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Optimisation and Quantitative Evaluation of the Qualities for Nd-YAG Laser Transformation Hardening

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The aim of this paper is to find the optimal process parameters and to evaluate quantitatively the quality characteristics of laser transformation hardening of SNCM 439 steel by a long pulsed Nd-YAG laser beam. The Taguchi methodology and fuzzy evaluation method are used. Using the Taguchi methodology, the surface hardness of the specimen was increased from $H_RC52.5$ to $H_RC63.9$. The depth of hardening was also increased from 0.11 mm to 0.21 mm. Moreover, the width of hardening was increased from 0.43 mm to 0.89 mm and the erosion was reduced from 69.55 mg to 40.94 mg. When these four factors are optimised simultaneously, the results show that improvements vary from 19.24% to 97.67% using the Taguchi method. A fuzzy method was also used to analyse and evaluate the processing qualities. The results obtained using the fuzzy method are similar to those obtained using the Taguchi method. The same methodology can be applied to the processing of other high-power laser material. We obtained a significant improvement in the quality of laser transformation hardening by Nd-YAG laser and the quantitative evaluation of the non-discriminating quality factors.

Keywords: Fuzzy; Laser; Optimisation; Quality; Taguchi; Transformation hardening

1. Introduction

Many previous researchers have attempted to improve the qualities of laser material processing [1–5]. The methods used can generally be classified as theoretical analysis methods or experimental methods. Because many important parameters are involved in laser material processing, and because of the serious interactions between the parameters, several assumptions are generally required for theoretical analytical methods [5]. Therefore, the analytical methods have either been too complicated to be accepted by the industry or too simplified to predict real situations accurately. In the experimental methods used by most of the researchers, only one parameter was adjusted in each experiment and there were too many experiments to perform before reaching the optimal condition. There has so far, to our knowledge, been no work published on using the Taguchi method for the high-power long pulse Nd-YAG laser transformation hardening processes. Results from using the Taguchi method to optimise the Nd-YAG laser transformation hardening condition will be presented here. In addition, the fuzzy evaluation method will be presented. This method was applied to evaluate the quality factors of the experimental results. A quantitative rank was given to the experimental results.

Until recently, most applications of laser transformation hardening used a CO_2 laser system. However, a high-power Nd-YAG laser system is normally more compact than a CO_2 laser system, and the beam quality of Nd-YAG systems has been significantly improved over the last few years. Compared with CO_2 laser material processing, some advantages can thus obtained by using a long pulsed Nd-YAG laser system. It is easily automated, can be guided by optical fibre, costs less, is easy to maintain, and applies local heat treatment with only small distortion. Applications of the Nd-YAG laser system for material processing are rapidly being developed and are widely accepted by industry, resulting in an urgent need now to improve the processing quality.

The Taguchi method was developed between 1950 and 1960 [6], and was first used by Japanese industries. In 1980, it was also widely accepted by many researchers in Western countries [3,7,8]. Tam et al. [8] tried to use the Taguchi method to improving the quality of laser marking on leadless chip carriers using a pulsed high-power Nd-YAG laser. In his study, seven parameters with 2 levels were designed in an L_{16} orthogonal array. Six interaction terms that affected the quality factors were obtained, and he reported that the parameter design successfully improved the qualities of marking contrast, marking depth, marking width, and spattering degree.

The use of fuzzy theory for multi-attribute evaluation in the design process has been reported in many papers [9–13]. Dubois and Prade [10] concluded that the fuzzy multi-attribute evaluation method might integrate the linguistic evaluation of each attribute to give a final value result and the rank of each attribute. This is known as the fuzzy ranking method. However,

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very few papers have been found relating to the quality evaluation of laser material processing using fuzzy theory. In one paper, Sun et al. [13] tried to measure quantitatively the hole qualities of laser drilling using the fuzzy evaluation method. In this paper, results will be presented using the fuzzy ranking method to measure quantitatively the quality of Nd-YAG laser transformation hardening. A comparison of the results of the Taguchi methodology and the fuzzy evaluation method will also be made.

2. Basic Theory

Many previous researchers have studied the laser transformation hardening process [2,4,5,14–16]. Since a great improvement in the surface hardness of steel is obtained after laser transformation hardening, laser transformation hardening applications have been rapidly accepted by industry. The system arrangement for the experiment in this study is shown in Fig. 1. The basic steps of the experimental design using the Taguchi methodology are given in Fig. 2, where the SN ratio is an evaluating index showing the average and variance. There are three characteristics of the SN ratio:

1. Smaller-the-better.

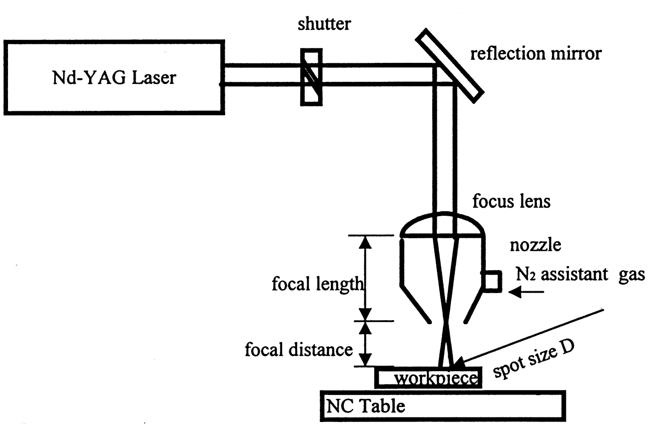

Fig. 1. Design of the the experimental setup.

