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OPTIMAL ANALYSIS ON Nd:YAG LASER MACHINING PROCESS

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Abstract A CNC pulsed Nd:YAG laser machining system has potential for precision machining operation on the small jobs. For achieving high precision machining characteristics during Nd:YAG laser cutting operation, the important process parameters such as the radio frequency of Q-switch, lamp current and cutting speed are to be optimally controlled because these controllable process parameters mostly affect the machining accuracy during laser cutting operation. In this present research, the square profile has been cut from 0.3mm thick aluminium sheet and the accuracy in angle and side length of a square profile are considered as the response of the Nd:YAG laser cutting operation. In this present set of experiments, the radio frequency of Q-switch has been set at three levels of 8.0, 7.0 and 6.0kHz respectively. The lamp current setting, considered for the experiments are 18.0, 18.5 and 19.0 amp respectively. The cutting speed values are set at three different level as 9, 12 and 15mm/sec respectively. In this present paper Taguchi method based parametric optimisation technique is applied for determining the optimal parametric combination for achieving high precision machining characteristics during Nd:YAG laser cutting operation. The analysis of variance (ANOVA) has been made to find out the contribution of each laser machining process parameters during Nd:YAG laser profile cutting operation. The verification test has also been carried out to predict and verify the adequacy of the additive model for determining the optimum machining characteristics during Nd:YAG laser cutting operation.

Keywords : Nd:YAG laser cutting; Square profile; Optimal analysis; Machining accuracy.

1.0 INTRODUCTION

The applications of laser in material machining are increasing at a faster rate because the laser machining system has ability to machine thin sheet materials with high machining accuracy. Pulsed Nd-YAG laser machining becomes an excellent process because of high laser beam intensity at low mean beam power , good focusing characteristics due to very small pulse duration, small kerf widths and narrow heat effected zones. The laser machining process can be utilised as a supplementary techniques to other non-conventional techniques such as EBM, EDM, ECM and WAJM etc. The Nd-YAG laser machining system can be continuously operated from a few watts to several hundred watts, but in most applications pulsed operation is preferred. The Q-switch operation is performed in order to achieve peak power of several kilowatts. Pulsed Nd-YAG laser machining system with computer numerical control (CNC), can be used effectively for geometrical profile cutting operation on thin sheet of materials (0.3mm). Although good number of fundamental research have already been made in the area of laser machining technology, the further research is still needed for optimal parametric analysis for achieving high quality machining characteristics i.e. dimensional accuracy during laser cutting operation. Keeping this consideration in view, this paper includes the parametric analysis for determining the optimal parametric combination for achieving improved angular and linear dimensional accuracy during square profile cutting operation using Taguchi method of robust design concept of Quality Engineering.

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2.0 MACHINING SET-UP OF CNC Nd-YAG LASER SYSTEM

For efficient profile cutting and drilling operation , the CNC Nd-YAG laser machining set-up consists of the various subsystems such as; Laser source and Beam delivery unit, Power supply unit, Radio Frequency (RF) Q-switch driver unit, Cooling unit and CNC Controller for X – Y and Z axis movement. Fig. 1.(a) shows the schematic representation of CNC Nd-YAG laser machining system.

In Nd-YAG lasers, Neodymium (Nd) atoms (lasing media) are embedded in Yittrium Aluminium Garnet (YAG) crystal host. The pump source is usually a Krypton arc lamp positioned parallel to the Nd-YAG crystal. The Nd-YAG rod is kept at one focus and the krypton arc lamp is kept another focus of a gold plated elliptical cavity for light to get amplified, the optical feedback is provided by a 100% reflectivity rear mirror and a front mirror which has reflectivity of about 80%. The acousto-optic Q-switch consists of a transparent materials (usually quartz) with a piezo-electric acoustic transducer mounted at one side of laser head. The Q-switching is an excellent method to produce very short pulse width and very high peak power pulse of light from a CW low power laser. The R.F. signal is supplied to Q-switch for its operation by RF Q-switch driver. The radio frequency (R.F.) of the Q-switch is one of the important controllable parameters in this laser system. The laser beam delivery system consists of beam bender and a focusing lens. The laser beam from the expander of the laser source is to be sent to the work piece surface by bending the beam at 90°, which is then focused by the focusing lens.

The main power supply unit controls the laser output by controlling the intensity of light emitted by Krypton arc lamp which is used for pumping the Nd atoms in Nd-YAG rod. Once the discharge in the lamp is produced by triggering with high voltage pulse, then by changing the current flowing through the lamp, intensity of light emitted by the lamp can be controlled. The lamp current is an important controllable parameters of this Nd-YAG laser machining system.

