OPTIMIZATION OF PROCESS PARAMETERS FOR CUT QUALITY IN CO₂ LASER CUTTING USING TAGUCHI METHOD

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Abstract

Laser cutting is a popular manufacturing process utilized to cut various types of materials. There are many non-linear interaction factors responsible for the performance of the laser cutting process. Identification of dominant factors that significantly affect cut quality is important. In this paper, the effect of the process parameters is analysed on the laser cut quality of an uncommon alloy, the tungsten alloy sheet with thickness of 1 mm. The experiments are conducted at three levels of the selected process parameters such as assist gas type (oxygen, air and nitrogen) and assist gas pressure. Taguchi design of experiments is used to obtain the optimum conditions through the study of signal to noise ratio for three quality characteristics such as kerf width, heat affected zone and surface roughness. Results of this study indicate that the optimal assist gas pressure is entirely different for kerf width, heat affected zone and surface roughness. The nitrogen as assist gas is suggested as the optimal assist gas for all of three quality characteristics.

Keywords: CO₂ laser cutting; cut quality; process parameters; Taguchi method; tungsten alloy.

1. Introduction

Laser cutting is one of the important applications of lasers in industry, especially for machining materials that are difficult to cut. Compared with other conventional machining processes, laser cutting removes little material, involves highly localized heat input to the work piece, minimizes distortion, and offers no tool wear [1]. Particular interests of manufacturers using laser cutting are the productivity and the quality of components made by the laser cutting process. Both aspects are managed by selection of appropriate laser process parameters, which are unique for each material and thickness. Most work reviewed in the literature considers only one or two characteristic properties of the laser cut surface to describe quality [2]. Kerf width, surface roughness and size of heat affected zone are often used to describe laser cut quality. Some researchers [3] show that the size of heat affected zone increases with increase of the laser power and decreases with increase of the cutting speed and gas pressure. Oxygen gas as assist gas produces better surface roughness compared to air and nitrogen during laser cutting of tungsten composite materials using pulsed Nd: YAG [4]. They also observe that the nitrogen assist gas develops an oxide free surface and a low discoloration, while the oxygen assist gas surface is strongly oxidized and discoloured. The effect of laser power, cutting speed and oxygen assist gas pressure on

the cut quality in laser cutting of tungsten alloy is analysed in [5]. They define optimal cutting parameters in laser cutting examined alloy by using oxygen as assist gas.

There are various aspects of laser beam machining that can be modelled with different methods in order to predict quality characteristics which are essential for any manufacturing process [6]. In [7] technique to predict surface roughness in the laser cutting process is developed for the first time by analysing the dynamic phenomenon that happens within the cutting front. The quality characteristics (such as kerf width, surface roughness and cut edge slope) were observed for the various cutting parameters such as laser power, cutting speed and assist gas pressure during pulsed CO₂ laser cutting of Al6061/SiCp/Al₂O₃ composite [8]. Hybrid approach of grey based response surface methodology for predicting the optimal combination of laser cutting parameters is used. A grey relational analysis is used to determine a single optimized set of cutting parameters in precision laser cutting of three different thermoplastics [9]. It is found that the laser power has dominant effect on heat affected zone for all thermoplastics. The relation between process parameters and quality characteristics in CO₂ laser cutting of tungsten alloy was modelled with artificial neural network [10]. It is shown that the proposed model could be useful tool for surface roughness and kerf width prediction. In [11] comparison of surface roughness during CO₂ laser cutting of tungsten alloy plate using oxygen as assist gas, based on control charts made by statistical process control (SPC) approach is reported. For further analysis, it is especially interesting to analyse uncommon materials and alloys where the common knowledge is not applicable [12].

Comprehensive review of the literature shows that research work in the area of laser cutting of tungsten alloy is limited. Hence, this paper aims to investigate the effect of laser cutting process parameters on the cut quality features and then to obtain the optimal cutting conditions by using Taguchi design of experiments through the study of signal to noise ratio that would lead to the desired quality features. The process parameters such as assist gas type (oxygen, nitrogen and air) and assist gas pressure are considered as the experimental variables. The experimental work is carried out on tungsten alloy sheet with thickness of 1 mm in CO₂ laser cutting process.

