OPTIMIZATION OF PROCESS PARAMETERS IN LASER SHEET METAL BENDING

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By

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CERTIFICATE

This is to certify that the work in this thesis entitled "**OPTIMIZATION OF PROCESS PARAMETERS IN LASER SHEET METAL BENDING**" by **Birendra Kumar Maharana** has been carried out under my supervision in partial fulfilment of the requirements for the degree of Bachelor of Technology in Mechanical Engineering during session 2010-11 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

To the best of my knowledge, this work has not been submitted to any other University/Institute for the award of any degree or diploma.

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ABSTRACT:

Laser sheet metal bending is a die less sheet metal forming process and a non-contact method. It is a thermo mechanical process where by a focussed or partially focused laser beam is used to induce localized heating and consequently deflection of the sheet along the incident beam occurs. The bending occurs because of internal thermal stresses developed as a result of irradiation instead of external forces. It can be very helpful in the process of rapid prototyping of various sheet metal parts because of its process flexibility and ability to design intricate shapes which are the major advantage against conventional methods. In the experiment Nd:YAG laser is used and the work-piece is AISI 304 stainless steel. Various process parameters in the experiment are laser power, scanning speed, beam diameter, pulse duration and number of passes. The effect of each process parameters is observed with respect to total deflection at the free end and bending angle by keeping other parameters constant. Design of experiment (DOE) is done with the help of Taguchi method. The results are analysed graphically and also with the help of 'Analysis of variance' and S/N ratios, so as to determine the optimum values of the process parameters and their individual effectiveness towards the net bending effect.

Key Words:

Laser bending; die-less forming; sheet metal.

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Chapter 1

1. INTRODUCTION

1.1 Laser Bending:

Laser sheet metal bending is a die less sheet metal forming process. It is basically a non- contact forming process whereby no dies or rigid tools are used and there is no external force involved in the entire process. So it can be referred as a case of ‘Virtual Tooling’ as there is no mechanical contact. It comes out to be an effective replacement in the manufacturing industries where previously stamping dies and presses were used for shaping of metallic and non-metallic components and rapid prototyping works. The force involved is the internal thermal stresses developed as a result irradiation of laser beam. Laser bending can use mixture of straight and curve scan lines to produce two dimensional and three dimensional bending effects. Initial stresses and surface conditions make it uncertain as what type of bending will be formed. So some heat treatment processes can be used to relieve the material from pre-stresses and improve its surface quality and material properties.

Laser bending is a non-contact practice of 2D bending and 3D shaping. It is accomplished as a result of introducing thermal stresses in the work-piece with the help of a focussed or partially defocussed laser beam that results in controlled elastic-plastic deformation or buckling as a result of plastic strain induced in the work-piece material and subsequently the required deformation can be attained. With the help of laser bending pre-set contours can be obtained with very slightest amount of distortion as compared to other manufacturing processes. Other vital advantages include no mechanical ‘spring back effect’, controlled shaping and flexibility of application. The surface heats rapidly as the laser beam is scanned across the material surface. Normally the surrounding space only acts as the sink which results in fast quenching and hardening phase transformations. In case of this, desired bulk properties like ductility & toughness remains constant yet a hardened surface layer is produced. Bending of the ferrous alloys are easily and much effectively achieved as compared to non-ferrous alloys**.** The resulting deformation of the material is permanent. A basic advantage in it is that the thermal stress is induced without practically melting the work-piece.

The behaviour of material components under this process is influenced by a specific combination of laser process parameters, geometric and material parameters. As per active mechanism and geometry parameters like sheet thickness, a number of scans or passes of laser beam may be required to get the required bending or forming. With the help of overlapping of multiple passes or by increasing of number of adjacent parallel lines bends and curvatures of a desired angle and radius can be obtained.

Types of laser include Gas Lasers, Chemical Lasers, Dye Lasers, Metal Vapour Lasers, solid state lasers, semiconductor lasers.

Based on the direction of bending of the work-piece after the incident of the laser beam, laser bending can be divided into two-types:

Positive laser bending : if the bending of the work-piece occurs towards the incident beam then it is called as positive laser bending. Normally it is witnessed in most of the cases.

