6	2	1440	14	571.63	532.79
7	2	2400	2	545.23	487.01
8	2	2400	8	474.68	471.57
9	2	2400	14	483.16	519.77
10	3	480	2	654.60	599.07
11	3	480	8	591.65	554.77
12	3	480	14	743.64	631.40
13	3	1440	2	615.28	571.48
14	3	1440	8	555.43	546.55
15	3	1440	14	586.27	586.65
16	3	2400	2	559.62	512.07
17	3	2400	8	476.97	530.42
18	3	2400	14	499.95	575.47

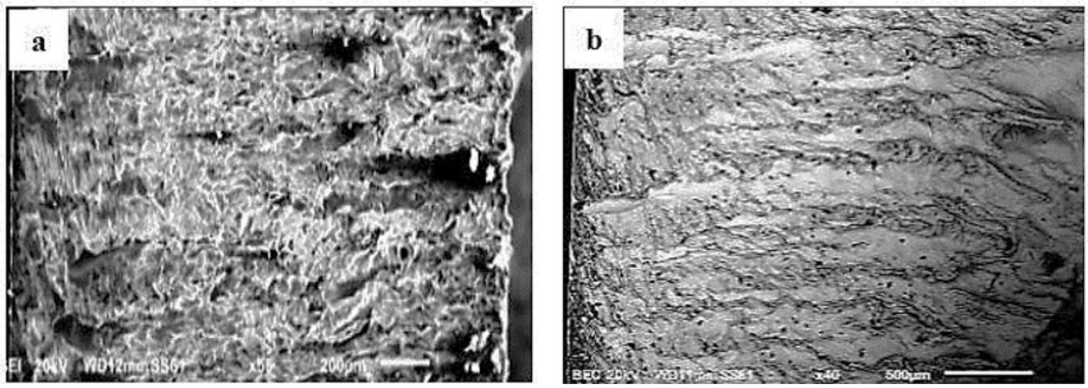

Fig. 26.1 SEM micrographs of laser cut kerf surfaces at laser power $Pu = 3$ kW, the cutting speed $V = 480$ mm/min and the gas pressure $p = 2$ bars: (**a**) Ti-6Al-4 V alloy and (**b**) pure Titanium

26.4 Results and Discussion

CO$_2$ Laser gas assisted cutting of titanium alloy (Ti-6Al-4V) and pure Titanium (Ti), is carried out. The effect of laser output power and cutting speed on the kerf width size variation is analyzed.

Figures 26.1 and 26.2 show SEM micrographs of laser cut kerf surfaces of the workpieces for two different conditions of laser output power and cutting speeds. The kerf surfaces appear to be almost similar for metallic materials; in which case, some striations with flow of liquid metal are observed. The rapid solidification of the liquid metal at the surface, due to the convection cooling effect of the high pressure assisting gas, gives rise to the formation of the cast layer at the kerf surface.

In the case of high power or low speed cutting process Fig. 26.1a, b, the cracks are partially extended on the kerf surface unlike the low power and high speed cutting process. This behavior is attributed to the thickness of the melt cast layer, which increases with the laser output power or the low cutting speeds.

In the case of high speed cutting or low power Fig. 26.2a, b, the cast layer formed at the kerf surface remains thin while resulting in attainment of high temperature gradients. This situation results in the crack network formation on the kerf surface [3].

Moreover, in the case of titanium alloy, the striation depth remains large at the kerf surface. This is associated with the high oxidation potential of titanium, which results in sideways burning and deep molten layer formation at the kerf surface.

