A study on the optimal cutting condition of a high speed feeding type laser cutting machine by using Taguchi method

Sang-Heon Lim[1], Choon-Man Lee[2,#] and Won Jee Chung[2]

1 School of Mechanical Design & Manufacturing, Changwon National University, Changwon, South Korea
2 Department of Mechanical Design & Manufacturing, Changwon National University, Changwon, South Korea
Corresponding Author / E-mail: cmlee@sarim.changwon.ac.kr, TEL: +82-55-279-7572, FAX: +82-55-263-5221

KEYWORDS : Laser cutting machine, Design of experiment, Optimal cutting condition, Taguchi method

Cutting by a high speed laser cutting machine is one of most effective technologies to improve productivity. This paper has presented the cutting characteristics and optimal cutting conditions in a high speed feeding type laser cutting machine by using Tacuchi method in the design of experiment. An L9(34) orthogonal array is adopted to study the effect of adjustment parameters. The adjustment parameters consist of cutting speed, laser power, laser output duty and assistant gas pressure. The surface roughness of sheet metal is regarded as a quality feature. Analysis of variance is performed in order to evaluate the effect of adjustment parameters on the quality feature of laser cutting process.

Manuscript received: February 24, 2005 / Accepted: April 29, 2005

1. Introduction

An application of laser to material processing was begun from late 1960's and extended to cutting, welding, drilling, scribing of ceramics, plastics, woods, and composite materials. Laser cutting has been spread with comparatively fast speed because its process is more economic than other laser processing such as laser welding and heat treatment. A high speed feeding type laser cutting machine has been developed for the precise cutting of sheet metal. Laser cutting is divided into three types, i.e., laser fusion cutting, laser sublimation cutting and laser-assisted cutting.[1] The laser-assisted cutting has been popular because it is more profitable and economic than other processes in terms of cutting thickness and cutting speed.[2-6]

The important parameters which have an influence on laser cutting performance are the output of laser power, characteristics of material, assisted-gas jet, cutting head, laser output efficiency, and so on.[7]

Generally, the principle of material elimination in laser cutting process can be shown as in Fig. 1. First, a material is heated over melting point by laser beam. Second, the melted or evaporated material is blown using assisted gas jet. The laser cutting is accomplished through two processes.[1] In the first process, it can be considered that laser power and output efficiency are important parameters. In the other process, it can be considered that laser-assisted gas jet is an efficient parameter.

This paper has focused on obtaining the cutting performance evaluation and optimal cutting conditions for a high speed feeding type laser cutting machine. Therefore, we performed an experiment for evaluation of cutting characteristics by using Taguchi method in the design of experiment. Based on the measurement data by the experiments, the major influencing cause of the data has been verified by using the analysis of variance (ANOVA).

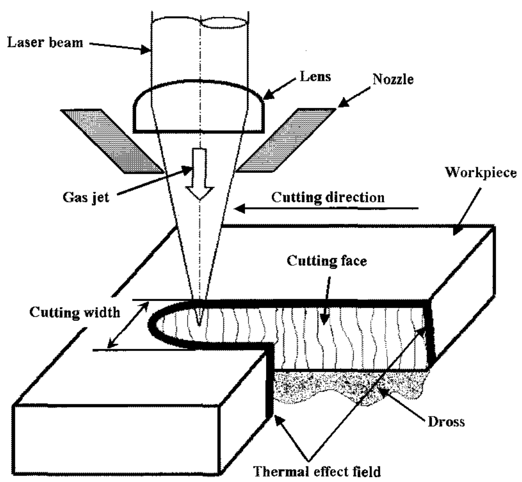


Fig. 1 Principle of a laser cutting system

2. Background Theory

2.1 Taguchi Method[8-10]

Taguchi method has been known as a powerful tool for the design of a high-quality manufacturing system. For instance, experiments should be performed to investigate the effects of various factors on overall phenomena when the factors are engaged in the phenomena with complexity. Moreover, the mixed factors must be carefully selected for the reliability of analysis result from experiments. In the design of experiment before Taguchi method, experiments were selected with a full combination of factors and an orthogonal array was used in order not to distort the result of experiments. But the total number of combination overall factors is so large that the number of experiments increases rapidly. For this reason, an analysis method is proposed by Taguchi using an orthogonal array for analyzing the effect of each parameter. The effect of parameters can be confirmed through Taguchi method, which results in less experiments, compared to those of full combinations of factors. In Taguchi method, the parameters are divided into control and noise factors. In addition, a method to find out the optimal combination of control factors was proposed. Compared to the classical design of experiment using complex statistics, this method is easy to be understood as a practical alternative, which can provide the basis of robust design.