Negative laser bending : if the bending of the work-piece occurs away from the incident beam then it is called as negative laser bending.

The type of bending i.e.to know if the bending will be a case of positive or negative bending can be predicted with the help of Fourier number F_0 [8], which can be defined as :

$$F_0 = a_d d/s^2 V_s$$

Where: a_d = thermal diffusivity,

d= beam diameter,

s = sheet thickness,

V_s= scanning speed.

d/V_s =time that a point on the surface on the centre line of the scan is exposed to the laser, s^2/a_d = is the character time for heat to propagate through the sheet.

The smaller value of the Fourier number F_0 refers to positive bending which is mainly based on Temperature Gradient Mechanism or TMG. The larger value of F_0 refers to negative bending which is a case of buckling mechanism or BM. By changing the range of process parameters, normally the laser parameters both type of bending can be attained in the same work piece. It also depends on the material properties as in most cases positive bending is observed.

Applications in the industry sectors include automotive, aerospace, ship building and micro-electronics. Sheet metal parts made used in aircraft industries are normally formed with the laser technique. Apart of that the interest of laser bending in micro-electronics is highly increasing.

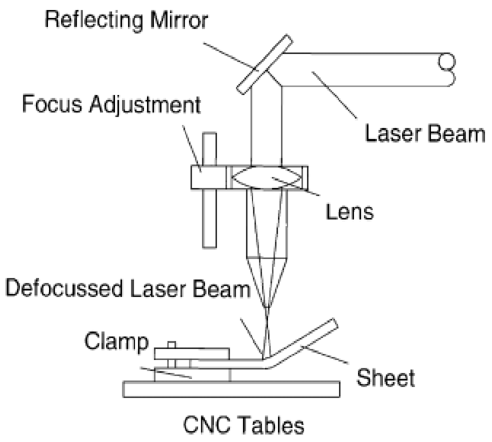

Fig 1.1: Line diagram of Laser Setup

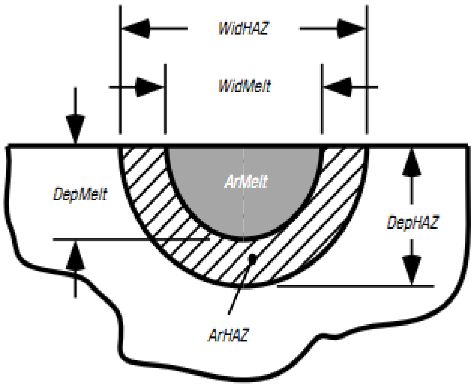

Fig 1.2 HAZ after laser beam is incident

Fig 1.1 shows a simple line drawing of a laser setup and the w/p and clamping device.

Fig 1.2 shows the HAZ area after the laser beam is scanned on the w/p.

1.2 Empirical Process Parameters

Laser Parameters

- Power
- Pulse diameter
- Scanning velocity
- Pulse duration
- Frequency

Material Parameters

- Thermal expansion coefficient
- Conductivity
- Heat capacity
- Poisson’s ratio
- Absorption coefficient

Geometric Parameters

- Thickness
- Length
- Width

1.3 Energy parameters

Laser bending depends on the energy absorption into the metal sheet as the process is based on the surface heating by a laser beam irradiation. The heat flux on the surface of the sheet metal by a laser beam follows a normal distribution, and it can be expressed as a function of beam radius as:

$$\mathbf{q}(r) = 2\eta p/\pi R^2 \exp(-2r^2/R^2)$$

where:

q= heat flux density

ɳ=absoptivity of the sheet metal surface

P= laser beam power

R= laser beam radius

r= the distance from the centre of laser beam.

1.4 ADVANTAGES & DIS-ADVANTAGES

The laser forming technique has the following advantages as compared to the conventional forming operations

- The high cooling rate favours the formation of a fine microstructure, and this normally imparts improved mechanical properties.
- As there is no spring-back effect in the process, so precise deformation can be achieved.
- No separate quenching medium is required, as the surrounding surface proves to be an effective sink.
- Effective work area is not limited here, as it is a non-contact method.