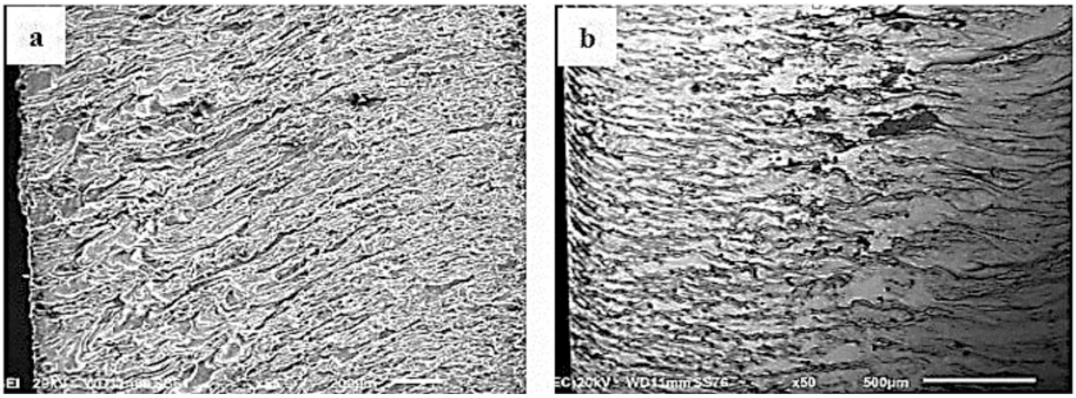

Fig. 26.2 SEM micrographs of laser cut kerf surfaces at laser power $Pu = 2$ kW, the cutting speed $V = 2400$ mm/min and the gas pressure $p = 2$ bars: (**a**) Titanium alloy Ti-6Al-4 V alloy, (**b**) pure Titanium Ti

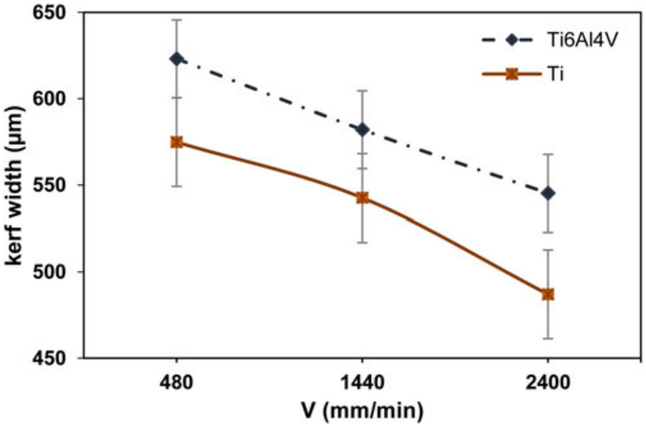

Fig. 26.3 Kerf width size variation with the laser cutting speed for Ti-6Al-4V and pure Titanium Ti at $Pu = 2$ kW and $p = 2$ bars

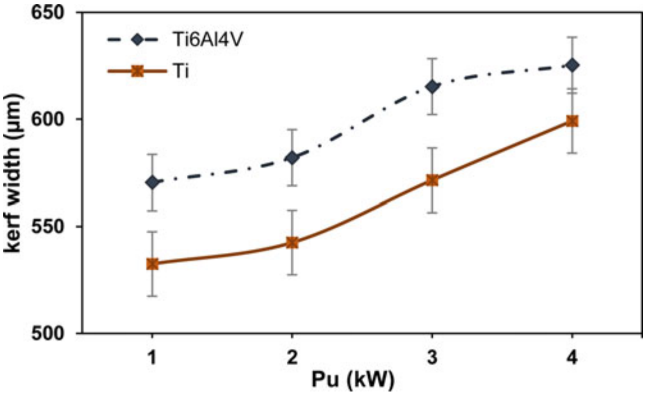

Fig. 26.4 Kerf width size variation with the laser power for Ti-6Al-4V and pure Titanium Ti at $V = 1440$ mm/min and $p = 2$ bars

It should be noted that high temperature exothermic reactions results in excessive energy generation contributing to the laser beam energy in the cutting section [16]. This causes deep striation patterns at the surface [17].

Figures 26.3 and 26.4 show the effect of two output laser parameters; cutting speed (V) and Laser power (Pu) on the kerf width variation for two different materials; Titanium alloy (Ti-6Al-4V) and pure Titanium (Ti).

It is evident from Fig. 26.3 that the kerf width size decreases as the cutting speed increases. This is associated with the formation of large molten layer due to the excessive energy provided via ectothermic reactions in the cut section. In fact, when using slow cutting speed more heat would be introduced to the specimen and then more materials will be melted and ejected causing the kerf to increase.

