Minia Journal of Engineering & Technology (MJET), Vol. 38, No. 1. January 2019

STUDY OF LASER MACHINING PROCESS FOR STEEL X10

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Abstract:
The current investigation presents a study of laser machining for steel X10.The affect of working parameters, laser power (P),gas pressure (GP) feed rate (F) and motor speed (S) on the process of grooving machining. The groove dimensions depth of cut (DC), upper cut width (UC) and lower cut width (LC), root round error and metal removal rate (MRR) were studied under different working parameters. For this purpose a test rig was designed and fabricated. The experimental results are mathematically modeled by response surface methodology (RSM). The results showed that, depth of groove and width of the cut and roundness error increase with the increasing the Laser power and gas pressure, but MRR decrease with the increase of feed rate. The motor speed has a moderate effect on the machining process for steel under investigation. A trail has been given to optimize the process characteristics under different working conditions.

Keywords :), Depth of cut (DC), Upper cut width (UC), Lower cut width (LC), Roundness error (RE), Response surface methodology (RSM).

1-Introduction:
Dhupal. D, et al. [1], investigated Pulsed Nd: YAG laser turning of micro-groove on aluminum oxide ceramic (AL_2O_3). The observed optimal process parameter settings are lamp current of 22.517 A, pulse frequency of 1.477 kHz, pulse width of 2.394% of duty cycle, cutting speed of 10.4283 rpm and assist air pressure of 1.3 kgf/cm² for achieving minimum upper deviation, lower deviation and depth of laser-turned micro-grooves, and finally the results were experimentally verified. From the analysis, it was found that proper control of the process parameters lead to achieve minimum upper deviation, lower deviation and depth of laser-turned microgrooves produced on cylindrical work piece of AL_2O_3. Dhupal.D, et al. [2], studied Modeling and optimization on Nd: YAG laser turned micro-grooving of cylindrical ceramic material. It was observed that, the optimal process parameter settings are found as lamp current of 19A, pulse frequency of 3.2 kHz, pulse width of 6% duty cycle, cutting speed as 22 rpm and assist air pressure of 0.13N/mm² for achieving the predicted minimum deviation of upper width of 0.0101mm, lower width 0.0098 mm and depth 0.0069 mm of laser turned micro-grooves. Dumitrescu. P. [3],it was observed that, laser assist was found to obviate catastrophic fracture of the used carbide tools, improve tool life by as much as 100%, suppress machining chatter and saw tooth chip formation, and reduce the thrust component of the cutting force. Furthermore, laser heating was of no significant thermal detriment to the machined surface. Bejjani. R. [4], introduced Laser assisted turning of Titanium Metal Matrix Composite. It was observed that laser assist machining (LAM) can significantly increase tool life up to 180%. The phenomenon of improved tool life at higher speeds and under laser assist machining LAM conditions were explained through the analysis of the chip morphology and micro-structure. Jae-hyun., K. [5], studied Estimation of deformed laser heat sources and thermal analysis on laser assisted turning of square member. It was observed that, the maximum temperature of the calculation results, 1 407.1 °C, is 8.5 °C higher than that of the square member, which is 1 398.6 °C. In a LAT process for a square member, the maximum temperature is 1 850.8 °C. It is recognized that a laser power control process is required because square members show a maximum temperature that exceeds a melting temperature at around a vertex of the member according to the rotation. Ding, H. [6], investigated Laser-assisted machining of hardened steel parts with surface integrity analysis. It is shown that LAM produces about150MPa more compressive surface

axial residual stresses than hard turning and reduces the variation in hoop stress than those produced by hard turning. Kim,K .,and Lee,C.[7], reviewed research and development of laser assisted turning. It was found applied the laser assist turning (LAT) process for performing an effective machining process for a composite of AL_2O_3p/Al, which is classified as one of difficult to machining materials. As a result, the cutting force and tool wear decreased by30~50% and 20~30%, respectively, compared with that of the conventional turning process. Also, the surface quality was also improved. Brecher, C. [8], it is found that, forces were reduced by 73-90%. In addition to the process forces the wear of polycrystalline diamond (PCD) was also significantly reduced. The aim of the present investigation is to develop models to correlate the inter-relationships of various laser turning parameters of steel X10 such as laser power (P), gas pressure (GP), feed rate (F) and motor speed (S) on the process characteristics such as metal removal rate (MRR), upper cut width (UC), lower cut width (LC), depth of cut and roundness error (RE). This work is based on the response surface methodology (RSM) approach. It is expected that the models fitted to the experimental data will contribute towards the selection of the optimum process conditions, thus, enabling the production engineer to define suitable working parameters which save time and money and enhances the quality of the product.

