Parametric Optimization for Laser Marking Performance via Taguchi Approach

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Abstract-This paper parametrically optimizes the laser marking process for marking stainless steel AISI 316L for marking's quality and time using Taguchi method wherein the rationale is to ensure the compatibility of the process with material being processed. Four parameters namely "laser frequency", "number of layers removed", "laser power" and "scanning speed" are investigated herein. Main effect for means and signal to noise ratio have been done to study & optimize the effects of variables on stated performance measures respectively. The process is mathematically formulated via linear regression model. It is found that among the factors studied herein, major contributing factor for marking time is "number of layers removed" whereas "scanning speed" effects surface roughness the most. Optimum levels for minimizing marking time are determined to be: level 1 for "laser frequency" and "number of layers removed", level 2 for "laser power" and level 3 for "scanning speed". On the other hand, for minimization of surface roughness, optimum levels are found to be: level 1 for "laser frequency", "number of layers removed" and "laser power" and level 3 for "scanning speed". The mathematical model developed herein is found to be statistically significant at 95% confidence level with contributions of model terms to be 98.92% for marking time and 96.84% for surface roughness. The developed models are validated by the confirmatory run wherein good agreement between predicted and experimental values is obtained.

Keywords-Laser Marking, Taguchi Method, Surface Roughness

I. Introduction

Laser beam marking process uses a highly focused laser light that falls on the surface of the work part to engrave or mark the object. The process has wide applications in various types of food industries for engraving number and dates on food packages as well as for marking and printing logos and bar codes on printed circuit boards, electronic components and other products for the purpose of product identification and traceability [i-iii]. The process provides higher flexibility, accuracy, ease of automation and reproducibility as compared to other conventional marking techniques such as hot stamping, mechanical scribing or inkjet [i]. The non-contact nature of the process allows wide variety of materials such as plastics, wood, metal and ceramics to be used as work piece that furthers the usefulness of the process [ii, iv].

The principle of operation is based on ablation wherein the interaction between material and the laser beam, which comes from a laser system and passes through a focusing lens (convex lens), leads to the vaporization and melting of work material. As a result, the material is removed from the work piece in layers via ablation mechanism [i, v]. Fig. 1 shows the principle of operation for a laser marking machine.

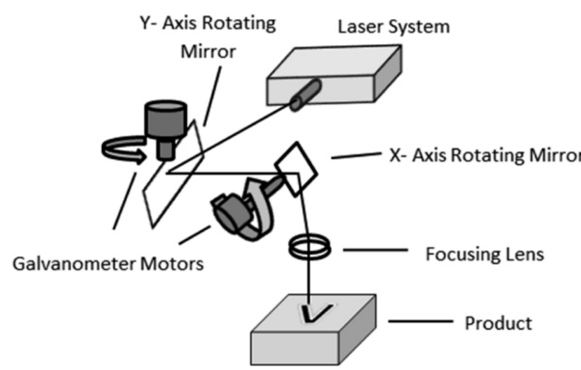

Fig. 1. Principle of operation for a laser marking machine [i]

Several studies have been done on the parametric optimization in order to improve the quality of marked parts [v-x]. Results of these studies show that process parameters can be adjusted to optimize the process for number of applications. Some researchers [vii] have used Artificial Neural Networking (ANN) while optimizing the process whereas others have used Taguchi method to improve the quality of marked parts [v]. No considerable work, however, could be found for the optimization for marking time. Considering, that the marking time is related to the cost dynamics of the process it is imperative that a study is undertaken to minimize the marking time yet maximizing the quality of the engraving. This would ensure the compatibility of the process with material being processed. The rationale behind this research is thus to ensure the compatibility of the process with material being processed.

This paper reports on the optimization of laser marking process for enhanced surface quality and operation time reduction for the case of Stainless Steel AISI 316L that has good heat and corrosion resistance properties [xi]. It is mostly used in shafts, pumps and equipment for processing chemical foods [xii]. Taguchi method is used herein while investigating four process parameters namely "pulse frequency", "number of layers removed", "laser power" and "scanning speed". "Pulse frequency" is defined as number of pulses emitted from laser system per unit time, "number of layers removed" refer to the total number of layers ablated in the process after multiple passes, "laser power" is the average power of the pulsed laser and "scanning speed" is the distance per unit time covered by the laser head as it scans the selected area during machining. [xiii-xiv]. Main effect plot for means and signal to noise ratio are used to analyze and optimize the process respectively while regression modeling is done to understand the relations between the process parameters.