According to Fig. 26.4, kerf width size variation demonstrates the opposite behavior to that for the laser output cutting speed. In fact, increasing laser output power increases the kerf width size, which is more pronounced for the titanium alloy. This is due to the high temperature exothermic reactions, which provide excess energy in the cutting section. Since the assisting gas used is nitrogen, the presence of the oxygen remains low in the cutting section. However, high oxygen affinity of titanium alloy gives rise to the oxidation reactions taking place locally in the cutting section. Therefore, localized thermal erosion is resulted at the kerf surface while causing the deep striation formations. In addition, this gives rise to the formation of varying kerf width size along the cut edges. Consequently, kerf width size increases with increasing output Laser power.

26.5 Kerf Width Optimization

Taguchi method of robust parameter design is an offline statistical quality control technique in which the level of controllable factors or input process parameters are so chosen to nullify the variation in responses due to uncontrollable or noise factors.

In Taguchi method, the experimental values of quality characteristics are used to compute the quality loss values for each quality characteristic in all experimental runs. In the present case the smaller value of kerf width is desired, therefore the S/N ratio for smaller-the-better case will be used which is given below in equation form [18].

$$\frac{\mathrm{S}}{\mathrm{N}} = -10\log\frac{1}{n}\left(\sum y^2\right) \tag{26.1}$$

Where n is the number of observations and y the observed data or each type of the characteristics. S/N ratios obtained from this equation are given in Table 26.4.

As shown in Table 26.4 and according to the Taguchi method, the optimum cutting conditions is found as S/N equal to −53.53 and − 53.47 for kerf width *Kw* of Titanium alloy Ti-6Al-4V and *Kw* of pure Titanium Ti respectively. Thus, the optimum cutting conditions which were the laser power of 2 kW, the cutting speed of 2400 mm/min and the gas pressure of 8 bars.

The interpretations can be made according to the level values of *Pu*, *V*, and *p* factors obtained for kerf width *Kw* of Ti-6Al-4V given in Table 26.5 and for *Kw* of pure Titanium Ti given in Table 26.6. The different values of S/N ratio between maximum and minimum are (main effect) also shown in these tables. Figures 26.5 and 26.6 show the graphic of the level values given in Tables 26.5 and 26.6 respectively.

The cutting speed and the gas pressure are two factors that have the highest difference between values 1.94 and 0.94 respectively for Titanium alloy and 0.91 and 0.81 respectively for pure Titanium Ti. Based on the Taguchi prediction the

Table 26.4 S/N Ratios values

EXP. No	*Pu (kW)*	*V (mm/min)*	*p (bar)*	*[Ti6Al4V] S/N ratios*	*[Ti] S/N ratios*
1	2	480	2	−55.89	−55.19
2	2	480	8	−55.36	−54.27
3	2	480	14	−55.67	−54.99
4	2	1440	2	−55.30	−54.69
5	2	1440	8	−54.56	−53.69
6	2	1440	14	−55.14	−54.53
7	2	2400	2	−54.73	−53.75
8	2	2400	8	−53.53	−53.47
9	2	2400	14	−53.68	−54.32
10	3	480	2	−56.32	−55.55
11	3	480	8	−55.44	−54.88
12	3	480	14	−57.43	−56.01
13	3	1440	2	−55.78	−55.14
14	3	1440	8	−54.90	−54.75
15	3	1440	14	−55.36	−55.37
16	3	2400	2	−54.96	−54.19
17	3	2400	8	−53.57	−54.49
18	3	2400	14	−53.98	−55.20

Table 26.5 S/N response table for *Kw* [Ti-6Al-4 V] factor

Level	*Pu (kW)*	*V(mm/min)*	*p(bar)*
1	−54.87	−56.02	−55.50
2	−55.30	−55.17	−54.56
3		−54.07	−55.21
Delta	0.43	1.94	0.94

Table 26.6 S/N response table for kerf width *Kw* [Ti] factor

Level	*Pu (kW)*	*V(mm/min)*	*p(bar)*
1	−54.32	−55.15	−54.75
2	−55.06	−54.70	−54.26
3		−54.24	−55.07
Delta	0.74	0.91	0.81

