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Experimental Investigation on Pulsed Nd: Yag Laser Cutting Of Hastelloy C-276 Sheetm Using Taguchi Method

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Abstract : Pulsed Nd:YAG Laser offers an excellent role for various micro-machining operations of a wide range of engineering materials such as ceramics, composites, diamond etc. The micro-machining of ceramics are highly demanded in the present industry because of its wide and potential uses in various field such as automobile, electronic, aero-space, and bio-medical engineering applications etc..The present research paper deals with the response surface methodology based mathematical modeling on machining characteristics of pulsed Nd:YAG laser cutting operation on a work piece of Hastelloy C-276 Sheet. In this present study, lamp current, pulse frequency, pulse width, assist air pressure and cutting speed of laser beam are considered as machining process parameters during pulsed Nd:YAG laser cutting operation.The results of above experiments will be reflected on the knowledge base to generate optimal cutting path of the laser. Investigation of Cutting Characteristics in the thickness of work piece for the Case of Cutting of a Hastelloy C-276 Sheet using High-power CW Nd:YAG Laser.

Keywords: Laser cutting operation, Multiple Regression Analysis, Taguchi Method, L9 Array ANOVA

1. INTRODUCTION

Laser beam machining is a non- traditional machining process. Increasing demand for advanced difficult to process materials and the availability of high power lasers has stimulated interest in research and development related to laser machining. In recent years there is an increasing trend towards miniaturization of various components involving different applications, such as MEMS, electronics, photonics, bio-medical devices.

In view of this, micromachining techniques have become important in the fabrication of micro-components and micro- assemblies. So lasers are also increasingly employed for a precise micromachining because their beams can be focused accurately on microscopic areas.

Increasing interest in the use of lasers for manufacturing can be attributed to several unique advantages which are generally applicable to the entire range of materials processing applications, such as high productivity, noncontact processing, elimination of finishing operations, adaptability to automation, reduced processing cost, improved product quality, greater material utilization, minimal heat-affected zone (HAZ) and green manufacturing, etc. Materials processed by laser beam machining, range from metals and alloys to inorganic as well as organic non-metals, composites and rocks, etc.

The laser drilling process is one of the most widely used thermal energy based non-contact type advance machining process which can be applied across a wide range of materials.

Laser beam machining is based on the conversion of electrical energy into light energy and then into thermal energy to remove the material from work piece. The material removal process is by focusing laser beam onto the work material for melting and vaporizing the unwanted material to create a hole.

Laser beam machining (LBM) has a great potential in the modern day production scenario. LBM is a high energy density process that works fast on complex shapes and is applicable to any type of material, generates no mechanical stress on work piece, reduces waste, provides ecologically clean technology and has the ability to do work in the micro range.

1.1 Nd: YAG Laser Machining Setup And Working

For efficient laser cutting and drilling operation on hard non-conducting work piece materials (with lower reflectivity and high absorption capability) the laser machining system (fig), consist of the following sub-system:

Fig1 Photographic view of laser beam micro machining system

Nd:YAG is a four level laser system. The pumping of neodynium (Nd^{3+}) ions to upper state (E4) is done using krypton arc lamp. Thus optical pumping is used in this laser. The wavelength of light of wavelength 7200 Å to 8000 Å excites the ground state (E1) Nd^{3+} ions to E4 states. From E4 states, they make a non-radiative transition and come to E3 state.

E3 is the metastable state so population inversion is achieved between the levels E3 and E2. After this, the process of stimulated emission will occur. (I have already explained the process of stimulated emission in detail in my previous articles).

Thus, the laser emission will occur in between the levels E3 and E2 with the process of stimulated emission. So E3 is the upper laser level and E2 is the lower laser level. Then Nd^{3+} ions come back to the ground state E1. Laser emission will have wavelength of 10600 Å so occur in the infrared range of spectrum.