II. Materials and Experimental Setup

A. Work piece Details

A 6.35 mm (1/4-inch) thick plate of Stainless Steel (AISI 316L) is employed for the presented work. The material's chemical composition is given in Table I.

TABLE I
Chemical Composition of Stainless Steel (AISI 316L)

AISI 316L		
Element	**% Wt. (Actual)**	**% Wt. (Standard) [xi]**
Cr	17	16 - 18
Ni	10.50	10.0 - 14.0
Mn	1.20	0 - 2.0
Si	1.00	0 - 1.0
S	0.02	0 - 0.03
C	0.06	0 - 0.03
P	0.03	0 - 0.045
Mo	2.50	2.0 - 3.0
Fe	Balance	Balance

A. Marking Details

Marking is done on the work piece using laser marking machine (TruMark station 5000, TRUMPF, Germany) with Ultraviolet (UV) laser as the beam. The machine used for experimentation is shown in Fig. 2.

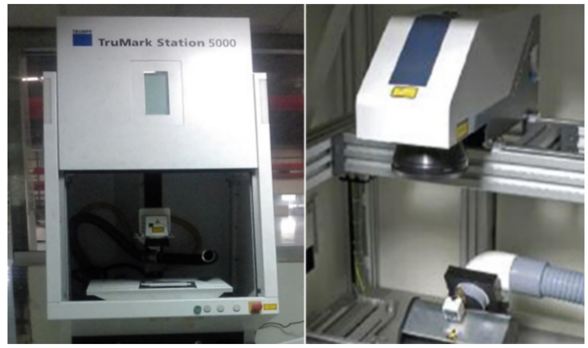

Fig. 2. Laser marking machine used for the marking operation on the work piece

C. Experimental Conditions

A convex lens with focal length of 163 mm is used in the way of laser beam to focus the laser beam on the work piece with an input voltage of 230 volts. A mix hatching mode scanning strategy is adopted herein because in multi-layer machining cycles, surface roughness is reported to be reduced by changing the scanning direction [xv], In this mode, the laser head moves in different directions (i.e. angles) in successive passes of machining cycle to remove the layers. In the work presented herein, angles of the hatching pattern are fixed (as opposed to random hatching) so that in each experiment a similar hatching pattern can be re-produced.The hatched lines make angles of 45^{o}, 90^{o}, 135^{o} and 180^{o}. Hatching mode with scanning directions is shown in Fig. 3.

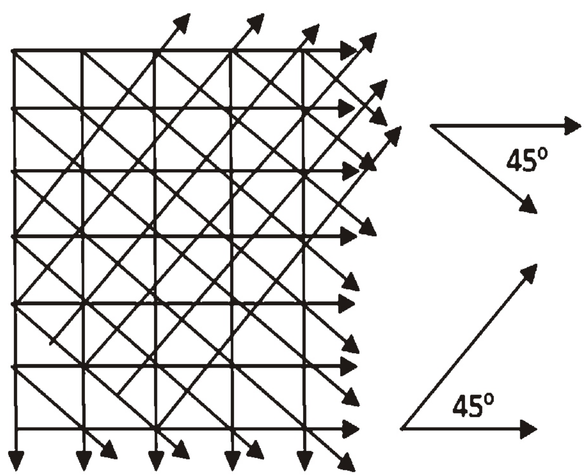

Fig. 3. Mix hatching pattern with scanning directions

Three replications are done to ensure repeatability of experiments as is the general approach [xvi-xvii] with average values reported herein.

D. Design of Experiments

Taguchi's orthogonal array L9 is used herein to optimize the effects of four process parameters. The column namely "Working Range" shows the overall range of parameters' values whereas three levels are taken for each process parameter. For each parameter investigated, level 1 is the minimum value whereas level 3 is the maximum value of the chosen value set. Table II lists process parameters with units and values of the levels selected herein.

