Deep Engraving Process Of PMMA Using CO_2 Laser Complemented By Taguchi Method

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Abstract. This work studies the effect of laser parameters on the engraving process. A CO_2 laser beam with a wavelength 10.6μm was used for engraving a solid bulk of PMMA matter. A number of closely spaced parallel lines were used for filling the area of the matter to be engraved. This method has many advantages as compared with the traditional way such as, contact-less with the machine, high-speed, flexibility, versatility, high accuracy as well as complex forms and machining different material. In this paper, design of the experiment was done using L25 Taguchi methodology. The laser process parameter that has been used during the engraving process are laser beam power, scanning speed and line overlaps of the scanned beam each of them has different value (20,30,40,50,60 W), (100,300,500,700,1000 mm min^{-1}) and (0.01,0.03,0.05,0.1,0.2 mm) respectively. To estimate the deep engraving and minimum surface roughness of the engraved surface. Furthermore, the results show that the engraving depth and surface roughness (Ra) interaction changes depending on the process parameter.

Keywords: Engraving process, surface roughness, engraving depth, Taguchi method.

1 Introduction

The laser technology gets a widely interesting in the recent year due to their variety application like in industry, metallurgy, medical, military and electronics [1]. Also, there are many advantages of this technique, contact-less with the machine, high accuracy, a low heat-affected zone, high-speed, flexibility, versatility and easy automation and computer control, In addition to little processing times and little cost [2–6]. One of the most important reasons for laser machining technology development is their machining with a fine accuracy, as well as complex forms and machining different material like, metallic[7–9], wood[10–12], polymeric[13–16], ceramic[17,18],leather[19].

Laser machining technology attracted great development, especially in laser engraving and marking. Which are used for identification for product information and engraving readable barcodes, imprinting distinctive logos printing, Engraving on jewelry, intaglio printing (e.g., banknotes and passports), stamping manual scribing etching and sandblasting [20]. Laser engraving is a surface process, where the focused laser beam is converted into heat energy on the substrate and leads to removes a part of layer from the surface to a specific depth[2,5]. It was a very versatile and practical technology with very accurate,high quality complex form and clean engraving could obtain from this technique[3–6,21]. Also, it has many advantages like no need skilled craftsmanship, little time cost to engrave a lot of pieces and engraving different type of material in the same machine [4,5,22]. There are many types of laser which are used in industry for engraving and marking like Q-switched Nd:YAG laser, CO_2 laser, excimer laser, semiconductor laser and fiber laser [2,4–6,21]. The CO_2 is the most proficient and reasonable gas laser for etching organic materials, for example, polymer, which are bad conductors for temperature and electricity, also its wavelength of 10.6µm the laser can readily absorb through most organics which absorb 10µm wavelength[19].

Furthermore, it was an effective technique for machining the Polymethyl methacrylate (PMMA) for good absorption of PMMA of laser beam [13–15,23,24]. Polymethyl methacrylate (PMMA) have been attracted significant attention over the past decade due to their wide range of application which replace the metal and wood by PMMA for its satisfactory properties and it was produced at lower cost[25].

The level of accuracy of the shape relies upon the ability to remove a thin layer of material, on the laser engraving process the material removal rate and the surface quality entirely rely upon the material properties, laser source characteristics and the process parameters [10,26,27]. Therefore, it has become important to optimize the choosing of process parameters like wavelength, scanning speed, power and overlapping of the parallel line or step [15].

There are many previous works has been done on laser engraving optimization using different laser, different material and different parameters. Sefika Kasma and I.Etem Saklakoglu study the effect of deep engraving on surface roughness and depth using 30W solid state ytterbium doped fiber laser on tungsten carbide and AISI H13. In each work they show the effect of using different power, scan speed, frequency, fill spacing and beam diameters [7,9]. Nafissa Khanafi-Benghalem and et al study the engraving process on glass using a CO_2 laser and show the effect of laser parameter on engraving process. They have been used different power of laser source which was ranged (0-25W) with various speeds many numbers of passes [28]. S. Genna and et al investigated the effect of the pulse and continues CO_2 laser on milling the PMMA material. They showed the effect of using two mode laser on depth, roughness and material removal rate. Also, much research has been done on laser engraving wood using CO_2 and Q-switched Nd:YAG laser [15].

