Surface Quality of Ti-6Al-4V Titanium Alloy Parts Machined by Laser Cutting

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Abstract-**This paper investigates high power CO_2 laser cutting of 5mm-thick Ti-6Al-4V titanium alloy sheets, aiming to evaluate the effects of various laser cutting parameters on surface roughness. Using multiple linear regression, a mathematical model based on experimental data was proposed to predict the maximum height of the surface *Sz* as a function of two laser cutting parameters, namely cutting speed and assist-gas pressure. The adequacy of the proposed model was validated by Analysis Of Variance (ANOVA). Experimental data were compared with the model's data to verify the capability of the proposed model. The results indicated that, for fixed laser power, cutting speed is the predominant cutting parameter that affects the maximum height of surface roughness.**

Keywords-laser cutting; titanium alloy; cutting speed; gas pressure; maximum height of surface roughness

I. INTRODUCTION

Titanium alloys, including Ti-6Al-4V, are characterized by good mechanical and chemical properties such as high tensile strength and toughness, excellent resistance to corrosion and oxidation, light weight, resistance to extreme temperatures, and high strength-to-weight ratio. As a result, they are increasingly used in aerospace, spacecraft, automotive, biomedical, chemical and petrochemical, offshore oil and gas, water desalination, and power generation industries [1-8]. To overcome the difficulties encountered when using traditional machining techniques with super alloys, such as titanium alloys, engineering workshops resort to non-conventional techniques. These include Electrical Discharge Machining (EDM), Ultrasonic Machining (USM), Abrasive Water Jet Machining (AWJM) and Laser Machining (LM) [5, 9-10]. Laser cutting is a thermal-cutting process using a laser to cut materials, typically used in industrial manufacturing applications. This is achieved by focusing a high-power, coherent, and monochromatic laser beam, having a wavelength ranging from ultra-violet to infrared, onto the surface of a workpiece. Laser beam's energy is absorbed by the workpiece, resulting in rapid increase of material's temperature at the focused spot. The temperature is so high that, depending on the material's characteristics and beam's intensity, the material melts or vaporizes and may undergo chemical transformation, and is then removed using an assist gas at high pressure [11-19]. Surface roughness of materials and mechanical components plays an important role in determining their characteristics and performance for the intended applications. Therefore, it is crucial to quantify the roughness of finished materials and parts in order to ensure high quality and performance of the product [11, 20-29]. The quality of laser cutting, such as surface roughness, depends on many parameters such as thermal and optical properties of the material, laser power, cutting speed, type and pressure of the assist gas [13-14, 16, 22]. The effects of laser cutting parameters on the topographic quality of different metals have been the subject of many studies. For example, researchers in [30] used Nd:YAG laser to cut stainless steel sheets finding that in CW mode the surface became smoother as cutting speed increased. The surface roughness of Ti-6AL-4V cut with a pulsed Nd:YAG laser was investigated in [13] as a function of cutting speed, gas pressure, pulse width and pulse frequency, by employing an Artificial Neural Network (ANN) approach to successfully model and optimize surface roughness. Authors in [31] studied the effect of cutting speed and assist-gas pressure on the roughness of the cut edge. Their work showed that surface roughness decreased as both cutting speed and gas pressure increased, whereas roughness was higher at the lower part of the cuts. This study used line parameters, as they are more appropriate for analyzing the 3D surface. The investigated parameter was the maximum height of the surface *Sz*, defined as the peak-to-valley height over an areal measurement, as established in ISO 25178-2 standard. The maximum height of the surface was investigated as a function of two laser cutting parameters, cutting speed and assist-gas pressure. Subsequently, an analytical model was developed using multiple linear regression and ANOVA analyses to predict the variation of *Sz* as a function of these parameters.

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II. EXPERIMENTAL PROCEDURE

A. Experimental Conditions

In order to investigate the effects of laser cutting, small Ti alloy samples were cut from 5mm-thick sheets using an AMADA AS 4000 E /CO_2 laser sheet metal cutting machine, (Figure 1), in CW mode, and nitrogen as assist-gas. Tables I and II list the chemical composition and the mechanical properties of the alloy. This work examined two laser cutting factors, namely cutting speed V (mm/min) and assist-gas pressure p (bar), at a fixed laser power of 2kW. Three levels were specified for each factor, as shown in Table III.