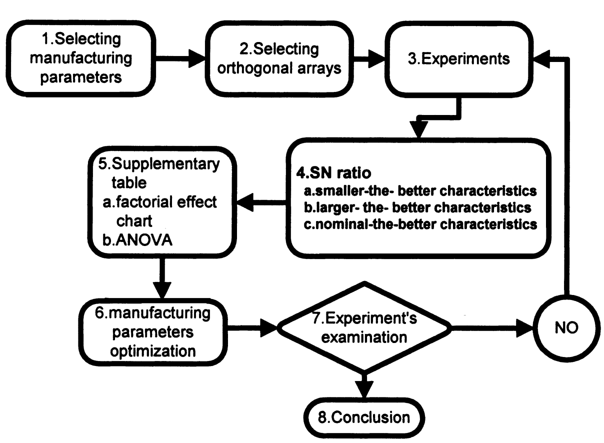

Fig. 2. Taguchi method for experiment design.

2. Larger-the-better.
3. Nominal-the-better.

The definition of SN is given as follows:

$$\mathrm{SN} = \pm 10 \log \frac{1}{n}\left(\frac{1}{y_1^2} + \frac{1}{y_2^2} + \ldots + \frac{1}{y_n^2}\right) \tag{1}$$

In Eq. (1), n is the sample size and y_1, y_2, …, y_n are the n values of the quality factor with smaller-the-better characteristics. The symbols "+" and "−", respectively, represent the SN value with larger-the-better or smaller-the-better characteristics. For the nominal-the-better condition, the SN is given as:

$$\mathrm{SN} = -10 \log \frac{1}{n}\left(\frac{S_m - S_e}{V_e}\right) \tag{2}$$

where S_m = variation of the mean, S_e = error variation, and V_e = error variance.

Using the average value of the SN ratio, a factorial effect chart for each quality factor (see Fig. 4) can be obtained. The steeper the slope the stronger the effects. The variation, variance and degree of contribution of each quality factor can be obtained from the supplementary table (Table 3). The results can be rearranged further as a variable analysis table. The optimum condition was obtained by comparing the calculated results. The experiments were then performed using the parameters for the optimum condition to examine the accuracy of the prediction process. Normally, the optimum condition could not be found from only one experiment, and it was necessary to rearrange the factors. Using previous experimental results, a new orthogonal array (L_{18} table) was obtained. The experiments were repeated until an optimum condition was obtained. If several quality factors are considered at the same time, the optimum conditions have to satisfy all the requirements of the quality factors. The experiments, however, were done separately for different quality factors. A description of the optimisation procedures is given as an example in Section 5.

The fuzzy design theory is well developed and its applications are widely accepted by industry. Here, only a brief description of the basic procedures for the fuzzy evaluation method is given [9, 10]:

1. Decide the attribute set for evaluation. If u_1, u_2, u_3, …, u_n are the attributes for evaluation, the attribute set U is $U = \{u_1, u_2, u_3, \ldots, u_n\}$. For example, the attribute set U for evaluating the quality of laser drilling is U = {taper of hole, hole accuracy at entrance, hole accuracy at exit, hole roundness at entrance, hole roundness at exit}.
2. Decide the attribute linguistic set V. Again, $V = \{v_1, v_2, \ldots, v_n\}$. For example, V = {excellent, good, fair, bad}.
3. Decide the attribute weight set $A = \{a_1, a_2, a_3, \ldots, a_n\}$. The effects of different attributes on the evaluation results must be given in this set. a_i represents the weight factor of the ith attribute, and the following relation should be satisfied:

$$\sum_{i=1}^{n} a_i = 1, a_i \leq 1$$

4. Calculate the fuzzy relation matrix R. R is defined as

$R = [r_{ij}]_{n \times m}$, n and m separately represent the number of components which are included in attribute set U and attribute linguistic set V. The r_{ij} represents the membership of both u_i (attribute set U) and v_j (attribute linguistic set V).

5. Calculate the fuzzy evaluation set B. Here, $B = A \cdot R = [a_1\ a_1\ \cdots\ a_n] \cdot [r_{ij}]_{n \times m} = [b_1\ b_2\ \cdots\ b_n]$.
6. Normalise the B set. After the normalised procedure, the B set was converted to $B' = \{b_1', b_2', \ldots, b_n'\}$ and $b_i' = (b_i/\Sigma b_i)$.
7. Decide the linguistic score set S. Each v_i in set V is given a score, s_i, for evaluation and then the score set S is defined as $S = [s_1\ s_2\ s_3\ \cdots\ s_n]^T$.
8. Quantify the fuzzy evaluation results to obtain a score set D. D is defined as $D = B \cdot S = [b_1'\ b_2' \cdots b_n'] \cdot [s_1\ s_2\ \cdots\ s_n]$. By comparing the score of each design in the score set D, the optimal condition can be found.