The robust design is focused on supplying consumers with the product of lean production and consumption costs at the shortest time under the effects of noise factors, such as an environment of products, a worker's expertness and levels of consumers. Here the consumption cost means all the expenses that a consumer has to pay additionally, when the product is not perfect. Taguchi method provides how to find out the influence of each design parameter and the procedure for preventing a possible problem at early stage of product development. It is one of various robust design techniques.

The objectives of Taguchi method for robust design are to establish the optimal combination of design parameters and to reduce variations in product quality. Taguchi method uses signal to noise (SN) ratio for robust quality maintenance from the influences of noise factors. The SN ratio means the ratio of the power of signal input to the power of noise output. If a factor corresponding to the big value of SN ratio of each control factor is selected, it will be robust when subjected to noise.

The definition of SN ratio is different according to an objective function, i.e., a characteristic value. There are three kinds of characteristic value: Normal is Best (NB), Lower is Better (LB) and Higher is Better (HB). In this paper, the characteristic value is selected by the surface roughness of cutting face. Since a good result is obtained by the small value of surface roughness, LB is preferred. The SN ratio of LB can be calculated by

$$SN = -10\log\left[\frac{1}{n}\sum_{i=0}^{n} y_i^2\right] \tag{1}$$

where n is the number of measurements, and y_i the measured characteristic value. The unit of SN ratio is dB (decibel).

2.2 Analysis of Variance

There are three kinds of methods of data analysis in the design of experiment: analysis of variance, correlation analysis and regression analysis. The analysis of variance (ANOVA) is selected in this paper.

A statistical ANOVA is performed to identify the process parameters that are statistically significant. It is widely used in the design of experiment. The dispersion of a characteristic value is obtained by experiments and expressed as the sum of squares. In addition, the method decomposes the sum of squares into components classified by factors. Finally, this analysis method searches for the source of most influence. Therefore the purpose of the analysis of variance is to investigate which factors significantly affect quality characteristics. A sum of squares of each source divided by the degree of freedom of the source equals the mean square of the source, and is compared with an error variance.

For some characteristics, if the sources are A, B, and C, for example, and the error is E, then the total variation (S_T) is expressed with each variation, i.e., sum of squares (S_A, S_B, S_C, and S_E), and is as follows :

$$S_T = S_A + S_B + S_C + S_E \tag{2}$$

This compares the error variation S_E with the sums of squares S_A, S_B and S_C. The A, B and C are defined as the sources of influences.

The variation created by the source A, namely, the sum of squares is clearly found. However, if the variation of errors is not identified, a statistically significant influence rate in the correlation of source and error is given below. We define S_A and S_E as the corresponding variation, namely the sum of squares, and Φ_A and Φ_E as the degree of freedom about source A and error E. Also, S_A / Φ_A, the mean square of A, is defined by V_A, while S_E / Φ_E is the error variation of E and by V_E. Then the ratio of above values is as follows :

$$F_0 = \frac{V_A}{V_E} \tag{3}$$

Thus, a large value of F_0 means that the change of the design parameter A has a significant effect on the quality characteristics compared with the error variation.[9]

3. Experiment

3.1 Experiment System and Specimens

In this experiment, the specimen of SS41 metal plate, widely used for laser cutting process, has been selected. The size of the specimen is 60 mm by 30 mm. Besides, the thickness of the metal plate is of two kinds, i.e., 2 mm and 3 mm. The developed laser cutting machine has the output power of 4 kW, which can cut a plate with a thickness of up to 20 mm. However, we selected the two kinds of thickness, as stated above, which are widely used in industry so that the result of this paper can be applied in actual work place. Figure 2 shows the cutting experiment using the developed laser cutting machine. The conditions for the measurement of cutting performance are listed in Table 1.