2- Experimental work

2.1. Chemical composition of steel (X10 Cr Ni Ti 18. 9)

Table 1: Chemical composition of steel X10

C%	Si %	Mn %	% P	S %	Cr %	% Ni		Fe %
0.08	1.00	2.00	0.045	0.016	18.72	9.79		Rest
Mo %	%Al	Co %	Cu %	V %	% W	Ti %	Sn %	
0.2309	0.0112	0.0518	0.0967	0.0458	0.0403	0.42	0.0092	

2.2. Test pieces

Micro – grooving operation (machining) was performed on cylindrical X10 work piece of 12 mm diameter and 50 mm length. Fig. (1) Shows the geometry of work piece and the targeted shape of micro- groove to be generated by laser turning.

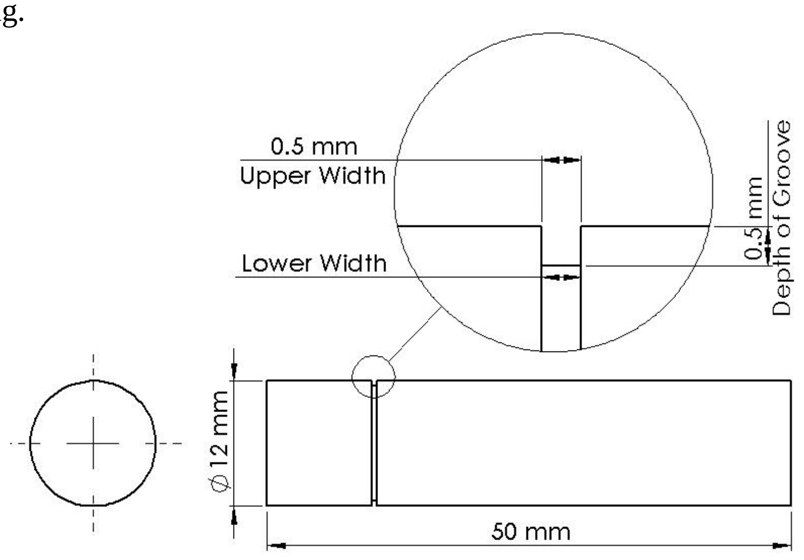

Fig.1. Test pieces geometry

The specimen were weighted before and after machining using a precise electrical balance

The metal removal rate was specified using the following equation:

$$MRR = [(W_b - W_a)/t] \quad (1)$$

Where:

MRR Metal removal rate (g/min).

W_b : Weight for specimen before machining (g).

W_a: Weight for specimen after machining (g).

t : laser turning time for each experiment (min).

2.3. Upper cut (UC), lower cut (LC) and depth of cut (DC).

Upper cut, lower cut and depth of cut was measured using Optical measuring microscope each value was obtained by averaging five measurements at various positions of the work piece surface for each machining condition

2.4. Roundness error (RE)

Roundness error was measured using Roundness testing machine.

The following steps were used to design experimental:

1- Primary experimental were performed to find the affective rang of the process parameters as shown in Table (2).
2- By Using the (RSM) it was made experimental design.
3- The working parameters by RSM were conducted experimentally.
4- The responses under consideration were feeding to the model as shown in Table (3).
5- Then the optimization working parameters can be determined.

Table 2: Coded and actual values of the input parameters

Input parameters	Symbols	Levels					Output parameters
		-2	-1	0	+1	+2	
Power ,Watt, (A),	X1	1000	1500	2000	2500	3000	MRR, (g/min) RE(μm) LC, UC &DC, (mm)
Gas pressure, bar, (B) [O2].	X2	0.2	0.3	0.4	0.5	0.6	
Feed rate, mm/min,(C)	X3	200	250	300	350	400	
Motor speed , rpm,(D)	X4	10	15	20	25	30	