3. Experimental Set-up

The main equipment for the experimental work in this research was a long pulsed Nd-YAG laser system(RSY-150 P1) with a raw beam diameter of 8 mm. A 3-axis NC table was used to move the specimen at the desired speed. The focal length of the focusing lens was 125 mm. Nitrogen was used to protect the specimen surface during the laser hardening process. A sample of SNCM439 steel was selected as the specimen. The composition of SNCM439 steel is: C % = 0.36–0.43; Si % = 0.15–0.35; Mn % = 0.60–0.90; P % $<$0.03; S % $<$0.03; Ni % = 1.60–2.00; Cr % = 0.60–11.00 and Mo % = 0.15–0.30. The main quality factors evaluated in this experiment were hardness (H_RC, depth of hardening (mm), width of hardening (mm), and amount of erosion (mg). The erosion tests were performed using an erosion wear test machine (see Fig. 3). The angle of the erosion nozzle was set at 60° in this study. The erosion nozzle was made of tungsten carbide with an orifice diameter of 6.3 mm. The distance between the specimen and the nozzle was 30 mm. Steel particles, accelerated by high-pressure air, passed through the nozzle and struck the surface of the specimen. The hardness of the steel particles was H_RC 56–60 and the diameter was 0.7 mm. The pressure of the compressed air was 4 kg/cm^{-2}. A total of 6 kg of ϕ 0.7 mm steel balls was used in each test.

4. Preliminary Experiments

The laser operating parameters selected for investigation in this study were focus distance (mm), processing speed (mm/min), pumping current (I), pulsing frequency (H_z) and pulse width (ms). The initial values of the selected laser operating parameters were obtained by evaluating the results of several preliminary experiments. The final results for initial parameters in these preliminary experiments were focus distance L = 6 (mm); processing speed V = 120 (mm/min); pumping current I = 70 (amp); pulsing frequency f = 50 (Hz); pulse width T = 1.5 (ms). These initial parameter values were used in an L_{18} orthogonal array (see Table 1). The experiments in this study were based on this table. Pumping current, I (A), is one of the original laser parameters recorded from the laser system. To make these parameters in Table 1 more meaningful for the operating conditions, these original parameters were translated into pulse energy (E_p, J/pulse), or energy intensity (E, J/mm^2), and repetition rate (R, pulse/mm). The energy figures supplied by the Rofin-Sinar operation manual [17] are essential for the calculation for obtaining E_p, E, or R. The final results of these preliminary experiments defined the initial values for further analysis: surface hardness H = 52.5 (H_RC); depth of hardening d = 0.11 (mm); width of hardening W = 0.43 (mm); wear quantity of erosion test Q = 69.55 (mg). The back tempering of the overlapped region made the analysis work more complicated. For the purpose of simplification, the overlapped laser hardening will be excluded in the experiments.

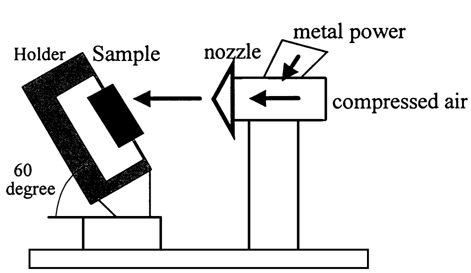

Fig. 3. Schematic diagram of erosion test.

5. Optimisation of Laser Operating Parameters

5.1 Hardness Optimisation

Using a micro-hardness meter, three H_RC hardness tests for each of the experiments 1–18 (H_1, H_2, H_3) were made. Using the larger-the-better characteristics (see Table 2), the supplementary table (Table 3) and the factorial effect chart (see Fig. 4) were then obtained from the SN results of Table 2. The results of variance analysis are given in Table 4. From Fig. 4 and Table 4, the optimal conditions were obtained, which were L (1), V (3), I (3), F (3), T (3). Here, to avoid over estimation, only the quality factors with larger effects were considered. They were L (23.97%), I (36.83%), and T (20.83%) (see Table 4). The SN value for these predicted optimisation parameters was

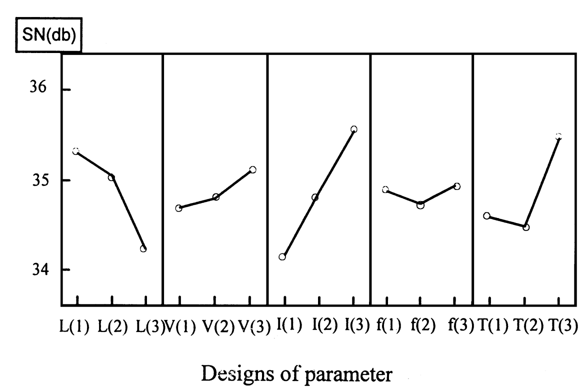

Fig. 4. Factorial effect chart of surface hardness.

Table 1. L_{18} table (L mm; V mm/min; I amp.; f Hz; T ms; R pulse/mm; E_p J/pulse; E J/mm^2).

Expt No.	e_1	e_2	L/D	V	I	e_6	F	T	R	E_p	E
1	–	–	4/0.256	60	50	–	30	1	30	0.44	51.6
2	–	–	6/0.384	120	70	–	50	1.5	25	1.11	72.3
3	–	–	8/0.512	180	90	–	70	2	23.3	2.15	98.0
4	–	–	4/0.256	60	70	–	70	2	70	1.48	404.7
5	–	–	6/0.384	120	90	–	30	1	15	1.08	84.4
6	–	–	8/0.512	180	50	–	50	1.5	16.7	0.66	21.5
7	–	–	4/0.256	120	50	–	50	2	25	0.88	86.0
8	–	–	6/0.384	180	70	–	70	1	23.3	0.74	45.0
9	–	–	8/0.512	60	90	–	30	1.5	30	1.62	94.9
10	–	–	4/0.256	180	90	–	50	1	16.7	1.08	70.3
11	–	–	6/0.384	60	50	–	70	1.5	70	0.66	120.3
12	–	–	8/0.512	120	70	–	330	2	15	1.48	43.4
13	–	–	4/0.256	180	90	–	70	1.5	23.3	1.62	147.7
14	–	–	6/0.384	180	50	–	30	2	10	0.88	22.9
15	–	–	8/0.512	60	70	–	50	1	50	0.74	72.3
16	–	–	4/0.256	180	70	–	30	1.5	10	1.11	43.4
17	–	–	6/0.384	60	90	–	50	2	50	2.15	280.0
18	–	–	8/0.512	120	50	–	70	1	30	0.44	30.1

Table 2. The experimental results and SN ratio of surface hardness using experiments 1–18.