1.2 Steps For Starting And Switching Off The Machine

Steps for Starting the Machine

1. Make sure that the shutter is 'OFF'.
2. Put 'ON' the stabilizer.
3. Check the voltage of the 3-phase either at the stabilizer or at the front panel of the laser system.
4. Start the MCB of the laser panel.
5. Start the water cooler in order to provide chilled water for laser head and wait until the present value of temperature (i.e.14ºC) of water is attained.
6. Start the pump for circulating the cold water through the laser head (source) at least two minutes before switching.
7. Switch 'ON' the RF drive unit. The first (power) indicator led of RF driver front panel should be 'ON'. If any other led indications is 'ON' then resolve the observed fault.
8. Switch on the MCB of the laser power supply and check that the 'inter link' led is glowing. Then press the laser 'ON' switch to take the system is to standby mode. Now press the control switch to take the system out of standby mode. Now by moving the current adjustment knob set it to the prescribed value where the desired optical output power is produced by the laser.
9. Now switch 'ON' the shutter.
10. Now start the computer with required program files.

1.3 Steps For Switching 'OFF' The Machine

1. Switch 'OFF' the shutter.
2. Exit from the software using "Esc" and turn 'OFF' the computer.
3. Switch 'OFF' the main power supply of accupos CNC controller unit.
4. Decrease the lamp current using the current control knob not less than 11 amp.
5. Switch 'OFF' the RF driver unit.
6. Now push the stand by switch of power supply to put the machine in steady mode.
7. Put 'OFF' the laser switch keeping the pump on for at least 2 min.
8. Now switch 'OFF' the pump on the heat exchanger and main MCB after 2 min after switching 'OFF' the laser power supply.
9. Switch 'OFF' the chiller unit after 2 min after switching 'OFF' the pump in the heat exchanger.
10. Switch 'OFF' the voltage stabilizer and then main power supply unit.
11. Before leaving the laser room, make sure the dust cover located at the bottom of the scanning unit is closed.

2. LITERATURE SURVEY

A theoretical model for high velocity laser fusion cutting of metals assuming that the light absorption occurs as per the classical Fresnel formulae has been given by W Schulz et al(1987). The dependence of the cutting depth and the mean absorbed laser power on the laser intensity and the mode number has been discussed and they have obtained an optimal choice for the laser focus position and the beam divergence.

Biswas *et al*. [1] has conducted an experimental investigation into pulsed Nd: YAG laser micro-drilling of gamma-titanium aluminide. A central composite design (CCD) and response surface method have been used to analyze the effect of the four major laser micro-drilling process parameters i.e., lamp current, pulse frequency, assist air pressure and thickness of the job. Two geometrical features, the circularity of the hole at exit and the hole taper are considered and model using a statistical approach.

Grevey *et al.* [2] has suggested a method to solve the problem of many laser processes that are associated with an undesired phenomenon of oxidation. This paper deals with the optimization of the protection gas device design as well as the gas flow in the case of laser welding and surface treatments. In order to achieve the goal the authors have recorded and analysed the pressure created by the gas flow on the sample surface with the operating parameters influence. This paper also shows the important role played by the shielding gas in minimizing the extent of plasma and to achieve the desired welding penetrations. The above phenomenon is assured by the nozzle system designed and presented by the author in this paper.

Lung Kwang Pan *et al*. [3] stated the use of an Nd:YAG laser for thin plate magnesium alloy butt welding and optimized using Taguchi analytical methodology. The parameters were evaluated by measuring the ultimate tension stress. The effectiveness of the Taguchi method lies in its ability of illuminating the factor that dominates complex interactions in laser welding. The factors can be the shielding gas, laser energy, convey speed of work piece, point at which the laser is focused, pulse frequency, and pulse shape. In addition 18 combinations of these six essential welding parameters were set and Taguchi's method followed exactly. In this paper various combinations of machining parameters for laser welding has been depicted and also shown how the inappropriate setting of the parameters can be exactly reflected onto the welded performance and degrade the tension stress.