TABLE II
PROCESS PARAMETERS AND LEVELS

Process Parameters	Units	Symbol of Units	Working Range	Level 1	Level 2	Level 3
F_p	Hertz	Hz	25-75	25	50	75
N_r	-	-	10-30	10	20	30
P	Watt	W	65-95	65	80	95
S_s	Micro-second	μ-sec	70-130	70	100	130

The work piece after marking operation is shown in Fig. 4.

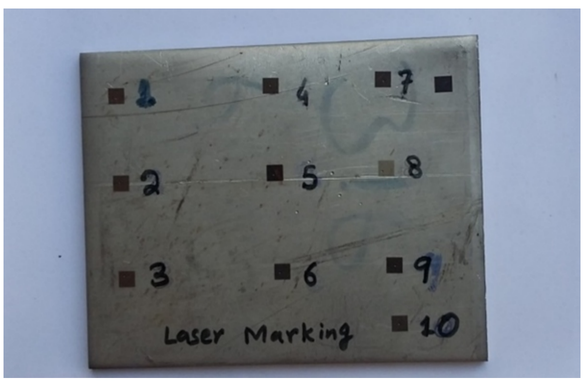

Fig. 4. Workpiece after marking operation.

III. MEASUREMENT & PROCEDURES

Marking time is noted for each experiment by using a stop watch while surface roughness data is taken by measuring R_a using profilometer[1] (Fig. 5). Three readings are taken with a cut-off length of 0.8 mm and an evaluation length of 4.0 mm and the average is reported herein.

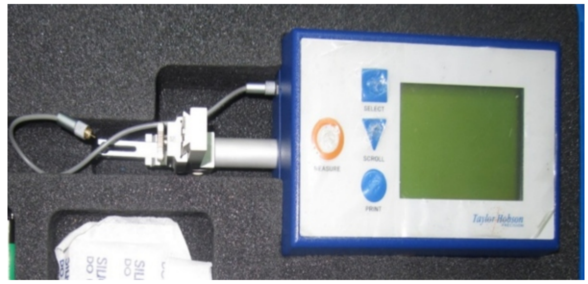

Fig. 5. Profilometer employed for the measurement of surface roughness (Ra).

IV. RESULTS, ANALYSIS[2] AND DISCUSSION

A. Making Time and Surface Roughness

Table III lists the average results of marking time (T_m) and surface roughness (Ra) for all the nine experiments.

TABLE III
TAGUCHI ORTHOGONAL ARRAY AND EXPERIMENT RESULTS FOR MARKING TIME AND SURFACE ROUGHNESS

Exp. No.	Process Parameters				Performance Measures	
	F_p	N_r	P	S_s	T_m	Ra
1	25	10	65	70	37.17	3.87
2	25	20	80	100	53.32	4.31
3	25	30	95	130	65.69	4.82
4	50	10	80	130	23.23	3.45
5	50	20	95	70	74.34	7.82
6	50	30	65	100	81.48	5.13
7	75	10	95	100	37.56	5.80
8	75	20	65	130	40.46	2.86
9	75	30	80	70	96.51	7.53

[1]Surface Profilometer: Surtronic S25, Taylor Hobson Ltd, United Kingdom
[2]Minitab 16.0 is used for the analysis

B. Main Effect Plots for Means

The effects of individual parameters on marking time and surface roughness are calculated by using data means. The values of data means for marking time and surface roughness are given in the Table IV and Table V respectively.

TABLE IV
RESPONSE TABLE (MEANS) FOR MARKING TIME

Process Parameters	Level 1	Level 2	Level 3	Delta	Rank
F_p	52.06	59.68	58.18	7.62	3
N_r	32.65	56.04	81.23	48.57	1
P	53.04	57.69	59.20	6.16	4
S_s	69.34	57.45	43.13	26.21	2

Table IV shows that process parameters F_p, N_r and P have a direct relation with the marking time while S_s has an inverse relation with marking time. Delta shows the intensity of the effect of process parameters on the response (marking time), it is calculated by the difference between the maximum and minimum values of data means for each variable, while ranking has been done on the basis of the higher delta values for each process parameter [xviii]. N_r is, hence, found to have an effect on the marking time the most followed by S_s.