- High processing speeds. Rapid starting and stopping and high production rate.
- Better case hardening can be obtained in case of ferrous alloy materials.
- Required deformation can be achieved with very negligible or even no contamination.
- It offers greater product design flexibility as the laser beam can pass through intricate shapes and contours with the change of irradiation patterns.
- It is possible to automate the process so that it can be directly integrated with computerized numeric controlled machines.
- Elimination of lead time to some extent is possible as no special hard tools are used as in conventional methods.
- Greater precision with lower energy input leads to comparatively less post treatment work.

Laser bending is presently in the development stage. So there are a lot of drawbacks also, which includes:

- Compared to traditional methods of stamp and die forming, this process is slow.
- Because of the low energy conversion factor of the laser source, it is quite an energy consuming process, so surfaces need to be painted black so that maximum energy can be absorbed.
- Because of reflectivity of the metallic surfaces, multidirectional reflection of the laser beam after irradiation on the metal occurs, so safety protections are highly necessary which increases the risk of accidents.
- The incident energy of the beam can’t be distributed uniformly throughout the surface leading to surface deteriorations around the predetermined contours of laser incident paths.
- Uniformity in the curvature variation to precise levels is very difficult to achieve.

Chapter 2

2. LITERATURE REVIEW:

Liu et al [5] investigated the laser bending where attention was concentrated mainly for producing negative bonding. Type of bending depended on the Fourier number [8] F_0 which is defined as $F_0= a_d d/s^2 V_s$ where a_d = thermal diffusivity, d= beam diameter, s = sheet thickness, V_s= scanning speed. d/V_s =time that a point on the surface on the centre line of the scan is exposed to the laser, s^2/a_d = is the character time for heat to propagate through the sheet. F_0 value is intentionally kept larger which results in negative bending that was dominated by buckling mechanism. It was seen that the value of negative bending was largely dependent on the amount of pre-stresses induced. CO_2 laser was used, with wavelength of 10.6 µm. AISI 304 stainless steel was used as work-piece with dimension of 10x5x0.1 mm. It was observed that in buckling mechanism the negative bending effect can be increased with larger laser beam diameter, lower scanning speed and larger power. But the bending direction was uncertain because of the presence of the initial stresses and surface properties of the work-piece specimen. Pre-stresses were developed by loading some iinitial displacement at the free end of the work-piece. It was found that taking into account the pre-stresses, qualitative bending angle was produced with laser power of 17.7W, scanning speed of 15mm/s and beam diameter of 0.7mm.

Walczyk and Vittal [1] carried out laser bending of Titanium sheet (Ti-6Al-4V) as an alternative to hot brake forming. Controllability over various laser parameters, bend geometries and material properties were tried to derive. The objective was to identify process variables, response variables and their mutual relation. ANOVA and Taguchi methods were used to analyse the results. It was seen, bending effect for a single laser pass was able to be controlled with simple changes to the power settings of an Nd:YAG laser and the work-piece feed rate. The bending angle increased almost in a linear fashion with the number of laser scans over the same scan path. This allowed for a very small or “tight” radius to be achieved. If a larger radius required, then that can be attained with parallel laser scans with a little larger distance between adjacent lines.

Golo et al [6] observed once the laser irradiating moves away, the heated zone or HAZ exposes both to cooling and shrinkage, which induces a bending angle either in the direction of laser or in the reverse direction of the laser. Final element analysis was done. In the finite element model, element mesh was taken, thermal boundary conditions were applied and material properties and mechanical boundary conditions were taken into considerations. Material used was Mild steel, cold rolled low carbon steel sheet. And Nd:YaG laser was used Work-piece Parameters were 100x100x1 mm^3 and (100x50x1) mm.

A stiff slope was observed in the beginning with variation of power, later the slope was a bit reduced. With decrease of scan velocity, bending angle was reduced. With increase in laser diameter, pulse duration the bending angle was increased. With increase in sheet thickness by keeping other basic input variable parameters constant, the bending angle decreased. With increase of pass number, the bending angle increased but we have to limit the number of passes beyond which the material will get deteriorated. The numerical and experimental results had a great resemblance as there was only a little variation observed. Apart from that it was observed that the factors among the variable parameters that were least effective were laser power and pulse duration highly effective parameters were velocity, sheet thickness, beam diameter and number of passes.

