# A Study on Surface Quality of Laser Drilled Holes: Parametric Optimization Using Harmony Search Algorithm

S. Chatterjee, K. Abhishek, and S. S. Mahapatra

***Abstract*—Micro-machining of stainless steel is difficult in conventional machining process due to excessive heat generation and micro-structural changes. Hence, lasers have been widely used to localize the heat affected zone in order to control the micro-structural changes. However, the major difficulty arises while performing laser drilling is the formation of spatter which affects the quality of holes. The present study focuses on reduction of spatter area in $CO_2$ laser drilling of stainless steel using Taguchi method embedded with Harmony search algorithm. The influence of machining parameters such as flushing pressure, laser power and pulse frequency on spatter area has been studied through Analysis of variance (ANOVA). It has been observed that flushing pressure and pulse frequency are the most influencing factors on formation of spatter. Harmony search algorithm has been used to evaluate the optimal parametric setting that attempts to minimize spatter area.**

***Index Terms*—$CO_2$ laser, harmony search (HS) algorithm, laser drilling, spatter.**

## I. Introduction

Micro-machining of advanced engineering materials such as stainless steels, titanium alloys, nickel alloys and ceramics is a challenging task due to properties like high strength to weight ratio, toughness, slenderness ratio and low thermal conductivity. Micro-machining of AISI 316 with high aspect ratio is a difficult task due to excessive heat generation, micro-structural changes and tool breakage. Laser beam machining (LBM) process is a suitable alternative machining process since it localizes the heat source to control the micro-structural changes. The difficulty arises during laser drilling because of spatter area and heat affected zone (HAZ) thickness which adversely affects the quality of laser drilled holes.Stainless steel of grade AISI 316 has various engineering applications in aviation, automobiles, medical and home appliance sectors due to its favorable properties such as high melting point, strength to weight ratio and corrosion resistance. Drilling on components made of stainless steel is generally carried out for joining or assembling purpose. Drilling of AISI 316 with high aspect ratio is a challenging task as tool failure occurs due to low thermal conductivity of stainless steel and improper heat dissipation. To overcome this, laser is one of the alternatives for drilling operation on stainless steel. Laser drilling has advantages like less machining time, non-contact machining process and with high accuracy.

Yilbas have studied the effect of laser parameters like pulse power and pulse time on quality of holes [1], [2]. Ghoreishi and Nakhjavani and Yilbas and Aleem have studied the effect of laser process parameters using design of experiment (DOE) approach and observed that ambient gas has significant influence on the quality of holes [3], [4]. Low *et al*. [5] and Kaur *et al*. [6] have studied the effect of control parameters such as laser energy, pulse duration and pulse frequency on the hole quality such as spatter deposition and taper of the hole during laser drilling of Nimonic 263 and Zirconium oxide ($ZrO_2$) respectively using Nd:YAG laser. Rajesh *et al*. [7] have studied the effect of laser parameters such as lamp current, pulse frequency, gas pressure and pulse width during laser drilling of austenitic stainless steel using statistical approach on the performance measures such as diameter at entry and exit and taper of the hole. It is observed that the regression model developed for the prediction of the machining outputs has close agreements with the experimental results.

Critical analysis of literature reveals that limited research works have been done in laser drilling of stainless steel using $CO_2$ laser. This study attempts to identify the effect of laser parameters on spatter deposition in drilling of AISI 316. Three process parameters such as flushing pressure, laser power and pulse frequency at three different levels have been considered to design the experimental layout. In order to reduce the experimental runs, design of experiment (DOE) approach has been adopted to obtain maximum information with less experimental runs. Analysis of variance (ANOVA) has been conducted to analyze the effect of aforesaid machining parameters on spatter area. In this study, the empirical model relating spatter area with process parameters has been developed using non-linear regression analysis. The Empirical equation is used as an objective function in the algorithm to obtain optimum parametric setting using meta-heuristic approach known as harmony search (HS) algorithm.

## II. Experimental Procedure

The experiments have been performed on ORION-3015 $CO_2$ laser cutting machine (LVD Company, Belgium) (Fig. 1 (a)) using nitrogen as an assistant gas for cleaning the extra