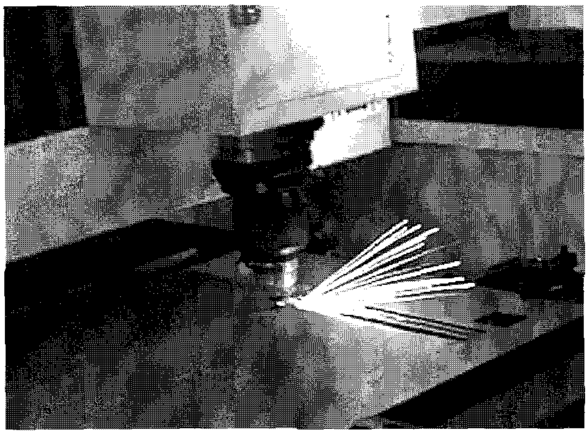


Fig. 2 Laser cutting process

Table 1 Cutting conditions

	Condition 1	Condition 2
Cutting speed [mm/s]	3200	2500
Power [W]	2300	2100
Efficiency [%]	85	85
Gas pressure [N/m^2]	58839.9	68648.4

After cutting a plate with the condition of Table 1, we used an instrument of stylus type (Surftest SV-600, Mitutoyo) for the measurement of a surface roughness. The measurement data of cutting face is calculated by the average value through 5 times of cutting for data reliability. The results of surface roughness are listed in Table 2. From Table 2, each surface roughness is different according to each cutting condition. This clearly shows that we need to obtain the optimal cutting condition using experiments.

Table 2 Results of cutting conditions

Thickness	Results [μm]	
	Condition 1	Condition 2
2 mm	2.914	3.125
3 mm	3.268	3.002

3.2 Experiment Setup

In this paper, the cutting performance of the machine is evaluated by Taguchi method so that an optimal cutting condition is obtained. This paper selected four factors as follows: cutting speed, laser output power, efficiency, and gas pressure. The levels of each factor are arranged at an even interval. The factors and levels are listed in Table 3. The factors and levels for surface roughness are arranged using the orthogonal array of $L_9(3^4)$ as shown in Table 4. The experiments are carried out twice by using the orthogonal array. After the measurement of center line average height (R_a) of each specimen, the SN ratio is calculated by using the commercial software, MINITAB®. Finally, we found the optimal cutting condition for the developed machine using the analysis of variance.[10]

Table 3 Factors and levels used in the experiment

Sign	Factor	Unit	Level		
			1	2	3
A	Cutting speed	mm/min	2000	2750	3500
B	Power	W	2000	2750	3500
C	Efficiency	%	80	90	100
D	Gas pressure	N/m^2	39227.6	68648.4	98069.1

Table 4 Orthogonal array table for $L_9(3^4)$

Experiment number	Factor			
	1	2	3	4
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
Sign	A	B	C	D

4. Results and Discussion

Figure 3 shows the mean values of surface roughness (R_a) when the metal plate of SS41 with a thickness of 2 mm is cut by the developed machine. According to the result of the mean values, the SN ratio listed in Table 5 is calculated by MINITAB software.

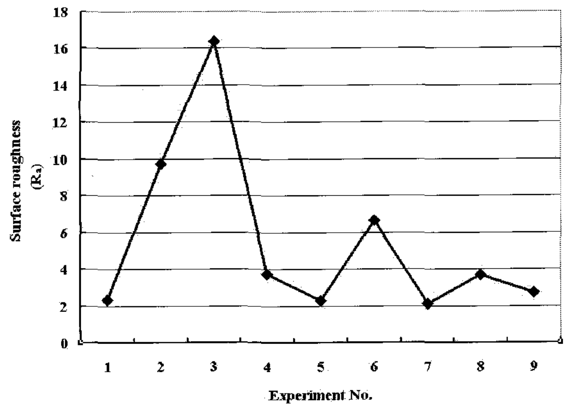


Fig. 3 Variation of surface roughness for the experiment number (SS41, 2 mm)

Table 5 Results of SN ratios (SS41, 2 mm)

Experiment number	Surface roughness (R_a)		SN ratio
	1	2	
1	2.444	2.244	-7.3992
2	2.842	9.638	-19.7712
3	16.277	16.423	-24.2704
4	3.73	3.738	-11.4435
5	2.293	2.243	-7.1129
6	6.641	6.629	-16.4368
7	3.001	1.181	-6.4071
8	3.577	3.781	-11.3146
9	2.631	2.831	-8.7264

Table 6 SN ratios for each level (SS41, 2 mm)

Level	A	B	C	D
1	-17.1469	-8.4166	-11.7169	-7.7461
2	-11.6644	-12.7329	-13.3137	-14.205
3	-8.816	-16.4779	-12.5968	-15.6761
Rank	1	2	4	3

Table 6 shows the SN ratios for each level, which is graphically shown in Fig. 4. As can be seen from Table 6 and Fig. 4, the influencing factors of surface roughness are : cutting speed, laser power, gas pressure, and efficiency. Here the influence of efficiency factor appears smaller than other factors. And also the cutting speed is shown as a major factor. Its influence on the surface roughness value is shown larger than other factors.