In the present work, the experimental study of the deep engraving process was done on Polymethyl methacrylate (PMMA) using 100 Watt CO_2 CNC machine. The process parameter which was used in this process, including laser power, scanning speed, parallel line overlapping and spot diameter for evaluating the process effect on surface roughness (Ra) and depth of engraving. Also, the design of experiment and optimization of the process was done using Taguchi methods.

2 Experimentation

2.1 Experimental planning

The engraving process was done using sealed off CO_2 CNC machine (UK-SCIENTIFIC LTD) working in fundamental wavelength 10.6 µm in CW mode operation the other detail of the machine listed in the table (1). The machine set-up shown in figure (1) where the laser beam was delivered from the source to the workplace by a delivery system which contain from a three mirrors which moves the laser beam toward the focusing lens to focus the beam on the sample surface with a focal length 55 mm. The laser system was controlled using a computer with special software programs, where the geometric shape was generated and process parameter the power, scanning speed and line overlapping are transmitted to the system. The sub-system of the machine including water cooling system and X-Y stage movement also the high voltage power supply excitation system.

Table 1. Shows the detailed characteristics of the laser system.

Characteristics	Value	Unit
Source type	Electrical discharge excitation	-
Wavelength	10.6	µm
Out put power	1 – 100	W
Scanning speed	0 – 60	m min^{-1}
Mine Power supply	110 – 240	V
Reposition accuracy	± 0.1	mm
Working delicacy	0.0254	mm
Maximum engraving range	900 * 600	mm
Focal length of lens	55	mm

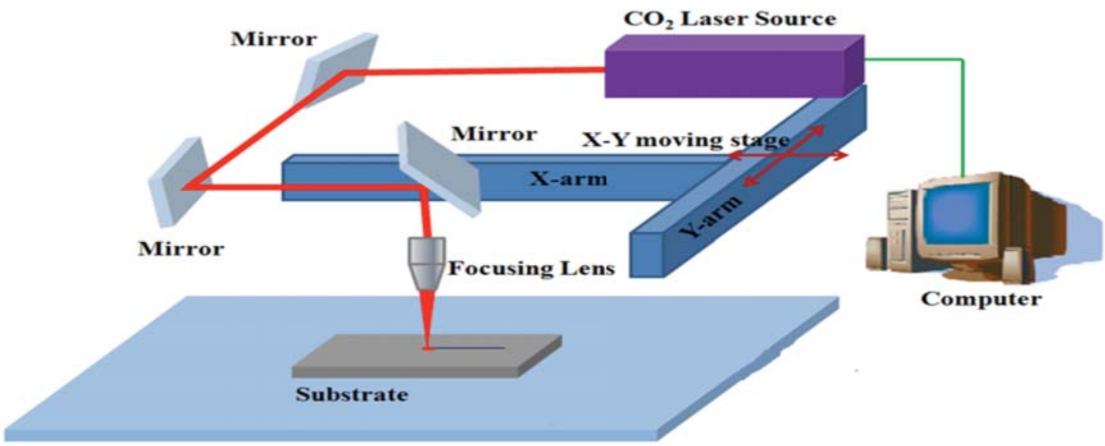


Figure 1. schematic diagram of CO2 laser machine setup

The commercial PMMA was adopted in this process with 6 mm in thickness and 180*180 mm^2 area of the sample sheet. This material was suitable for laser deep engraving for its many applications and an addition to its features like, absorption for CO_2 laser radiation about 92%, lower heat capacity, bad conductance to heat and lower temperature degradation (350-380 C°)[13]. When the laser beam hit the sheet surface, the

PMMA sheet absorbs the entire beam and temperature of the material surface increases rapidly. In this temperature, vaporization occurs due to random breaking in the chain of material [13].

The various process parameters are selected before designing the experiments which, depending on the literature review of laser engraving and cutting also a lot of experimental trials for reducing any unwanted phenomena like burning of material surface, vaporization, carbonization, etc. The various engraving parameters were used in this work is shown in table (2) and the response parameters are the surface roughness and depth of the engraving.

Table 2. engraving factor and their value

Engraving factor	Value
Laser power (W)	20 – 30 – 40 – 50 – 60
Scanning speed(mm min^{-1})	100 – 300 – 500 – 700 – 1000
Line overlapping(mm)	0.01 – 0.03 – 0.05 – 0.1 – 0.2
Spot size(µm)	148

For achieving the best quality of the engraving process, the Taguchi design of experiment method has been applied using L25 orthogonal array. For all the L25 orthogonal array experiment, a rectangle with 30*15 mm^2 in size was engraved as shown in figure (2) also surface roughness and depth of engraving were measured by roughness tester and optical microscope respectively which shown in figure 2. The L25 design of the experiment and the result of roughness and deep were summarized in table (3).