Fig. 1. The laser cutting machine AMADA AS 4000 E.

TABLE I. CHEMICAL COMPOSITION OF TI-6AL-4V (%)

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

TABLE II. BASIC MECHANICAL PROPERTIES OF TI-6AL-4V

Hardness (HRC)	36
Density (g/cm³)	4.43
Modulus E (MPa)	910
Elongation (%)	0.7
Tensile strength (MPa)	1000
Thermal conductivity (W/mK)	7.3

TABLE III. IMPORTANT PROCESS PARAMETERS AND THEIR LEVELS

Factors	**Levels**		
	Level 1	**Level 2**	**Level 3**
Cutting speed: *V* (mm/min)	480	1440	2400
Gas pressure: *p* (bar)	2	8	14

B. Experimental Design using Full Factorial Design

One of the most commonly used experimental designs in manufacturing is the full factorial at 2 and 3-levels. In these designs, all possible combinations of factors (input or process variables) are used in order to fully and systematically investigate their impact and significance level on the output of the studied process. A full factorial design was adopted in this study resulting in 9 experiments with different factors and levels.

III. EXPERIMENTAL RESULTS

The surface roughness *Sz* of the 9 specimens was measured using a 3D optical surface roughness profilometer (3D-SurfaScan from Somicronic, seen in Figure 2), and data were analyzed with MountainsMap software program. It should be noted that one new sample was used for each experiment, and the reported *Sz* value was the average of three measurements taken from the middle of the sample. The effects of cutting speed *V* and assist-gas pressure *p* on the maximum height of surface roughness *Sz* are illustrated in Figures 3 and 4 respectively. Figure 3 shows that S_z decreased as *V* increased from 480 to 2400mm/min at a laser power of 2kW, for three fixed values of *p*: 2, 8 and 14bar. The smallest value of *Sz* was obtained at the highest speed. Figure 4 shows that as gas pressure *p* increased, *Sz* almost remained unchanged. Note that smallest values of *Sz* were obtained for the highest speed regardless of pressure. Both Figures indicate that the effect of gas pressure was minimal within the chosen value ranges.

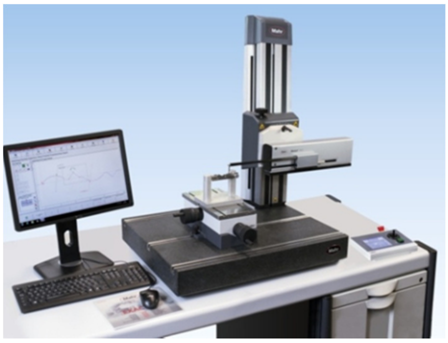

Fig. 2. The 3D-SurfaScan optical profilometer.

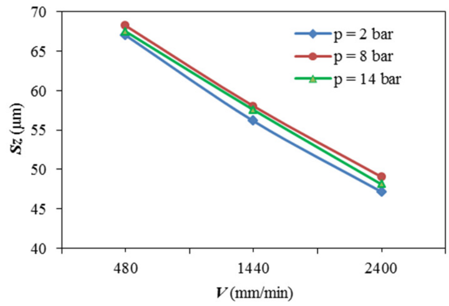

Fig. 3. *Sz* as a function of *V* for three values of *p*.

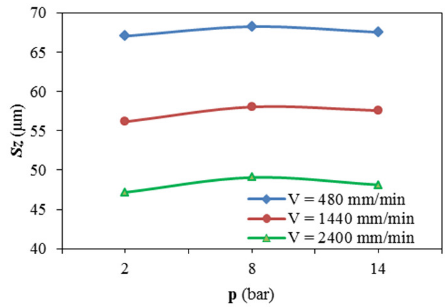

Fig. 4. *Sz* as a function of *p* for three values of *V*.