Table 3: Experimental design matrix and experimental results

Exp. No.	Input process parameters				Experimental results				
	Power watt	Gas pressure bar	Feed rate mm/min	Motor speed R.P.M	MRR g/min	DC mm	UC Mm	LC Mm	RE μm
1	1500	0.3	250	15	0.2400	0.43074	0.423792	0.167751	63.71
2	2500	0.3	250	15	0.1767	0.86963	0.421792	0.158251	92.37
3	1500	0.5	250	15	0.2967	0.46532	0.421582	0.115751	86.05
4	2500	0.5	250	15	0.2367	0.91009	0.459582	0.123251	92.71
5	1500	0.3	350	15	0.2587	0.45555	0.471876	0.273751	63.05
6	2500	0.3	350	15	0.3167	0.87273	0.393876	0.176251	65.19
7	1500	0.5	350	15	0.1560	0.49013	0.405666	0.206751	64.39
8	2500	0.5	350	15	0.2388	0.91319	0.367666	0.126251	44.53
9	1500	0.3	250	25	0.3462	0.42441	0.342666	0.117917	31.69
10	2500	0.3	250	25	0.3040	0.8773	0.512666	0.172417	60.87
11	1500	0.5	250	25	0.2567	0.43899	0.334708	0.137917	55.03
12	2500	0.5	250	25	0.1167	0.89776	0.544708	0.209417	62.21
13	1500	0.3	350	25	0.2867	0.47822	0.45875	0.194917	64.55
14	2500	0.3	350	25	0.2867	0.90939	0.55275	0.161417	67.21
15	1500	0.5	350	25	0.3466	0.4928	0.386792	0.199917	66.89
16	2500	0.5	350	25	0.2564	0.92985	0.520792	0.183417	47.55
17	1000	0.4	300	20	0.1239	0.14002	0.284	0.149001	48.6
18	3000	0.4	300	20	0.4311	1.01596	0.416	0.123001	57.92
19	2000	0.2	300	20	0.009	0.67221	0.460792	0.159001	63.4
20	2000	0.6	300	20	0.1789	0.72725	0.426624	0.129001	66.08
21	2000	0.4	200	20	0.1027	0.68883	0.501916	0.157668	71.92
22	2000	0.4	400	20	0.12245	0.74574	0.526084	0.237668	56.6
23	2000	0.4	300	10	0.116578	0.71386	0.411208	0.200002	89.24
24	2000	0.4	300	30	0.16	0.72419	0.483208	0.207334	60.24
25	2000	0.4	300	20	0.13	0.81906	0.47	0.200001	48.5
26	2000	0.4	300	20	0.185	0.8	0.484568	0.230001	48.3
27	2000	0.4	300	20	0.19	0.81	0.478988	0.220001	47.5
28	2000	0.4	300	20	0.17	0.79906	0.465555	0.207897	49
29	2000	0.4	300	20	0.12	0.81906	0.47	0.190001	48.5
30	2000	0.4	300	20	0.2	0.80906	0.48	0.200001	48.8