Tai-Chang *et al.* [4] has carried micromachining on sapphire and silicon using ultraviolet Nd: YAG laser. Specific results and optimized cutting conditions are shown in this paper for both sapphire and silicon. This paper shows that sapphire has better surface finish and slower ablation rate than silicon which leads to the possibility of laser ablation process of sapphire to be mixed photo thermal and photochemical process. In case of silicon the cratered morphology indicates laser-induced boiling at lower scan speeds and higher laser fluence.

Biswas *et al.* [5] investigated pulsed Nd: YAG laser micro drilling on gamma titanium aluminide alloy sheets. A central composite design (CCD) and response surface method (RSM) have been used to analyze the effect of four laser micro drilling process parameters, e.g. lamp current, pulse frequency, assist air pressure and thickness of the job. The hole characteristics like hole diameter at entry, at exit, and hole taper are considered and modelled by the statistical approach. The evolution of the heat affected zone (HAZ) is also an important hole characteristic during laser beam machining but it is not included in the present research. Multi- objective optimization analysis has also been carried out using MINITAB software.

Kurita *et al.* [6] has conducted research to clarify experimentally the relationship between the material removal volume and the pressure level of the processing sound for a small material removal volume by utilizing a low frequency Q-switched YAG laser beam, and also to confirm the application of these experimental results to laser grooving when a high frequency Q-switched YAG laser beam is applied. An AE (acoustic emission) sensor is usually used to monitor the state of laser processing, because the generated sound of laser processing contains high-frequency components up to 100 kHz. However, in this research, the processing sound was monitored with a microphone from the stand-point of practical application, and the characteristics of the sound frequency up to 20 kHz were analyzed with an FFT (Fast Fourier Transform).

Su Kim *et al.* [7] has investigated thermal birefringence compensated symmetric resonator in which two Nd:YAG laser rods have a curved end surfaces. The optimum condition for high output power and good beam quality was achieved by investigating the stability, beam quality, mode volume and the symmetry of mode volume inside laser rods depending on the temperature difference and rod separation.

B.S. Yilbas [8] has employed a design of factorial experiment including four factors at four levels to test the significance level of the factors that affect the hole quality. The author has considered three materials stainless steel, nickel and titanium. The response for the factorial design is obtained by the evaluation of the features of the resulting hole geometry. The results indicated that the main effects of factors considered were highly significant in the decreasing order of Lens, material properties, focus settings, workpiece thickness, energy and pulse lengths.

In this paper it has been found that work piece thickness, pulse length and focus setting along with their different level of interaction have significant effect on hole geometry.

Evekull *et al.* [9] has reported on the recent advances in passively aligned high-power diode-pumped solid-state lasers (DPSSL) using microstructure silicon carriers. With the help of this technology a compact yet efficient passively Q-switched Nd:YAG laser has been developed by the author. The advantage of this concept is the scalability to high pump power average output power. The passively Q-switched laser delivers an average output power of more than 2 W at 1064 nm, with 13:5 W launched pump power at 808 nm from a fiber coupled high-power diode. With these parameters it should be a useful tool for wide range of applications.

D.L. Yu *et al.* [10] has described the compact and simple 40 W CW Nd: YAG laser system, especially its diode-side-pumping configuration. The author has studied the birefringence, thermal lensing and pump energy distribution of the laser system under non-lasing condition. The output power and beam quality of the laser under different cavity parameters, cooling water temperature and an adjustable aperture inside the cavity is also presented in the paper.

Kuar *et al.* [11] has carried out an experimental investigation into Nd: YAG laser microdrilling of alumina. An effort has been made to achieve high quality microdrills and to minimize the defects such as hole taper and HAZ width. Taguchi method coupled with grey relational analysis is therefore used as statistical design of experiment tools for simultaneous optimization of both the quality characteristics. The effect of process parameters on microdrill qualities is also discussed in this paper.

Hanon *et al.* [12] has investigated the effects of the laser parameters such as peak power, pulse duration, focal plane position, repetition rate and the number of pulses on the ceramic substrate. Geometrical and micro structural properties have been evaluated using optical and SEM images. In addition to experimental studies, simulations have also been carried out using a software package Fluent v6.3.26. A comparison between the experimental and the simulations have been made in this paper to evaluate the differences in the dimensions (diameter & penetration depth) versus various peak powers and pulse durations for single laser pulse.