The decrease of roughness as speed increases is in agreement with the results obtained in [22] for Ti-6Al-4V, in [27] for carbon steel, in [31] for Ti-6Al-4V, in [32] for AISI316L stainless steel, and in [33] for ASTM stainless steel 304. In addition, in [34], 304 stainless steel showed at first a relatively rapid drop in roughness, which slowed as *V* increased indicating a possible plateau. Moreover, a drop in roughness with an increase in cutting speed of austenitic stainless steel was reported in [30], attributing it to the fact that at high speed there was not enough time for heat diffusion and formation of wider grooves. Contrary to this, in [35] it was showed, for 316L stainless steel, that roughness had an initial rapid increase as *V* increased, which levelled off at higher speeds. In [36], an almost constant value of roughness for certain values of cutting speed and an increase when the speed increased further was reported for 4130 stainless steel. This was explained by the possibility that speed may have reached an optimum value at which the roughness was minimum, noticing that this optimum value of V is also the value at which the frequency of striations started to increase, implying that roughness is strongly related to striations. The initial slight increase and then levelling off of Sz with an increase in p that was obtained is consistent with the results described in [33], where the roughness of 304 stainless steel increased as gas pressure increased. Likewise, authors in [30] also reported a small increase in roughness with an increase of pressure for austenitic stainless steel, explaining it by the increase in mechanical force due to the high pressure exerted on the molten material, which produced large peaks and valleys. The opposite was observed in [34] where the roughness of 304 stainless steel decreased slightly when p increased and then levelled off, indicating a negligible contribution of p. Similar results were also obtained in [31].

As the laser beam moves forward, the heated/molten material is affected by the convective cooling effect of the gas flow. This effect becomes relatively more pronouced as gas pressure increases [11, 37]. Moreover, the drag force exerted by gas on the molten metal increased as V increased. The combination of these two effects may have contributed to the small increase in Sz when p increased. Further increase in pressure may not increase the cooling effect, thus contributing less to the roughness change. The apparent agreement and disagreement of the results from this work with other studies show the interaction complexity of the process parameters and workpiece properties involved in laser cutting. The comparison is further complicated by the fact that the parameter value ranges are different. In this context, the results from the current investigation shed light on some aspects of laser cutting of metals and Ti-6Al-4V in particular. Hence, this work constitutes a positive contribution to the ongoing effort of better understanding this manufacturing process.

IV. MATHEMATICAL MODELING OF SURFACE ROUGHNESS

A mathematical model, which approximates the surface roughness of Ti-6Al-4V alloy as a function of the cutting speed and assist-gas pressure was developed. Linear regression analysis was used to achieve this goal. Subsequently, ANOVA was performed to estimate the level of significance of each factor's contribution to the regression model, considering only individual variables. Statistical analysis was conducted with the statistical software package Minitab.

A. Normality Test

Linear regression and ANOVA require a normal distribution of data. To this effect, a normal probability plot was generated, shown in Figure 5. As it is depicted, the residuals fall approximately along a diagonal straight line, indicating that data do not deviate severely from a normal distribution [38].

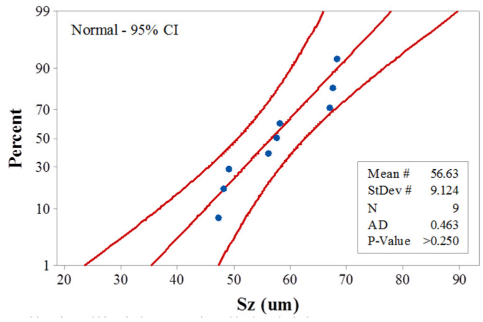

Fig. 5. Normality test of maximum surface roughness parameter Sz.

B. Regression Analysis

The validity of the model equation obtained by regression analysis is based on the assumption that the residuals or error terms are constant with a mean of zero [39].These assumptions were tested by plotting the residuals versus the produced fitted values, as depicted in the top right plot in Figure 6, showing that the residuals are randomly scattered around zero, and not forming any clusters or distinct patterns, suggesting that the errors have constant variance. In addition, the top left normal probability plot shows that the plotted points follow nearly a diagonal straight line, suggesting that the errors are almost normally distributed. Furthermore, the histogram in the bottom left plot shows no evidence in residuals' deviation from normality. Finally, the bottom right plot represents the residuals against the order in which data were collected, showing that there is no pattern, and they are scattered uniformly around 0, indicating that the error terms are independent from one another and the regression assumptions are satisfied [39-42].

