ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
DOI: 10.17559/TV-20130719101736

SURFACE QUALITY FINISH IN LASER CUTTING USING TAGUCHI DESIGN

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Original scientific paper

The present work aims at obtaining parametric combination to achieve the best surface finish and assess effects of selected process parameters on a laser cut quality for laser cutting. This helps to study the variation in response parameter (*Ra* value) for various levels of selected process parameters. In the present work mild steel specimen is used and the effect of the key parameters such as laser pulse frequency (pulse repetition rate), laser pulse width and cutting speed on surface finish are critically analysed. For experimental design and parametric analysis robust design is used i.e. a fractional factorial experimental design with an appropriate orthogonal array followed by variance and sound to noise ratio analysis.

Keywords: *cutting speed; factorial design; laser pulse width; orthogonal array; pulse repetition rate (PRR) or pulse frequency*

Kvaliteta završne obrade kod laserskog rezanja uporabom Taguchi dizajna

Izvorni znanstveni članak

Cilj je ovoga rada dobivanje parametrijske kombinacije kako bi se postigla najbolja završna obrada i procijenili učinci odabranih parametara obrade na kvalitetu laserskog rezanja kod uporabe lasera. To pomaže kod proučavanja promjena u parametru reakcije (vrijednost *Ra*) za različite razine odabranih parametara procesa. U ovom radu korišten je uzorak mekog čelika i kritički je analiziran učinak ključnih parametara kao što su frekvencija laserskog impulsa (brzina ponavljanja impulsa), širina impulsa i brzina rezanja na završnu obradu. Za plan pokusa i analizu parametara rabljen je robusni dizajn tj. frakcijski faktorski plan pokusa s prikladnim ortogonalnim nizom nastavljenim analizom varijance i odnosa zvuka i šuma.

Ključne riječi: *brzina ponavljanja impulsa (PRR) ili frekvencija impulsa; brzina rezanja; faktorski plan pokusa; ortogonalni niz; širina impulsa lasera*

1 Introduction

Unconventional technologies [1] such as Electrical discharge machining (EDM) [2, 3], Water Jet machining [4 ÷ 6]; plasma machining [7, 8] and laser machining [9] are one of the most extensively used non-conventional material removal processes. Laser is used to cut a wide range of materials. It is suitable for cutting thin workpieces. CO_2 laser and Nd:YAG laser are the most popular lasers in cutting, they can provide high peak powers (above 1 kW) for high-speed cutting. Laser cutting can be basically divided into two kinds [10, 11]. First is the direct evaporative laser cutting, in which laser provides the latent heat until the material reaches vaporization point and ablate in vapour state, such as laser cutting of organic materials - paper, cloth or polymers. Such materials have poor thermal conductivity; a non-reactive gas jet may be used to reduce charring. The second is laser cutting through melting or fusion, laser energy melts the target material and the assist gas jet blows the molten material away [10]. In this way the requirement of laser energy is lower compared with vaporization cutting [11]. The assist gas jet can be reactive or non-reactive. If the assist gas jet is reactive, laser heat combined with exothermic chemical reaction with the assisting gas provides the heat necessary for melting & vaporization of the target material. This is called reactive laser cutting. This helps to further reduction of the necessary laser energy. Although good number of fundamental research has been done in the area of laser cutting technology [12÷15] still further research is required to determine the combine effects of the process parameters for achieving high quality surface finish and dimensional accuracy. This will also help to develop knowledge based system and effective utilization of the process parameters for the desired results. Present work focuses on obtaining parametric combination to achieve the best surface finish and assess effects of various process parameters. Experiments were conducted on a Mild Steel specimen of thickness 0,65 mm by changing the process parameters (pulse frequency, pulse repetition rate and cutting speed) on a laser cut quality with pulsed beam Nd:YAG laser and the *Ra* value (response parameter) was observed. For this fractional factorial design (orthogonal array) was employed as a scientific approach for planning experiment followed by variance and signal to noise ratio analysis.