The cooling unit consists of the two subsystems such as a chiller unit for providing the chilled water to the laser head and Q-switch, and a pump for circulating the chilled water from chiller to the laser head via water heat exchanger. To avoid the thermal damage of laser cavity, Krypton lamp, Nd-YAG rod and Q-switch the heat is to be removed by the chilled water supplied by the cooling unit. Fig 1.(b) shows schematic flow diagram of cooling water supply system.

The work piece is held on a jig which is mounted on X-Y table and the movement of X and Y axis is controlled by CNC controller unit, for proper focusing of laser beam by means of focusing lens, the Z axis movement of lens is controlled by CNC Z axis controller unit. The CCD camera together with CCTV monitor is used for viewing the location of work piece and also for checking the proper focusing condition before laser machining parameter for achieving high quality machining characteristics of CNC Nd-YAG laser cutting operation.

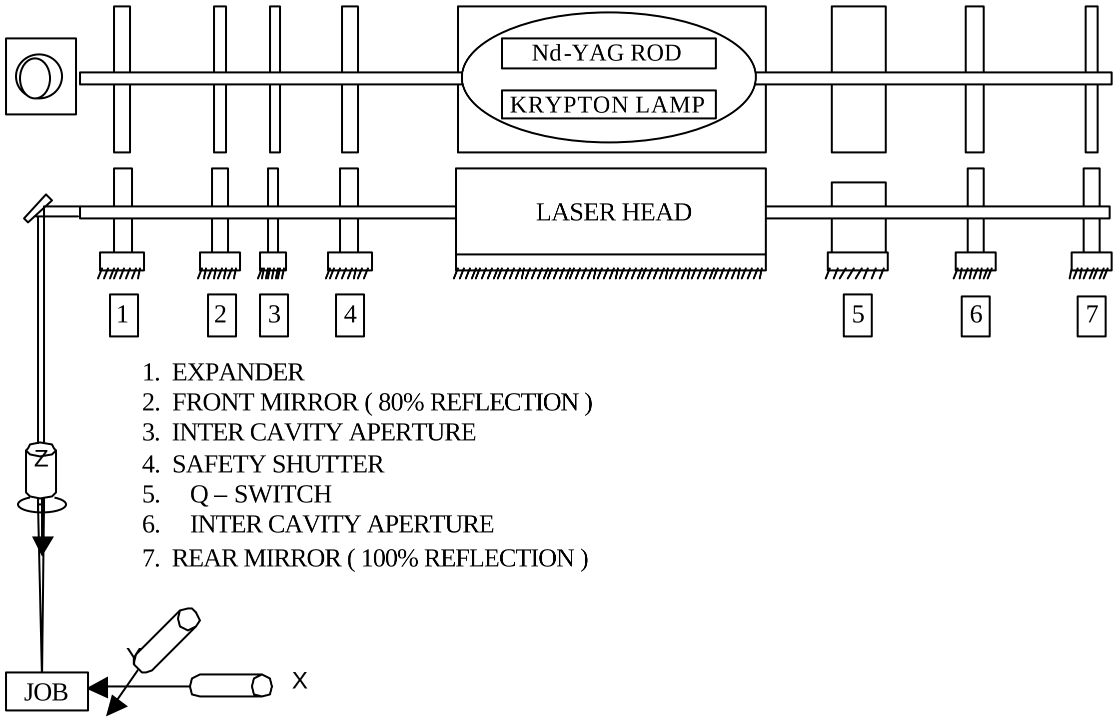

Fig. 1(a) Schematic Representation of CNC Nd-YAG Laser Machining System

3.0 OPTIMAL PARAMETRIC ANALYSIS USING QUALITY ENGINEERING APPROACH

After performing the basic experiments, the parametric analysis has been carried out using Quality Engineering approach. In this present parameter design, three levels of each machining parameters are selected and shown in Table 1.

Experiments on CNC Nd-YAG laser machining system have been carried out according to the designed plan based on standard orthogonal array (L_9) which has been selected because there are three controllable machining parameters and each machining parameter has three levels.