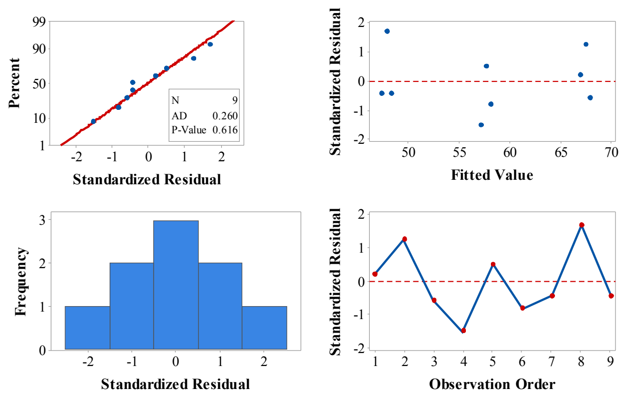

Fig. 6. Residual plots resulting from multiple linear regression analysis of the effects of V and p on Sz.

Based on these assumptions, multiple linear regression analysis was carried out at a 95% level of confidence. The first order linear equation resulting from the linear regression is:

$$Sz = 71.627 - 0.010146 \times V + 0.0794 \times p \quad (1)$$

where, Sz is measured in µm, V in mm/min and p in bars. The model described by (1) shows clearly that an increase in V will lead to a decrease in surface roughness, while an increase in p will increase it. Model's goodness of fit is measured by the coefficient of determination R^2. The value obtained from regression analysis, as seen in Table IV, indicates that 99.33% of the variability in the surface roughness is associated with the input parameters values. Hence, the high value of R^2 justifies the validity of the model.

TABLE IV. REGRESSION MODEL SUMMARY

S	R^2 (%)	R^2(adj. %)	PRESS	R^2(pred. %)
0.801300	99.33	99.11	7.66013	98.67

As noted in Table V, p-values, at a 95% level of confidence for *V*, are much lower than 0.05. This indicates that *V* plays a significant role and has a strong effect on *Sz*. However, p-value for *p* is 0.195, implying that, within the used range of values for *p*, there is not enough evidence to conclude that the assist-gas pressure has an effect on roughness. The Variance Inflation Factor (VIF) for the two parameters is 1, implying the absence of multicollinearity [38, 40].

TABLE V. COEFFICIENTS OF THE REGRESSION ANALYSIS AT 95% LEVEL OF CONFIDENCE

Term	Coef.	SE Coef.	95% CI	T-value	p-value	VIF
Constant	71.627	0.709	(69.892, 73.361)	101.06	0.000	
V (mm/min)	−0.010146	0.000341	(−0.010980, −0.009312)	−29.77	0.000	1.0
p (bar)	0.0794	0.0545	(−0.0540, 0.2129)	1.46	0.195	1.0

C. Analysis of Variance (ANOVA)

Once the linear model was generated, ANOVA was used to determine the level of significance of each parameter's contribution to surface roughness. The results of this analysis are displayed in Table VI.

TABLE VI. ANOVA FOR MULTIPLE LINEAR REGRESSION MODEL

Source	DF	Seq SS	Contri-bution (%)	Adj SS	Adj MS	F-value	p-value
Regression	2	570.569	99.33	570.569	285.284	444.31	0.000
V (mm/min)	1	569.206	99.09	569.206	569.206	886.50	0.000
p (bar)	1	1.363	0.24	1.363	1.363	2.12	0.195
Error	6	3.852	0.67	3.852	0.642		
Total	8	574.421	100.0				

In addition to the p-values, the Table also shows that the contribution of *V* (99.09%) is much higher than that of *p* (0.24%). This confirms that *V* is the dominant factor. Based on the results presented above, it is concluded that the regression model given by (1) is statistically significant with a value of R^2 equal to 99.33%. Both experimental and predicted values of maximum surface roughness for the 9 samples are plotted in Figure 7. It can be noted that model's results are very close to the experimental ones.

D. Interaction Plots

The interaction plots in Figure 8 show that all plots' lines are almost parallel. This indicates that the relationship between each parameter and surface roughness is independent from the other. It is worth mentioning that lines corresponding to assist-gas pressure are nearly parallel to the x-axis, meaning that within these value ranges this parameter had little effect on roughness.