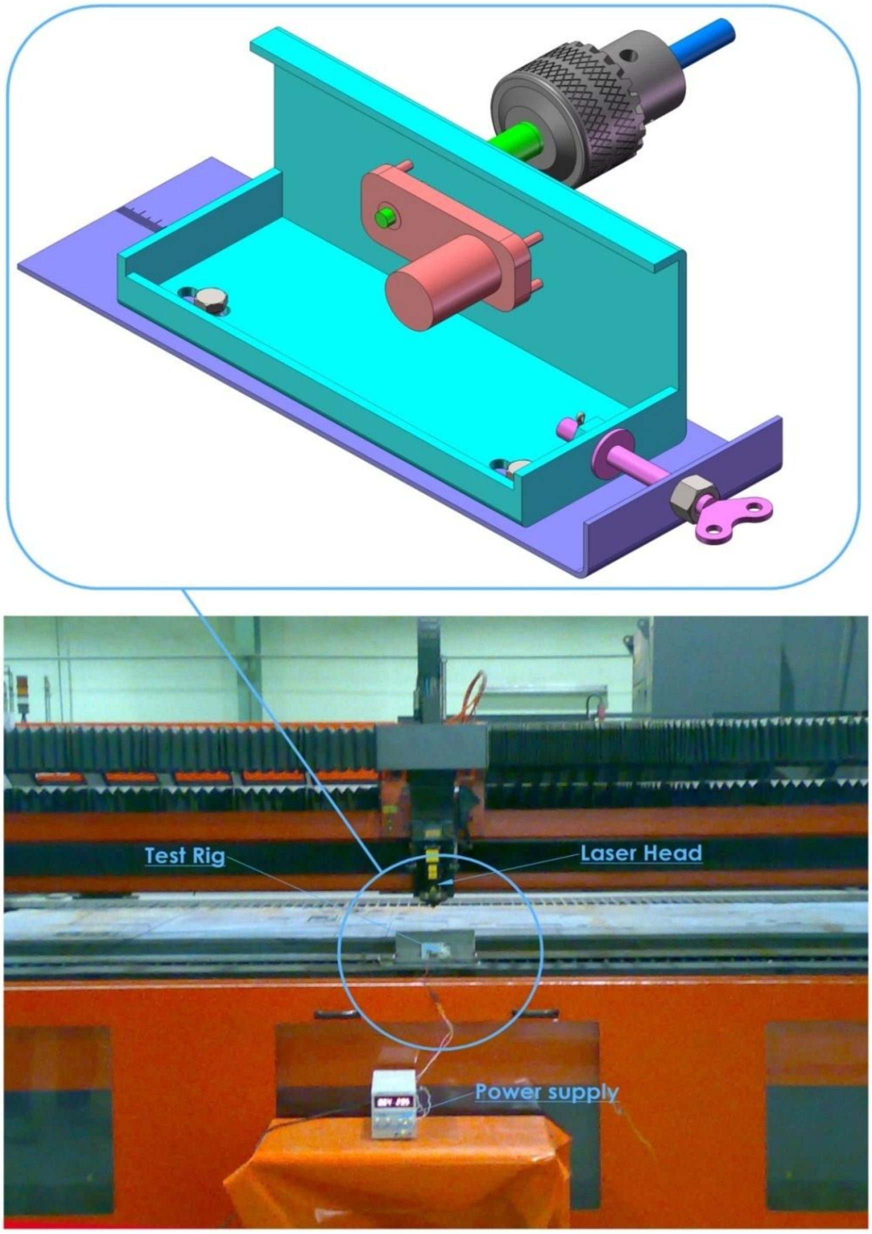

Fig. 2. CO_2 Laser machine and test rig

2.5. Mathematical modeling

The response surface methodology (RSM) is a useful tool to find the relationship between various process parameters and the machining criteria Furthermore; these models can be used to explore the effect of these parameters on the response criteria of the machining process. The objective of the response surface methodology is to develop the mathematical link between the response surface and the predominant machining parameters.

If all variables are assumed to be measurable, the response surface can be expressed as follows,

yu =f (X1, X2, X3…Xk) ± ξ (2)

Where yu is the corresponding response function (or response surface), X1, X2, X3…

Xk are coded values of the machining process Parameters and ξ is the fitting error of the uth observations.

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In this study, for four variables under consideration {Power (p), Gas Pressure (GP), Feed rate (F), and Motor Speed(S),}, a second-order polynomial regression model, which is called quadratic model, is proposed. The quadratic model of Yu [9] can

$$Y_u = b_o + \sum_{i=1}^{n} b_i X_{iu} + \sum_{i=1}^{n} b_{ii} X_{iu}^2 + \sum_{j>i}^{n} b_{ij} X_{iu} X_{ju} + \varepsilon \quad (3)$$

The coefficient b_o is the free term, the coefficients b_i are the linear terms, the coefficients b_{ij} are the interaction terms, and the coefficients b_{ii} are the quadratic terms, the full form of the derived models can be presented. The mathematical models of metal removal rate (MRR), depth of cut (DC), upper cut (UC), lower cut (LC) and round error (RE) can be expressed as follows;

$$MRR = +0.17 -127.03P-108.78 (GP) + 216.04 F + 95.71 S - 45.07 P^2 - 45.08 (GP)^2 + 2769.12 F^2-45.07 S^2 - 68.69 P (GP) +191.31 P F-212.44 P S+36.94 (GP) F - 83.31 (GP) S +51.69 FS \quad (4)$$