Table 1: Machining parameters and their levels

Symbol	Machining Parameters	Units	Level 1	Level 2	Level 3
A	Radio Frequency of Q-switch	kHz	8	7	6
B	Lamp Current	amp.	18.0	18.5	19.0
C	Cutting Speed	mm/s	9	12	15

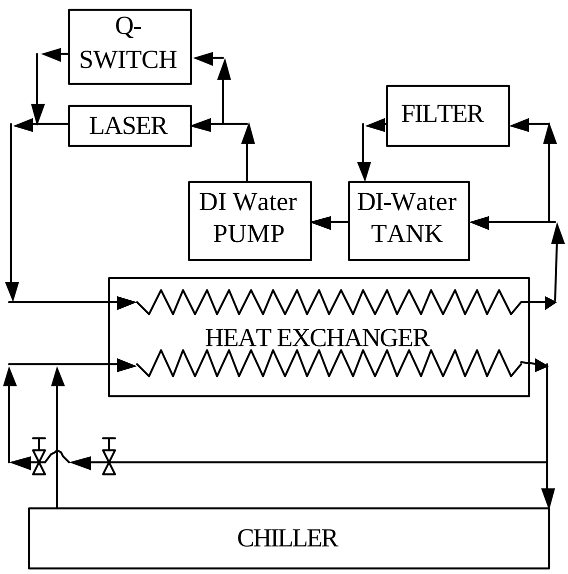

Fig. 1(b) Schematic Diagram Of Cooling Water Flow System.

3.1 Optimal Paramatric Conditions For Achieving High Quality LASER Machining Characteristics.

In Taguchi method, the Signal to Noise (S/N) ratio analysis has been carried out to determine the optimal machining parametric condition of Nd-YAG Laser machining process. Experiments are planned and the performance or responses i.e. deviation in angle and side length during square profile cutting are measured for each experimental run. In order to obtain optimal machining condition, the smaller the better principle for both the responses are considered for the present analysis. The S/N ratio for both responses for j-th experiment is defined as:

$$\eta_j = -10*\log_{10}(1/r* \sum_{i=1}^{r} y_{ij}^2) \quad ......(1)$$

where r is the number of replications and y_{ij} is the responses value of *i-th* replication test for *j-th* experimental condition. The measured values of deviation in angle of square profile and the corresponding S/N ratio are given in Table 2 using Eqn.(1). The mean S/N ratio for the frequency of Q-switch (A) at levels 1,2 and 3 can be calculated by averaging the S/N ratios for the experiments 1, 2, 3; 4, 5, 6 and 7, 8, 9 respectively. The average S/N ratio for all the levels of all machining parameters (factors) taking angular deviation as response is graphically exhibited in Fig.-2. The highest average S/N ratio gives the minimum deviation. It is clear from the S/N ratio response graph (fig.2) that for achieving minimum angular deviation the optimal condition of machining is $A_1B_2C_2$ i.e. frequency of Q-switch of 8kHz, lamp current of 18.5 amp. and cutting speed of 12 mm/sec. The observed values of linear deviation and the corresponding values of S/N ratio are also listed in Table 3 using Eqn.(1). The mean S/N ratio for deviation in side length for all the factors at different levels are determined. The S/N ratio graph for linear deviation is shown in Fig. 3. The greater average S/N ratio corresponds to the minimum deviation in side length. From the S/N ratio graph (Fig.3) it is concluded that the optimum parametric combination is $A_1B_2C_2$ i.e. frequency of Q-switch of 8 kHz, lamp current of 18.5 amp and cutting speed of 12mm/sec.

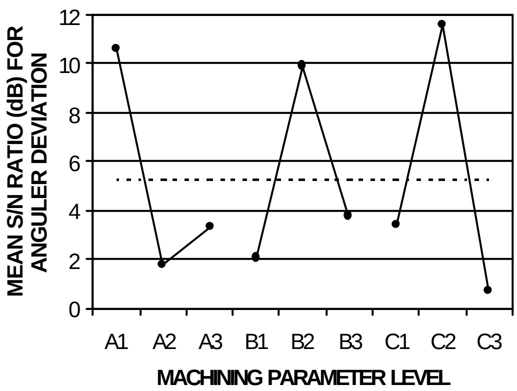

Fig. 2 S/N Ratio Graph For Deviation in Angle

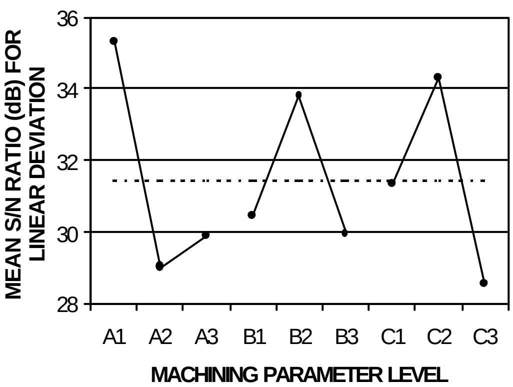

Fig. 3 S/N Ratio Graph For Deviation in Length

The decrease in radio frequency of Q-switch results in increase in the laser beam energy because more time is available to stimulate the energy of the laser beam. It is evident that while cutting material like aluminium having melting temperature of 658°C by CNC Nd:YAG laser, high energy laser beam mainly due to lower value of radio frequency of Q-switch results in increase in overcut. Moreover, in the present set of experiments, the value of Z axis feed per cut remains constant (i.e. 0.08mm). These parameter (i.e. Z-axis feed per cut) may effect in the increase of overcut during machining by relatively high energy of laser beam.