2 Taguchi method

The concept of Robust Engineering is based on the principles of Taguchi Methods used in many works dealing with (un)conventional technologies for prediction of output surface profile parameters [16÷26]. Genichi Taguchi [29] derived these principles after several years of research. The concept evolved systematically in 1950's. These principles are aimed at providing the companies a cost effective methodology to enhance their competitive position in the global market. Among the various approaches used the most frequently used approach to design a test is a full factorial experiment [17]. However, for full factorial experiments, there are n^f possible combination that must be tested where n is the levels and f is the number of factors. Therefore, it is very time-consuming when there are many factors at many levels [26÷28]. Taguchi methods were developed in Japan by Genichi Taguchi to improve the implementation of total quality control in Japan [29]. They are based on the design of experiments to provide near optimal quality characteristics for a specific objective. The real power of Taguchi methods comes from their simplicity of implementation. The goal is not just to optimize an arbitrary objective function, but also to reduce the sensitivity of engineering designs to uncontrollable factors or noise [16, 23, 24]. Taguchi methods are also called robust design in the USA. In the traditional experimentation strategy, one supposes that the factors, on which we act, are perfectly controlled and that their values remain constant throughout the experiment. The factors not included in the study are supposed not to vary. This concept is however too theoretical because one is never certain that these factors will remain constant indeed. To avoid the bias caused by these uncontrollable factors, the traditional experimental strategy consists of making the experiments in a random order. The effects of uncontrollable factors are then included in the experimental results dispersion. Thus one often seeks to eliminate all the possible variation sources, which is unfortunately often impossible in practice. Taguchi, on the other hand, considers that rather than to eliminate the causes from the variations, it is preferable to analyse them and to find experimental conditions for which these causes have a minimum effect. Thus, instead of seeking to eliminate the causes of variations (called noises by Taguchi), he proposes to minimize their influence. The factors are divided into two categories: the factors relating to the system on which one can easily act (called controllable factors) and the factors (called noise factors) whose possible variations are not (or with difficulty) controllable and can generate a degradation of the system characteristics. The major steps of implementing the Taguchi method are: (1) to identify the factors/interactions, (2) to identify the levels of each factor, (3) to select an appropriate orthogonal array (OA), (4) to assign the factors/interactions to columns of the OA, (5) to conduct the experiments, and (6) to analyse the data and determine the optimal levels. This work uses L9, three-level matrix for an initial experiment, where the numbers 0, 1 and 2 stand for the levels of the factors. In data analysis, signal-to-noise (S/N) ratios are used to allow the control of the response as well as to reduce the variability about the response. The use of ANOVA (analysis of variance) is to calculate the statistical confidence associated with the conclusions drawn.

3 Experimental conditions of experiment

A CNC controlled SI Laser SLP200 Nd: YAG laser with three-axis control (Fig. 1) was used for cutting.

Figure 1 Photograph of the ND:YAG laser

The machine basically consists of a laser resonator and beam delivery unit, power supply unit, cooling unit and CNC controller for *X*, *Y* and *Z*-axis movement. The specifications of the machine are given in Tab. 1. The material used for laser cutting was mild steel (carbon 0,1÷ 0,25 %) of thickness 0,65 mm with the assisting gas as Oxygen at a pressure of 3,5 kgf/cm^2 (to nozzle) For measuring the surface roughness of samples of thickness *b* = 0,65 mm a mounting fixture was developed consisting of five slots for holding the samples cut by the laser process. (Fig. 2). The surface roughness (*Ra*) measurements of the work pieces was done using Taylor-Hobson Surtronic machine provided by Taylor-Hobson. The measuring range of the instrument varies from the 0,01 to 150 μm with an accuracy of 2 %.

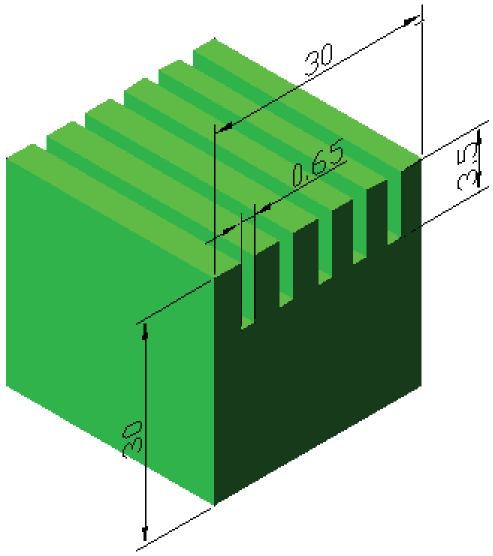

Figure 2 Holding fixture

Table 1 Technical specification of the machine

Model	SLP-200
Average power	200 W
Pulse energy @ 20 ms	50 J
Peak power	7 kW
Pulse width range	0,3 ÷ 20 ms
Pulse repetition rate	1 ÷ 250 Hz
Work table size	450 × 600 × 150 mm
Power requirements	3 PHASE 440VAC 20 AMPS
Cooling method	chilled water with external cooling