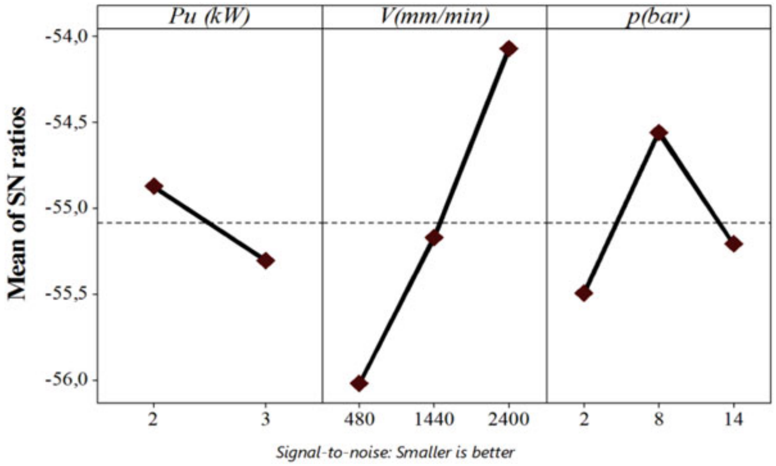

Fig. 26.5 The graphic of mean of S/N ratios for kerf width *Kw* [Ti-6Al-4V]

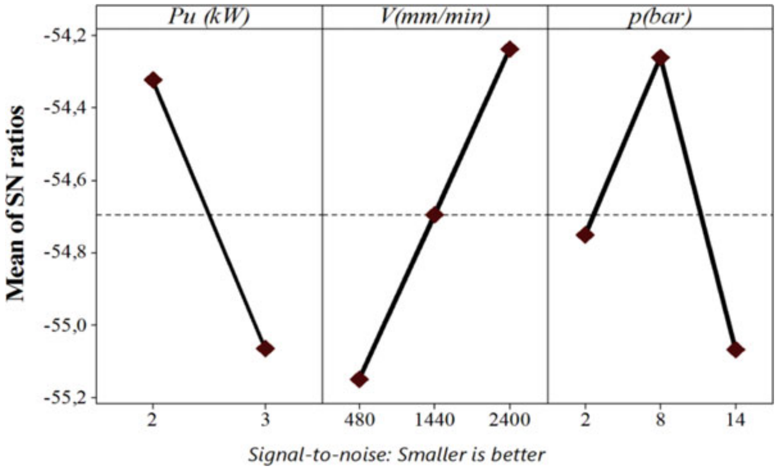

Fig. 26.6 The graphic of mean of S/N ratios for kerf width *Kw* of pure Titanium [Ti]

larger different between value of S/N ratio will have a more significant effect on Kerf width size. According to Table 26.5, the first level of laser power, the third level of cutting speed and the second level of gas pressure are higher. Consequently, the optimum cutting conditions determined under the same conditions for the experiments to be conducted will be 2 kW for laser power, 2400 mm/min for cutting speed and 8 bars for gas pressure for Ti-6Al-4V. For pure Titanium the same results are showed, hence, the optimum cutting conditions determined will be 2 kW for laser power, 2400 mm/min for cutting speed and 8 bars for gas pressure (see Table 26.6).

26.6 Conclusion

The present research consist of parametric study and analysis of influence of cutting parameters in CO_2 laser cutting of Titanium alloy (Ti-6Al-4V) and pure Titanium (Ti). The cutting parameters selected during experiments are laser power (*Pu*), cutting speed (*V*) and gas pressure (*p*), while the response parameter taken is the kerf width variation.

Basing on the results of conducted experimental research and their analysis, following conclusions were drawn:

- In the case of high power or low speed cutting process, the cracks are partially extended on the kerf.
- In the case of high speed cutting or low power, the cast layer formed at the kerf surface remains thin.
- In the case of titanium alloy, the striation depth remains large at the kerf surface.
- For both materials; Titanium alloy Ti-6Al-4V and pure Titanium Ti, the kerf width size decreases as the cutting speed increases.
- For both materials; Titanium alloy Ti-6Al-4V and pure Titanium Ti, the kerf width size increases with increasing output Laser power.
- The kerf width is proportional to laser power and inversely proportional to cutting speed.
- Kerf width Kw [Ti-6Al-4V] and Kw [Ti], S/N ratios are found as a result of experiments conducted according to the L_{18} orthogonal array. The maximum value was found by using the S/N ratio equation of “the smaller-the better,” the maximum S/N ratio yielded optimum cutting parameters.
- The optimum cutting conditions for Titanium alloy Ti-6Al-4V and pure Titanium Ti determined will be 2 kW for laser power, 2400 mm/min for cutting speed and 8 bars for gas pressure.

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