Expt No.	H_1	H_2	H_3	SN
1	51.6	51.4	52.8	34.31
2	52.8	52.1	52.6	34.40
3	63.0	63.2	62.4	35.97
4	60.2	61.1	60.8	35.71
5	59.5	60.1	59.7	35.53
6	46.9	46.3	46.7	33.37
7	54.5	55.8	55.3	34.84
8	55.7	55.5	54.8	34.86
9	49.6	50.2	49.8	33.96
10	63.5	63.0	63.7	36.0
11	52.0	51.2	52.4	34.3
12	56.4	57.8	57.0	35.1
13	62.6	63.0	62.0	35.9
14	58.4	58.0	58.2	35.3
15	49.8	50.6	50.6	34.0
16	56.0	57.2	56.4	35.0
17	62.6	61.8	61.6	35.8
18	44.3	44.0	44.7	32.9

Table 3. Supplementary table of hardness 3.

Factor level	L	V	I	f	T
1	35.31	34.69	34.18	34.88	34.62
2	35.04	34.79	34.87	34.76	34.50
3	34.23	35.10	35.55	34.95	35.47

$$SN = \bar{T} + (A_1 - \bar{T}) + (C_3 - \bar{T}) + (E_3 - \bar{T}) \tag{3}$$

From Eq. (1), the predicted optimisation hardness with SN=36.61 was found to be H_RC 67.69. However, the experimental results for L (1), V (3), I (3), F (3), T (3) were H_RC 63.90. The difference between the predicted value and the experimental result was H_RC 2.79. The prediction error was about 5.6%. It is worth mentioning that the hardness was improved from the initial value of 52.5 to 63.9. Although the percentage improvement was only 21.71%, a hardness of H_RC 63.90 (very close to the maximum hardness H_RC 66.0) was obtained for carbon steel using the transformation hardening process (see Fig. 5, [18]). The above results imply that the Taguchi methodology can be used to find the optimal conditions for laser transformation hardening and can improve the quality of the hardening. A similar procedure was then used to optimise the other quality factors. The results are given in the following sections, but the details of the optimisation procedures will not be discussed again.

Table 4. Variance analysis table of surface hardness; F (freedom), S (variation), V (variance), P (degree of contribution, %).

Factor	F	S	V	P (%)
L	2	3.78	1.89	23.97
V	2	0.53	/	0.27
I	2	5.64	2.82	36.83
f	2	0.12	0.06	–
T	2	3.33	1.66	20.83
e	7	1.08	0.15	–
(e)	11	1.71	0.16	18.37
T	17	14.48	0.85	100

5.2 Hardening Depth Optimisation

Hardening depth is a quality factor with larger-the-better characteristics. Examining the experimental photographs, hardening depths for experiments 1–18 (L_{18} orthogonal array Table 1) were obtained. Using these data and similar optimisation steps to those already described, the optimised hardening depth was found to be 0.213 mm. The experimental result for this parameter design was 0.207 mm. The percentage improvement was about 85%. From the literature examined, the hardening

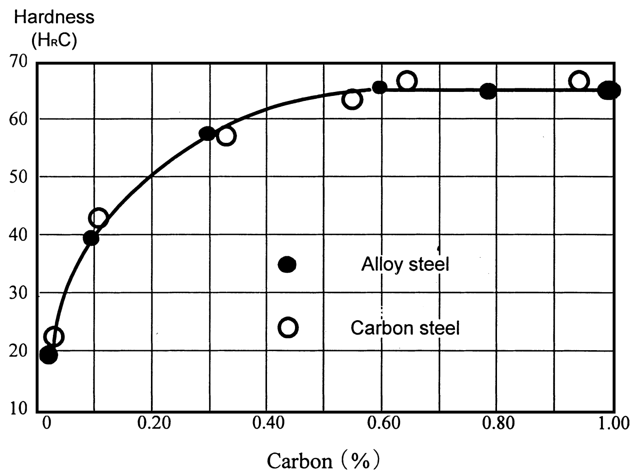

Fig. 5. The relationship between the percentage of carbon and the hardness may be reached by transformation hardening.

depth obtained with a CW mode CO_2 laser over 1000 W, was known to be generally about 0.30–0.50 mm, and the maximum hardening depth using laser transformation processes was known to be 2.5 mm [2,4,5,14–16]. The average power of the long pulsed Nd-YAG laser used in this study was only 150 W. This is the main reason why the hardening depth is smaller than the results announced in earlier literature. The photographs of experiments 1–3 and 13 are shown in Fig. 6. The hardening depth and width were significantly increased from experiment 1 to experiment 3. Although a long focal distance of 8 mm and a very fast processing speed of 180 mm/min were used in the experiment 3 design, high average power (I = 90), pulsing frequency f = 70 Hz, and long duration time (2 ms) produced a very good transformation hardening result. The result of experiment 13 is given in Fig. 6(d). In the photographs of optimised hardening depth (Fig. 6), it can be seen that the hardening depth is significantly improved, owing to the short focal distance (only 4 mm) and the relatively high power intensity (I = 90).