$$\text{Depth of cut} = + 0.81+ 0.22P+0.014 (GP) + 0.014F + 2.583 \times 10^{-3}S - 0.058 P^2 - 0.027 (GP)^2 - 0.023F^2 - 0.023S^2+1.470\times10^{-3}P (GP) -5.429\times10^{-3}PF +3.499\times10^{-3}PS +5.0307\times10^{-17} (GP)F - 5.000\times10^{-3}(GP)S +7.249\times10^{-3}FS \quad (5)$$

$$\text{UpperCut}=+0.47+0.033P-8.542\times10^{-3}(GP)+6.042\times10^{-3}F+0.018S -0.031 P^2-7.786\times10^{-3}(GP)^2 +9.787\times10^{-3}F^2 - 6.911\times10^{-3}S^2 +1.000\times10^{-2} P (GP)-0.019 P F +0.043 P S-0.016 (GP)F -1.437\times10^{-3} (GP)S +0.017FS \quad (6)$$

$$\text{Lower Cut} = +0.21- 6.500\times10^{-3}P-7.500\times10^{-3}(GP) + 0.020F+1.833\times10^{-3}S-0.018 P^2 - 0.016 (GP)^2 - 2.579\times 10^{-3}F^2 - 1.079\times10^{-3}S^2 + 4.250\times10^{-3}P (GP) - 0.022 PS +0.016 PS - 3.750\times10^{-3}(GP) F + 0.018 (GP) S -7.250 \times 10^{-3}FS \quad (7)$$

$$\text{Roundness error} = + 48.43 + 2.33 P_1 + 0.67(GP) - 3.83 F -7.25S +1.21 P^2 + 4.08 (GP)^2 + 3.96 F^2 +6.58 S^2 - 5.50 P (GP) -6.63PF + 0.13 PS - 5.25 (GP) F + 0.25 (GP) S + 8.38FS \quad (8)$$

3. Results and Discussion

A single response optimization algorithm provides a single optimal solution. However, most of the multi-response problems, in principle, give rise to a set of optimal solutions instead of a single optimal solution. In the present work, five responses have been considered, i.e. MRR, Depth of cut, Upper cut, and Lower cut and RE. For the production purpose, the best combination of parameter level should produce the maximum MRR, DC, UC, and LC minimum RE. A single optimal solution will not serve our purpose, as these objectives are conflicting in nature. Also the choice of MRR, DC, UC, LC and RE depends on user and machining condition.

A multiple response method called desirability. It is an attractive method for industry to optimize multiple quality characteristic problems [10]. The method makes the use of an objective function, D (X), called the desirability function (utility transfer function) and transforms an estimated response into a scale free value (di) called desirability. The desirable range was ranging from zero to one (least to most desirable respectively). One represents the ideal case; zero indicates that one or more responses are outside their acceptable limits. Composite desirability is the weighted geometric mean of the individual desirability's for the responses. The factor settings with maximum total desirability are considered to be the optimal parameter conditions. The simultaneous objective function is a geometric mean of all transformed responses. The optimization is accomplished as follows:

Combining the individual desirability's to obtain the combined or composite desirability (CD) [11].

If the importance is the same for each response, the composite desirability is:

$$CD = (d1*d2*\ldots\square\ dn)1/n = [\prod (di\ wi)]1/W \quad (9)$$

Where n = number of responses. To reflect the possible difference in the importance of different responses, where the weight wi satisfies 0<wi<1 and w1+ w2+ w3+ ……+ wn□= 1

In the present study, five responses MRR, DC, UC. LC and RE have been optimized simultaneously using developed models, Eqs. (9) based on composite desirability optimization technique.

3.1. Effect of Machining Parameters on Metal Removal Rate (MRR).

The following symbols are used during the current discussions.

X1=A=Power, (Watt) X2=B= Gas pressure, (bar)

X3=C=Feed rate, (mm/min) X4=D= Motor speed, (r.p.m)

