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Research Article

EXPERIMENTAL INVESTIGATION OF LASER DEEP ENGRAVING PROCESS FOR AISI 1045 STAINLESS STEEL BY FIBRE LASER

Anita Pritam

Department of Mechanical Engineering, CET, Bhubaneswar, Odisha, 751029, India

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ABSTRACT

Laser marking and engraving processes are very much important industrial micro-applications. The effects of process parameters such as laser power scan speed, frequency and fill spacing on the laser deep engraving of AISI 1045 stainless steel has been studied here. The optimum parameter conditions for minimization of the surface roughness and maximization of the engraving depth are also found out in this study. An experimental study consisting of 108 different parametric combinations is carried out to find out the process parameters which contribute surface roughness and engraved depth. It is seen that both surface roughness and engraving depth significantly decrease with an increase in the scan speed and a decrease in the laser power.

INTRODUCTION

In recent years, the significance of micro-technology and non-traditional machining process has increased vastly (Gillner *et al*., 2005). Among them, the laser-assisted machining methods are one of the non-traditional machining processes and use the thermal energy to remove material from the work-piece surface. All of the laser machining methods are non-contact removal process and therefore, the complex geometries and difficult to machine materials can be fabricated easily without any tool-based problem. Due to these advantages, laser processes have become established within micro-technology (Gillner *et al*., 2005). The main application areas of lasers are marking, drilling, micro milling, cutting, engraving, welding and heat treatment/hardening in the automotive, aircraft and microelectronic industries. Laser engraving process is also used to produce cavity in molds and dies. The deep cavity can be achieved by multi passes of laser beam on the geometry, therefore the number of laser beam passes (scan times), which affect the heat input, is the major control parameter and should be increased in order to achieve deep cavity results. There are many studies on the laser-assisted material machining methods. Most studies investigate the effect of process parameters on the surface roughness and the lasers. However, a few studies exist on the engraving of metals. Yasa *et al*. (2010) studied on selective laser erosion of the AISI 1045 steel. In their study, they studied to determine the effect of process parameters on the surface roughness using the Nd.YAG laser source.

***Corresponding author: AnitaPritam**
Department of Mechanical Engineering, CET, Bhubaneswar, Odisha, 751029, India

Their results indicate that the scan overlap, pulse overlap and laser parameters have significant effect on the minimum surface roughness. Wendland *et al*. (2005) investigated deep engraving of aluminum grade 5251 and stainless steel grade 316 by laser for high removal rates and surface modification at different process condition. Campanelli *et al*. (2007) used the design of experiments to investigate the effect of process parameters (scan speed, frequency, power, overlapping and scan strategy) on the surface roughness and the depth of removed material. Pham *et al*. (2007) carried out many experiments to investigate the effect of laser milling process parameters (frequency, scan speed, pulse duration and wavelength) on the material removal characteristics. For the experiments, the ceramic components were used. Pham *et al*. (2005) studied the effect of laser milling process parameters on the responses (surface finish, aspect ratio, accuracy, minimum feature size, etc.).

They reported that accuracy and surface finish are influenced by laser material interaction and shorter pulse duration. Leone *et al*. (2009) studied the influence of the process parameters (multiple laser scanning, varying the pulse frequency, the scanning speed and the number of scanning repetitions) on the material removal rates by engraving panels made of different types of wood using a Q-switched diode-pumped Nd:YAG green laser working with a wavelength $\lambda = 532$ nm. They found that the engraved depth is strongly affected by the mean power, the pulse frequency, the beam speed and the number of repetitions. Chen *et al*. (8) used the Taguchi method to investigate the effect of five process parameters (beam expansion ratio, focal length, average laser power, pulse repetition rate and engraving speed) on the engraving line width using a Q-switched Nd: YAG laser. Hence, the brief literature review shows that the most studies in the laser-assisted removal process were focused on the surface roughness using different techniques. The LDE process uses different process parameters when compared with the basic laser machining parameters. But, it is well known that various process parameters at different values, type of laser system and material affect the machining operation and process performances. This study was done by using the fiber laser system. The motive of this study is to explore the effect of laser engraving process parameters on the surface roughness and engraving depth. After the experimental analysis, a second order regression model was constituted to conduct a mathematical model and find out which parameters have significant effect on the responses of the process.

