Simultaneous Optimization of Multiple Quality Characteristics in Laser Beam Cutting Using Taguchi Method

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Taguchi methods have been used for a long time to improve the product quality and process performance of a manufacturing system. Few researchers have applied this methodology in laser beam cutting (LBC) of sheet metals and found the considerable improvement in cut qualities. In all experimental investigations of LBC so far, the objective was to optimize the single quality characteristic at a time. In this paper the simultaneous optimization of multiple quality characteristics such as Kerf width and material removal rate (MRR) during pulsed Nd:YAG LBC of thin sheet of magnetic material (high Silicon-steel) has been presented using Taguchi's quality loss function. The results show the considerable improvement in multiple S/N ratio as compared to initial cutting condition. Also, the comparison of results from single and multi-objective optimization have been presented and it was found that the loss in quality is always possible shifting from single quality to multiple quality optimization.

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NOMENCLATURE

k = number of control factors or process parameters
L_{ij} = the quality loss for the i^{th} quality characteristic at the j^{th} trial condition or run
L_{i*} = maximum quality for the i^{th} quality characteristic among all the experimental runs
n = total number of experimental runs
p = number of responses or quality characteristics
w_i = weight assigned to i^{th} response or quality characteristic
y_i = response or observed quality value for i^{th} experimental run
y_{ij} = normalized quality loss value for i^{th} experimental run and j^{th} quality characteristic
Y_j = total normalised quality loss value in j^{th} experimental run
η_j = multiple S/N ratio of j^{th} trial condition or experimental run
η_o = predicted value of multiple S/N ratio at optimal parameter setting
η_m = mean value of multiple S/N ratios of all experimental runs
η_i = average multiple S/N ratio corresponding to i^{th} control factor at optimum parameter level

1. Introduction

Laser beam cutting has wide application in the field of fine cutting of sheet metals since 1960. The attractive features of LBC are the non-contact nature, flexibility, and the cutting capability of almost whole range of materials. It is a thermal energy based non-conventional machining method in which material is removed due to melting, vaporization or by chemical changing, and the molten material is ejected with the flow of high pressure assist gas.[1] The schematic of LBC process has been shown in Fig. 1. Since its introduction LBC has always been a major research area for getting the exceptionally good quality of cut. The quality of cut solely depends on the setting of parameters such as laser power, type and pressure of assist gas, cutting speed, mode of operation (Continuous or pulsed mode), material thickness, and its composition.

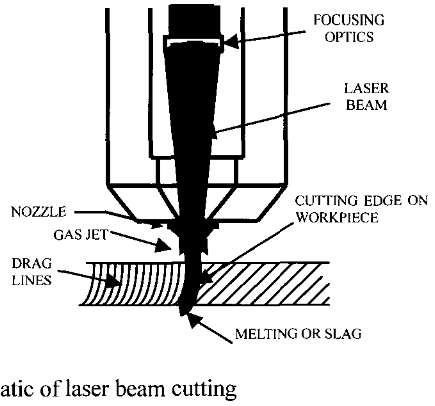

Fig. 1 Schematic of laser beam cutting

A lot of experimental investigations have been done to analyze the effect of these parameters on cut geometry, surface quality, and mechanical properties. The experimental investigations of continuous mode LBC of steel sheets[2-7] have shown that the kerf width is mainly affected by laser power, cutting speed, assist gas pressure, and the focal plane position. In pulsed mode LBC of sheet metal the kerf width mainly depends on spot overlap which is a function of cutting speed and pulse frequency.[8] In most of the experimental investigations researchers have used the variation of one factor at a time (OFAT) technique to record the variation in a quality characteristic. It has been found by some investigators that application of design of experiments (DOE) techniques such as Response Surface Methodology (RSM) and Taguchi Methodology (TM) can be applied in LBC to optimize the cut qualities.[9-15]

The DOE based studies on LBC have concentrated so far to optimize the single quality characteristic at a time. Antony[16] has suggested a multi-objective optimization technique using Taguchi quality loss function to simultaneously optimize the multiple quality characteristics in manufacturing processes. In the present paper the Taguchi methodology has been applied to optimize the multiple quality characteristics such as Kerf width (KW), and material removal rate (MRR) during pulsed Nd:YAG laser beam cutting of thin sheets of magnetic material (grain oriented silicon steel sheets used in transformers). The quality characteristics of two different nature (Kerf width is of smaller-the-better type and MRR is of higher-the-better type) have been selected and the results of multi-objective optimization have also been compared with that of results from single objective optimization.