Mishra *et al.*[13] has developed a 2D axi-symmetric FEM-based thermal model, incorporating the effects of temperature dependent thermal properties, optical properties and phase change phenomena to determine the transient temperature distribution in the sheet form of difficult to machine thin nickel based super alloy (Inconel 718) sheet. The temperature profile so obtained is further utilized to obtain the Ta, MRR and extent of HAZ. Multi-objective optimization of the LBPD process has been made using the coupled approaches o GRA and PCA.

Kuar *et al.* [14] has carried an experimental investigation on CNC pulsed Nd:YAG laser micro-drilling of zirconium oxide (ZrO2). In this paper the author has also studied the influence of laser machining parameters on HAZ thickness and phenomena of tapering of machined micro-holes. Attempt has also been made to carry out optimal parametric analysis on pulsed Nd: YAG laser micro-machining process, to achieve better control of machined micro hole quality on ZrO2 ceramics. To determine the multi-parametric optimal combinations for pulsed Nd: YAG laser beam micro-drilling process of non-conducting engineering ceramics, experiments have been carried out according to the central composite rotatable second-order design based on Response Surface Methodology (RSM).

B. S. Yilbas, S. J. Hyder, and M. Sunar(1998) [15] have used Taguchi method to classify the relevant parameters such as waviness and flatness, Cutting speed, oxygen pressure, and workpiece thickness. Scanning electron microscope photography is used to examine the resulting cut surfaces. They have found that the cut quality is mainly affected by the oxygen gas pressure and cutting speed. Shang-Liang Chen(1999) has investigated CO2 laser cutting performance on 3 mm thick mild steel plate with assistant-gas pressures of up to 10 bar. The results have shown that for laser cutting of mild steel up to 3mm oxygen is the most suitable assist gas.S. M. Shariff, G. Sundararajan, and S. V. Joshi (1999) have studied the influence of two major process parameters namely laser power and cutting speed on cut surface quality attributes such as surface roughness, kerf width, heat affected zone. The oxygen-assisted cutting involving an exothermic oxidation reaction, which contributes significantly to the overall energy input to the cutting front is also studied.

The theoretical based on power, cutting speed, gas pressure, pulse energy are the parameters of laser machining process. The present work deals with these parameters with kerf deviation and MRR by Taguchi method.

3. METHODOLOGY

3.1 Experimental Setup

Nd:YAG laser system has been used in this work. The specifications of Nd: YAG laser machine is mentioned in the table given below

Specifications	Description
Laser type	Nd: YAG laser
Wave length	1064nm
Mode of operation	Q-switched(pulsed)
Nozzle diameter	1mm
Focal length of lens	50mm
Pulse frequency	10Hz
Cutting length	15mm

Table 3.1 Specifications of Nd: YAG laser machine

3.2 Work Piece Material

In the present experiment laser cutting of Hastelloy has been carried out. Hastelloy (Ni-65.6%, Mo-16%, Cr-15%, Fe-6%, W-3.5%). Hastelloy is Nickel, Chromium, Molybdenum based super alloy .these alloy generally used in high corrosive resistance and high temperature applications.

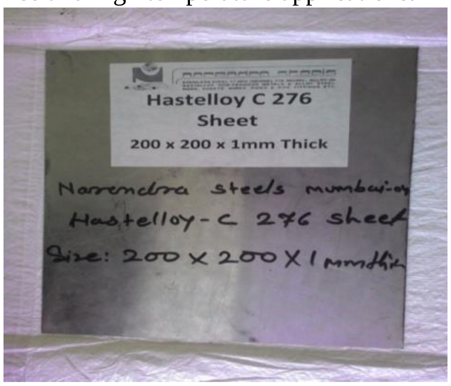

Fig Hastelloy C-276 sheet

3.3 Experimental Plan Taguchi's Approach To Parameter Design

Taguchi's approach provides the designer with a systematic and efficient approach for conducting experimentation to determine near optimum settings of design parameters for performance and cost. The method emphasizes passing quality back to the design stage, seeking to design a product/process, which is insensitive to quality problems. The Taguchi method utilizes orthogonal arrays to study a large number of variables with a small number of experiments. Using orthogonal arrays significantly reduces the number of experimental configuration to be studied. The conclusion drawn from small-scale experiments are valid over the entire experimental design spanned by the control factors and their settings. This method can reduce research and developmental cost by simultaneously studying a large number of parameters.

