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Optimization of Process Parameters for the Machining of Microslot on Copper Workpiece Using LBM by Grey Relational Analysis and ANOVA

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ABSTRACT

Laser-beam machining is a non-conventional machining process. Laser-beam machining is a thermal material-removal process that utilizes a high-energy, coherent light beam to melt and vaporize particles on the surface of metallic and non-metallic workpieces. LBM is newer thermal technique also widely accepted in industry today. Laser beam machining is based on the conversion of electrical energy into light energy and then to thermal energy. The main purpose of this paper is to analyse the impact of the parameters associated with the CO_2 laser cutting of the micro slot having a width of 0.3 mm and a length of 20 mm on a copper plate of 4 mm thickness. Micro-slots or micro-channels are one such type of feature which has more applications in the fabrication of miniature devices, micro-fluidic devices or heat exchangers. The experiments are planned and conducted on the basis of the typical L27 Taguchi orthogonal array with three laser cutting parameters viz. Laser power, gas pressure, cutting speed and organised at three stages. The result showed that the parameter like power has greater influence on MRR and cutting Speed has greater influence on Kerf Width and gas pressure has less significance compare to both.

Keywords: Copper material, Microslot, Design of experiments, Grey Relational Analysis, ANOVA.

INTRODUCTION

Due to growing demand for micro parts and structures of various industries, micro manufacturing techniques have become so important. Micro structures, including micro holes, micro slots, micro shafts, and micro gears are widely used micro products required in industries. Micro-slots or micro-channels are one such type of feature which has immense applications in the fabrication of miniature devices, micro-fluidic devices, micro-heat-sinks, or heat exchangers etc. Using CO2 lasers, much laser cutting is carried out. In the industry, CO2 lasers dominate. Mild steel and stainless-steel laser cutting has a long tradition and has been one of the major uses for CO2 lasers. The diameter of the laser beam is usually 0.3 mm with a power of 3-6 KW. The acronym for Light Amplification by Stimulated Radiation Emission is Laser. Maiman showed the world's first laser by using a ruby crystal (Maiman 1960). Laser cutting is a thermal-based non-contact device capable of cutting complicated contours of high precision and precision materials. It includes the process of heating, melting and evaporating material in a small well-defined region capable of cutting almost all materials. Lasers have a wide variety of uses, ranging from military weapons to medical equipment. Laser is used in factories as an unconventional cutting and welding tool. The biggest advantage of laser cutting is that it is a non-contact operating technique from which it is possible to produce a successful accurate cut of complex shapes. Lasers may also be used to cut different materials such as wood, ceramics, rubber, plastic and some metals. Their poor infrared laser light absorption makes it impossible to cut these metals. Copper and brass, particularly in their solid state, are good reflectors of infrared laser light. In its solid state, pure copper represents >95% of the near-IR radiation. As the metal warms up, the reflectivity of copper and other reflective metals reduces and falls dramatically until the substance melts. These metals in the molten state consume considerably more laser energy. A laser beam rapidly melts the surface of reflective materials by selecting tailored laser, optics, and cutting processes to connect with the more absorbent molten metal and initiate an efficient, stable cutting operation. Wrong laser/optical configuration selection or the use of non-optimal process parameters will lead to excessive laser dwelling with the solid metal and thus excessive back-reflected light quantity. In turn, too much reflection results in the inefficiency of the method of cutting and possible damage to optics. The beginning of the process particularly the penetrating stage where the laser interacts with solid metal, is the crucial stage in cutting reflective metal. The laser beam interacts more with the molten material after the cut is made.