2. Experimental details (Materials, test conditions and measurement)

The experimental studies were performed on a 200 W pulsed Nd:YAG laser beam machining system with CNC work table (supplied by Suresh Indu Lasers Pvt. Ltd., Pune, India). The Oxygen is used as an assist gas. The variable process parameters (or control factors) taken are Oxygen pressure, pulse width, pulse frequency, and cutting speed. Focal length of lens (50.0 mm), nozzle diameter (1.0 mm), nozzle tip distance (1.0 mm), and material thickness (0.5 mm) were kept constant throughout the experiments. The quality characteristics analyzed are Kerf width and MRR. The 0.5 mm thick sheet of magnetic material (grain oriented Si-steel sheet used in transformer) was used in the experiments as workpiece material. Two cuts each of 20 mm length were obtained in each experimental run. The kerf width was measured using the Tool Makers Microscope (Model RTM-900, RADICAL Instruments, India) at 10× magnification. The Kerf widths taken are the mathematical average of three measurements of top kerf in each cut. The MRR is calculated by using the following formula:

MRR (mg/min) = loss of mass during each cut × cutting speed / cut length

The MRR given is the average of two cuts. The loss of mass was found out by weighing the specimen before and after the cutting using Electronic Balance (Model A×120, Shimandzu Corporation, Japan).

3. Analysis and verification of results

3.1 Selection of control factors, their levels, and quality characteristics (or responses)

The control factors (or input parameters) taken are the Oxygen pressure (1.5 – 3.5 kg/cm^2), pulse width or pulse duration (1.0 – 1.4 millisecond), pulse frequency (20 – 28 Hz), and cutting speed (25 – 75 mm/min). The numerical values of factors at different levels are shown in Table 1. An exhaustive pilot experimentation is done to decide the parameter range for quality cut. The quality characteristics measured are Kerf width and MRR. The initial setting of parameters is: Oxygen pressure – 1.5 kg/cm^2, pulse width – 1.0 ms, pulse frequency – 18 Hz, and cutting speed – 25 mm/min.

Table 1 Control factors and their level

Symbol	Factors	Units	Level		
			1	2	3
A	Oxygen pressure	kg/cm^2	1.5	2.5	3.5
B	Pulse width	ms	1.0	1.2	1.4
C	Pulse frequency	Hz	20	24	28
D	Cutting speed	mm/min	25	50	75

3.2 Selection of Orthogonal Array for matrix experimentation

Selection of the orthogonal array is based on the calculation of the total degree of freedom of all the factors. Orthogonal arrays are special matrix in which entries are at various levels of input parameters, and each row represents individual treatment condition[17-18]. In orthogonal array, for any pair of column all combinations for each factor level occur and they occur in equal number of times (this is called balancing property).

Degree of freedom related to a process can be calculated as[17]:

dof = (number of levels - 1) for each factor + (number of levels - 1) (number of levels - 1) for each interaction + 1

In present case of four parameters at three different levels assuming no interaction between factors the degree of freedom is calculated as:

$$\text{dof} = (3-1)4+1 = 9$$

Hence, an standard L_9 OA as suggested by Taguchi[17] is selected which is given in Table 2.

