Multi-objective optimization of quality in laser cutting based on response surface model

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***Abstract*—Prediction and optimization of quality characteristics is an important means to improve the quality of laser cutting. Kerf width (KW) and material removal rate(MRR) are selected as the quality characteristics in this paper. The fitting response surface models (RSM) of KW and MRR are considered as the optimization objective function in pulsed Nd: YAG laser cutting of alloy steel for multi-objective optimization. An improved Pareto genetic algorithm is used in the optimization, and the significant factors have been found. The predicted results are basically consistent with the experimental. Therefore, the method used in this paper can be used for optimization of KW and MRR in pulse Nd: YAG laser cutting. The study can provide theoretical basis for the prediction and optimization of quality in laser cutting.**

Keywords-laser cutting; multi-objective optimization; RSM; improved Pareto genetic algorithm

I. INTRODUCTION

Since its introduction, laser cutting has always been a major area of research for improving the quality of cutting. In order to analyze and improve different quality characteristics, many researchers conducted theoretical and experimental study[1,2]. In most experimental studies, the researchers change one processing parameter at one time to analyze its impact on the quality characteristics. So, the study requires a lot of experiments. To overcome this problem, some researchers began the study to change different input parameters simultaneously. For this purpose, the design of experiment(DOE), such as factorial design, Taguchi method and response surface method, is applied to the parameter optimization and modeling[3-5]. The study based on DOE is mainly focused on the optimization of single quality characteristic[6].The experiment results show that the optimization of single characteristic parameter may cause the deterioration of other quality characteristics. In the last few years, there has been growing interest in the use of pulsed Nd:YAG lasers for precision cutting of thin sheet-metals and for these applications that demands narrow kerf widths, small HAZ and intricate cut profiles[7,8]. Therefore, the studies in this paper concentrate on multi-objective optimization of pulse Nd: YAG laser cutting.

The relationship between input and output parameters in laser cutting process is non-linear and complicated. The conventional methods of modeling and optimization require large amount of experiments. To overcome these difficulties, the method of modeling and optimization based on artificial intelligence, such as artificial neural network, fuzzy logic and genetic algorithm are used[9-11]. Pareto genetic algorithm is an optimization method based on the extension of conventional genetic algorithm, and has a very good advantage on multi-objective optimization. The Pareto genetic algorithm is used in this paper to conduct the simultaneous of KW and MRR, and the set filter is improved. When the relationship between the response and factors is non-linear, the response surface method becomes the best tool for optimization of process parameters. In this paper, the fitting second-order response surface models are used as the objective function of KW and MRR, and the improved Pareto genetic algorithm is used to predict KW and MRR. The optimization process takes fully advantage of the genetic algorithm and RSM model in the disposing of non-linear problem.

II. RSM MODEL

Response surface method gets the second order mathematical relation model as a real function approximation by fitting the response output and influence factors. The method carries on the analysis and optimization, and it defines a set of factors and levels to achieve optimal response variables. The second-order response surface model by least squares fitting is shown as expression 2.1.

$$\hat{y}_j = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i=1}^{k} \hat{\beta}_{ii} x_i^2 + \sum_{i<j}^{k} \hat{\beta}_{ij} x_i x_j \qquad (2.1)$$

Where all $\hat{\beta}'s$ are the regression coefficients, determined numeri-cally by using leasts quare fit method, x_i are the different control factors changing from $i = 1$ to k, k is the total number of control factors, $\hat{y}_j$ are the different responses (j are the numbers of response used).In this study $j = 2$, $i = 4$, has been used.

A. Models of KW and MRR

The final models for KW and MRR are developed from the experimental data obtained from CCRD experimental matrix. The coefficients for second order regression models are determined with the help of Matlab 7.0. The final models obtained are as follows.

$$KW = 0.2841 + 0.0007x_1 + 0.3620x_2 - 0.0127x_3 - 0.0008x_4 + 0.0028x_1^2 - 0.0292x_2^2 + 0.0005x_3^2 - 0.0066x_1x_2 - 0.0001x_1x_4 - 0.0092x_2x_3 + 0.0001x_2x_4 \quad (2.2)$$

$$MRR = -10.3643 - 11.5384x_1 - 121.4368x_2 + 5.0106x_3 + 1.8571x_4 + 3.4007x_1^2 - 40.4445x_2^2 + 0.1679x_3^2 - 0.0004x_4^2 + 45.7952x_1x_2 - 2.8905x_1x_3 + 0.1182x_1x_4 + 2.2334x_2x_3 + 0.1857x_2x_4 - 0.0452x_3x_4 \quad (2.3)$$

Where x_1 is gas pressure(kg/cm^2), x_2 is pulse width(Ms), x_3 is pulse frequency (Hz), and x_4 is cutting speed(mm/min). In order to test the accuracy of the fitted models, F-values, P-values and coefficients of KW and MRR are calculated. The results are shown in Table Ⅰ.