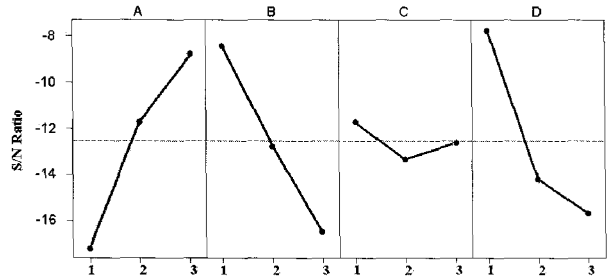


Fig. 4 Plot of SN ratios (SS41, 2 mm)

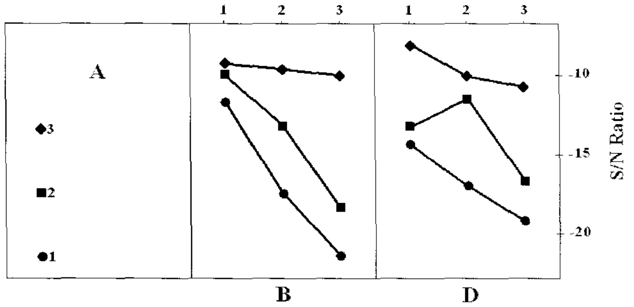


Fig. 5 Plot of interaction of SN ratios (SS41, 2 mm)

This result leads us to the conclusion that the increase of the feeding speed can be obtained with less influence of gas, owing to the principle of laser-assisted gas cutting. As shown in Fig. 5, there is no interaction among the factors. This verifies that the optimal cutting condition can be obtained using SN ratios. Based on Fig. 4, the optimal cutting condition is obtained with A3, B1, C1, and D1 in terms of SN ratio. On the other hand, the condition used in work place, which is A2, B1, C1, and D1, is included in this paper. This is delineated in detail as shown in Table 7. The estimated values of SN ratios according to the present and optimal conditions are listed in Table 8.

As illustrated in Table 8, the optimal condition has improved the SN ratio by 2.848. In the sense of cost, the loss of money can be reduced by a factor of $10^{0.284} = 1.926$. The result of optimal condition has been obtained by using the convenient process based on SN ratios. The ANOVA was used to verify the optimal condition. Table 9 shows the result of ANOVA table followed by the pooling of the efficiency. Here the pooling means the judgment by using error factors. The evaluation of the pooling factor is done by F-test[9].

Table 7 Present and optimal condition (SS41, 2 mm)

	Present condition	Optimal condition
Cutting speed [mm/min]	2750	3500
Power [W]	2000	2000
Efficiency [%]	80	80
Gas pressure [N/m^2]	39227.6	39227.6

Table 8 SN ratios from the present and optimal condition (SS41, 2 mm)

	Present condition	Optimal condition
SN ratio	-1.91665	0.931707

Table 9 ANOVA table for R_a after pooling

Factor	S	Φ	V	F_0	F(0.1)
A	8.3309	2	4.1655	9.7213*	9.0
B	8.0612	2	4.0306	9.4052	9.0
C	Pooled factor				
D	7.0900	2	3.5450	8.2723	9.0
E	0.6752	2	0.3376		
T	24.1573	8			

* : 90% confidence level

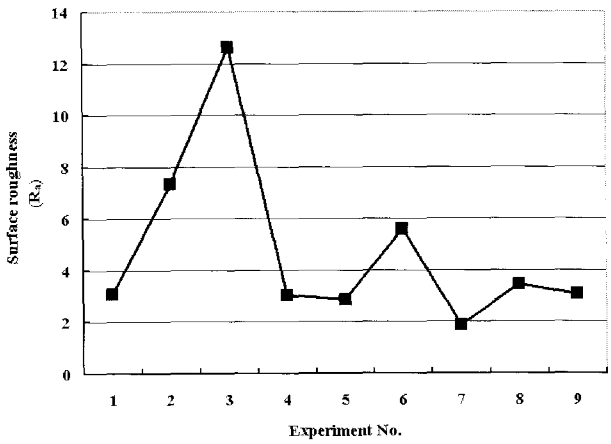


Fig. 6 Variation of surface roughness for the experiment number (SS41, 3 mm)