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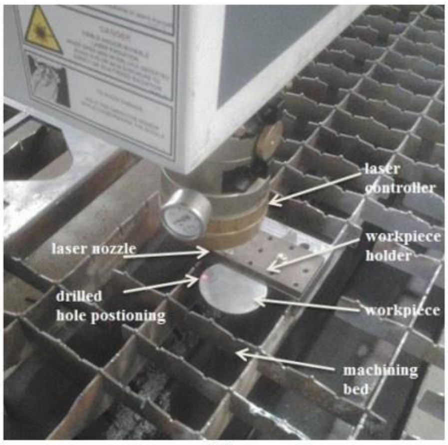
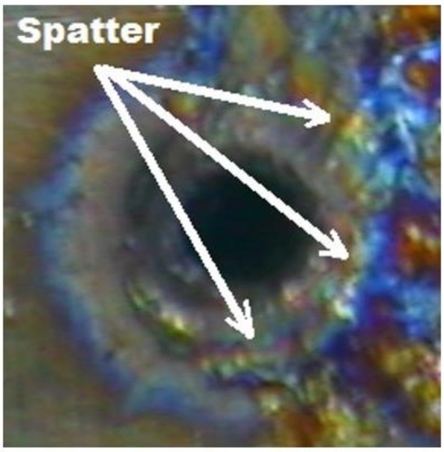
material after machining (flushing). It is controlled by Fanuc CNC controller. CADMAN-L 3D software is used for controlling laser processing set up. The work piece is exposed to focus stationary laser beam with coaxial $CO_2$ gas jet. As the temperature increases, melting of work material occurs leading to depression at center. The removal of the molten metal is carried out using Nitrogen as an assistant gas with flushing pressures ranging between 34 to 40 bars. The laser process parameters and their levels are presented in Table I. Taguchi $L_9$ orthogonal array has been adopted to design the experimental run (Table II). To measure the spatter area (Fig. 1(b)), the machined work material is observed under optical microscope (RADIAL INSTRUMENT with Samsung camera setup, 30-X magnification). The images are so acquired is analyzed in image processing tool in MATLAB 2015a to measure the spatter area.




(a)




(b)

Fig. 1(a). Experimental setup ORION-3015 $CO_2$ laser cutting machine and 1(b). Spatter deposition near the laser drilled holes at 30X magnification at flushing pressure of 37Pa, laser power of 2000W and pulse frequency of 2000Hz.

TABLE I: MACHINING PARAMETERS AND THEIR LEVELS

| Machining Parameters | Units | Symbol | Levels | | |
|---|---|---|---|---|---|
| Flushing Pressure | [bar] | A | 34 | 37 | 40 |
| Laser Power | [W] | B | 2000 | 2250 | 2500 |
| Pulse Frequency | [Hz] | C | 1600 | 1800 | 2000 |

TABLE II: EXPERIMENTAL SETUP

| Exp. No. | Flushing Pressure | Laser Power | Pulse Frequency |
|---|---|---|---|
| 1 | 34 | 2000 | 1600 |
| 2 | 34 | 2250 | 1800 |
| 3 | 34 | 2500 | 2000 |
| 4 | 37 | 2000 | 1800 |
| 5 | 37 | 2250 | 2000 |
| 6 | 37 | 2500 | 1600 |
| 7 | 40 | 2000 | 2000 |
| 8 | 40 | 2250 | 1600 |
| 9 | 40 | 2500 | 1800 |

## III. HARMONY SEARCH (HS) ALGORITHM

Harmony search (HS) algorithm is meta-heuristic algorithm which is based on natural musical performance processes that occur when a musician searches for a better state of harmony, such as during jazz improvisation. HS algorithm includes a several optimization operators such as harmony memory (HM, stores the feasible vectors), the harmony memory size (HMS, number of solution vectors in harmony memory), the harmony memory considering rate (HMCR), and the pitch adjusting rate (PAR) [8]-[10].

Following are the procedural steps involve in HS algorithm [9]-[12].

- Defining the objective function and set the required parameters for the algorithm.
- Randomly generated the HM and improvising new HM with the existing HM.
- Updating the HM from the existing with new best harmony. Repeat the last steps until termination criteria is achieved.

## IV. RESULTS AND DISCUSSION

To analyze spatter area and identify the significant factors in laser drilling of AISI 316, analysis of variance (ANOVA) is performed. ANOVA for spatter area shows that pulse frequency has higher percentage of contribution (54.10%) on spatter deposition during laser drilling of AISI 316 (Table III). Whereas flushing pressure has contribution of 29.64%. The main effect signal to noise (S/N) ratio plot has been done (Fig. 2). Fig. 2 illustrates that with increase in laser power spatter area increases.