3.1.1. Effect of laser power on MRR (X10- gas O_2).

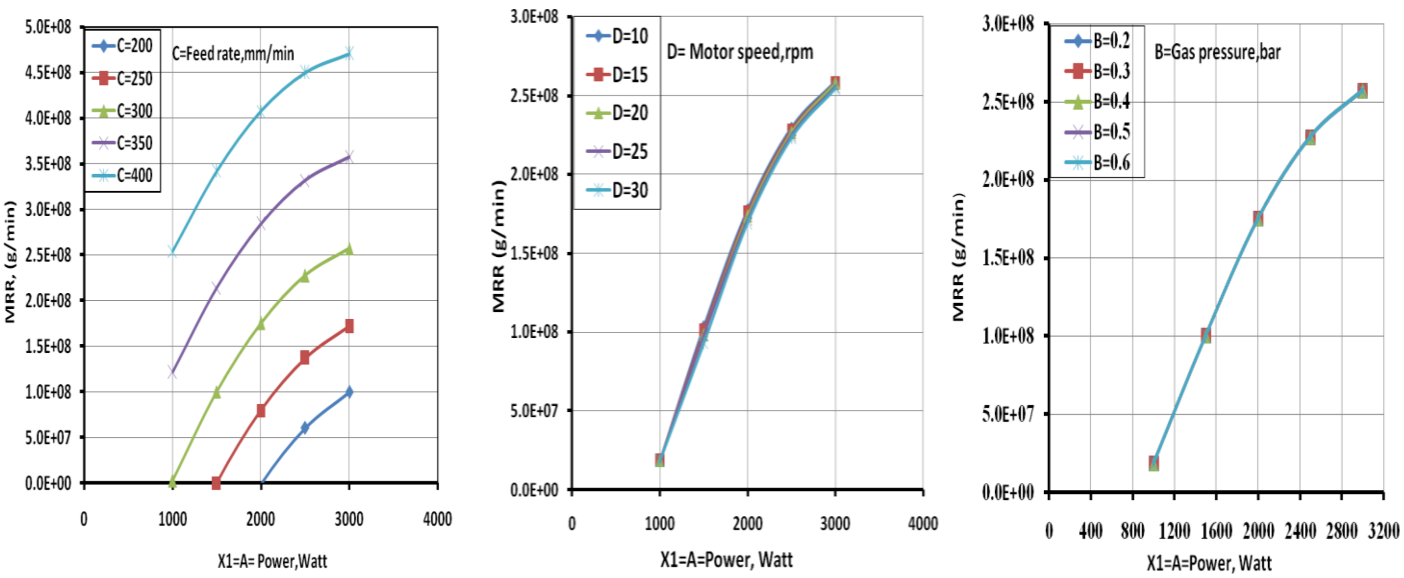

Fig.3 (a) Fig.3 (b) Fig.3 (c)

Fig.3 Effect of the laser power on the MRR at various values of (a) feed rate, (b) motor speed (c) gas pressure.

Fig.3. (a, b and c) illustrates the effect of the laser power on the MRR at various values of feed rate, motor speed and gas pressure respectively. The non linear variation of the MRR with laser power has been recorded generally; the MRR increases as the laser power is increased and this may be explained in terms of heat generated during the laser process. Increase of the laser power means an increase in the energy laser beam for penetration so the effective energy for penetration to the work piece more and more amount of material is removed from the surface of the groove.

3.1.2. Effect of gas pressure on MRR.

Fig.4 illustrates the effect of gas pressure on the MRR at various values of feed rate and motor speed respectively. The linear variation of the MRR with the gas pressure has been recorded. The MRR increases as gas pressure is increased and this may be explained because laser energy melts the target material and the gas jet blows away the molten material.