Chapter 3

3. EXPERIMENTAL DETAILS

3.1 Work-piece

AISI 304 stainless steel

Table 3.1 Chemical composition of AISI 304 stainless steel

Material	C	Si	Cr	Mn	Fe	Ni	P	S
AISI 304 stainless steel	0.08max	1.00max	18-20	2.00max	66-74	8-10.5	0.045max	0.03max

Dimension of the specimen:

Length- 80mm

Breadth - 40mm

Thickness- 0.5mm

3.2 Process Parameters

Range of Laser Parameters-

Frequency:	20Hz max.
Pulse diameter:	2mm max.
Pulse duration:	20ms max
Scanning speed:	20mm/s max.

Input Parameters:

Laser power, Pulse diameter, Pulse duration, Scanning speed

Output parameters:

Total deflection at the Free End,

Bending Angle

3.3 Clamping of the Work-piece:

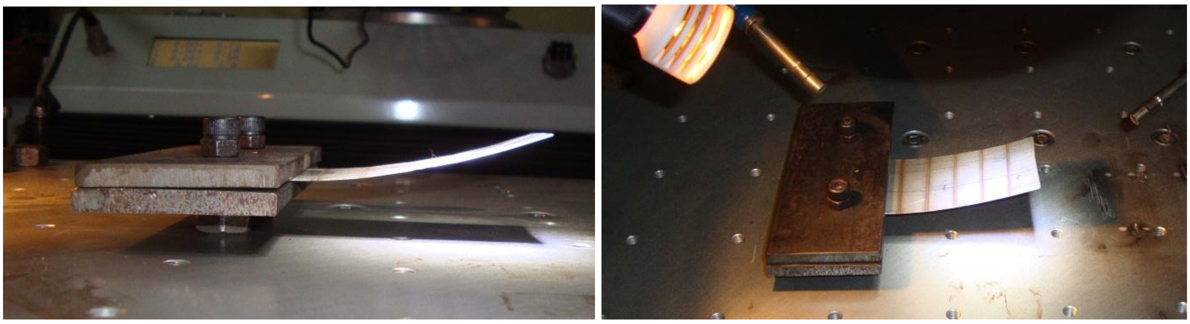

Fig: 3.1 clamping of the work piece

To make sure of no movement of the work-piece during the irradiation clamping is very necessary. The work piece is fixed in a cantilever type position so that the work piece will remain firm and fixed during the incidence of the laser beam. Cantilever beam is best suited for this experiment. There can be a little adverse effect because of clamping as the part of the work piece very nearer to the clamping will behave in a self-restraint way to the bending effect and the bending effect close to the fixed end will be less. So, the bending shouldn't be done very nearer to the clamping and a sufficient gap has to be maintained from the fixed end of clamping.

3.4 Machine Specifications:

Laser Machine Used – Nd:YAG laser

Type-ALT 500 digital

Weight- 600kg

Dimension-1200x1360x1260

Electric parameters- 400V, 50-60 Hz, 16A

Technical data of working table-

Work plate- 600x475mm

Maximum load- 400kg, central load

X-Y-Z Positioning System-

Maximum possible moving path	X axis	Y axis	Z axis
(in mm)	500	400	350

3.5 Working of Laser Machine:

LASER stands for Light Amplification by Stimulated Emission Radiation. Laser beams are highly coherent, directional with high energy density. The ease of focusing is another unique characteristic of laser beams. The laser beam is a typically narrow beam which is diffraction-limited. Laser beams can be focused to very tiny spots, achieving a very high irradiation and they can be launched into a beam of very low divergence in order to concentrate their power at a large distance.

Fig : 3.2 Laser machine showing clamping and the work plate

The term pulsed, is used because it is practically not a continuous wave, so that the optical power appears in pulses of some duration as per our input to the machine at some repetition rate. In other cases the application requires the production of pulses having as large an energy as possible. Since the pulse energy is equal to the average power divided by the repetition rate, this goal can sometimes be satisfied by lowering the rate of pulses so that more energy can be built up in between pulses. For example a small volume of material at the surface of a work piece can be evaporated if it is heated in a very short time, whereas supplying the energy gradually would allow for the heat to be absorbed into the bulk of the piece, never attaining a sufficiently high temperature at a particular point.