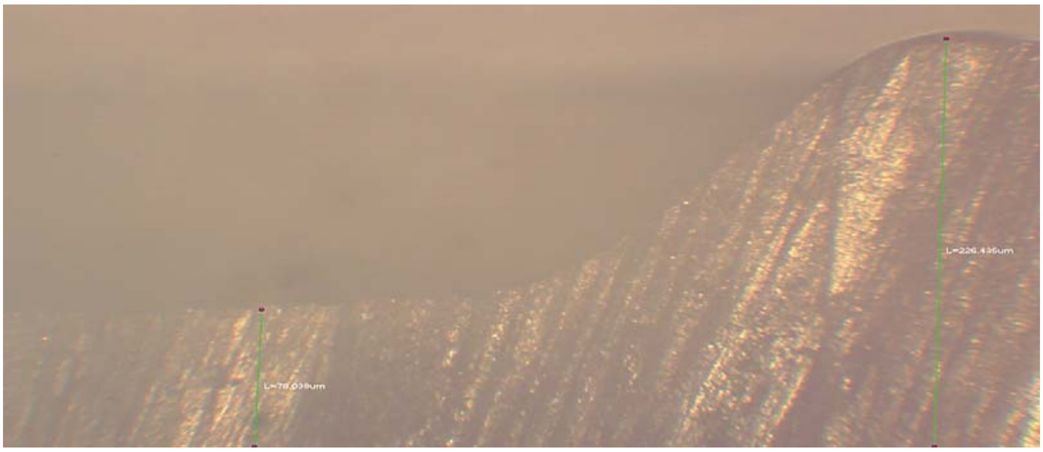


Figure 2. Shown one case for measuring the surface roughness using optical microscope

2.2 Taguchi optimization methodology

For estimate the effect of each factor on the surface roughness and engraving depth the means and signal to noise (S/N) for all controlled factors. The signal to noise ratio for surface roughness using the smaller the better categories which is calculated from the following equation[29–32] :

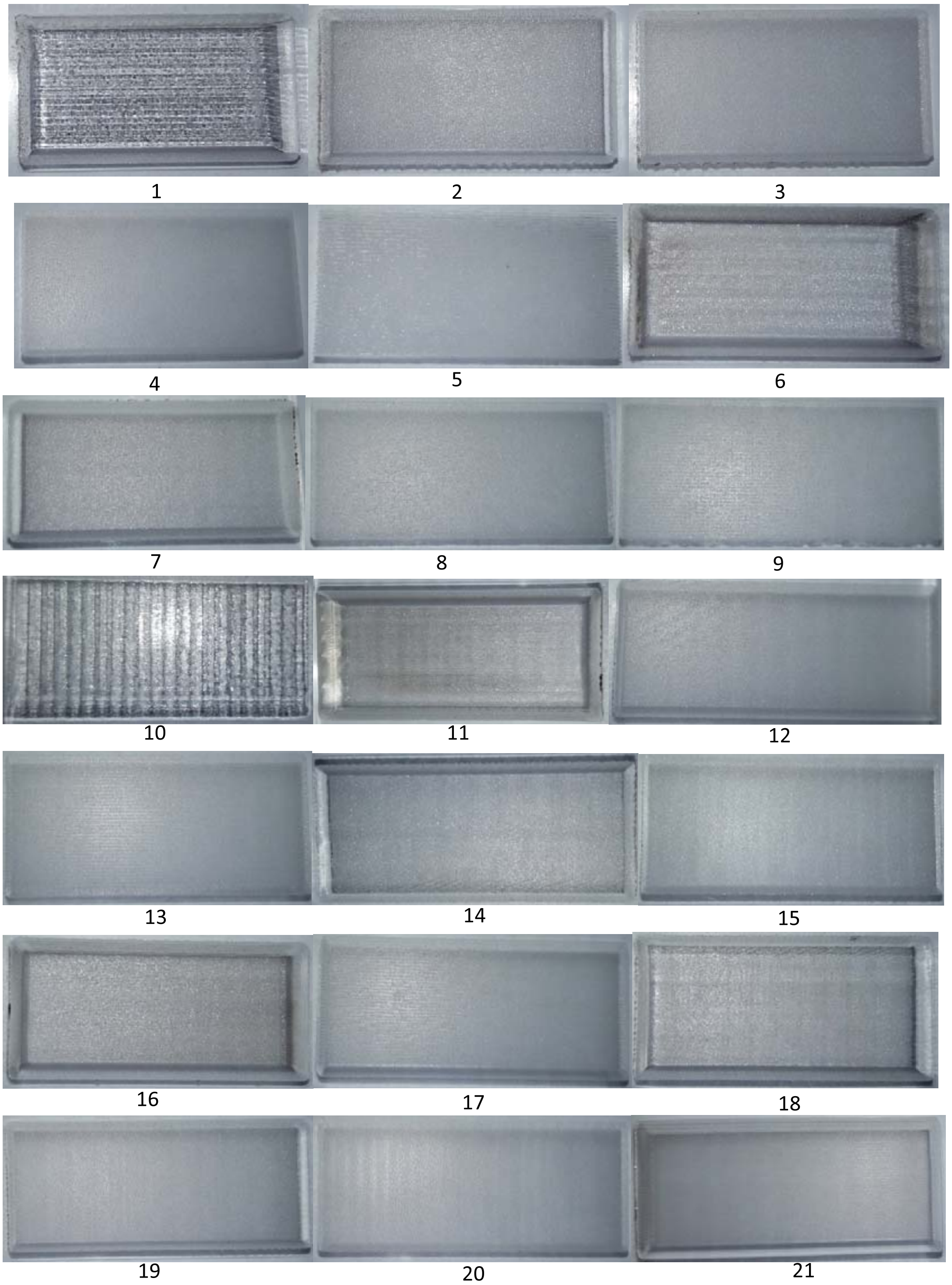
$$\frac{S}{N} = -10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (1)$$