2. Experimental procedure

The experiments are carried out on a Rofin CO₂ laser system with a nominal output power of 2000 W in CW mode at a wavelength of 10.6 μ m with a high quality beam, as shown in figure 1. The experimental investigations are conducted at the University of Applied Science Jena in Germany. Tungsten alloy sheet (92.5 % pure tungsten in a matrix of nickel and iron) with thickness of 1 mm is used for this experiment. The laser beam is focused using a 127 mm focal length lens. Assist gases are used coaxially with the laser beam via a 2 mm exit diameter nozzle. Focus position, nozzle stand off distance (stand-off), laser power and cutting speed are kept constant throughout the main experimentation. The constant process parameters are shown in table 1.

Assist gas type	Laser power	Cutting speed	Stand-off	Focus position
Oxygen	2000 W	4000 mm/min	1.00 mm	-0.50 mm
Nitrogen	2000 W	1750 mm/min	0.75 mm	-0.50 mm
Air	2000 W	1500 mm/min	1.00 mm	- 1.00 mm

Table 1. Constant process parameters and their values

Assist gas type and pressure are selected as variable process parameters. Process parameters with their units and values at different levels are listed in table 2. Testing the effect of one parameter on the cut quality requires the variation of one parameter while keeping the other parameters at the pre-selected values.

Parameter	Unit	Level 1	Level 2	Level 3
Assist gas type	---	Oxygen	Air	Nitrogen
Assist gas pressure	bar	10	12.50	15

Table 2. Process parameters and their different levels

Observed quality characteristics are top kerf width, heat affected zone (HAZ), surface roughness and dross formed at bottom side. Visual inspections of each cut are carried out to ensure that no pitting and burrs are present within the cut areas. Measurements and sample geometry are shown in figure 2.

Surface roughness of the cut edge is measured in terms of the average roughness R_a , using a Taylor-Hobson stylus instrument. Roughness is measured along the length of a cut approximately in the middle of the thickness. Five consistent surface roughness values of each sample are measured and an average value is calculated for each sample.

The top kerf width and size of heat affected zone are measured using Stemi optical microscope fitted with a video camera and a zoom lens. Kerf width and heat affected zone are measured in the microscopic images of each sample at five different places and an average value is calculated for each sample and each controlled parameters. The dross formed at bottom side is observed using a TesaVisio microscope.

Fig. 1. CO₂ laser system

Fig. 2. The measured characteristics of cut quality

3. Experiment design

Taguchi method is used widely in engineering analysis to optimize performance characteristics by the means of settings of design parameters [13]. Taguchi methodology for robust parameter design is an off-line statistical quality control technique in which the level of controllable factors or input process parameters are chosen in a way to nullify the variation in responses due to uncontrollable factors such as humidity, vibration, noise etc. The objective of Taguchi approach is to determine the optimum setting of process parameters or control factors, thereby making the process insensitive to the sources of variations due to uncontrollable factors [14]. Taguchi has tabulated 18 basic types of designed experimental matrixes known as orthogonal arrays. The selection of orthogonal arrays is based on the number of controllable factors and their levels and interactions [15]. In this method main process parameters or control factors which influence process results are set as input parameters and the experiment is performed per specifically designed orthogonal array. More than one test per trail can be used to conduct the experiments. It increases the sensitivity of experiments to detect small changes in averages of responses. Economic consideration too can be performed for conducting the repeated experiments with the same experimental run.

In this study L₉ Taguchi orthogonal array design is selected. Measured experimental values obtained for different quality characteristics in each experimental run are given in table 3.

Exp. no	Process parameter level		Measured parameters		
	Gas Type	Gas Pressure	Kerf width, mm	HAZ, mm	Ra, μm
1	1	1	0.282	1.386	5.805
2	1	2	0.306	1.322	7.532
3	1	3	0.310	1.326	7.303
4	2	1	0.240	1.477	6.150
5	2	2	0.244	1.395	7.026
6	2	3	0.247	1.357	7.073
7	3	1	0.200	1.457	5.167
8	3	2	0.174	1.322	5.917
9	3	3	0.175	1.196	6.215

Table 3. Kerf width, heat affected zone and surface roughness obtained from experiments

Taguchi method uses the S/N ratio to measure characteristic deviating from the desired value. The S/N ratio is the ratio of the mean to the standard deviation. Taguchi method suggests that the signal to noise ratio (S/N) can be used as a quantitative analysis tool. Since smaller kerf width, heat affected zone and surface roughness values are desired in this experiment the signal-to-noise ratio is chosen as:

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right) \quad (1)$$

where: y_i is the observed data of quality characteristic at the i -th trial and n is the number of repetitions at the same trial. The S/N ratio represents the desired part/ undesired part and the aim is always to maximize the S/N ratio whatever nature of quality characteristics are. Based on the experimental results S/N ratio for each controlled parameters is obtained as shown in table 4.