TABLE V
RESPONSE TABLE (MEANS) FOR SURFACE ROUGHNESS

Process Parameters	Level 1	Level 2	Level 3	Delta	Rank
F_p	4.33	5.47	5.40	1.14	4
N_r	4.37	4.99	5.83	1.46	3
P	3.95	5.10	6.15	2.20	2
S_s	6.41	5.08	3.71	2.70	1

The case of surface roughness is depicted in Table V. Here S_s affects the surface roughness of the work part the most whereas F_p is found to have a minimal effect on the surface roughness. Fig. 6 presents the main effects plot for means for marking time whereas Fig. 7 shows the same for surface roughness.

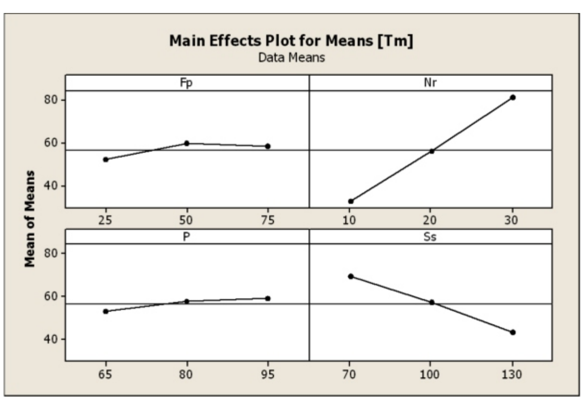

Fig. 6. Main effect plot (means) for marking time.

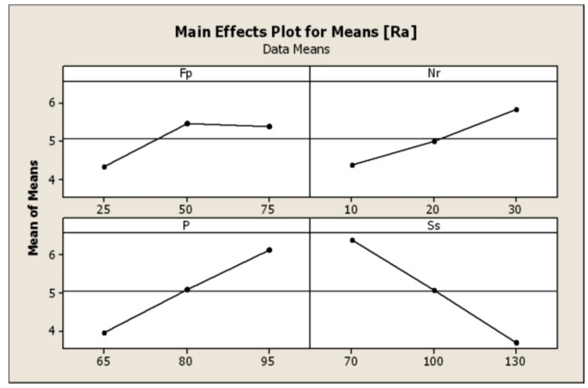

Fig. 7. Main effect plot (means) for surface roughness.

The major contributing factor for marking time is number of layers removed followed by scanning speed. The results can be explained; here the number of removed layers represent the number of complete hatched patterns. Higher the number of complete hatched patterns, the thicker the marked impression. Each hatched pattern takes some time for its completion i.e the time for the complete movement of the laser beam. Therefore, higher the number of removed layers, greater will be the marking time for the laser process. Second important factor for marking time is scanning speed. Scanning speed is the speed of the laser beam during its hatching mode. It is clear that lower the scanning speed, more is the time that the laser beam needs to machine the surface [xiii].

For surface roughness, scanning speed is the most contributing factor for surface roughness followed by laser power. The influence of scanning speed in coordination with laser power on surface roughness could be explained on the basis that a focused laser beam provides energy for vaporization of the unwanted material in order to generate a marked impression in laser marking machine. Laser beam is result of light amplification of monochromatic lights. The higher the intensity of laser, higher would be the power and hence thicker will be the marked impression [i, xix]. Therefore, power of the laser beam increases the surface roughness but it may not affect the surface roughness as much when movement of the laser beam i.e scanning speed is fast. On the other hand, when movement is slow, surface quality deteriorates.

C. *Main Effect Plot for Signal to noise Ratio (SNR)*

The type of the Signal to Noise Ratio analysis used herein is “smaller the better” for both “marking time” and “surface roughness”. This indicates that the smallest values of both marking time and surface roughness are preferable. The formula for measuring “smaller the better” signal to noise ratio (SNR) is given in the Eq (1) [xvii].

$$SNR = \eta = -10\log_{10}[\frac{1}{n}\sum_{i=1}^{n} y_i^2] \quad (1)$$

Where SNR is represented by η and y_i is the ith reading [xvii].

Table VI and Table VII list the average SNR values for marking time and surface roughness using the above equation.