TABLE I. RESULTS OF ANOVA FOR DEVELOPED MODELS

Parameter	KW	MRR
Correlation coefficient r^2	0.9297	0.9684
F-value	14.1593	20.6165
P-value	0.0000	0.0000
Residual sum of squares	0.0001	69.3498

From Table 1, it can be seen that the coefficient of KW and MRR is 0.9297 and 0.9684 respectively. F-value is 14.1593 and 20.6165 respectively. F-values and P- values are both within the allowed range. P-values are less than 0.0001. All shows that the fitting for KW and MRR is good, and the developed regression models are appropriate.

B. *Parameters analysis*

As can be seen from expression 2.2 that x_2, x_3 ,square effect of x_1 ,square effect of x_2, and interaction effect of x_2 and x_3, interaction effect of x_1 and x_2 are significant factors of KW. The coefficients of these parameters are higher than others. Similarly, x_1, x_2, square effect of x_2, interaction effect of x_1 and x_2 are significant factors of MRR.

III. PREDICTION OF KW AND MRR

A. *Modelling*

KW, cutting surface roughness, heat affected zone, solidified layer, adhesion debris, MRR, etc. are used to characterize the quality of laser cutting. KW and MRR are selected in this paper. According to the experimental analysis, KW is the smaller the better, while MRR is the bigger the better. So the model of the quality optimization can be described by the following mathematical formula.

$$\begin{cases} \min\ KW = f_1(x_1, x_2, x_3, x_4) \\ \max\ MRR = f_2(x_1, x_2, x_3, x_4) \end{cases}$$

Where, x_1 is gas pressure, x_2 is pulse width, x_3 is pulse frequency, x_4 is cutting speed.

The formula 2.2 and 2.3 are selected as the objective function of KW and MRR in this paper.

B. *Prediction based on the improved Pareto genetic algorithm*

Pareto genetic algorithm [12]has a very good advantage on multi-objective optimization. Because it is multi-objective optimization, the options for practical Pareto solutions are many, the filter volume of Pareto solution set is particularly important. If it is set too large, the computation amount will be too large, and the search speed of Pareto algorithm will be influenced; if be set too small, the good solution will be missed, and the accuracy will be affected. To balance the precision and the speed, the improved Pareto solution filter used in reference [13] is adopted, and the simultaneous optimization of KW and MRR is conducted in this paper.

The control parameters used in Pareto genetic algorithm are shown as follows. The population size is 60; the max generation is 100; hybrid probability is 0.8; mutation rate is 0.1; the Pareto solution set filter size is 40; d_{pre} is set to be 5; β is 15^0.

IV. RESULTS AND ANALYSIS

In order to verify the accuracy of the above algorithm in the actual laser cutting, KW and MRR are predicted in pulse Nd:YAG laser cutting (200W), and compared with the experiment results.

A. *Processing parameters*

Auxiliary gases: oxygen; focal length:50.0mm;nozzle diameter:1.0mm; nozzle distance:1.0mm; thickness of Aluminum alloy steel material: 0.5mm. The specific parameters are shown in Table Ⅱ.

TABLE II. CUTTING PARAMETERS

Cutting parameters	level	values
Gas pressure	kg/cm^2	1.5-4.0
Pulse width	Ms	1.0-1.4
Pulse frequency	Hz	20-28
Cutting speed	mm/min	25-75

B. *Comparison with experiment results*

The comparison of the predicted results with the experimental results is shown in Figure 1. It can be seen that the predicted results agree with the experimental results. The developed models in this paper can be used as the models of KW and MRR.