Laser Deep Engraving Process

The laser deep engraving is a thermal machining process in which the material on the geometry is removed by a laser beam. The laser beam like a cutting tool moves over the geometry and then an interaction occurs between the laser beam and the material. During the interaction, an amount of energy is delivered to the material. If the energy intensity is high enough which can be occurred only at the focal position, the temperature reaches up to vaporization temperature. This energy first heats the surface locally and then vaporizes the material at the focal area. The process is very fast and complex. The surface roughness and the volume of removed material in the interaction zone are affected by the energy input which is determined by the engraving process parameters.

The selected process parameters are the laser power, scan speed, frequency and fill spacing which can be defined as follow:

- The laser power is the output power used laser system,
- The laser scan speed is the velocity during the movement of laser beam on the surface,
- The laser frequency is the number of pulses per second from the laser (4),
- The fill spacing is the distance between two successive scan lines at the same direction.

EXPERIMENTAL METHODS

The Laser Deep Engraving experiments on the AISI 1045 stainless steel were carried out using different process conditions. The performance characteristics of the engraving process were identified by the surface roughness (SR) and the engraving depth (D_E).

The material used for this experimental study was AISI 1045 stainless steel. The chemical composition of the material is given in Table 1. The samples were cut with a dimension in 50 mm × 200 mm ×20mm and polished by grinding for dimensional accuracy on the surfaces.

Table 1. The chemical composition of AISI 1045 (wt%)

C	Cr	Mn	Ni	Mo	Si	Fe
0.056	18.73	1.54	9.86	2.08	0.61	Bal.

A laser marking machine shown in fig-1 equipped with a ytterbium-doped fibre laser having a wavelength of 1,064 nm was used for preparing the engraving experiments.

The maximum laser output power is 30W. During the experiments, the laser beam was focused onto the workpiece surface at a 170 mm focal length which yields a beam spot diameter of about 100 µm. The motion of the laser beam and the process parameters were controlled by a PC and software. The deep engraving test sample was stationary and mounted on an aluminium plate. Each machining area (a square of the 10mm×10 mm) was scanned 20 times at the parallel scan direction (180^o) to achieve deep cavity result. All of the experiments were performed in the atmospheric conditions. The depth and the surface roughness of engraved geometry are changed as a function of the work-piece material and the process parameters. The process parameters are adjusted according to software. In this context, basically six different parameters namely laser output power, scan speed; frequency, fill spacing, focal distance and scan strategy can be adjusted during the engraving process. Before constituting the test matrix of the experiments, preliminary tests were carried out to investigate the effects of process parameters on the deep engraving performance. It is well known that the focal distance directly affects the energy input. The focal distance of 170 mm corresponds to the highest level of the energy input for used machine. Therefore, the focal distance was set at this distance during the experiments. Scan strategy (direction) defines the beam movement direction. According to preliminary experiments, the deep cavity is achieved when scan direction at 180^o.

Fig.1.

The studies showed that four main parameters play important role on the engraving depth and the surface roughness. These are the laser power (P), scan speed (SS), frequency (F) and fill spacing (FS). It is well known that the power affects the amount of removed material and surface roughness at the interaction area. Previous studies showed that the lower power produces good surface but the amount of removed material decreases. In order to improve the surface quality and achieve deep cavity, the laser output power was set at four different value which are 12, 18, 24 and 30W. These values represent best and worst values for both surface roughness and depth. The scan speed values were selected within the values which will give the best surface quality and deep cavity. In the process software, the frequency is input between 20 and 80 kHz. The previous studies showed that it can be difficult to achieve a cavity at high frequencies (>60 kHz).Therefore, the frequency was selected lower than 60 kHz. And in order to achieve better cavity, the fill spacing must be smaller than the effective beam diameter.

The previous studies showed that if the fill spacing and frequency were bigger than 0.05 mm and 60 kHz at high scan speed (>500 mm/s), the engraving was not performed on the surface. Therefore, the fill spacing is selected between 0.01 and 0.04 mm. Other process parameters (such as beam spot diameter, material and scan times) were kept constant during the engraving experiments. The selected values for process parameters are given in Table 2.