The high value of lamp current leads to high material removal and it causes higher overcut. Hence, the moderate value of the lamp current setting will result in high precision machining characteristics. At lower range, the effect of lamp current is very less on machining accuracy.

Usually precision machining can be achieved by low cutting speed. But in case of laser cutting of low melting temperature, material having very low cutting speed results in the increase in time available for melting and vapourisation of the materials by laser beam and hence more overcut is obtained. Therefore a moderate cutting speed gives the better results.

3.2. Relative Contributions on Optimal Responses of CNC Nd-YAG LASER Machining Parameters

In this present investigation, the analysis of variance (ANOVA) is performed to find out the relative contributions of machining parameters in controlling the responses of the Nd-YAG Laser machining process. To accomplish the analysis of variance (ANOVA), the total sum of square deviation (*SST*) from the mean S/N ratio η_m can be determined as :

$$SST = \sum_{j=1}^{N} (\eta_j - \eta_m)^2 \quad \ldots\ldots(2)$$

Where N is the total number of experiments and η_m = grand mean of S/N ratio.

The results of ANOVA for angular deviation are shown in Table 4. The calculated SST value is used to measure the relative influence of the factors. The large value of SST the more influential the factor is for controlling the responses of Nd-YAG laser machining process. So the value of SST can be used to determine the percentage contribution of factors. From the results of ANOVA it is concluded that the cutting speed is the most influencing factor for controlling angular deviation and the radio-frequency of Q-switch has moderate effect on angular deviation during laser machining. The lamp current has comparatively less effect on angular deviation of the Nd-YAG laser machining operation.

Table 5. shows the results of ANOVA for linear deviation during square profile cutting operation. It is also found that the radio-frequency of Q-switch has most significant effect on linear deviation during Nd-YAG laser machining process. The cutting speed has moderate contribution in controlling the deviation in length during angular profile cutting. The lamp current of CNC Nd-YAG laser has less contribution on linear deviation during laser machining operation.

4.0 VERIFICATION TEST RESULTS

After the selection of the optimal level of design parameters, the final step is to predict and verify the adequacy of the additive model for determining the optimum quality characteristics of the Nd:YAG Laser machining process. The predicted optimum value of S/N ratio $\eta_{opt.}$ can be determined as:

$$\eta_{opt} = \eta_m + \sum_{j=1}^{p} (\eta_j - \eta_m) \quad ..(3)$$

where η_m is the grand mean of S/N ratio, η_j is the mean S/N ratio at the optimum level, and p is the number of the main design parameter that affect the quality characteristics. The predicted S/N ratio using the optimal machining parameter for angular deviation can then be obtained and the corresponding minimum angular deviation can also be calculated using eqn(1). Table 6 shows the comparision of the predicted Angle Deviation with the actual angular deviation using the optimal machining parameter. A good agreement between the predicted and actual angular deviation is observed. The predicted error of S/N ratio is calculated taking the difference between the actual & predicted optimum value of S/N ratio.

From the results of ANOVA for angular deviation, the variance of error is obtained as $65.0627dB^2$. The value of the variance of the prediction error of the S/N ratio for angular deviation is then obtained as $72.2847dB^2$ [5]. The corresponding two-standard deviation confidence limits for the prediction error of the S/N ratio for angular deviation are ±16.132dB. The calculated value of the prediction error of the S/N ratio (5.2567dB) is within the confidence limits (±16.132dB) and hence the additive model of angular deviation is adequate for determining the angular deviation of the Nd:YAG Laser machining process.

The comparison of the predicted linear deviation with the actual linear deviation using the optimal machining parameter is shown in Table 7. From the results of ANOVA for linear deviation the variance of the error of S/N ratio is obtained as $41.0489dB^2$. The variance of the prediction error of S/N ratio for linear deviation is determined as $45.6053\ dB^2$ [5]. The corresponding two standard deviation confidence limits for the prediction error of the S/N ratio is ±12.814dB. The calculated value of the prediction error of the S/N ratio for linear deviation (1.1389dB) is within the confidence limits (±12.814dB) and hence the additive model of linear deviation is adequate for determining the optimum linear deviation under optimal machining parametric conditions of the Nd:YAG Laser machining process.