4 The results measured during the experiment

The basic objective of the experimentation was to obtain parametric combination to achieve the best surface finish (*Ra* value) and assess effects of various process parameters on *Ra* value. Therefore laser pulse width, pulse repetition rate and cutting speed were taken as the key parameters identified to be the most influencing in controlling the response parameter (*Ra* value). The experiments were carried out in two stages. Initially, different parameters were varied individually keeping others at a value which yields better results. Accordingly a continuous range of each parameter was established which resulted in best values of selected quality parameter *Ra* value (response parameter in Taguchi robust design terminology). Keeping these ranges of various processes parameters (control factors/parameters in Taguchi robust design terminology); the parameters were varied individually so as to attain information regarding the particular parameter. For all the experiments all other process parameters including the gas pressure and nozzle height were kept constant. The range of pulse width for best cutting is from 2 to 25 ms; for pulse repetition rate it is from 20 Hz to 30 and cutting speed ranges from 1 to 3 mm/s for the sheet thickness 0,65 mm. The surface roughness measurements of the work pieces were done using Taylor-Hobson Surtronic machine. The range of above-mentioned control parameters was divided into three levels, each as shown in Tab. 2. For each control parameter 0 indicates a level with low value, 1 indicates medium and 2 indicates high value. For such three factor three level experiments the suitable orthogonal array (i.e. L9(3)4 orthogonal array) (Tab. 3) was selected. Orthogonal array (O.A.) facilitates statistical analysis of influence of individual control factors & their interaction. Three-factor O.A. saves lot of experimentation as in case of varying one factor at a time. Robust design is an engineering methodology for optimizing the product and process conditions which are minimally sensitive to the various causes of variation and which produce high-quality products with low development and manufacturing costs. Taguchi's parameter design is an important tool for robust design. Taguchi's tolerance design can also be classified as a robust design. In a narrow sense robust design is identical to parameter design, but in a wider sense parameter design is a subset of robust design. This work tries to obtain the best parametric combination for quality surface finish (*Ra* value) with two Robust Design tools like S/N ratio analysis and orthogonal array and subsequent variance analysis. Experiments resulting from the orthogonal array (Tab. 3) were carried out with all other process parameters kept unchanged.

Table 2 Various factors and their levels

A (Cutting speed mm/s)			B (Pulse width ms)			C (Pulse freq./Pulse repetition rate Hz)		
A_0	A_1	A_2	B_0	B_1	B_2	C_0	C_1	C_2
1 mm/s	2 mm/s	3 mm/s	1,5 ms	2 ms	3,9 ms	10 Hz	15 Hz	20 Hz

Table 3 Orthogonal array [L9(3)4] and resulting experiments

Experiment No.	Column No.				Condition	Exp. Data $Ra_{Avg} = Ra_1 + Ra_2 + Ra_3$	S/N ratio (db)
	1	2	3	4			
1	0	0	0	0	$A_0B_0C_0$	131	−42,41873
2	0	1	1	1	$A_0B_1C_1$	115	−41,80272
3	0	2	2	2	$A_0B_2C_2$	100	−40,00000
4	1	0	1	2	$A_1B_0C_2$	122	−43,16461
5	1	1	2	0	$A_1B_1C_0$	225	−47,33265
6	1	2	0	1	$A_1B_2C_1$	146	−43,33027
7	2	0	2	1	$A_2B_0C_1$	157	−43,91187
8	2	1	0	2	$A_2B_1C_2$	180	−45,10545
9	2	2	1	0	$A_2B_2C_0$	256	−48,16480
Basic mark	a	B	ab	ab2		Total→	−395,2311
Assignment	A	B	e	C		Avg. →	−43,91457

Table 4 Effect of factors at various levels

Levels→ Factors↓	0	1	2
A	2,50742 *	−0,69461	−1,81803
B	0,7495 *	−0,83237	0,08288
C	−2,057603	0,89882	1,15788 *

Table 5 Computation of variation for L9 (3)4 O.A.