5.3 Hardening Width Optimisation

An optimised parameter design was obtained using the same approach as described in the previous two sections for the larger-the-better characteristics. It was L (1), V (1), I (3), f (3), T (3). The predicted result using the Taguchi method for this optimised parameter design was 0.7 mm. An experimental result of 0.89 mm was obtained using the same parameter design. The difference between the predicted value and the experimental value was 0.12 mm, a difference of about 15.6%. After comparing this with the result from the initial parameter set, the hardening width was increased from 0.43 mm to 0.89 mm. The percentage improvement was about 107%.

5.4 Erosion Amount Optimisation

With the smaller-the-better characteristics, the parameter design was L (1), V (1), I (3), f (3), T (3). To avoid overestimation, only L (1), V (1), I (3), T (3) were considered in this parameter design for predicting the optimised result. The predicted result with the optimised parameter design was 44.67 mg. The difference between the predicted value and the experimental value was 3.73 mg. The percentage prediction error was 8.4%.

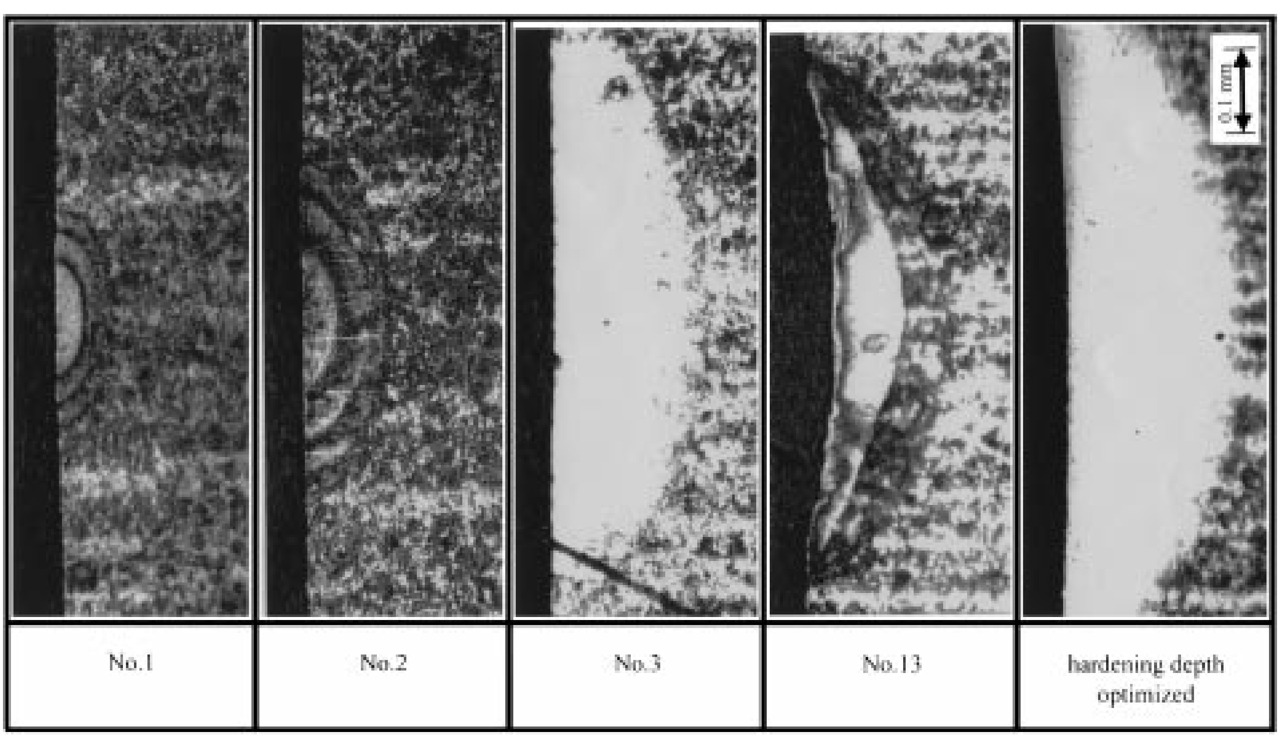

Fig. 6. Photographs of the results of experiments 1, 2, 3 and 13.

Compared with the result from the initial parameters, the improvement was about 41.14%. The erosion amount was significantly decreased from 69.55 mg to 40.94 mg.

The specimen used in this erosion experiment was an SNCM39 circular steel plate of 20 mm diameter. The surface of the specimen was machined on a CNC milling machine with a 16 mm diameter end mill at 1200 r.p.m. and feed value of 2 mm s^{-1}. The distance between hardening strips was 1.5 mm. A comparison between 5, 17, 18 and the optimised condition is given in Fig. 7. In Fig. 7, the darker strips are the traces after transformation hardening. The steel balls (particles) passed through the nozzle and struck the workpiece surface at an angle of 60°. The erosion test result for 5 is given in Fig. 7(*a*). It was found that the area of darker strip was significantly narrower, the transformation hardening depth shallower, and the substrate materials were eroded from the specimen along with the hardened layer. In Fig. 7(*b*), the darker area was also seriously eroded. This was because the hardened layer of design 18 was not very wide or deep. In Fig. 7(*c*) (17), the hardened layer was very wide and the quality was good, and so the erosion was very low. The optimised condition, resulting in a very wide and deep hardened layer with very little erosion, is shown in Fig. 7(*d*).