Fig:3.2- Laser Machine Set-up

One of the most common high power lasers include pulsed Nd:YAG laser which is a solid state laser with operational wavelength of around 1.064 µm. the pump source is normally flash lamp or laser diode. Nd:YaG laser are most used in the modern industries because of its process flexibility. Narrow HAZ (heat affected zone), smaller kerf width and highly focusing characteristics can be obtained in a better qualitative way than CO2 laser. Because of its shorter wavelength, the comparatively higher amount of energy can be absorbed even after falling on a reflectivity surface.

Fig:3.3 w/p before laser beam scan

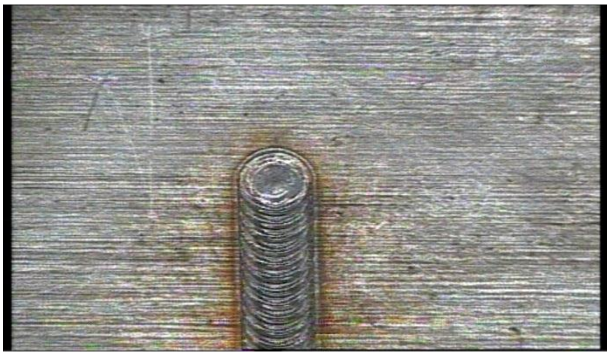

Fig: 3.4 w/p during laser beam scan

3.6 Experimental design:

Design of the experiment is done by Taguchi Method. L-16 orthogonal array was selected. The basic design was selected by considering four Laser parameters (laser power, pulse diameter, scanning speed, number of adjacent lines) and four levels for each parameter were selected. With the help of these parameters S/N ratios are derived for each case of L-16 based on S/N analysis. As there can be three categories of analysing quality characteristics i.e. bigger S/N ratio-the-better is the result, smaller the S/N value-better is the result, and the nominal the S/N value-better is the result. In this case as the ultimate aim is to get maximum bending effect with the change of parameters, so larger the S/N ratio better is the result which corresponds to the optimum level of process parameters.

ANOVA or a statistical analysis of variance was also performed to designate the most effective statistically significant parameters. The individual contribution of the process parameters that contributes the most and the least affecting factors towards the net effect can be calculated. With the help of that, the optimal combination of the process parameters so as to achieve a particular type of bending can then be predicted. The use of ANOVA is as to investigate which bending process parameters significantly effects on the response and its effective contribution.

Control Factors and their Selected Levels:

Table 3.2 Control factors and their selected levels.

SL No	Factors	Symbol	Level_1	Level_2	Level_3	Level_4
1	Power	P	1.2	2.0	2.8	3.6
2	Pulse dia.	D	0.5	1.0	1.5	2.0
3	Scanning Speed	S	20%	40%	60%	80%
4	No. of Lines	N	1	3	5	7

Units: Power=kW,

Pulse Diameter=mm,

Scanning Speed=mm/s(*Maximum Value= 20mm/s)

Chapter 4

4. RESULT ANALYSIS AND DISCUSSION:

4.1 Graphical Analysis:

4.1.1 Power V/s Deflection & Bending Angle

Constant Parameters: Pulse Diameter=1.5mm,
Pulse Duration= 2.0ms
Scanning Speed= 4mm/s
Frequency= 18 Hz

Variable Parameters= Power
Deflection
Bending Angle

Table 4.1 : Power V/s Deflection & Bending Angle

S. L No	**Voltage (V)**	**Pulse Diameter (mm)**	**Pulse Duration (ms)**	**Scanning Speed** **(max=20mm/s)**	**Frequency (Hz)**	**Energy (Joule)**	**Power (kW)**	**Deflection (mm)**	**Bending Angle (α)**
1	190	1.5	2.0	20%	18	0.58	0.3	0	0°
2	220	1.5	2.0	20%	18	1.4	0.7	5	3.97°
3	250	1.5	2.0	20%	18	2.5	1.2	10.5	8.30°
4	280	1.5	2.0	20%	18	4.1	2.0	11.5	9.07°
5	310	1.5	2.0	20%	18	5.7	2.8	13.5	10.62°
6	340	1.5	2.0	20%	18	7.3	3.6	8.5	6.73°
7	370	1.5	2.0	20%	18	9.2	4.6	12.75	10.04°
8	400	1.5	2.0	20%	18	11.2	5.6	8	6.34°