	Source	A			B			E			C		
	Level	0	1	2	0	1	2	0	1	2	0	1	2
	Data	131	122	157	131	115	100	131	115	100	131	115	100
		115	225	180	122	225	146	146	122	225	225	146	122
		100	146	256	157	180	256	180	256	157	256	157	180
1	Level sum	346 *	493	593	410 *	520	502	457	493	482	612	418	402 *
2	Sum of (1) (T)	1432			1432			1432			1432		
3	(Level sum)2	119716	243049	351649	168100	270400	252004	208849	243049	232324	374544	174724	161604
4	Sum of (3)	714414			690504			684222			710872		
5	(4)/3	2; 38; 138			230168			228074			236957,33		
6	C.T.= (T)2 /9	2; 27; 847,11			227847,11			227847,11			227847,11		
7	(5)-(6)	10291			2321			227			9110		

(* Indicates the optimum level, hence optimum is $A_0B_0C_2$)

Table 6 Computation of variance

Factor↓	S.O.S	D.O.F	V (M.S.)	F0	F (0,05)
A (Cutting speed)	10291	2	5145	45,33	19
B (Pulse width)	2321	2	1160	10,22	19
C (Pulse frequency)	9110	2	4555	40,13	19
E (Error)	227	2	113	-	-
T (Total)	21949	8	-	-	-

Table 7 Percentage contribution of various factors

Factor	% contribution to variation in *Ra* value
Cutting speed (A)	45,85
Pulse width (B)	9,54
Pulse frequency (C)	40,47
Error (e)	2,07

5 S/N ratio analysis

For the less good problem as this one (1):

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum y_i^2\right) \tag{1}$$

The S/N analysis of the orthogonal array (Tabs. 3, 4) has indicated the optimum combination is A0B0C2 that is cutting speed v = 1 mm/s, pulse width 1,5 ms, pulse frequency or repetition rate 20 Hz which was not among the tested conditions & was carried out later. It resulted in *Ra* = 100 μm, which is the best of the tested conditions hence; it confirms the prediction of S/N analysis. The values (Tab. 4) indicate the variation over mean value of S/N ratio (−43,91457). The variance analysis (Tabs. 5, 6) indicates that the optimum parametric combination is A0B0C2 that is the same as indicated by the S/N analysis and has been confirmed experimentally. The analysis indicates that the cutting speed and pulse frequency are the most influential factors and contribute 45,85 % & 40,47 % respectively (Tab. 7), (Fig. 3).

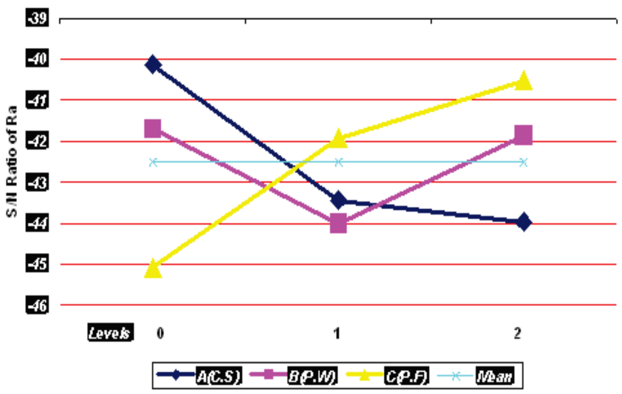

Figure 3 Effects of control factors on *Ra* value

6 Conclusion

Laser machining process is one of the most important non-traditional machining processes that has an ability to cut a wide range of materials ranging from mild steel (MS) to ceramics & diamond with great precision. The process of Laser Cutting is controlled by three parameters laser pulse frequency (pulse repetition rate), laser pulse width and cutting speed. These factors have their particular effect as well as combined effect on the surface finish obtained. Earlier works have made it clear that apart from the effects of these three parameters alone, it is only laser pulse width and cutting speed which have a combined effect. To the best of our knowledge there has been no work in the direction of determining the amount of effect by these parameters.

The S/N analysis and the variance analysis (Tabs. 4, 5, 6) make it clear that the cutting speed & pulse repetition rate are the most influencing factors in controlling surface roughness and the optimum parametric combination of selected parameters (control factors) for the given experiment is cutting speed 1 mm/s, pulse repetition rate 20 Hz, pulse width 1,5 ms. The interaction between the three selected control factors is non-synergetic. Surface finish deteriorates with increase in the value of cutting speed from 1mm/sec to 3 mm/s. Surface finish (*Ra* value) improves as pulse frequency is increased from 10 to 15 Hz but remains stable when pulse frequency is further increased.

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