In order to analyze the results, the Taguchi method uses a statistical measure of performance called signal-to-noise (S/N) ratio. The S/N ratio takes both the mean and the variability into account. The S/N equation depends on the criterion for the quality characteristics to be optimized. After performing the statistical analysis of S/N ratio, an analysis of variance (ANOVA) needs to be employed for estimating error variance and for determining the relative importance of various factors. In the signal-to-noise (S/N) ratio, signal refers to real value which is desired and noise refers to undesired factors in measured values. There are three basic categories to determine the best results of experiments: smaller the better characteristics, larger the better characteristics and nominal the best.

The methodology of Taguchi for four factors at two levels is used for the implementation of the plan of orthogonal array experiments. An L9 orthogonal array with seven columns and ten rows is employed in this work. The experiments are carried out according to the arrangement of the orthogonal array.

Based upon previous literature survey and some preliminary experimentation power, cutting speed, gas pressure, pulse energy has been considered as process variables as shown in table 3.3. Apart from these process variables it is expected that the position of the work piece with respect to focal plane as well as thickness of work piece is expected to have significant effect on response variables. However to make this modeling and optimization technique applicable for a range of thickness and as well as to understand the influence of thickness, it has been considered as a process variable in the design of experiment. All factors and their levels as shown below.

s.no	Parameter	Unit	Low	Medium	High
1	Power	W	150	180	210
2	Cutting speed	mm/min	10	12	14
3	Gas pressure	Kg/cm^2	5	7	9
4	Pulse energy	J	2	3.5	5

Table 3.3 Factors and their levels

Hastelloy sheets of size 200x200x1 mm are used as work piece material. The material is cut by Nd:YAG laser emitting at different parameter settings as per experimental model. Oxygen is used as assist gas in the experiments.

In this experiment we compare MRR and kerf deviation by using Taguchi method.

MRR-The loss of mass during each cut is called MRR and it was measured using contech electronic balance (Model CAS 234). The empirical formula for MRR is

MRR (mg/min) = (Loss of mass during each cut X Cutting speed/length of cut)

KD- The difference between the maximum and minimum top kerf width along the length of cut is called kerf deviation. Mathematically it can be written as;

KD (mm) = (Maximum top kerf width - Minimum top kerf width)

4. ANALYSIS AND RESULTS

4.1 Experimental Results

After successful completion of the experiments the results are tabulated in the table 6.1 respectively

Exp. Run	Power W	Cutting speed mm/min	Gas pressure Kg/cm^2	Pulse energy J	MRR	KD
1	150	10	5	2	135.4	0.0101
2	150	12	7	3.5	141.3	0.0124
3	150	14	9	5	150.8	0.0116
4	180	10	7	5	149.2	0.0124
5	180	12	9	2	151.3	0.0108
6	180	14	5	3.5	145.6	0.0115
7	210	10	9	3.5	139.8	0.0112
8	210	12	5	5	145.5	0.011
9	210	14	7	2	152.3	0.0128