5.5 Multipurpose Optimisation

Several quality factors, are usually required simultaneously to satisfy the design requirements for industrial components. For

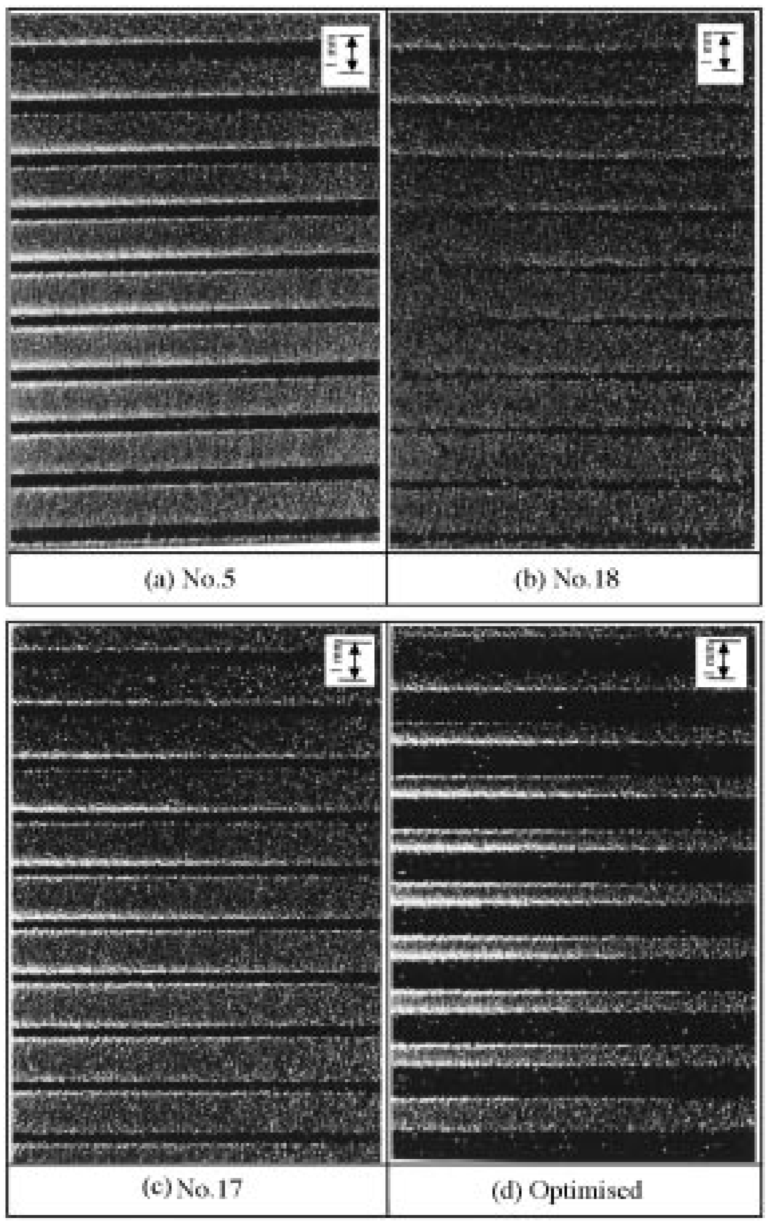

Fig. 7. Erosion amount optimisation.

example, one component may be required to satisfy the following three conditions:

1. Surface hardness greater than H_RC 55.
2. Hardening depth greater than 0.2 mm.
3. Hardening width greater than 0.8 mm.

Therefore, multipurpose optimisation of laser operating parameters is likely to be much closer to the practical requirements in industry. The SN ratio is an indicator representing the factorial effects of each quality factor. A methodology for multipurpose optimisation was addressed in this study. A weight factor ($0 < w_i < 1$) was introduced to represent the importance of each quality factor. For laser transformation hardening processes, the weight factors selected in this research were {hardness, hardening depth, hardening width, erosion amount} = {0.5, 0.3, 0.1, 0.1}. The weight factor was multiplied by the SN ratio for each quality factor. The summation of the products forms the optimised multipurpose SN ratio. In this study, the optimised conditions were *L* (1), *V* (1), *I* (3), *T* (3). To examine the feasibility of simultaneous optimisation of multiple conditions, some experiments were designed and performed. The experimental results for quality factors with multipurpose optimisation was summarised in Table 5. It was found that using this multipurpose methodology significantly aided the optimisation of the laser operation parameters. The comparisons between single and multipurpose optimisation are also given in Table 5. They were was found to be quite similar, possibly because the same parameter design in the orthogonal array L_{18} was used.

6. Quantitative Evaluation with Fuzzy Evaluation Method

To compare the fuzzy evaluation method with the Taguchi methodology, the eighteen data sets obtained from the parameter design with L_{18} orthogonal arrays were used again. The attribute set *U* was defined as *U* = {hardness, hardening depth, hardening width, erosion amount}. To simplify the explanation, a brief description of the result using the fuzzy evaluation method is given in the following paragraph, based on the parameter design of 1–4 only. In this study, the weight factor was assumed to be *A* = {0.5, 0.3, 0.1, 0.1} to show the effects of each attribute. The effect of each attribute represents its relative importance in a practical industrial application. This means that the weight factor set *A* should be varied depending on the requirements of the real situation. Therefore, a good and reasonable weight factor set should be decided after discussion with the system designer, component designer and company manager.