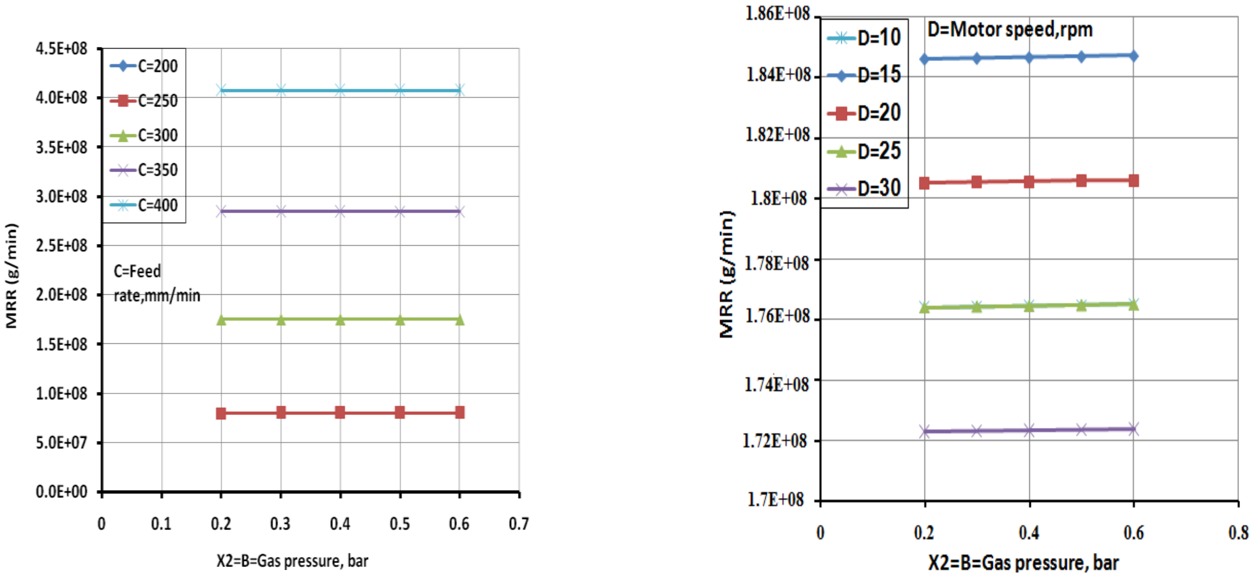

Fig.4 (a) Fig.4 (b)

Fig.4 Effect of gas pressure on the MRR at various values of (a) feed rate (b) motor speed.

3.1.3. Effect of feed rate on MRR.

Fig. 5 (a, b) illustrates the effect of the feed rate on the MRR at various values of motor speed. The MRR decreases as the feed rate is increased and this may be explained in terms of increase in feed rate causes slower rate of laser beam interaction with work piece, so material removal rate is slow and the lower cut becomes negative.

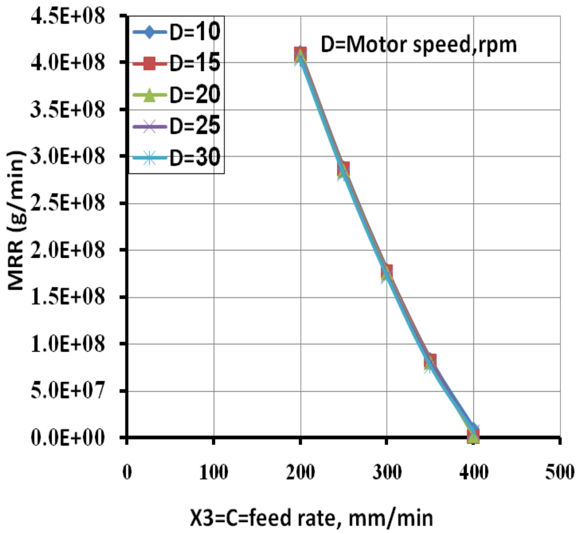

Fig. 5 Effect of feed rate on MRR at a various motor speed.

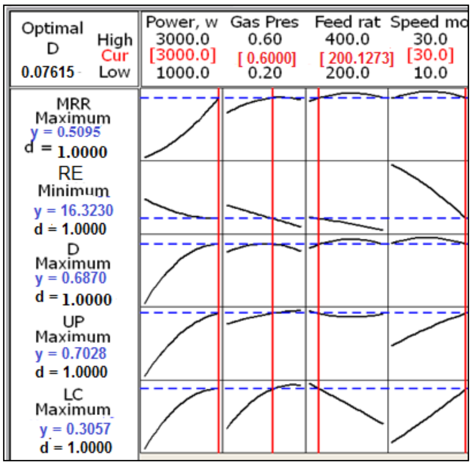

Fig.6 Multi-objective optimization results of CO_2 laser turned micro-grooving.

Fig.6 represent the optimized graphs of the five responses (MRR, DC, UC, LC, and RE) and also the optimization results for specimens machined by Laser turning machine. The vertical lines inside the cells represent current optimal parametric settings, and the horizontal dotted lines represent the current response values. Table (4) shows the constraints and optimum parameters. Table (5) shows Optimum predicted responses at the required goal.

Table 4: Constraints parameters and optimum parameters for specimens machined by Laser turning process.

Parameter	Constraints	Optimum parameters
Power, (P), Watt	1000 – 3000	3000
Gas Pressure, (*GP*), bar	0.2 – 0.6	0.6
Feed rate (*F*)mm/min	200 – 400	200.1273
Motor Speed(*S*), *r.p.m*	10 – 30	30

Table 5: Predicted optimum responses for specimens machined by Laser turning process.