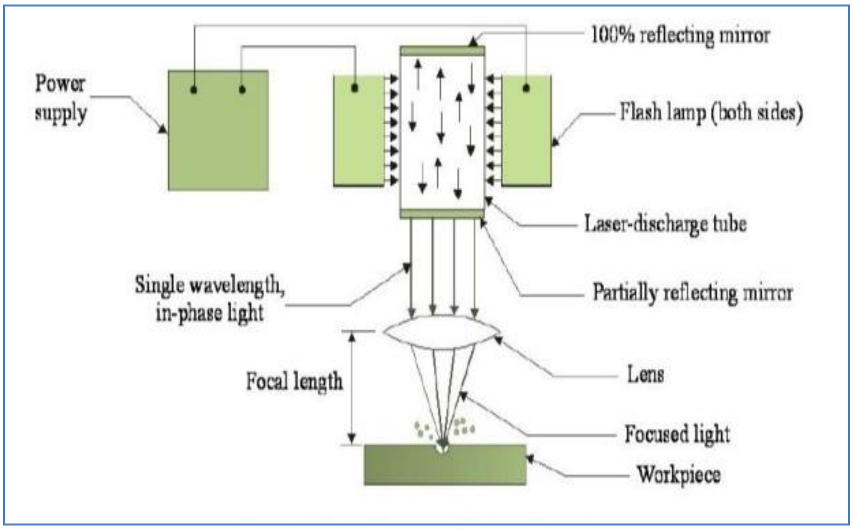

Figure 1: Schematic Diagram of Laser Beam Machining

LITERATURE REVIEW

R.S. Barge1 et. al [1] studied the effect and optimization of Laser Beam Machining Parameters using Taguchi and GRA Method. **Darshan R et. al** [2] investigated the optimization of process parameters using Fibre Laser on the cutting quality of stainless steel-304 using design of experiment approach. **Pravin R et. al** [3] have done the experimental investigation of effect of laser beam machining on performance characteristics in machining OHNS E0300. **Prof. Rahul D. Shelke et. al** [4] have done the optimisation of sheet metal cutting parameters of laser beam machine. **Teeraphat Kongcharoen et. al** [5] studied the effects of the Laser Process Parameters on Kerf Quality. **A. Parthiban et. al** [6] investigated the effect of process parameters of fuzzy logic based modeling of CO_2 laser cutting for stainless steel sheet. **Sandeep Kumar Singh et. al** [7] reviewed the laser beam machining process parameter optimization. **Tushar V. Jadha et. Al** [8] have studied the parameters optimization of laser beam machine. **V. Senthilkumar et. al** [9] analysed the optimization of laser machining parameters. **Vadhel Ajay Jethabhai et. al** [10] analysed the parametric analysis of CO_2 laser for quality of weldox-700 material. **Anil P. Varkey et. al** [11] studied the effect of edge quality during CO_2 laser cutting of titanium alloy. **Miloš Madić et. al** [12] investigated the surface roughness optimization in CO_2 laser cutting using taguchi methodology.

Selection of Orthogonal Array

Table 1: Process Parameters with Levels

Levels & Parameters	Level 1	Level 2	Level 3
Power (w)	3000	3250	3500
Cutting speed (m/min)	1	1.2	1.4
Gas Pressure (bar)	2	2.5	3

Selection of a suitable orthogonal series, depending on the number of process parameters and their levels. The orthogonal array L27 is chosen as the number of parameters is 3 and the number of levels is 3.

Table 2: Taguchi L27 Orthogonal Array Parametric Combinations

Exp. No	Power (W)	Cutting speed (m/min)	Gas Pressure (Bar)
1	3000	1	2
2	3000	1	2.5
3	3000	1	3
4	3000	1.2	2
5	3000	1.2	2.5
6	3000	1.2	3
7	3000	1.4	2
8	3000	1.4	2.5
9	3000	1.4	3
10	3250	1	2
11	3250	1	2.5
12	3250	1	3
13	3250	1.2	2
14	3250	1.2	2.5
15	3250	1.2	3
16	3250	1.4	2
17	3250	1.4	2.5
18	3250	1.4	3
19	3500	1	2
20	3500	1	2.5
21	3500	1	3
22	3500	1.2	2
23	3500	1.2	2.5
24	3500	1.2	3
25	3500	1.4	2
26	3500	1.4	2.5
27	3500	1.4	3

EXPERIMENTAL SETUP

Workpiece Material

Copper possesses excellent properties therefore it is widely used in electrical power, light and other new industries and some high-tech fields. Copper has high thermal conductivity so it is mainly used in heat exchanger applications.

METHODOLOGY

In the experiment copper has dimensions 25mm×12mm×4mm and cut into 27 pieces. High laser power is needed to cut copper due to low copper laser absorptivity and back reflection. Because of the high-power performance of this CO2 laser relative to other lasers, the CO2 laser has a wavelength of around 10.6 µm. CO2 lasers can also be used to remove copper and copper-based alloys. In the current investigation, a CO2 laser-machining centre with a maximum output power of 6 kW at a wavelength of 10.6 µm working in CW mode was used to perform the cutting experiments. 20 mm long and 0.3 mm wide microslot to measure the diameter of the kerf and MRR. Copper utilise nitrogen to assist gas of 99.95 percent purity. The system used for this machining was the TRUMPF Truflow 3030 with a 0.3 mm diameter nozzle which was used for the cutting. The laser strength, cutting speed and pressure of the gas aid are three parameters.