Exp. no	Process parameter level		S/N ratio		
	Gas Type	Gas Pressure	Kerf Width	HAZ	Ra
1	1	1	10.99	-2.83	-15.27
2	1	2	10.28	-2.42	-17.54
3	1	3	10.17	-2.45	-17.27
4	2	1	12.39	-3.39	-15.78
5	2	2	12.25	-2.89	-16.93
6	2	3	12.14	-2.65	-16.99
7	3	1	13.98	-3.27	-14.26
8	3	2	15.19	-2.42	-15.44
9	3	3	15.14	-1.55	-15.87

Table 4. S/N ratio calculated for kerf width, heat affected zone and surface roughness

4. Results and discussion

4.1. The effect process parameters on top kerf width

The analysis of the experimental results revealed the assist gas type as the most important parameter determining the kerf width (see figure 3). The kerf width slightly changes as the assist gas pressure increases.

Fig. 3. Experimental observation for kerf width

Fig. 4. The effect of process parameters on kerf width for S/N ratio

From S/N ratio analysis shown in figure 4 optimal process parameters for kerf width are determined as assist gas pressure 12.5 bar and nitrogen as assist gas. Also it can be observed from figure 5 that kerf width slightly increases as assist gas pressure increases. Narrowest kerf width is obtained in laser cutting when used nitrogen as assist gas for all of three levels assist gas pressure. While the largest kerf width is made during CO₂ laser cutting when used oxygen as assist gas.

Fig. 5. The effect of process parameters on kerf width for the means

4.2. The effect process parameters on heat affected zone

Measured experimental values obtained for the size of heat affected zone are shown in figure 6. It can be observed that the largest heat affected zone is obtained in CO₂ laser cutting when used air as assist gas. The reason for this may be that the lowest cutting speed is selected when air is used as an assist gas in comparison to two other assist gases that are used in the experiments.

Fig. 6. Experimental observation for heat affected zone

The effect of process parameters on the size of heat affected zone for the S/N ratio and for the means are shown in figures 7 and 8, respectively. From the S/N ratio analysis shown in figure 7 optimal process parameters for the heat affected zone are determined as assist gas pressure 15 bar and nitrogen as assist gas. From figure 8 it can be observed that the size of heat affected zone decreases as the assist gas pressure increases. Smallest size of heat affected zone is obtained when nitrogen as assist gas is used.

Fig. 7. The effect of process parameters on heat affected zone for S/N ratio

Fig. 8. The effect of process parameters on heat affected zone for the means

4.3. The effect process parameters on surface roughness

The measured experimental values obtained for surface roughness are shown in figure 9. It can be observed that the smallest surface roughness is obtained when nitrogen as assist gas is used. It can be seen that surface roughness increases as the assist gas pressure increases for all of three assist gasses which are used in the experiments. On the microscopic images shown in figure 9 it can be seen that the dross is formed on the bottom side of sample along the entire length of a cut at nitrogen pressure of 10 bar, while this is not the case at a nitrogen pressure of 12.5 bar.

From the S/N ratio analysis shown in figure 10 optimal process parameters for surface roughness are determined as assist gas pressure 10 bar and nitrogen as assist gas. Also it can be observed from figure 11 that surface roughness slightly increases as assist gas pressure increases over 12.5 bar. It can be concluded that the measured experimental values of surface roughness which are obtained for all of three levels assist gas pressure belonged to the same class of roughness.

Fig. 9. Experimental observation for surface roughness

Fig. 10. The effect of process parameters on surface roughness for S/N ratio

Fig. 11. The effect of process parameters on surface roughness for the means

5. Conclusion

In this paper the effect of the process parameters on the quality characteristics such as top kerf width, heat affected zone and surface roughness in CO₂ laser cutting of tungsten alloy with thickness of 1 mm is analysed using Taguchi orthogonal arrays method. Type of assist gas has the most significant effect on the cut quality in CO₂ laser cutting process.

Medium level of assist gas pressure and nitrogen as assist gas as the optimal process parameters for desired cut quality in CO₂ laser cutting of tungsten alloy are recommended.

Future work should include application of Taguchi orthogonal arrays method in laser cutting process, including the effect of different process parameters such as laser power, cutting speed, focus position and other parameters.

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