Table 2. Laser deep engraving parameters and their values

Symbol	Parameters	Values			
P	Laser power (W)	12	18	24	30
SS	Scan speed (mm/s)	200	400	600	800
F	Frequency (kHz)	25	35	45	55
FS	Fill spacing (mm)	0.01	0.02	0.03	0.04

According to parameters and their values, a experimental design matrix was constituted which includes 108 different experimental conditions. All of the engraving experiments were carried out on the surface of the stainless steel sample according to the experimental design matrix. Two different performance characteristics which are surface roughness and engraving depth were selected as the responses of Laser Engraving process.

The Surface Roughness Measurements

The surface characterization was determined with the average surface roughness (Ra). The Ra values of the sample were measured using a Mitutoyo SJ 301 stylus profilometer with a measurement field size of 4 mm. For each process condition, six measurements were taken on the machined area in order to eliminate the effect of measurement errors. The mean result of those six values was recorded as the final Ra.

The Engraving Depth Measurement

The engraving depth was measured by a Mitutoyo SJ 301 stylus profilometer. The parameter "D" was used to determine the engraving depth. For each process conditions, six measurements were taken in the machined area. The mean result of those six values was recorded as the final D.

RESULTS

After the experiments have been conducted, the effects of the process parameters on the performance characteristics (surface roughness and engraving depth) were studied. The effect of each parameter was plotted by keeping all other parameters constant.

The Effects of the Laser Power

The effect of laser power on the surface roughness is shown in Fig. 2 for varying process conditions at the powers of 12– 30W. It is seen that the surface roughness increases with the increase of laser power. The lowest and highest surface roughness values are obtained with the laser power of 12 and 30 W, respectively. Simultaneously the effect of the laser power on the engraving depth is shown in Fig. 3. It also seen that an increase in the power results in an increase of the engraving depth.

The highest value for the engraving depth is obtained at a power of 30 W and lowest value is obtained at the power of 12 W.

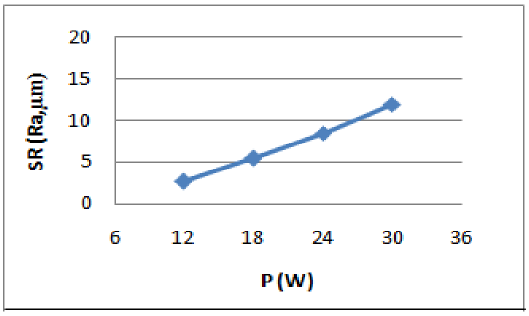

Fig. 2.

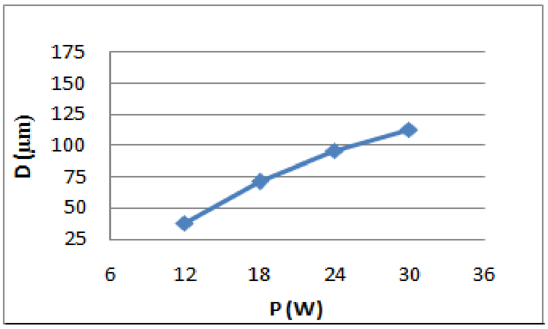

Fig. 3.

The Effects of the Frequency

Fig- 4 shows the effect of the frequency on the surface roughness for varying process conditions. It is seen that the surface roughness decreases between 25 and 45 kHz and, increases between 35 and 55 kHz. However it is noticed that the changes on the mean value of surface roughness (see Fig-4) are very small.

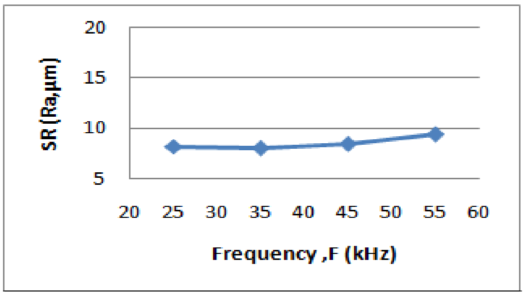

Fig. 4.