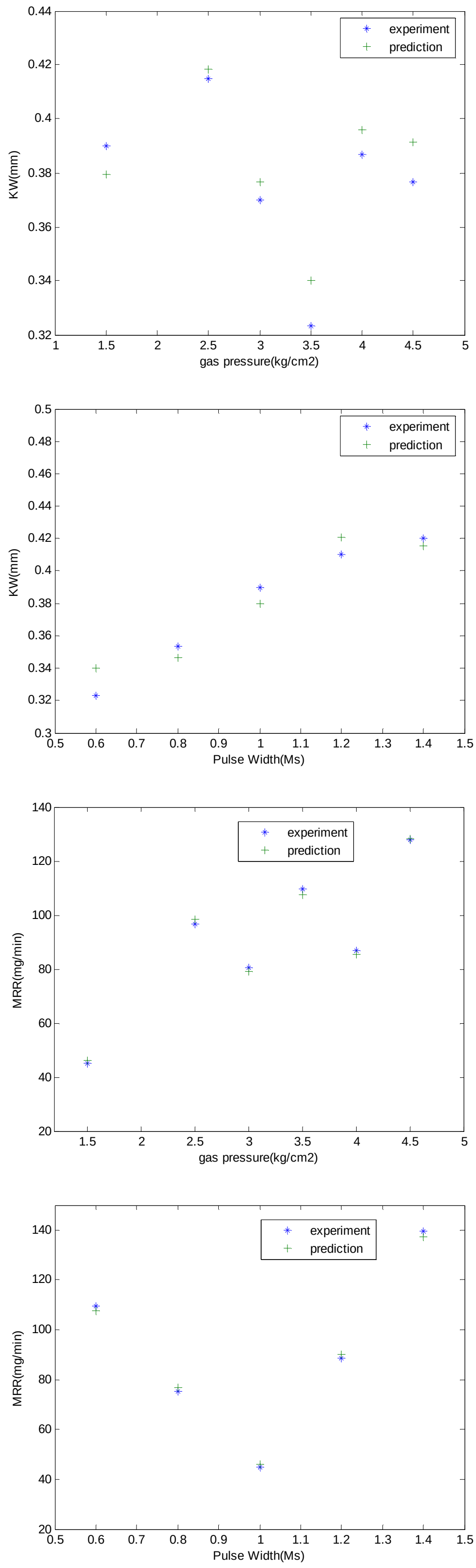

Figure 1. comparison with the experimental results

C. *Comparison with unimproved algorithm*

The comparison of the improved Pareto genetic algorithm with the traditional algorithm is shown in figure 2. As can be seen, the improved Pareto genetic algorithm has certain advantage; its frontier of the solution set is more uniform.

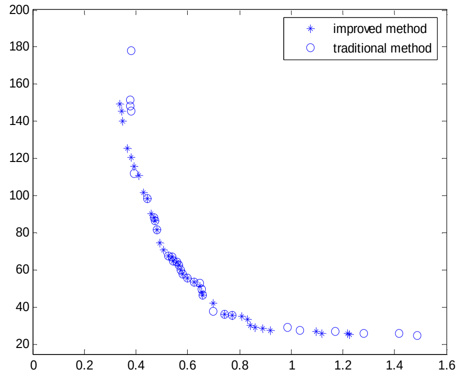

Figure 2. Comparison of the improved method with traditional

D. *Optimization results*

Since in the Pareto front, none of the solution may be said absolutely better than the other solutions. All sets of solutions in the Pareto front are optimal solutions depending upon the requirement of the actual processing. The aim of this paper is to improve both of the quality characteristics (KM and MRR) simultaneously.Since the optimum levels of control factors will be that levels for which both of the quality characteristics are showing better values. Considering equal importance of both the KW and MRR, The values of KW and MRR corresponding to the optimum level of control factors have been found as 0.3412 and 164.1342. The correspond processing parameters are $x_1 = 3.5 kg / cm^2$, $x_2 = 0.6 Ms$, $x_3 = 28\ Hz$, $x4 = 100\ mm / \min$.

V. CONCLUSIONS

The models of KW and MRR are developed in this paper. The F-values of KW and MRR are both in the permitted range. Also, P-values are suitable. So, the developed models are adequate for KW and MRR, and selected as the objective function of the improved Pareto genetic algorithm. Compared with the traditional Pareto genetic algorithm, the solution set frontier of the improved method is more uniform. The prediction results are basically consistent with the experiments. It can be seen that the developed models can be used as the models of KW and MRR, and the improved Pareto genetic algorithm can be used to predict and optimize for KW and MRR in Nd:YAG laser cutting.

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