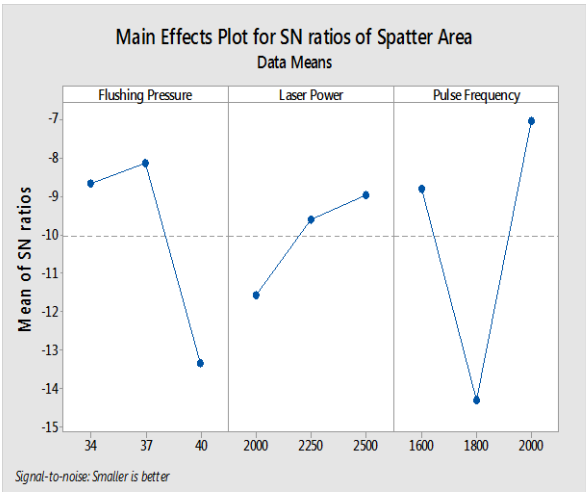



Fig. 2. Main effect S/N plot of Spatter Area.

TABLE III: ANOVA FOR SPATTER AREA

| Factors | DF | Seq SS | Adj SS | Adj MS | F | % Contribution |
|---|---|---|---|---|---|---|
| A | 2 | 7.7972 | 7.7972 | 3.8986 | 3.63 | 29.64 |
| B | 2 | 0.8126 | 0.8126 | 0.4063 | 0.38 | 3.09 |
| C | 2 | 15.546 | 15.546 | 7.7734 | 7.23 | 59.10 |
| Residual Error | 2 | 2.1503 | 2.1503 | 1.0752 | | |
| Total | 8 | 26.307 | | | | |

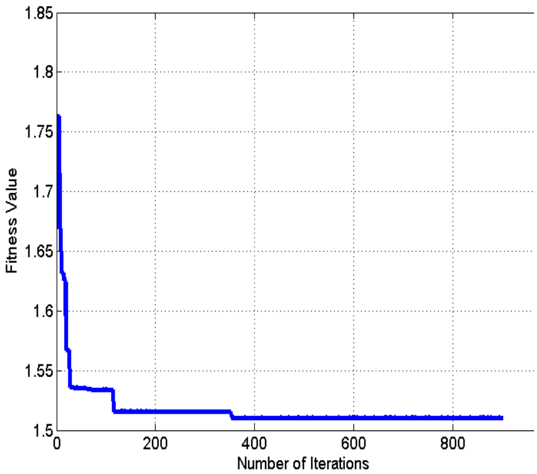



Fig. 3. Convergence curve for spatter area having fitness value of 1.5123 at flushing pressure of 34 Pa, laser power of 2494 W and pulse frequency at1992 Hz.

TABLE IV: HS ALGORITHM OPTIMUM PARAMETRIC SETTING, FITNESS VALUE AND CONFORMITY TEST RESULTS

| Method | A | B | C | Fitness Value (Spatter Area) | Relative Error [%] |
|---|---|---|---|---|---|
| HS Algorithm | 34 | 2494 | 1992 | 1.5123 | 5.024 |
| Confirmatory Test | 34 | 2490 | 1990 | 1.5923 | |

As spatter deposition leads to reduction of quality of laser drilled holes, it is necessary to minimize the spatter formation. An empirical equation (Eq. 1)is developed using non-linear regression analysis between the process parameters such as flushing pressure (A), laser power (B) and pulse frequency (C)with spatter area (S).

$$\text{Spatter Area},\ \ S = 0.001 \times A^{3.82} \times B^{-0.215} \times C^{-0.552} \quad (1)$$

To predict the optimum setting, the empirical equation is treated as objective function for the HS algorithm. For predicting the spatter area in HS algorithm, code has been developed in MATLAB. After few experimental trials, the optimal setting is obtained at 900 iterations (Fig. 3) shown by convergence curve. The bandwidth ranges between 0.1 and 0.9 and pitch adjustment rate ranges between 0.5-0.8 in implementing HS algorithm [9]-[15]. The optimal parametric setting and the fitness value is shown in Table IV. As the optimum setting is not present in the experimental trial, it is necessary to perform the confirmatory test. The conformity test is performed with some adjustment of the process parameters depending on available machine setting (e.g. laser power, 2494 W ≈ 2494 W and pulse frequency, 1992 Hz ≈ 1990 Hz). The experiments are performed five times and average result is enlisted in Table IV. The results are within 10% shows the adequacy and effectiveness of the algorithm.

## V. CONCLUSION

The present study highlights the effect of machining parameters on spatter area in $CO_2$ laser drilling of AISI 316. It has been noticed that pulse frequency is the most significant factor (59.10% contribution) on influencing spatter deposition. The study also utilized the harmony search algorithm (HS) in order to assess the optimal parametric setting that attempts to minimize spatter area. The fitness value thus obtained by exploring HS algorithm is confirmed by conformity test. It is observed that predicted fitness value at the optimal setting is in close agreement (5.024% relative error) as compared to the confirmatory experiment which reflects the effectiveness of HS algorithm.

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