Figure 2: Experiment Setup

Table 3: Machine Specifications

Mechanism of process	Evaporation
Power	3000-6000w
Type	TRUMPF Trulaser 3030
Nozzle diameter	0.3mm
Nozzle stand-off distance	1.7mm
Materials that can be machined	All metallic and non-metallic.

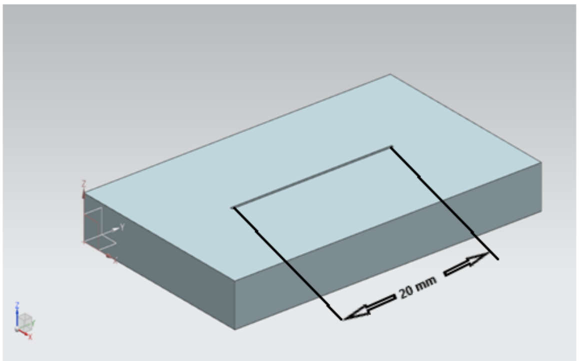

Figure 3: Auto Cad Design of Microslot on Copper Workpiece

Figure 4: 27 Pieces After Machining on Single Piece

Metal Removal Rate (MRR)

It is calculated based on difference in workpiece weight to the machining time.

$$MRR = \frac{W_{bm} - W_{am}}{T} \; Gm/sec$$

Whereas,

W_{bm} = Original workpiece weight prior to machining in gm

W_{am} = Final workpiece weight after machining in gm

T=machining time

Kerf width

Dimensional analysis of Microslot has done by stereo microscope. An Stereo Microscope with 6X magnification is used for measuring the Kerf Width

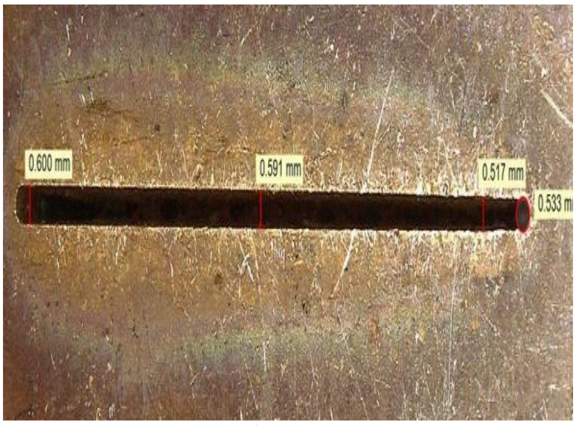

Figure 5: Kerf Width Measurement

Table 4: Experiment Results for MRR and Kerf Width

S. No.	Process Parameters			Output Values	
	Power (W)	Speed (m/min)	Gas Pressure (bar)	MRR (gm/sec)	Kerf Width (mm)
1	3000	1	2	0.02079	0.3090
2	3000	1	2.5	0.02194	0.2900
3	3000	1	3	0.02344	0.3000
4	3000	1.2	2	0.02044	0.2840
5	3000	1.2	2.5	0.01798	0.3120
6	3000	1.2	3	0.01678	0.3040
7	3000	1.4	2	0.01432	0.2920
8	3000	1.4	2.5	0.01678	0.2781
9	3000	1.4	3	0.02372	0.2790
10	3250	1	2	0.02436	0.2693
11	3250	1	2.5	0.02465	0.2950
12	3250	1	3	0.02440	0.3010
13	3250	1.2	2	0.02640	0.2833
14	3250	1.2	2.5	0.02939	0.2912
15	3250	1.2	3	0.03177	0.2953
16	3250	1.4	2	0.03104	0.2732
17	3250	1.4	2.5	0.03380	0.2780
18	3250	1.4	3	0.03550	0.2792
19	3500	1	2	0.02680	0.2988
20	3500	1	2.5	0.02790	0.3020
21	3500	1	3	0.02899	0.3120
22	3500	1.2	2	0.02788	0.2799
23	3500	1.2	2.5	0.02882	0.2833
24	3500	1.2	3	0.03212	0.2866
25	3500	1.4	2	0.03519	0.2752
26	3500	1.4	2.5	0.03752	0.2769
27	3500	1.4	3	0.04010	0.2774

Grey Relational Analysis

In order to address multi-attribute decision making issues (multi-response optimization), Taguchi based Grey Relational Analysis is commonly implemented. Gray Relational Analysis (GRA), also referred to as Deng's type of Grey Incidence Analysis.