Table 2 L$_9$ Orthogonal Array (OA)

Experiment no.	Factor level			
	A	B	C	D
1.	1	1	1	1
2.	1	2	2	2
3.	1	3	3	3
4.	2	1	2	3
5.	2	2	3	1
6.	2	3	1	2
7.	3	1	3	2
8.	3	2	1	3
9.	3	3	2	1

3.3 Execution phase

Experiments are conducted to get responses according to the orthogonal array selected. Care should be taken while conducting experiments that no treatment condition should be left and factor levels should be set at appropriate values because failure to set factor levels correctly could destroy the valuable property of orthogonality. The results of experiments for responses Kerf width (mm) and MRR (mg/min) are shown in Table 3.

3.4 Computation of quality loss for each quality characteristic

In Taguchi method[14, 19], a quality loss or mean square deviation (MSD) function is used to calculate the deviation between the experimental value and the desired value. The MSD is different for different types of problems e.g.

for Smaller-the-better type problem

$$\text{MSD} = (y_1^2 + y_2^2 + y_3^2 + \ldots) / n \tag{1}$$

and for Higher-the-better type problem

$$\text{MSD} = (1/y_1^2 + 1/y_2^2 + 1/y_3^2 + \ldots) / n \tag{2}$$

Where, y_1, y_2, y_3,... y_n are results of the experiments (responses), and n is the number of repetitions of y_i. In present case the Kerf width is smaller-the-better (SB) type and MRR is higher-the-better (HB) type. The quality loss values for each quality characteristic against different experimental runs are given in Table 4.

Table 3 Experimental results using L_9 OA

Exp. No.	Kerf width (mm)	MRR (mg/min)
1.	0.3900	44.9375
2.	0.4100	88.7500
3.	0.4200	139.4826
4.	0.3800	126.1717
5.	0.4150	96.5000
6.	0.4000	46.5625
7.	0.3933	92.0000
8.	0.3933	118.8601
9.	0.4000	50.1875

Table 4 Quality loss for Kerf width and MRR

Exp. No.	Quality loss (dB)	
	Kerf width	MRR
1.	0.1521	4.952×10^{-4}
2.	0.1681	1.270×10^{-4}
3.	0.1764	0.514×10^{-4}
4.	0.1444	0.628×10^{-4}
5.	0.1722	1.074×10^{-4}
6.	0.1600	4.612×10^{-4}
7.	0.1547	1.181×10^{-4}
8.	0.1547	0.7078×10^{-4}
9.	0.1600	3.970×10^{-4}

3.5 Computation of normalized quality loss for each quality characteristic

Let L_{ij} be the quality loss for the i^{th} quality characteristic at the j^{th} trial condition or run in the experimental design matrix. As each quality characteristic has different unit of measurements, it is important to normalize the quality loss.[16] The normalized quality loss can be computed using:

$$y_{ij} = L_{ij} / L_{i*} \tag{3}$$

Where, y_{ij} = normalized quality loss
L_{i*} = maximum quality loss for the i^{th} quality characteristic among all the experimental runs. Therefore, y_{ij} varies from a minimum of zero to a maximum of 1. The computed normalized quality loss for Kerf width and MRR is given in Table 5.

3.6 Computation of total normalized quality loss (TNQL)

For computing the total normalised quality loss (Y_j) corresponding to each trial condition, we must assign a weighting factor for each quality characteristic considered in the optimisation process. If w_i represents the weighting factor for the i^{th} quality characteristic, p is the number of quality characteristics and y_{ij} is the loss function associated with the i^{th} quality characteristic at the j^{th} trial condition, then Y_j can be computed using:

$$Y_j = \sum_{i=1}^{p} w_i y_{ij} \tag{4}$$

In present case, p = 2, and assuming unequal weights i.e. $w_1 = 0.8$ for Kerf width, and $w_2 = 0.2$ for MRR, as the removal of material in laser beam cutting of thin sheets of Si – steels is not a difficult task but the most important thing is the quality of cut i.e. width of cut. The MRR has been taken as a quality characteristic with the view to take the two qualities of different nature (here, higher MRR and lower Kerf width is required). The total normalised quality loss in each experimental run is shown in Table 6.