TABLE VI
RESPONSE TABLE (SIGNAL TO NOISE RATIOS) FOR MARKING TIME

Parameters	Level 1	Level 2	Level 3	Optimum Level
F_p	-34.10	-34.32	-34.44	-34.10
N_r	-30.07	-34.70	-38.09	-30.07
P	-33.92	-33.85	-35.09	-33.85
S_s	-36.17	-34.75	-31.94	-31.94

TABLE VII
RESPONSE TABLE (SIGNAL TO NOISE RATIOS) FOR SURFACE ROUGHNESS

Parameters	Level 1	Level 2	Level 3	Optimum Level
F_p	-12.70	-14.27	-13.98	-12.70
N_r	-12.59	-13.23	-15.13	-12.59
P	-11.69	-13.66	-15.60	-11.69
S_s	-15.72	-14.05	-11.18	-11.18

Results from the response tables using signal to noise ratios (Table VI and Table VII) have been used to plot the marking time (Fig. 8) and surface roughness (Fig. 9).

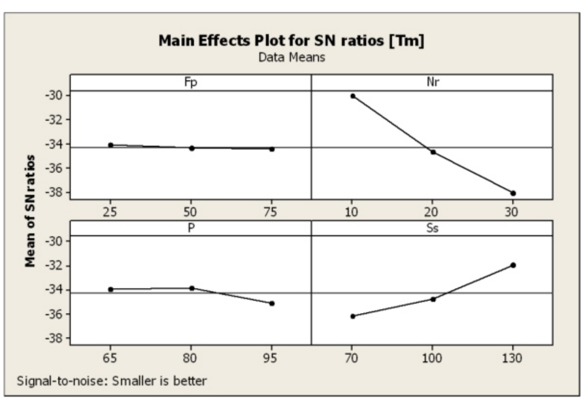

Fig. 8. Main effect plot (Signal to noise) for marking time.

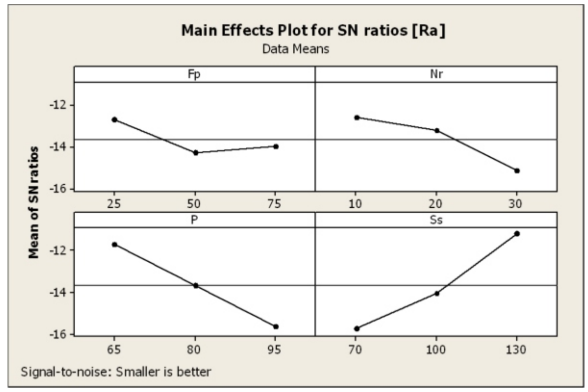

Fig. 9. Main effect plot (signal to noise) for surface roughness

Since Taguchi approach is built on the basis that selection of appropriate levels of the process parameters would weaken the effects of noise factors [xviii] so the point is to select the level of process parameter with highest SNR. Correspondingly, for marking time, level 1 of the first two process parameters (F_p and N_r) is regarded as the optimum level, for P it is level 2 whereas level 3 is the optimum level for the last process parameter S_s. For surface roughness on the other hand, level 1 is the optimum level for F_p, N_r and P whereas level 3 is the optimum level for S_s.

D. *Mathematical Modelling*

General linear regression analysis has been used in order to formulate the process. The regression equation for the marking time has been given in Eq (2).

$$T_m = 29.2122 + 0.1223F_p + 2.4287N_r + 0.2053P - 1.4369S_s \quad (2)$$

To determine the statistical significance of the developed model and to quantify contribution made by each individual process parameter, analysis of variance (ANOVA) has been done for the regression model for marking time as shown in Table VIII. The contribution of regression terms account to 98.92% against the error contribution of only 1.08%. Moreover, P-value for the regression modeling comes out to be 0.000348 which is less than the selected α value of 0.05 that thus validates the statistical significance of the model with 95% confidence level.