4.1 Response of L9 experiment

4.2 Parametric Analysis Of MRR

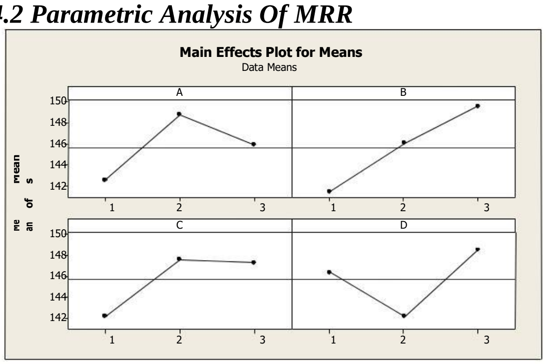

Fig. 4.2.1 S/N ratio curve exhibiting MRR

4.3 Analysis Of MRR

From the graph if we increase power MRR increase and again increase it will be decrease. Cutting speed increase MRR increase and again increase it is also increase. Gas pressure increases MRR increases and after it will decrease slowly. Pulse energy is increased MRR decreased and again increase of pulse energy MRR will be increased.

Source	DF	Seq SS	Adj SS	Adj Ms	F	P
Power	2	64.889	64.889	32.444	*	*
Cutting speed	2	57.556	57.556	28.778	*	*
Gas pressure	2	227.556	227.556	113.778	*	*
Pulse energy	2	48.222	48.222	24.111	*	*
Total	8	398.222				

4.2 ANNOVA for MRR

	DF	Seq SS	Adj SS	Adj MS	F
Power	2	0.45222	0.45222	0.226109	*
Cutting speed	2	0.43302	0.43302	0.216509	*
Gas pressure	**2**	1.73969	1.73969	0.869845	*
Pulse energy	2	0.37667	0.37667	0.188334	*
Total	8	3.00159	3.00159		

4.2 ANNOVA for KD

Versus order

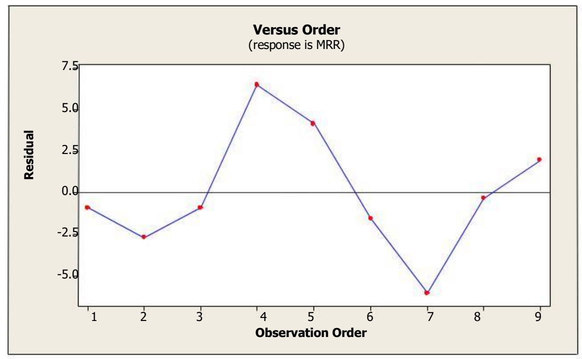

Fig.4.2.2 versus order

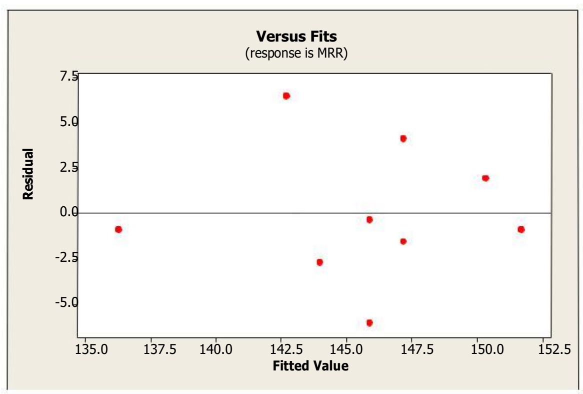

Fig.4.2.3 versus order

Versus order gives the experiment is correct or not. It must be in one array will be above the zero line and next array will be below zero line then only the experiment is correct.

Normal probability line

This line gives the probability of the experiment. If the line in "S" shape then only experiment is correct. In our experiment it is correct.