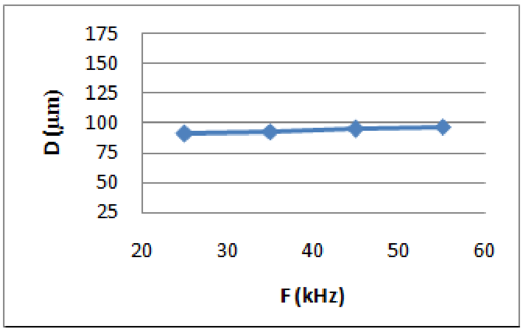

Fig. 5.

Hence it can be concluded that the effect of frequency on the surface roughness is not significant. The results of the engraving depth as a function of the frequency are shown in Fig-5. This figure shows the mean value of engraving depth and it is clearly seen that the engraving depth increases with the increase of frequency. However, the effect of frequency on the depth can be neglected due to the small change in the depth.

The Effects of the Scan Speed

The relationship between the scan speed and the surface roughness is shown in figure-6 which shows that the surface roughness value is significantly decreased with an increase in the scan speed. Considering the results and the distribution of points, when scan speed increases, the variation in the surface roughness gradually decreases. The highest surface roughness value is obtained at the scan speed of 200 mm/s, whereas the lowest surface roughness value is obtained at the scan speed of 800 mm/s. Similarly the results of the engraving depth as a function of the scan speed are shown in Fig- 7. As can be seen in the distribution of points, the role of the scan speed on the engraving depth is very significant. The engraving depth decreases with the increase of scan speed. The highest depth value of scan speed is obtained at the scan speed of 200 mm/s, whereas the lowest depth value of scan speed is obtained at the scan speed of 800 mm/s.

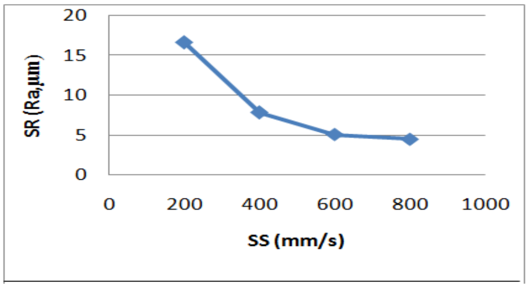

Fig. 6.

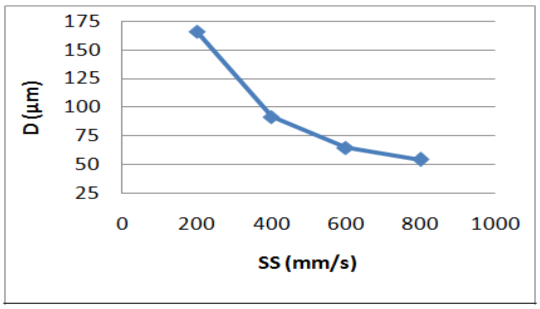

Fig.7.

The Effects of the Fill Spacing

The results of surface roughness as a function of fill spacing are shown in Fig-8. In the experiments range from 0.01 to 0.04 mm, the surface roughness shows significant reduction between the fill spacing 0.01 and 0.03 mm, and then starts to increase up to 0.04 mm. The lowest surface roughness value is obtained at the fill spacing of 0.03 mm. The results of the engraving depth as a function of the fill spacing are shown in Fig. 9. It is clearly seen that the engraving depth is decreased with increase in fill spacing. The drop in the engraving depth shows linear trend. The highest engraving depth value is obtained at the fill spacing of 0.01 mm.

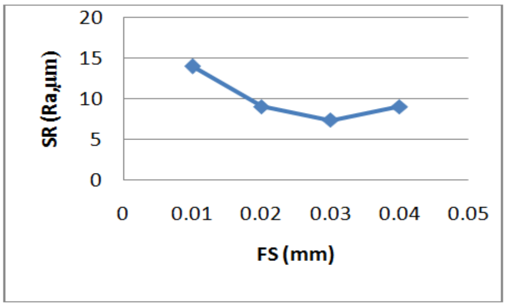

Fig. 8.