The maximum hardness of H_RC 62.9 was obtained from parameter design 3 and H_RC 44.4 from parameter design 18 was the minimum, while H_RC 60.0 was considered good enough for most practical applications. Therefore, in the membership function, hardness above H_RC 60.0 was defined as excellent and hardness below H_RC 45.0 was defined as poor, and hardnesses between H_RC 60.0 and H_RC 45.0 were divided between, “good” and “ordinary”. Similar procedures and algorithms were applied to decide the membership function for hardening depth, hardening width, and erosion amount. The cut-off values used in this study are shown in Fig. 8. The attribute set for parameter designs 1–4, U_1, U_2, U_3, U_4 is summarised as follows:

$$\begin{aligned} U_1 &= \{51.9 \quad 0.08 \quad 0.26 \quad 64.16\} \\ U_2 &= \{52.5 \quad 0.11 \quad 0.43 \quad 69.55\} \\ U_3 &= \{62.9 \quad 0.18 \quad 0.72 \quad 46.27\} \\ U_4 &= \{60.7 \quad 0.16 \quad 0.64 \quad 54.32\} \end{aligned} \tag{4}$$

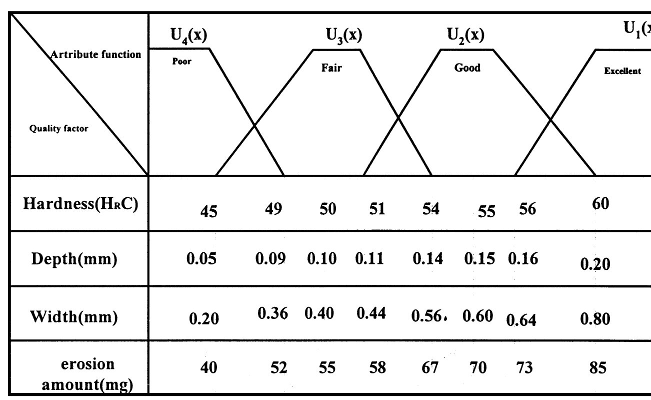

Fig. 8. The membership function of surface hardness, hardening depth, hardening width, and erosion amount.

Table 5. The improvement of quality factor with optimisation of multipurpose parameters.

Quality factor	Initial value	Multipurpose *L*(1) *V*(1) *I*(3) *T*(3)			Single-purpose		
		Weight	Results	Improvement %	Parameters	Results	Improvement %
Hardness (H_RC)	52.5	0.5	62.6	19.24	*L*(1) *V*(1) *I*(3) *F*(3) *T*(3)	62.9	21.71
Depth (mm)	0.112	0.3	0.20	78.6	*L*(3) *V*(1) *I*(3) *F*(3) *T*(3)	0.21	87.5
Width (mm)	0.43	0.1	0.85	97.67	*L*(1) *V*(1) *I*(3) *F*(3) *T*(3)	0.89	107.0
Erosion amount (mg)	69.55	0.1	41.0	41.04	*L*(1) *V*(1) *I*(3) *F*(3) *T*(3)	40.94	41.14

Table 6. The quantitative evaluation with the fuzzy evaluation and the Taguchi method.

Expt No.	Fuzzy score	Fuzzy order
1	65.36	14
2	69.05	12
3	91.46	1
4	87.80	3
5	79.63	6
6	55.15	17
7	70.85	11
8	72.50	10
9	66.25	13
10	80.00	5
11	65.33	15
12	75.05	7
13	7.80	3
14	74.44	9
15	61.63	16
16	74.87	8
17	91.12	2
18	50.18	18

Table 7. The SN ratio for multipurpose optimisation with weight factor = {0.5, 0.3, 0.1, 0.1}.

Expt No.	SN	Taguchi order
1	5.70	15
2	7.08	9
3	9.96	1
4	9.27	3
5	7.4	6
6	3.58	17
7	6.20	12
8	6.69	11
9	7.02	10
10	7.65	5
11	5.79	14
12	7.32	7
13	9.25	4
14	6.18	13
15	5.26	16
16	7.26	8
17	9.84	2
18	1.70	18

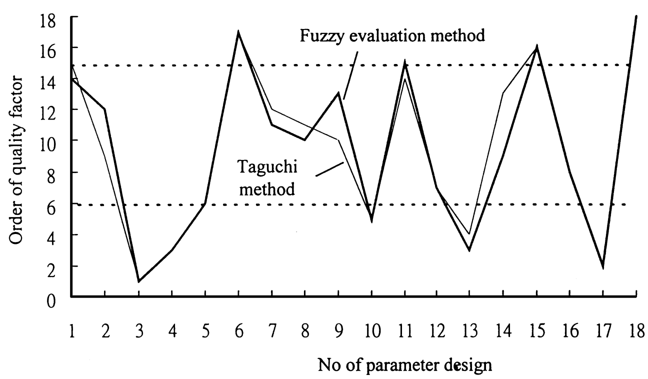

Fig. 9. The comparison of quality with the fuzzy evaluation method and Taguchi method.