Signal-To-Noise Ratios (S/N Ratios)

The initial step is the translation of response values to S/N ratios. Equations of 'larger the better',' smaller the better' and 'nominal the better' are used for the calculation of S/N ratios. Subsequent research is carried out on the basis of these values of the S/N ratio

Type1: Larger the better,

$$S/N_{LB} = -10\log_{10}\left[\frac{1}{n}\Sigma\frac{1}{y_{ij}^2}\right]$$

Type2: Smaller the better,

$$S/N_{SB} = -10\log_{10}\left[\Sigma\frac{y_{ij}^2}{n}\right)$$

Type3: Nominal the better,

$$S/N_{NB} = -10\log_{10}\left[\Sigma\frac{1}{S^2}\right]$$

Where Yij is the value of the response 'j' in the ith experiment condition, with i=1, 2, 3, …n; j= 1,2…k and S^2 are the sample mean and variance.

Normalization of S/N Ratios

Larger the better:

$$Z_{ij} = \frac{Y_{ij} - \min(Y_{ij}, i = 1,2,3..n)}{\max(Y_{ij}, i = 1,2,3..n) - \min(Y_{ij}, i = 1,2..n)}$$

Smaller the better

$$Z_{ij} = \frac{\max(Y_{ij}, i = 1,2,3..n) - Y_{ij}}{\max(Y_{ij}, i = 1,2,3..n) - \min(Y_{ij}, i = 1,2..n)}$$

Table 5: Normalized Signal-to-Noise ratios and GRG values for copper

S. No.	Normalized Values for MRR	Normalized Values for Kerf	Grey Relational Grade	Rank
1	0.251	0.070	0.375	25
2	0.296	0.515	0.461	17
3	0.354	0.281	0.423	23
4	0.237	0.656	0.494	16
5	0.142	0.000	0.351	27
6	0.095	0.187	0.368	26
7	0.000	0.468	0.409	24
8	0.095	0.794	0.532	13
9	0.365	0.773	0.564	11
10	0.390	1.000	0.725	4
11	0.401	0.398	0.454	20
12	0.391	0.258	0.427	22
13	0.469	0.672	0.544	12
14	0.585	0.487	0.520	15
15	0.677	0.391	0.529	14
16	0.649	0.909	0.716	5
17	0.756	0.796	0.691	7
18	0.822	0.768	0.710	6
19	0.484	0.309	0.456	18
20	0.527	0.234	0.454	19
21	0.569	0.000	0.435	21
22	0.526	0.752	0.591	8
23	0.562	0.672	0.569	10
24	0.690	0.595	0.585	9
25	0.810	0.862	0.754	3
26	0.900	0.822	0.785	2
27	1.000	0.810	**0.862**	1

RESULTS AND DISCUSSION

Results from ANOVA

In order to asses influence of factors on response means and s/n for each control factor to be calculated. The main aim of ANOVA is to apply a statistical method in order to identify the effect of individual factors. The Results of ANOVA and percentage of contribution of each parameter for MRR are shown in table.

Table 6: ANOVA Results for MRR

Factors	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	% of Contribution
Power	2	0.000731	0.000731	0.000365	30.23	0.000	63.68%
Cutting Speed	2	0.000126	0.000126	0.000063	5.19	0.015	10.94%
Gas Pressure	2	0.000049	0.000049	0.000025	2.04	0.156	4.31%
Error	20	0.000242	0.000242	0.000012			21.07%
Total	26	0.001148					100%

From the Table 6 The % of contribution of values for MRR it is observed that Power (63.68%) Cutting Speed (10.94%), Gas pressure (4.31%). It is observed that The Power has greater influence on MRR. Since this analysis is a parameter-based optimization design, from the above values it is clear that Power is the major factor to be selected to get the good MRR.

Table 7: ANOVA Results for Kerf WIDTH

source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	% of contribution
Power	2	0.000395	0.000395	0.000198	2.28	0.129	9.81%
Cutting speed	2	0.001622	0.001622	0.000811	9.35	0.001	40.28%
Gas pressure	2	0.000274	0.000274	0.000137	1.58	0.231	6.81%
Error	20	0.001736	0.001736	0.000087			43.10%
Total	26	0.004027					100%

From the Table 7 The % of contribution of values for Kerf Width it is observed that Cutting Speed (40.28%), Power (9.81%), Gas pressure (6.81%). It is observed that The Cutting Speed has greater influence on Kerf Width. Since this analysis is a parameter-based optimization design, from the above values it is clear that cutting speed is the major factor to be selected to get the good kerf width.