Table 5 Normalized quality loss for Kerf width and MRR

Exp. No.	Normalized quality loss	
	Kerf width	MRR
1.	0.8622	1.0000
2.	0.9529	0.2565
3.	1.0000	0.1038
4.	0.8186	0.1269
5.	0.9762	0.2169
6.	0.9070	0.9313
7.	0.8770	0.2385
8.	0.8770	0.1429
9.	0.9070	0.8017

Table 6 Total normalized quality loss (TNQL) and multiple S/N ratio (MSNR)

Exp. No.	TNQL	MSNR (dB)
1.	0.8898	0.5073
2.	0.8136	0.8958
3.	0.8208	0.8578
4.	0.6803	1.5598
5.	0.8243	0.8389
6.	0.9119	0.4007
7.	0.7493	1.2534
8.	0.7302	1.3657
9.	0.8859	0.5260
Mean MSNR (η_m)		0.9117

3.7 Computation of multiple S/N ratio (MSNR)

After the total normalised quality loss (Y_j) corresponding to each trial condition has been calculated, the next step is to compute the multiple S/N ratio at each design point. This is given by:

$$\eta_j = -10 \log_{10}(Y_j) \tag{5}$$

The multiple S/N ratios along with total normalised quality losses in each trial condition is shown in Table 6.

In single quality optimization using Taguchi methodology, sections 3.5 and 3.6 are omitted, and in place of a multiple S/N ratio, separate S/N ratios corresponding to each quality characteristics is computed where the Y_j are the quality loss values of different quality characteristics. Other steps are same as in multi-objective optimization.

3.8 Determination of factor effects and optimal settings

Next step is to determine the average effect of each factor on multiple quality characteristic at different levels. This is equal to, the sum of all S/N ratios corresponding to a factor at particular level divided by the number of repetition of factor level

The factor levels corresponding to maximum average effect are selected as optimum level. The average factor effect has been shown in Table 7 and response plot is shown in Figure 2. The optimum setting of parameters is A_3 B_1 C_2 D_3.

Table 7 Effect of factor levels on MSNR

Factors	Mean MSNR (dB)		
	Level 1	Level 2	Level 3
Gas pressure	0.7536	0.9331	1.0484*
Pulse width	1.1068*	1.0335	0.5948
Pulse frequency	0.7579	0.9939*	0.9834
Cutting speed	0.4780	0.9960	1.2548*

* optimum parameter level

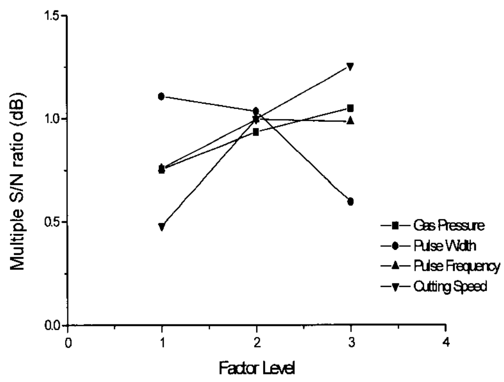

Fig. 2 Response plot for MSNR

3.9 Analysis of variance (ANOVA)

A better feel for the relative effect of the different factors can be obtained by the decomposition of the variance, which is commonly called (ANOVA). It is a computational technique to estimate quantitatively the relative significance (F-ratio), and also the percentage contribution (PC) of each factor. The sum of squares (SS) and mean sum of squares or variance (V) for each factor, and error (EP) obtained by pooling of factors A and C are computed first, to evaluate the F value and PC.[17] The degree of freedom (df) for each factor is calculated as:

df = number of level – 1

The ANOVA given in Table 8 shows the contribution of different factors in increasing order as: Pulse frequency (3.25%), Oxygen pressure (8.085%), pulse width (28.08%), and cutting speed (57.32%).