Table 2 Design of Experiments, measured values of Angular Deviation (Degree) and the corresponding S/N ratio.

Expt. No.	Design of Experiments			Angular Deviation (degree)			S/N Ratio (dB)
	A	B	C	y1	y2	y3	
1	8.0	18.0	9.0	-0.7432	-0.9606	-0.6479	1.995
2	8.0	18.5	12.0	-0.0568	0.0432	-0.0320	26.906
3	8.0	19.0	15.0	-0.6818	-0.6596	-0.7935	2.926
4	7.0	18.0	12.0	-0.5839	-0.5562	-0.8643	3.318
5	7.0	19.0	15.0	-1.1350	-1.1544	-1.3630	-1.740
6	7.0	19.0	9.0	-0.4602	-0.6928	-0.7642	3.714
7	6.0	18.0	15.0	-0.9472	-0.8875	-0.8857	0.845
8	6.0	18.5	9.0	-0.5399	-0.5514	-0.6836	4.507
9	6.0	19.0	12.0	-0.4490	-0.6761	-0.6152	4.613

Table 3 Design of Experiments, measured values of Linear Deviation (mm) and the corresponding S/N ratio.

Expt. No.	Design of Experiments			Linear Deviation (mm)			S/N Ratio (dB)
	A	B	C	y1	y2	y3	
1	8	18.0	9	-0.02	-0.03	-0.04	30.147
2	8	18.5	12	0	0.01	0.01	41.761
3	8	19.0	15	-0.02	-0.02	-0.02	33.979
4	7	18.0	12	-0.02	-0.02	-0.02	33.979
5	7	18.5	15	0.06	0.06	0.06	24.437
6	7	19.0	9	-0.04	-0.03	-0.04	28.643
7	6	18.0	15	-0.04	-0.04	-0.05	27.212
8	6	18.5	9	-0.01	-0.02	-0.02	35.229
9	6	19.0	12	-0.04	-0.05	-0.04	27.212

Table 4 Results of ANOVA for Angular Deviation (degree)

Parameter / Factor	Degrees of Freedom	Sum of Squares	Mean Squares	F-Statistics	Percentage Contribution
A (radio frequency of Q-switch)	2	133.77	66.8857	1.0280	31.1018
B (lamp current)	2	102.02	51.0075	0.7840	23.7171
C (Cutting Speed)	2	194.39	97.1930	1.4938	45.1810
Error	2	130.13	65.0627		
Total	8	560.30			

Table 5 Results of ANOVA for Linear Deviation (mm)

Parameter / Factor	Degrees of Freedom	Sum of Squares	Mean Squares	F-Statistics	Contribution
A (radio frequency of Q-switch)	2	69.42	34.7084	0.8455	47.5625
B (lamp current)	2	26.49	13.2435	0.3226	18.1563
C (Cutting Speed)	2	50.04	25.0181	0.6095	34.2813
Error	2	82.10	41.0489		
Total	8	228.04			

Table 6 Verification Test Results for Angular Deviation (degree)

	PREDICTED OPTIMUM	ACTUAL OPTIMUM
LEVEL	A1B2C2	A1B2C2
Deviation in Angle (degree)	±0.083	-0.032, 0.0432, -0.0568
S/N Ratio (dB)	21.6493	26.906
Predicted Error of S/N Ratio :	5.2567	dB
Confidence Limits :	±16.132	dB

Table 7 Verification Test Results for Linear Deviation (mm)

	PREDICTED OPTIMUM	ACTUAL OPTIMUM
LEVEL	A1B2C2	A1B2C2
Deviation in Length (mm)	±0.009	+0.01, 0.00, +0.01
S/N Ratio (dB)	40.6221	41.761
Predicted Error of S/N Ratio :	1.1389	dB
Confidence Limits :	±12.814	dB

5.0 CONCLUSIONS

The CNC Nd-YAG laser angular profile cutting operation on aluminium sheet can be successfully performed and optimally controlled. From the Taguchi method based optimisation analysis it is concluded that the cutting speed has the greatest contribution in controlling the angular deviation and radio frequency of Q-switch is the most influencing factor in controlling linear deviation during profile cutting operation. Low radio frequency of Q-switch; medium lamp current and medium cutting speed are the optimal machining conditions during Nd:YAG laser profile cutting operation for achieving high precision machining characteristics i.e.; minimum angular and linear dimensional deviation. For achieving high quality precision machining characteristics of CNC Nd-YAG laser machining operation, the present set of optimal analysis is very much effective and fruitful to the manufacturing process engineers, who are working in the area of laser machining technology.

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