Where n is the number of experiments and y is the experiment value. As well as the signal to noise ratio of engraving depth was calculated using the larger the better categories from the following equation[29–32]:

$$\frac{S}{N} = -10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \quad (2)$$

Table 3. Taguchi design of experiment with deep and roughness measurement results

Exp. No	L25			Mean value		S/N ratio	
	Power (W)	Speed (mm min^{-1})	Overlap (mm)	Surface roughness (μm)	Depth of engraving (mm)	Surface roughness (dB)	Depth of engraving (dB)
1	20	100	0.01	2.70	3.8	-8.6273	11.596
2	20	300	0.03	6.00	1.48	-13.3536	5.802
3	20	500	0.05	6.38	0.317	-14.471	-5.431
4	20	700	0.1	2.99	0.0484	-13.661	-20.388
5	20	1000	0.2	3.37	0.0204	-13.1927	-27.544
6	30	100	0.03	2.835	5.8	-12.7234	-26.752
7	30	300	0.05	5.725	1.7	-13.1658	-26.0832
8	30	500	0.1	3.055	0.208	-12.8566	-25.538
9	30	700	0.2	3.95	0.0302	-12.763	-26.435
10	30	1000	0.01	1.955	0.0856	-12.402	-26.124
11	40	100	0.05	1.72	4.6	-12.0614	-25.710
12	40	300	0.1	4.195	0.827	-12.0956	-25.334
13	40	500	0.2	4.405	0.193	-12.161	-25.0149
14	40	700	0.01	6.245	1.232	-12.5668	-24.694
15	40	1000	0.03	5.315	0.224	-12.7273	-24.415
16	50	100	0.1	4.50	3.8	-12.749	-24.135
17	50	300	0.2	4.805	0.185	-12.806	-23.902
18	50	500	0.01	5.835	2.95	-12.9916	-23.654
19	50	700	0.03	5.58	0.779	-13.1186	-23.421
20	50	1000	0.05	3.255	0.119	-13.0123	-23.27
21	60	100	0.2	7.00	1.9	-13.302	-23.059
22	60	300	0.01	4.215	4.2	-13.2685	-22.857
23	60	500	0.03	5.84	1.6	-13.3816	-22.665
24	60	700	0.05	4.96	0.479	-13.405	-22.484
25	60	1000	0.1	4.104	0.119	-13.365	-22.378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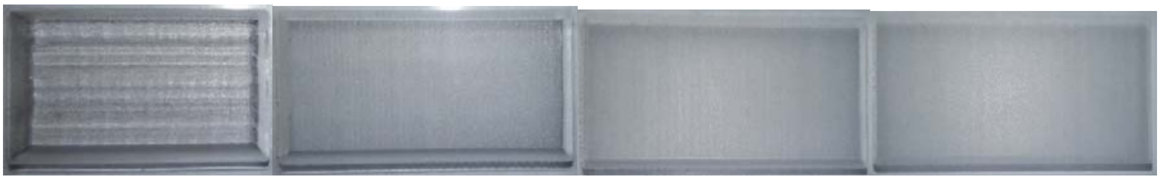