3.10 Confirmation Experiment

Conducting a verification experiment is a crucial final step of a robust design. Its purpose is to verify that the optimum conditions suggested by the matrix experiment do indeed give the projected improvement. The confirmation experiment is performed by conducting a test with optimal settings of the factors and levels previously evaluated. The predicted value of multiple S/N ratio at optimum level (η_o) is calculated by following formula:

$$\eta_o = \eta_m + \sum_{i=1}^{k} (\eta_i - \eta_m) \qquad (6)$$

Where, k is the no. of factors and η_m is the mean value of multiple S/N ratios in all experimental runs, η_i are the multiple S/N ratios corresponding to optimum factor levels.

The predicted value of multiple S/N ratio and that from confirmation test are shown in Table 9. The improvement in multiple S/N ratio at the optimum level is found to be 1.3090 dB. The value of Kerf width (mm) and MRR (mg/min) at this optimum level are 0.3733 mm and 124.1095 mg/min against the initial parameter setting of 0.3900 mm and 44.9375 mg/min.

Table 8 ANOVA table for Kerf width and MRR

Factor	SS	df	V	F	PC (%)
A	0.1324#	2	0.0662	1.1079	8.0840
B	0.4600	2	0.2300	3.8494	28.0865
C	0.1066#	2	0.0533	-	3.2545
D	0.9388	2	0.4694	7.8561	57.3208
EP	0.2390	4	0.0598	-	-
Total	1.6378	8	-	-	100

\#Pooled factors

Table 9 Results of confirmation experiment

	Initial setting	Optimum values	
		Prediction	Experiment
Level	$A_1B_1C_1D_1$	$A_3B_1C_2D_3$	$A_3B_1C_2D_3$
KW (mm)	0.3900	-	0.3733
MRR (mg/min)	44.9375	-	124.1094
MSNR (dB)	0.5073	1.6688	1.8163

Improvement of MSNR = 1.3090 dB

4. Comparison of multi-objective and single objective optimization results

The results of single quality optimization for Kerf width, and MRR are summarized in Table 10 to Table 14 and response plot is shown in Fig. 3 and Fig. 4. The results of multi-objective optimization (MOO) and single-objective optimization (SOO) using Taguchi methodology has been compared in Table 15. The results show that the quality values at optimum settings are different in each case. The results of MOO basically depends on weights assigned to quality values e.g. in present case the most important quality assumed was Kerf width with weight 0.8, and result is almost same to that of optimum Kerf width (obtained SOO) while the optimum MRR value in SOO is more as compared to MRR obtained from MOO. Therefore, chance of quality loss is always there, when the aim is to optimize the multiple quality characteristics simultaneously. The multi-objective optimization is useful in the sense that at same optimum parameter level one can get the optimum quality value of multiple quality characteristics at the same time rather than a single optimum quality characteristic.

Table 10 S/N ratios for Kerf width and MRR in single quality optimization

Exp. No.	S/N ratio (dB)	
	Kerf width	MRR
1.	8.1787	33.0522
2.	7.7443	38.9634
3.	7.5350	42.8904
4.	8.4043	42.0192
5.	7.6390	39.6905
6.	7.9588	33.3607
7.	8.1055	39.2758
8.	8.1055	41.5007
9.	7.9588	34.0119
Overall mean (m)	7.9589	38.3072

Table 11 S/N response table for Kerf width

Factors	Mean S/N ratio (dB)		
	Level 1	Level 2	Level 3
Gas pressure	7.8193	8.0007	8.0566*
Pulse width	8.2295*	7.8296	7.8175
Pulse frequency	8.0810*	8.0358	7.7599
Cutting speed	7.9255	7.9362	8.0150*

Table 12 S/N response table for MRR

Factors	Mean S/N ratio (dB)		
	Level 1	Level 2	Level 3
Gas pressure	38.3020	38.3568*	38.2628
Pulse width	38.1157	40.0515*	36.7543
Pulse frequency	35.9712	38.3315	40.6189*
Cutting speed	35.5849	37.1999	42.1368*

* optimum level

Table 13 Results of confirmation experiment for Kerf width (KW)

	Initial setting	Optimum values	
		Prediction	Experiment
Level	$A_1B_1C_1D_1$	$A_3B_1C_1D_3$	$A_3B_1C_1D_3$
KW (mm)	0.3900	-	0.3700
S/N ratio (dB)	8.1787	8.5054	8.6359