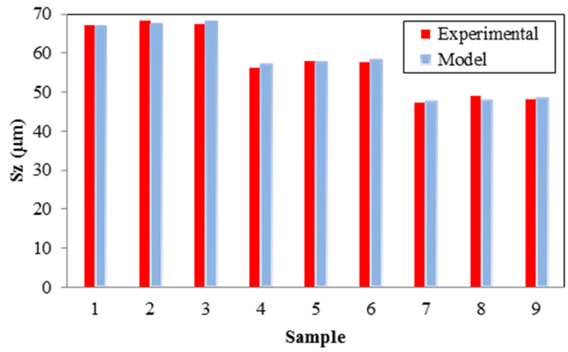

Fig. 7. Comparison between experimental and predicted data for maximum surface roughness.

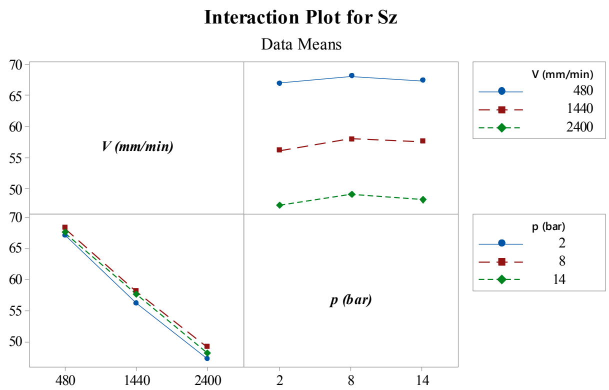

Fig. 8. Interaction plot showing the effects of cutting speed *V* and assist-gas pressure *p* on surface roughness *Sz*.

E. Contour Plots

Contour plots representing *Sz* against *V* and *p* are depicted in Figure 9 to determine the optimum working zone.

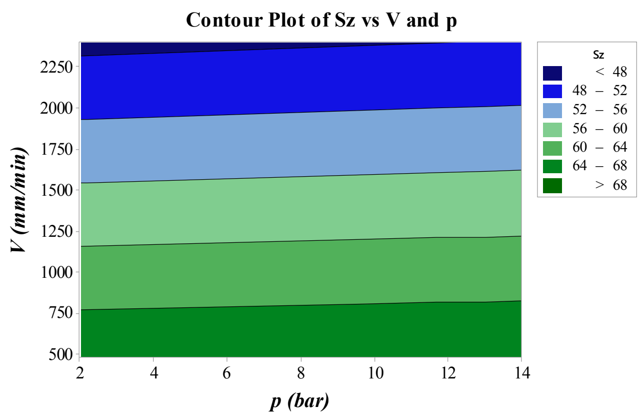

Fig. 9. Contour plot of surface roughness *Sz* versus cutting speed *V* and assist-gas pressure *p*.

It is inferred that, for a fixed laser power of 2kW the desired working zone lies between 2250 and 2400mm/min, for assist-gas pressure between 12 and 14bar.

V. CONCLUSION

This study investigated the effects of laser cutting parameters, namely cutting speed V and assist-gas pressure p, at a fixed laser power, on the maximum height of the surface roughness Sz of Ti-6Al-4V titanium alloy sheets. Using experimental data, a mathematical model was developed to provide the relationship between the surface roughness and the laser cutting parameters. To accomplish this task, multiple linear regression analysis was employed, followed by ANOVA to validate the model. Within the used control parameters' value ranges, the salient conclusions of this experimental study are:

- Cutting speed is the dominant factor affecting surface roughness. Increasing it leads to roughness decrease.
- Assist-gas pressure has no significant effect on surface roughness.
- A simple first-order regression model using the two laser cutting parameters was developed. Its goodness of fit R^2 was 99.33%, confirming its adequacy.
- The model's ANOVA showed that the effect of gas pressure is almost insignificant contributing only 0.24% to surface roughness compared to cutting speed with 99.09%.
- Excellent agreement between the experimental and predicted results was obtained.
- This model can be deployed during manufacturing to choose the right values of cutting parameters in order to achieve the desired surface quality, leading to a reduction in machining time and cost.

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