TABLE VIII
ANOVA FOR REGRESSION ANALYSIS OF MARKING TIME

Source	DoF	Sum of Squares (SS)	Mean Squares (MS)	Variance Ratio (F)	P	Cont. (%)
Regression	4	4682.80	1170.70	91.452	0.0003	98.92
F_p	1	56.12	56.12	4.384	0.1043	1.18
N_r	1	3539.05	3539.05	276.461	0.0000	74.76
P	1	56.92	56.92	4.446	0.1026	1.20
S_s	1	1030.71	1030.71	80.516	0.0008	21.77
Error	4	51.21	12.80			1.08
Total	8	4734.01				

For surface roughness, the regression analysis provides the mathematical formulation as given be Eq (3).

$$Ra = 1.19444 + 0.0212667 F_p + 0.0726667 N_r + 0.0731111 P - 0.0449444 S_s \quad (3)$$

Here too analysis of variance (ANOVA) has been done for the regression model for surface roughness (Table IX) to determine the statistical significance of the developed model and to quantify contribution made by each individual process parameter. A P-value lower than selected α of 0.05 shows the statistical significance of the regression model at 95% confidence level. The contribution of regression terms account to 96.84% against the error contribution of only 3.16%.

TABLE IX
ANOVA FOR REGRESSION ANALYSIS OF SURFACE ROUGHNESS

Source	DoF	Sum of Squares (SS)	Mean Squares (MS)	Variance Ratio (F)	P	Cont. (%)
Regression	4	22.9884	5.7471	30.6244	0.0029	96.84
F_p	1	1.6960	1.6960	9.0375	0.0396	7.14
N_r	1	3.1683	3.1683	16.8827	0.014	13.35
P	1	7.2161	7.2161	38.4521	0.003	30.4
S_s	1	10.9080	10.9080	58.1253	0.001	45.95
Error	4	0.7507	0.1877			3.16
Total	8	23.7390				100

E. Confirmatory Experiment

In order to validate the conclusions drawn from the regression analysis, the confirmatory runs involve prediction and verification of the performance measures under optimal levels of process variables. Confirmatory experiments were performed with the optimum levels of process parameters and results were compared to the predicted values. Results of confirmatory experiments for marking time, surface roughness are shown in Table X. The confirmatory runs show very good agreement (error 2.23% for marking time and 3.7% for surface roughness) between predictedand experimental results. The results of the confirmatory run validate the parametric optimization obtained for the laser marking process with parameters investigated herein.

TABLE X
CONFIRMATORY TESTS FOR MARKING TIME AND SURFACE ROUGHNESS

Performance Measures	Test conditions (optimum parameters)	Experimental value	Predicted value	Relative error
Marking time	F_{p1} N_{r1} P_2 S_{s3}	11.81	12.08	2.23%
Surface Roughness	F_{p1} N_{r1} P_1 S_{s3}	1.30	1.35	3.70%

V. CONCLUSIONS

Laser marking process has been investigated for optimization of process parameters for marking time and surface roughness of stainless steel AISI 316L using Taguchi method. Four process parameters i.e. “laser frequency”, “number of layers removed”, “laser power” and “scanning speed” are investigated in this study. Main effect plot for means and signal to noise ratios have been done to analyze the process while regression modeling is used to formulate the process. Following conclusions can be drawn from the research study:

For marking time, number of layers removed is found to be the major contributing process parameter followed by scanning speed.

For surface roughness, scanning speed is found to be the major contributing factor for surface roughness followed by laser power and number of layers removed whilst pulse frequency is found to be the least contributing factor.

Signal to noise ratio results show that

- o Marking time is minimized at the optimum level of process parameters which for F_p (laser frequency) and N_r (number of layers removed) is level 1, for P (laser power) it is level 2 and for S_s (scanning speed) it is level 3.
- o Surface roughness is minimized at the optimum level of process parameters which for F_p (laser frequency), N_r (number of layers removed) and P (laser power) is level 1 whereas for S_s (scanning speed) it is level 3.

Mathematical modelling provides useful mathematical relations among the process parameters for marking time and surface

Roughness. The model is found to be statistically significant at 95%confidence level with error contributing to only 1.08% for the model developed for marking time and 3.16% for the model developed for surface roughness.

Confirmatory tests are conducted to validate the mathematical formulations. A good agreement (2.23% error for marking time and 3.70% error for surface roughness) was found between the experimental and predicted results.

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NOMENCLATURE

F_p = Laser frequency

N_r = Number of layers removed

P = Laser power

S_S = Scanning speed

T_m = Marking time

Ra = Surface roughness