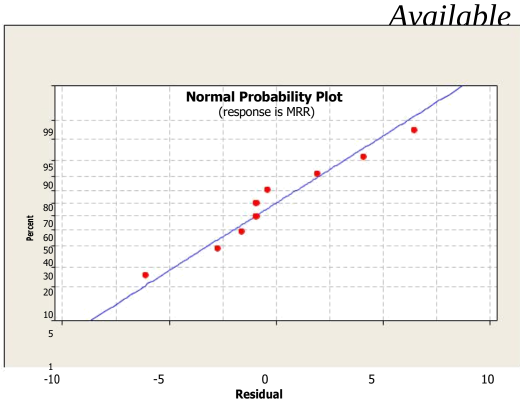

Fig.4.2.4 Normal probability line

4.4 Parametric Analysis Of Kerf Deviation

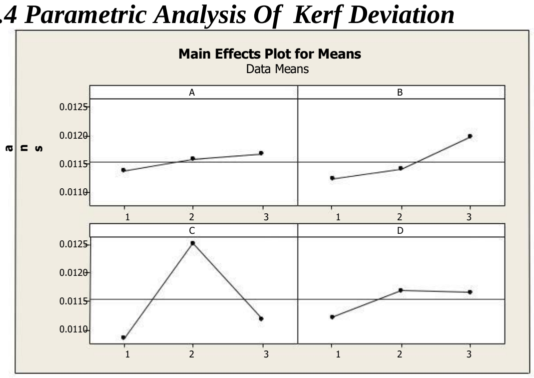

Fig.4.2.5 S/N ratio curve exhibiting KD

4.5 Analysis Of Kerf Deviation (KD)

In this experiment power is increased KD also increased from one level to another level and again increased it will increased. If we increase cutting speed KD will increase slowly and again increasing KD will be increase suddenly. Increasing of gas pressure KD will increase and again increase it will decrease suddenly. If we increase pulse energy KD will increase and again increase it will decrease slowly.

Versus order

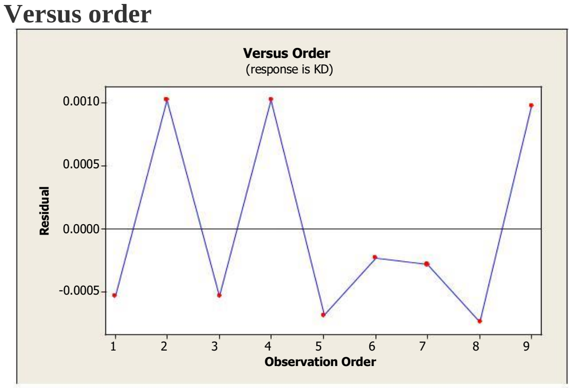

Fig.4.2.6 versus order

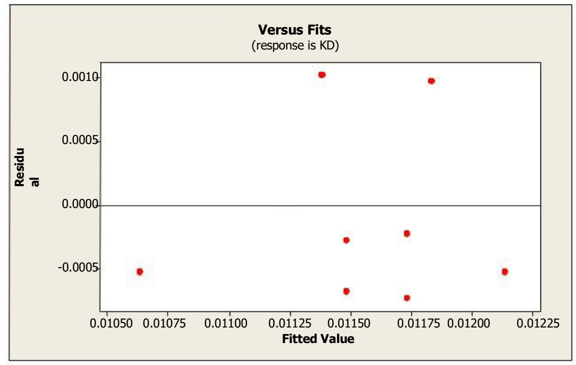

Fig.4.2.7 versus order

Normal probability line

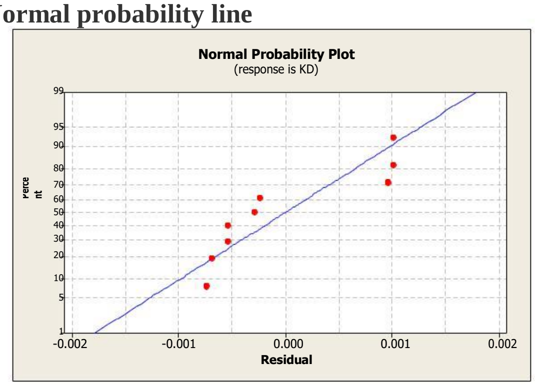

Fig.4.2.8 Normal probability line

Response table for means of MRR and KD

Level	Power	Cutting speed	Gas pressure	Pulse energy
1	142.5	141.5	142.2	146.3
2	148.7	146.0	147.6	142.2
3	145.9	149.6	147.3	148.5
Delta	6.2	8.1	5.4	6.3
Rank	3	1	4	2

Table.4.4 Response table for MRR

Level	**Power**	**Cutting speed**	**Gas pressure**	**Pulse energy**
1	0.01137	0.01123	0.01087	0.01123
2	0.01157	0.01140	0.01253	0.01170
3	0.01167	0.01197	0.01120	0.01167
Delta	0.00030	0.00073	0.00167	0.00047
Rank	4	2	1	3

Table.4.5 Response means for KD

For MRR cutting speed is got first rank. In this cutting speed increase more noise will come and after that pulse energy and then gas pressure, power.