Table 8: ANOVA Results for GRG

Factors	DF	Seq SS	Adj SS	Adj MS	F-Value	p-Value	% of Contribution
Power	2	0.152407	0.152407	0.076203	10.37	0.001	29.93%
Cutting Speed	2	0.206376	0.206376	0.103188	14.05	0.000	40.52%
Gas Pressure	2	0.003485	0.003485	0.001742	0.24	0.791	0.68%
Error	20	0.146926	0.146926	0.007346			28.87%
Total	26	0.509193					100%

ANOVA Table 8 shows that factor Cutting Speed having maximum percentage of contribution, i.e. 40.52% Therefore it is most significant parameter for all the responses. From Table 5.6 it is observed that the P value of the parameters is less than 0.05 thus indicating that the input parameter, i.e. Power and Cutting Speed are significantly contributing towards machining performance. P value of the parameters is Greater than 0.05 then it is insignificant. Gas pressure is insignificant towards machining performance

Table 9: S/N response table for GRG

Levels	Power	Cutting Speed	Gas Pressure
1	0.4420	0.4679	**0.5627**
2	0.5908	0.5057	0.5353
3	**0.6102**	**0.6694**	0.5449
Delta	0.1682	0.2014	0.0274
Rank	2	1	3

Figure 6: Main effect plot for GRG

In Grey Relational Analysis Mains Effect plot for GRG shows that the optical parameter combination as A3B3C1 i.e., Power-3500W, Cutting Speed 1.4 m/min and Gas Pressure 2 bar.

Confirmation Test

The Response Table for GRG from Table 9 indicates that the optimal process parameter collection of A3B3C1 has strong multiple output characteristics among the 27 experiments, which can be contrasted with forecast values. The comparison of the experimental findings with the predicted values using the orthogonal array A3B3C1 is shown in Table 8. The predicted values are obtained by

$$\alpha_{Predicted} = \alpha_m + \Sigma_{i=1}^{3}(\alpha_o - \alpha_m)$$

Where, α_o = average grey relational grade of the optimal level,

α_m = overall mean grey relational grade

Table 10: Confirmation Results

	Optimal Values	
	Predicted	**Experimental**
Level	A3B3C1	A3B3C1
MRR (gm/sec)	0.03519	0.03519
Kerf Width (mm)	0.2752	0.2752
GRG	0.731	0.754

CONCLUSIONS

An indigenous LBM configuration is used to carry out microslot machining on copper workpieces.

The foregoing results are taken from the present work:

- Through microslot, the control parameters such as strength, cutting speed and gas pressure differ with LBM on copper work pieces of 4 mm thickness.
- In depth, the effects of process parameters on output parameters such as MRR and Kerf Width are addressed and the component results are collected.
- Results from ANOVA show that in deciding the MRR, force plays a prominent role. Laser strength, cutting speed and gas pressure contribute 63.68 percent, 10.94 percent and 4.31 percent respectively to the MRR efficiency characteristics.

- Data from ANOVA suggest that cutting pace plays a prominent role in deciding the width of the kerf. The contribution of cutting speed, laser power and gas pressure assistance to the Kerf breadth of quality features is 40.28 percent, 9.81 percent and 6.81 percent respectively.
- Cutting speed and laser power are the most significant parameters majorly affecting the MRR and kerf width whereas the assist gas pressure is much smaller.
- Based on performance curves by increasing the cutting speed Kerf Width decreases and MRR increases because contact time between nozzle and workpiece decreases.

The conclusions drawn from the S/N plots are as shown below

- Optimal parameter combination for maximum material removal rate are observed that Power-3500W, Cutting speed 1.4 m/min and Gas pressure 3bar.
- Optimal parameter combination for minimum Kerf Width are observed that Power- 3250W, Cutting speed 1.4 m/min and Gas pressure 2bar.
- The optimum parameters at maximum GRG (0.862) are obtained by Grey Taguchi Method is 3500 W, 1.4 m/min Cutting Speed and 2 Bar.
- The optimum settings of parameters the experimental GRG calculated is 0.754.
- The predicted value of GRG at the same optimum levels of the parameters was given as 0.731.
- Using Taguchi techniques, the optimum cutting parameters are calculated to balance the experimental values with minimal errors.

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