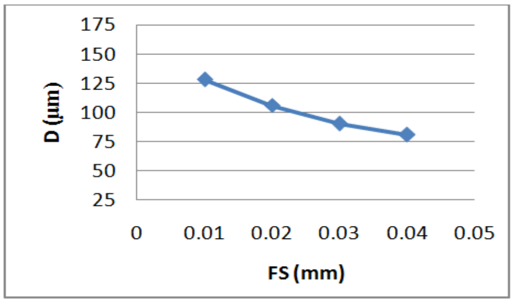

Fig. 9.

Selection of the Optimal Parameter Value

The optimal values correspond the value of minimum surface roughness and maximum engraving depth. For this purpose the laser engraving process was conducted in order to determine the lowest (minimum) surface roughness and the highest (maximum) engraving depth at the selected values of process parameters. According to the Figs. 2, 4, 6 and 8, the optimal condition for the minimum surface roughness is the power at 12W, the frequency at 35 kHz, the scan speed at 800 mm/s and, the fill spacing at 0.03 mm. The similar analysis is performed for engraving depth. It is seen from the Figs.3, 5, 7, and 9, the optimal condition for the maximum engraving depth is the power at 30 W, the frequency at 45-55 kHz, the scan speed at 200 mm/s and, the fill spacing at 0.01 mm.

DISCUSSION

The two characteristic responses (surface roughness and engraving depth) of the laser deep engraving process were evaluated according to results of experimental studies. These results, which measured on machined area, are the physical responses of the parameters. However, it is required to know the reason of physical response. After physical measurement, the contribution of energy density is involved in this section. It is well known that the laser-assisted machining methods use thermal energy which can be controlled by the process parameters. This thermal energy causes physical alteration on the surface which depends on the volume of energy density (*Ev)*, type of the materials and interaction time of the beam/material (Lee *et al*., 2009; Stavrev *et al*., 2009). The *Ev* is calculated with Eqs. (2)–(4).

$$P_d = \frac{P}{A}\ (W/mm^2) \tag{2}$$

$$\tau = \frac{D}{SS}\ (s) \tag{3}$$

$$E_v = P_d \ \ \tau \ (J/mm^2) \ \Rightarrow \ E_v = \frac{P\ D}{A\ SS} \quad (4)$$

Where E_v is the volume energy density (J/mm^2), P_d is the power density, P is the initial laser power (W), τ is the interaction time, A is the machined area (mm^2) SS is the scan speed (mm/s) and D is the beam spot diameter (mm). The laser beam spot diameter was kept constant at all experiments. The scan speed and the laser power have significant effect on the E_v. According to Eq. 4, an increase in the laser power and decrease in the scan speed increases the E_v per unit area. Higher E_v increases the heat input. In order to obtain deep cavity, the E_v must be increased on the machined area. Besides, the heat input decreases when the interaction time decreases, that means lower heat input decreases both the surface roughness and engraving depth. Therefore, the scan speed should be decreased in order to increase the interaction time and to maximize the engraving depth and increased in order to decrease the interaction time and to minimize the surface roughness. The experimental results show that both the surface roughness and engraving depth decrease when the scan speed increases, which support the above discussion. It is clear that the theoretical approaches and experimental results show the similar pattern.

CONCLUSION

The deep engraving experiments of the AISI 1045 stainless steel was performed using the fibre laser marking machine. The effects of the parameters such as the laser power scan speed, frequency and fill spacing on both the surface roughness and engraving depth were determined and results are summarized below:

- Both surface roughness and engraving depth increase with increase in laser power.
- Also the surface roughness and engraving depth decrease with the increase of scan speed.
- For two high value of scan speed, the variation in surface roughness and engraving dept is so small as compared to low scan speeds.
- Engraving depth is higher at low scan speed because of the high input energy due to increased interaction time.
- The results indicate that the regression model can be used to predict the surface roughness and engraving depth with less error value.
- The engraving depths are mainly affected by scan speed, laser power and fill spacing.

For the laser deep engraving process, it is concluded that the scan speed and laser power have main effect on precision of the surface roughness. For higher scan speed and lower laser power, surface roughness is better; therefore, in order to achieve deeper cavity result, the scan repetition rate should be increased at lower power and higher scan speed.

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