The fuzzy relation matrices for parameter designs 1–4, R_1, R_2, R_3, R_4 were then obtained by combining the attribute linguistic evaluation set V = {excellent, good, fair, poor} and the membership function of each quality factor (see Fig. 8). The results were as follows:

$$R_1 = \begin{bmatrix} 0 & 0.300 & 0.700 & 0 \\ 0 & 0 & 0.682 & 0.318 \\ 0 & 0 & 0.375 & 0.625 \\ 0 & 0.316 & 0.684 & 0 \end{bmatrix} \quad R_2 = \begin{bmatrix} 0 & 0.500 & 0.500 & 0 \\ 0 & 0.067 & 0.933 & 0 \\ 0 & 0 & 1.00 & 0 \\ 0 & 0 & 1.00 & 0 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} 1.000 & 0 & 0 & 0 \\ 0.567 & 0.433 & 0 & 0 \\ 0.500 & 0.500 & 0 & 0 \\ 0.440 & 0.560 & 0 & 0 \end{bmatrix} \quad R_4 = \begin{bmatrix} 1.000 & 0 & 0 & 0 \\ 0.067 & 0.933 & 0 & 0 \\ 0 & 1.000 & 0 & 0 \\ 0 & 1.000 & 0 & 0 \end{bmatrix} \tag{5}$$

Introducing the attribute weight factor set A = [0.5, 0.3, 0.1, 0.1], the fuzzy evaluation value set B_1, B_2, B_3, B_4, was then obtained as:

$$\begin{aligned} B_1 &= A \cdot R_1 = [0.00 \quad 0.18 \quad 0.66 \quad 0.16] \\ B_2 &= A \cdot R_2 = [0.00 \quad 0.27 \quad 0.73 \quad 0.00] \\ B_3 &= A \cdot R_3 = [0.76 \quad 0.24 \quad 0.00 \quad 0.00] \\ B_4 &= A \cdot R_4 = [0.52 \quad 0.48 \quad 0.00 \quad 0.00] \end{aligned} \tag{6}$$

The normalised B_1, B_2, B_3, B_4 results are shown as follows:

$$\begin{aligned} B_1 &= [0.00 \quad 0.18 \quad 0.66 \quad 0.16] \\ B_2 &= [0.00 \quad 0.27 \quad 0.73 \quad 0.00] \\ B_3 &= [0.76 \quad 0.24 \quad 0.00 \quad 0.00] \\ B_4 &= [0.52 \quad 0.48 \quad 0.00 \quad 0.00] \end{aligned} \tag{7}$$

To quantitatively evaluate the hardening quality, the linguistic score set S, corresponding to the attribute linguistic set V = {excellent, good, fair, poor}, was assumed to be S' = $[95, 80, 65, 50]^T$. The fuzzy evaluation score D_1, D_2, D_3, D_4 of parameter designs 1–4 was then obtained from the operation of B and S, which is:

$$\begin{aligned} D_1 &= B_1 \cdot S = 65.36 \\ D_2 &= B_2 \cdot S = 69.05 \\ D_3 &= B_3 \cdot S = 91.46 \\ D_4 &= B_4 \cdot S = 87.80 \end{aligned} \tag{8}$$

Using the fuzzy evaluation score set, it was then possible to evaluate quantitatively the quality of 1–4. Using the experimental data of parameter designs 1–18 (L_{18} orthogonal array) and adopting the same procedures discussed in the above section, a fuzzy evaluation score set was obtained, as summarised in Table 6. It was found that parameter design 3 was the optimal condition in this study. The SN ratio for multipurpose optimisation with weight factor set A = {hardness, hardening depth, hardening width, erosion amount} = {0.5, 0.3, 0.1, 0.1} is summarised in Table 7. In the Taguchi method, The larger the SN ratio, the better the quality, Therefore, the predicted

SN ratio was used to represent the order of the quality factor in this research. In Fig. 9, the comparisons of the evaluation results using fuzzy evaluation and Taguchi methodology are given. It is worth noting that the comparisons were based on the same weight factor for each quality factor. From the comparison in Fig. 9, it was found that both the fuzzy evaluation method and Taguchi methodology produced the same evaluation within the orders 1–5, and 16–18. This implied that both methods can give an effective and reasonable evaluation for laser operating parameters for both the optimal condition and the poor condition. There was no significant difference in the middle range between the two methods. From the predicted results of the quality evaluation order in Tables 5 and 6 and in Fig. 9 , both the fuzzy evaluation method and the Taguchi method were considered to be effective and practical for evaluating quantitatively the quality of the long pulsed Nd-YAG laser transformation hardening process. This conclusion is very significant and may be extended to other high-power laser transformation hardening processes. Further research is required to investigate the effect of impact loading on the hardened layer.

7. Summary

The Taguchi methodology was used in this study to improve and optimise the long pulse Nd-YAG laser transformation hardening processes. The hardness, hardening depth, hardening width and erosion amount were improved. Under optimal conditions, the hardness was improved from H_RC 52.5 to H_RC 63.9; the hardening width was improved from 0.43 mm to 0.89 mm; and the erosion amount was improved from 69.55 mg to 40.94 mg. For multipurpose optimisation, there was a 19–98% quality improvement for each quality factor. The quality of the hardened layer was significantly improved with the application of the Taguchi methodology. Quantitative evaluation using the fuzzy evaluation method was also investigated based on long pulsed Nd-YAG laser transformation hardening processes. The fuzzy evaluation score was obtained and the quality evaluation order was found. Based on the experimental results in this study, both the single purpose and multipurpose evaluation methods performed equally well in the prediction of both optimal conditions and worst conditions for laser transformation hardening. It was concluded that both the fuzzy evaluation method and Taguchi methodology were effective and applicable for evaluating quantitatively the quality of the long pulsed Nd-YAG laser transformation hardening processes.

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