Improvement of S/N ratio = 0.4572 dB

Table 14 Results of confirmation experiment for MRR

	Initial setting	Optimum values	
		Prediction	Experiment
Level	$A_1B_1C_1D_1$	$A_2B_2C_3D_3$	$A_2B_2C_3D_3$
MRR (mg/min)	44.9375	-	145.0319
S/N ratio (dB)	33.0522	46.2424	43.2293

Improvement of S/N ratio = 10.1771 dB

Table 15 Comparison of results from single objective and multiple objective optimization

	SOO results		MOO results	quality loss (%)
	KW	MRR	KW & MRR	
Level	$A_3B_1C_1D_3$	$A_2B_2C_3D_3$	$A_3B_1C_2D_3$	-
KW (mm)	0.3700	-	0.3733	0.8919
MRR (mg/min)	-	145.0319	124.1095	14.4286

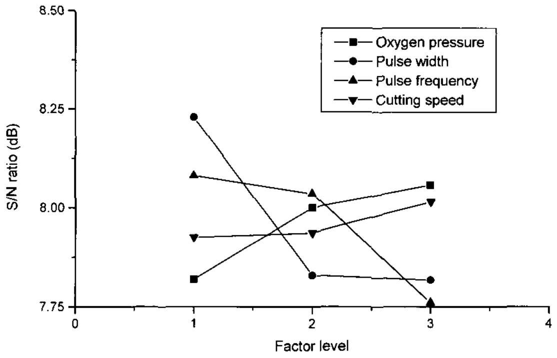

Fig. 3 Response plot for Kerf width

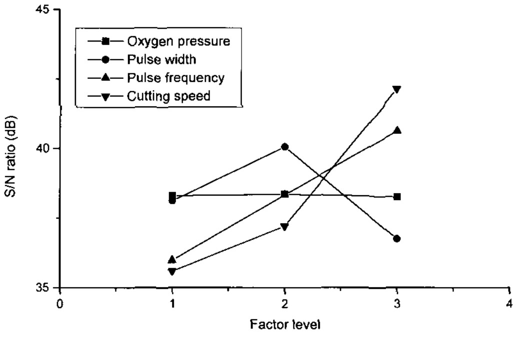

Fig. 4 Response plot for MRR

5. Conclusions

The conclusions drawn from above results are summarized as:

1. The Taguchi's quality loss function can be used to optimize the multiple quality characteristics. A significant increase in S/N ratio (1.3090 dB) has been registered at optimum parameter setting in the present experimental investigation. Also, both the quality characteristics (Kerf width and MRR) have been considerably improved as compared to initial parameter settings of the experiment.
2. The optimum parameter values in the present operating conditions are: Oxygen pressure – 3.5 kg/cm^2, pulse width – 1.0 ms, pulse frequency – 24 Hz, and cutting speed – 75 mm/min.
3. The percentage contribution of factors in increasing order is: pulse frequency (3.2545%), Oxygen pressure (8.0840%), pulse width (28.0865%), and Cutting speed (57.3208%).
4. The loss of quality is always possible during optimization of multiple quality characteristics at a time. The deviation of quality from its optimum value depends mainly on the weight assigned to it. Therefore, a careful selection of weights for different quality values plays a crucial role in multi-objective optimization.