Response	Goal	Predicted optimum responses
MRR , (g/min)	Maximize	0. 5095
DC , (mm)	Maximize	0.6870
UC , (mm)	Maximize	0.7028
LC , (mm)	Maximize	0.3057
RE, (µm)	Minimize	16.3230

5. Confirmation Experiment

(Table.6) indicates the predicted optimum responses, experimental responses and error (%).

Table 6: Predicted optimum responses, experimental responses and error (%).

Response	Predicted optimum responses	Experimental optimum responses	Error (%)
MRR , (g/min)	0. 5095	0.5238	2.8
DC , (mm)	0.6870	0.6979	1.6
UC , (mm)	0.7028	0.7126	1.4
LC , (mm)	0.3057	0.3129	7.8
RE, (µm)	16.3230	17.0575	4.5

6- Conclusions:

The following CONCLUSIONS can be drawn as follows:

1-The metal removal rate, depth of cut, upper width of cut, lower width of cut and roundness error increases with the increase Laser power and gas pressure, but MRR decrease with the increase of feed rate, While the motor speed has a moderate effect .

2- The optimal process parameters are Laser power 3000 watt, gas pressure 0.6 bar, feed rate 200 mm/min and motor speed 30 rpm.

3- (Error %) was not more than 7.8%.

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NOMENCLATURES

DC	Depth of cut
LAM	Laser Assist Machining
LAT	Laser Assist Turning
MRR	Metal Removal Rate
SEM	Scanning Electron Microscope
UC	Upper Cut
LC	Lower Cut
RE	Roundness Error
ND:YA	Solid states lasers (Neodinium: Yttrium-Aluminum-Garnet)
LBM	Laser Beam Machining
RSM	Response Surface Methodology
PCD	Polycrystalline Diamond

Minia Journal of Engineering & Technology (MJET), Vol. 38, No. 1. January 2019

دراسة عملية التشغيل بالليزر للصلب الذى لا يصدأ

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الدكتور / وسام محمد فاروق – مدرس بقسم الهندسة الميكانيكية بهندسة بنها

الملخص **العربى**

يقدم هذا البحث دراسة عن اختيار ظروف التشغيل المثلى باستخدام اشعة الليزر لسبيكة الصلب الذى لا يصدأ. استخدم نسق الاستجابة السطحى لتحليل وتحديدالظروف المثلى لخراطة هذه السبيكة باشعة الليزر . تم تقييم معايير اداء العملية بتحديد كلا من العرض العلوى والعرض السفلى للقطع وعمق القطع ومعدل ازالة الصلب ونسبة الخطا فى الاستدارة.تم توظيف نسق الاستجابة السطحى لاستنتاج نماذج رياضة للربط بين معايير الاداء ومتغيرات التشغيل المختلفة مثل طاقة الليزر وضغط الغاز ومعدل التغذية وسرعة الموتور.اختبرت مصداقية النماذج الرياضية باستخدام التحليل التابينى. تم تصميم تجهيزة معملية لاجراءالتجارب على ماكينة القطع بالليزر، وبعد تشغيل العينات باستخدام ماكينة الليزر تم وزن العينات قبل وبعد التشغيل لتحديد معدل ازالة الصلب.كما تم دراسة ابعاد القطع بواسطة الميكرسكوب الالكترونى لقياس ابعاد االقطع (العرض والعمق)، وتم قياس نسبة الخطا فى الاستدارة. اثبتت عملية التشغيل باشعة الليزر انها طريقة كافية لتشغيل الصلب المدرع بحيث تحقق نسبة مقبولة من معدل ازالة الصلب وابعاد قطع مقبولة و نسبة استدارة جيدة للسطح المشغل. معدل ازالة السبيكة يزداد بصورة عامة بازدياد قيمة كل من طاقة الليزر، ضغط الغاز ، معدل التغذية وكذلك سرعة الموتور يكون لها تأثير متوسط على معدل ازالة السبيكة. صممت الدراسة للحصول على اقصى معدل ازالة واقصى عمق قطع واقصى عرض للقطع واقل نسبة خطا فى الاستدارة تحت ظروف تشغيل مختلف.