The mean value of surface roughness (R_a) of the metal plate of SS41, with the thickness of 3 mm is shown in Fig. 6. The results are arranged by the same experiment and analysis, as stated above. According to Fig. 6, the result of cutting face is similar to that of Fig. 3. Based on the reasons mentioned above, it can be deduced that the result of optimal cutting condition in this case is similar to the result in the previous case.

Table 10 Results of SN ratios (SS41, 3 mm)

Experiment number	Surface roughness (R_a)		SN ratio
	1	2	
1	3.185	2.945	-9.7286
2	7.556	7.136	-17.3210
3	12.54	12.74	-22.0349
4	3.341	2.707	-9.6116
5	2.994	2.752	-9.1667
6	5.466	5.746	-14.9731
7	1.810	1.970	-5.5292
8	3.499	3.397	-10.7513
9	3.011	3.123	-9.7343

Table 11 Response table of SN ratios (SS41, 3 mm)

Level	A	B	C	D
1	-16.3615	-8.2898	-11.8177	-9.5432
2	-11.2505	-12.413	-12.2223	-12.6078
3	-8.6716	-15.5808	-12.2436	-14.1326
Rank	1	2	4	3

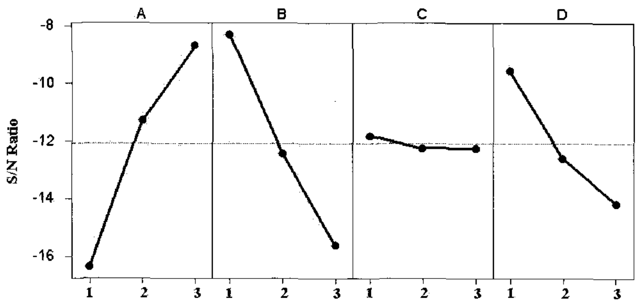


Fig. 7 Plot of SN ratios (SS41, 3 mm)

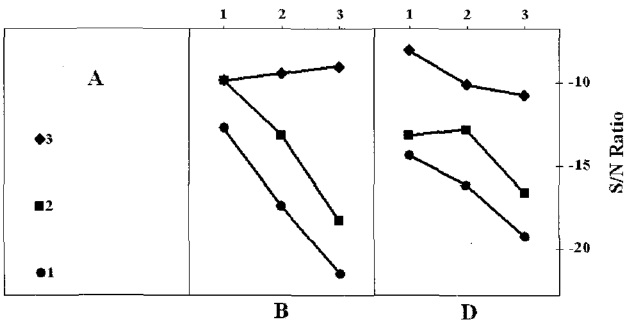


Fig. 8 Plot of interaction of SN ratios (SS41, 3 mm)

It can be found that Table 11 and Fig. 7 have almost the same characteristics as in Table 6 and Fig. 4, respectively. As shown in Fig. 8, there is no interaction among the factors. Thus the optimal cutting condition in this case is obtained by using SN ratios. Figure 7 shows that A3, B1, C1, and D1 are optimal. Besides, the condition widely used in work place is included in this paper, which is A2, B1, C1, and D1. It is illustrated in detail in Table 12.

Table 12 Present and optimal condition (SS41, 3 mm)

	Present condition	Optimal condition
Cutting speed [mm/min]	3500	3500
Power [W]	2000	2000
Efficiency [%]	100	80
Gas pressure [N/m^2]	39227.6	39227.6

Table 13 SN ratios from present and optimal condition (SS41, 3 mm)

	Present condition	Optimal condition
SN ratio	-2.44334	-2.03871

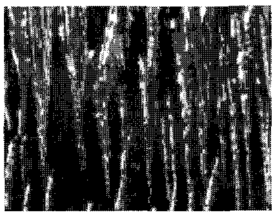
Table 14 ANOVA table for R_a after pooling

Factor	S	Φ	V	F_0	F(0.1)
A	9.0021	2	4.5011	10.0213*	9.0
B	8.5322	2	4.2661	9.4982	9.0
C	Pooled factor				
D	5.5519	2	2.7760	6.1805	9.0
E	1.3283	2	0.6642		
T	24.4145	8			

* : 90% confidence level

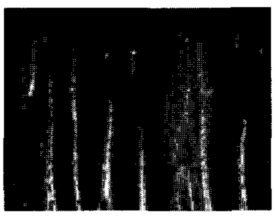
The estimated values of SN ratio corresponding to the present and optimal conditions are listed in Table 13. Table 14 shows the table of ANOVA. The result of calculation illustrates that the optimal condition improved the SN ratio by 0.4046 (= (-2.03871) - (-2.44334)), compared with the present condition. This can be converted to cost saving by a factor of $10^{0.04046} = 1.097$.