Figure 3. Shows the 25 experimental samples which done depending on the L25 Tagochi design shown in table 2

3 Result and Discussion

In the present work, the surface roughness and engraving depth have been measured for deep laser engraving on PMMA surface. For both responses the signal to noise ratio have been calculated for better surface quality indication also dimensional accuracy of deep laser engraving. Therefore, the surface roughness are referred as "smaller-the-better" type and the engraving depth referred as "beggar-the-better" type. The average values results of surface roughness and the engraving depth which obtained experimentally are summarized in table 3. Also the corresponding values of the S/N ratio of the experimental parameters setting as per to L25 Taguchi orthogonal array tabulated in table 3. The spot size of laser which has been used was constant at 145.5µm focused at the material surface.

3.1 The parameters effect on surface roughness

The signal to noise ratio plot for the surface roughness with regard to laser parameters, power, speed, line overlaps is shown in figure 4. This figure exhibited that the surface roughness increases with increasing the power more than 30W reaches to 60 W, also it's shown that surface roughness decrease from 20W to 30W which reach its minimum value at this point (30W). The increases of surface roughness with power because of the increasing in energy deliver to the surface by the laser beam which increases the material removal rate of material surface which leads to irregulation and micro turning generation on the surface. Also, the increase of surface roughness in low power, this because of the energy of the laser beam which hits the surface do not have enough energy to remove the material from the surface so that some part will remove and other do not make irregular surface. From the same figure its illustrates that, the Ra increases rapidly by increasing the scanning speed from 100 to 300, 500 and decreased again from 700 to 1000 mm min^{-1}. The increasing of Ra at 300,500 mm min^{-1} because the interaction time between the surface and the laser beam result in removing part of material from the surface and some amount of melted material again re-solidifies on the already micro-turned surface at this speed. At high speed the material surface doesn't have the enough time for removing material from the surfaces which reducing in the irregulation or micro-turned of surface and this result have good agreement with S. Genna and et al work [15]. But at low speed 100 mm min^{-1} all surfaces take a sufficient time for interaction with laser beams and evaporated result in deep engraving with low Ra. It can be observed that the surface roughness fluctuated as response to the line overlapping because this parameter was affected by the power and speed variation. It can be observed that the surface roughness fluctuated as a response to the overlapping, this is because overlapping value affected by the power and speed variation.

3.2 The parameters effect on engraving depth

Figure 6 shows the S/N ratio of engraving depth for laser parameters, power, scanning speed, line overlaps. From these figures, it was clear that the scanning speed and line overlap both have the relation

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with engraving depth where it was decreasing with increasing both parameters. The decreasing of the depth by increasing the scanning speed appears because of the increasing in speed the interaction time between laser beam and the material surface decreased, which lead to decreased the removing of material layer from the surface and decreasing the engraving depth. As well as, the depth decreasing with increasing the engraved line overlap because of on low engraved line overlap the laser beam pass at the same or near the engraved line more than one time, which increase the removed layer from the surface and increasing the depth where at the high overlapping line the laser beam go far from the past engraved line which reducing the material removing rate from the material surface lead to decrease the engraving depth. Furthermore, the depth of engraving increase with increasing the power because it increases the energy of the laser beam that will interact with the material surface and remove more layers from the surface which increase the depth and this result have good agreement with S. Genna and et al work [15].

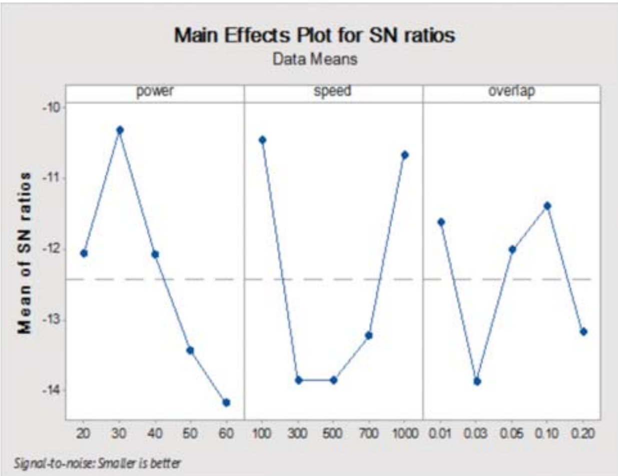

Figure 4. the main effect plot of the S/N ratio for L25 Taguchi design for surface roughness with laser parameters, power, scanning speed and overlapping lines respectively.