REFERENCES

1. Chryssolouris, G, "Laser Machining- Theory and Practice (Mechanical Engineering Series)," Springer-Verlag, pp. 47-57, 1991.
2. Ghany, K. A. and Newishy, M., "Cutting of 1.2 mm thick austenitic stainless steel sheet using pulsed and CW Nd:YAG laser," Journal of Materials Processing Technology, Vol. 168, Issue 3, pp. 438-447, 2005.
3. Lamikiz, A., Lacalle, L. N. L., Sanchez, J. A., Pozo, D., Etayo, J. M. and Lopez, J. M., "CO_2 laser cutting of advanced high strength steels(AHSS)," Applied Surface Science, Vol. 242, Issues 3-4, pp. 362-368, 2005.
4. Chen, S. L., "The effects of high-pressure assistant-gas flow on high-power CO_2 laser cutting," Journal of Materials Processing Technology, Vol. 88, No. 1, pp. 57-66, 1999.
5. Rajaram, N., Ahmad, J. S. and Cheraghi, S. H., "CO_2 laser cut quality of 4130 steel," International Journal of Machine Tools & Manufacture, Vol. 43, pp. 351-358, 2003.
6. Karatas, C., Keles, O., Uslan, I. and Usta, Y., "Laser cutting of steel sheets: Influence of workpiece thickness and beam waist position on kerf size and stria formation," Journal of Materials Processing Technology, Vol. 172, No. 1, pp. 22-29, 2006.
7. Tuersley, I. P., Hoult, T. P., Tony, P. and Pashby, I. R., "Nd-YAG laser machining of SiC fibre/borosilicate glass composites," Part II, The effect of process variables, Composites Part A, Vol. 29A, pp. 955-964, 1998.
8. Thawari, G, Sarin Sundar, J. K., Sundararajan, G and Joshi, S. V., "Influence of process parameters during pulsed Nd:YAG laser cutting of nickel-base superalloys," Journal of Materials Processing Technology, Vol. 170, pp. 229-239, 2005.
9. Tam, S. C., Lim, L. E. N. and Quek, K. Y., "Application of Taguchi method in the optimization of the laser-cutting process," Journal of Materials Processing Technology, Vol. 29, pp. 63-74, 1992.
10. Lim, S. H., Lee, C. M. and Chung, W. J., "A study on optimal cutting condition of a high speed feeding type laser cutting machine by using Taguchi method," International Journal of Precision Engineering and Manufacturing, Vol. 7, No. 1, pp. 18-23, 2006.
11. Tam, S. C., Yeo, C. Y., Jana, S., Lau, W. S., Lim, E. N. and Yang, L. J., "Optimization of laser deep-hole drilling of Inconel 718 using the Taguchi method," Journal of Materials Processing Technology, Vol. 37, pp. 741-757, 1993.
12. Masmiati, N. and Philip, P. K., "Investigations on laser percussion drilling of some thermoplastic polymers," Journal of Materials Processing Technology, Vol. 185, Issues 1-3, pp. 198-203, 2007.
13. Li, C. H., Tsai, M. J. and Yang, C. D., "Study of optimal laser parameters for cutting QFN packages by Taguchi's matrix method," Optics & Laser Technology, Vol. 39, pp. 786-795, 2007.
14. Chen, Y. H., Tam, S. C., Chen, W. L. and Zheng, H. Y., "Application of Taguchi method in the optimization of laser micro-engraving of photomasks," International Journal of Materials & Product Technology, Vol. 11, No. 3/4, pp. 333-344, 1996.
15. Corcoran, A., Sexton, L., Seaman, B., Ryan, P. and Byrne, G, "The laser drilling of multi-layer aerospace material systems," Journal of Materials Processing Technology, Vol. 123, pp. 100-106, 2002.
16. Antony, J., "Simultaneous optimisation of multiple quality characteristics in manufacturing processes using Taguchi's quality loss function," International Journal of Advance Manufacturing Technology, Vol. 17, pp. 134-138, 2001.
17. Phadke, M. S., "Quality Engineering using Robust Design," Prentice-Hall, pp. 41-65, 1989.
18. Hong, D. K., Choi, S. C. and Ahn, C. W., "Robust optimization design of overhead crane with constration using the characteristic functions," International Journal of Precision Engineering and Manufacturing, Vol. 7, No. 2, pp. 12-17, 2006.
19. Han, S. R., Park, T. W. and Jeong, Y. D., "Effects of process variables on the gas penetrated part in gas-assisted injection molding," International Journal of Precision Engineering and Manufacturing, Vol. 7, No. 2, pp. 8-11, 2006.