Figure 9 shows the shape of cutting face captured by a tool microscope. It can be noticed from the results of cutting face using the present and optimal conditions that good surface roughness is obtained by the optimal cutting condition. According to these results, it can be concluded that the product quality has been improved.

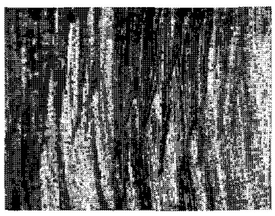


(a) SS41, 2 mm
Present Condition

(b) SS41, 2 mm
Optimal Condition



(c) SS41, 3 mm
Present Condition



(d) SS41, 3 mm
Optimal Condition

Fig. 9 Shape of cutting surface

5. Conclusions

The concluding remarks of this paper can be summarized as follows :

(1) Through the experiment on cutting performance of the developed laser cutting machine, the cutting characteristics were obtained according to the cutting condition. Especially the design of experiment was carried out using Taguchi method. Besides, we analyzed the cutting speed, laser output power, efficiency and gas pressure by using SN ratios and ANOVA. According to these processes, the optimal cutting condition has been obtained by the results of experiments.

(2) Based on the experiment and analysis, the crucial parameters of surface roughness were selected as cutting speed, laser power, gas pressure, and efficiency. Here the influence of efficiency factor was shown smaller than that of other factors. In addition, the cutting speed was shown as a major factor,

because the influence of surface roughness value is shown larger than that of other factors. We also suggested a simple process of obtaining optimal cutting condition to be used in a real work place.

(3) The results of the cutting face captured by using a tool microscope show that the optimal cutting condition has resulted in better surface roughness than the present cutting condition.

These results lead us to the conclusion that we can predict the product quality to be improved by using the proposed analysis method.

ACKNOWLEDGEMENT

This work was supported by Changwon National University funds and grant No. RTI04-01-03 from the Regional Technology Innovation Program of the Ministry of Commerce, Industry and Energy (MOCIE).

REFERENCES

1. Bang, S. Y. and Han, Y. H., "Nozzle and Gas Jet Flow in Laser Cutting," Journal of the KWS, Vol. 12, No. 2, pp. 1-10, 1994.

2. Burton, G. and Frankhouser, L., "Electron Beam Welding," Welding Journal, Welding Research Supplement, October, pp. 401-409, 1959.

3. Luxon, J. T. and Parker, D. E., "Industrial Lasers and their Applications," Prentice Hall, pp. 68-83, 1985.

4. Han, E. K., Park, T. W., Lee, B. S., Lee, M. H. and Lim, H. S., "The Effects on Cutting Performance by Machining Parameters of Nd : YAG Laser," Transactions of the Korean Society of Mechanical Engineers, Vol. 16, No. 1, pp. 1-12, 1992.

5. Lee, H. J., Cho, M. Y., Yoo, W. J. and Kim, J. D., "Effect of Assistant Gas Pressure In Laser Cutting of STS304," J. of the KSPE, Vol. 12, No. 3, pp. 15-22, 1995.

6. 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, pp. 57-66, 1999.

7. Wang, J., Wong, W. C. K., "CO_2 laser cutting of metallic coated sheet steels," J. of Materials Processing Technology, Vol. 95, pp. 164-168, 1999.

8. Choi, J. C., Kim, Y. H. and Park, J. H., "Optimal Reheating Condition of Semi-solid Material in Semisolid Forging by Neural Network," Int. J. of the KSPE, Vol. 4, No. 2, pp. 49-56, 2003.

9. Lee, S. B., "Introduction to Taguchi Method," Sangjosa, 2000.

10. Lee, S. B., "Application of Taguchi Method Using the MINITAB," ERETEC, pp. 91-171, 2001.