For KD Gas pressure is got first rank. In this gas pressure increases high noise comes and after that cutting speed, pulse energy and power.

4.6.1 Additive Of Laser Cutting Process

An additive model can be viewed as superposition model or a variable separable model. It can be noted that superposition model implies that the total effect of several factors is equal to the sum of individual factor effects. It is possible for the individual factor effects to be linear, quadratic or of higher order. In an additive model cross product terms involving two or more factors are not considered.

4.6.2 Regression model

The regression equation is obtained as follows

For MRR

MRR = 127 + 1.68 A + 4.05 B + 2.57 C + 1.08 D

For KD

KD = 0.00973 + 0.000150 A + 0.000367 B + 0.000167 C + 0.000217

In this

A-power ,B-cutting speed,C-gas pressure,D- pulse energy,R-Square value

For MRR

S = 0.0360047 R-Sq = 95.19% R-Sq(adj) = 90.00%

For KD

S = 0.0360047 R-Sq = 93.57% R-Sq(adj) = 88.10%

5. RESULTS AND DISCUSSION

5.1 *Effect Of Laser Power On MRR*

Though laser machining is a non contact process the extreme heat produced during the process affects the MRR rate. If oxygen is used as an assist gas the additional heat generated during oxidation process will produce further deterioration of the cut surface. So power increased MRR is increased and then it will be decreased next level.

5.2 Effect Of Cutting Speed On MRR

If cutting speed increases MRR also increases after increasing also MRR rate will be high. So cutting speed increases the MRR rate.

5.3 Effect Of Gas Pressure On MRR

If gas pressure increases MRR also increases and after it decreases slowly when increasing of gas pressure.

5.4 Effect Of Pulse Energy On MRR

If pulse energy increases MRR is decreased after it will increase suddenly when pulse energy increased.

5.5 Effect Of Power On KD

If power is increased KD will increase slowly after that also it will increase slowly when power is increased.

5.6 Effect Of Cutting Speed On KD

If we increase cutting speed KD will increase slowly and then it increase suddenly with increase of cutting speed

5.7 Effect Of Gas Pressure On KD

If we increase gas pressure KD will increase suddenly after that it will decrease suddenly when increase of gas pressure.

5.8 Effect Of Pulse Energy On KD

If we increase pulse energy KD will increase after it will decrease slowly when pulse energy is increased

6. CONCLUSIONS

Laser cutting process is highly localized, non-contact and is devoid of reactional forces. Negligible physical force is exerted by the laser on the work. This makes it useful for any type of material. The quality of cut surface is very good and a very small amount of material is lost in the process. The cut surface being smooth, finish cut quality can be achieved in single process. Sharp angles, small radius rounds and complex curves can be cut with high speed.

From the experimental cutting speed is main factor for MRR and gas pressure is main factor for Kerf deviation.

If we increase of cutting speed the MRR will be also increased. If we increase gas pressure then KD will increase and then suddenly decrease.

A Design of experiment using Taguchi method had carried out and the optimal value for level 1 (146.3 J) of Pulse energy, level 2 (148.7 W) of power, level 3 (149.6 mm/min) of cutting speed, and level 2 (147.6 Kg/cm^2) of Gas pressure, i.e. the optimum parameter setting for maximum MRR.

A Design of experiment using Taguchi method had carried out and the optimal value for level 1 (0.01137 W) of Power, level 2 (0.01253 Kg/cm^2) of Gas pressure, level 3 (0.01197 mm/min) of Cutting speed, and level 2 (0.01170 J) of Pulse energy, i.e. the optimum parameter setting for minimum KD.

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