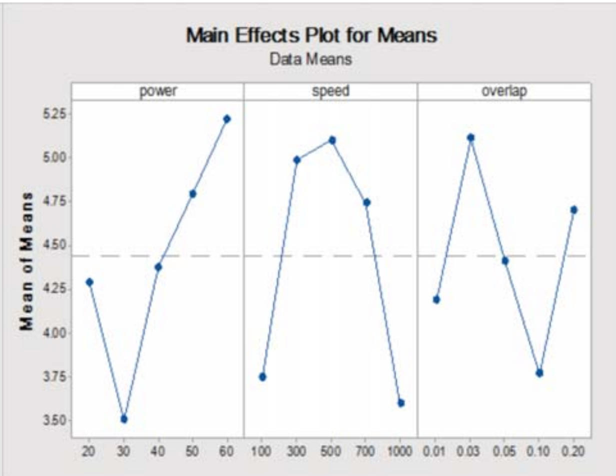

Figure 5. the main effect on the mean value for surface roughness with laser parameters, power, scanning speed and overlapping lines respectively.

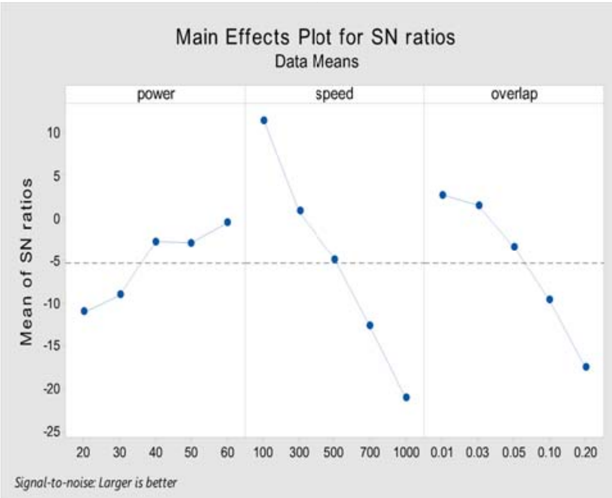

Figure 6. the main effect plot of the S/N ratio for L25 Taguchi design for engraving depth with laser parameters, power, scanning speed and overlapping lines respectively.

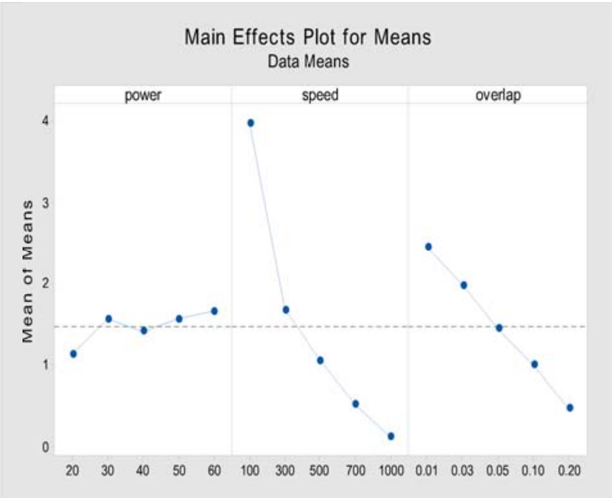

Figure 7. the main effect on the mean value of Tagochi design for engraving depth with laser parameters, power, scanning speed and overlapping lines respectively.

4 Conclusions

The following conclusions are obtained for investigation the effect of laser parameters on deep engraving and the surface roughness of PMMA material. Taguchi design of experiment methodology has been used for this purpose. Based on the experimental results following conclusions are obtained:

- The surface roughness increase with increasing the laser beam power due to the increasing interaction of a laser beam with the matter.
- The surface roughness increase with increasing the scanning speed because of the melting and re-solidification phenomena occur as a result of the interaction time of the laser beam with the material surface.
- The engraving depth increase with increasing the laser beam power due to removing more layer from the material surface with increasing the power.
- The engraving depth increase with decreasing both the scanning speed and overlapping lines due to decreasing the interaction time between the laser beam and the material surface.

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