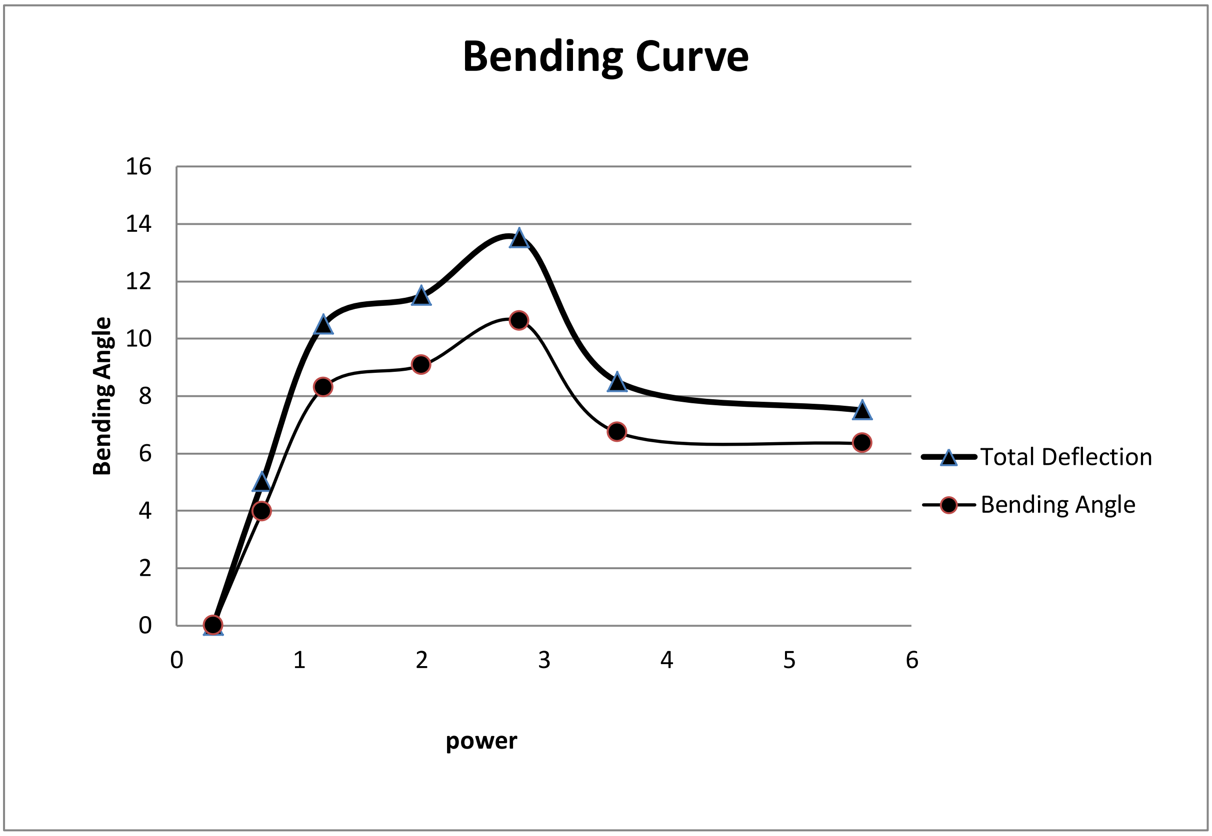

Fig. 4.1: Variation of deflection & bending angle w.r.t change in power

Graphs between Power Vs Total Deflection and Power Vs Bending Angle are drawn by keeping other laser parameters like Scanning velocity, pulse duration, pulse diameter, frequency constant. Up to certain minimum level of laser power there was no bending effect observed or the effect was very negligible. This value comes out to be 0.3kW. With further increase in power the bending effect increased continuously. The maximum bending effect is observed at 2.8kW. With further increase in power the effect decreases because of more energy density incident on the w/p. Even because of this, deterioration of the work piece was observed and the sheet no more remained flat and it became curved although clamping was provided.

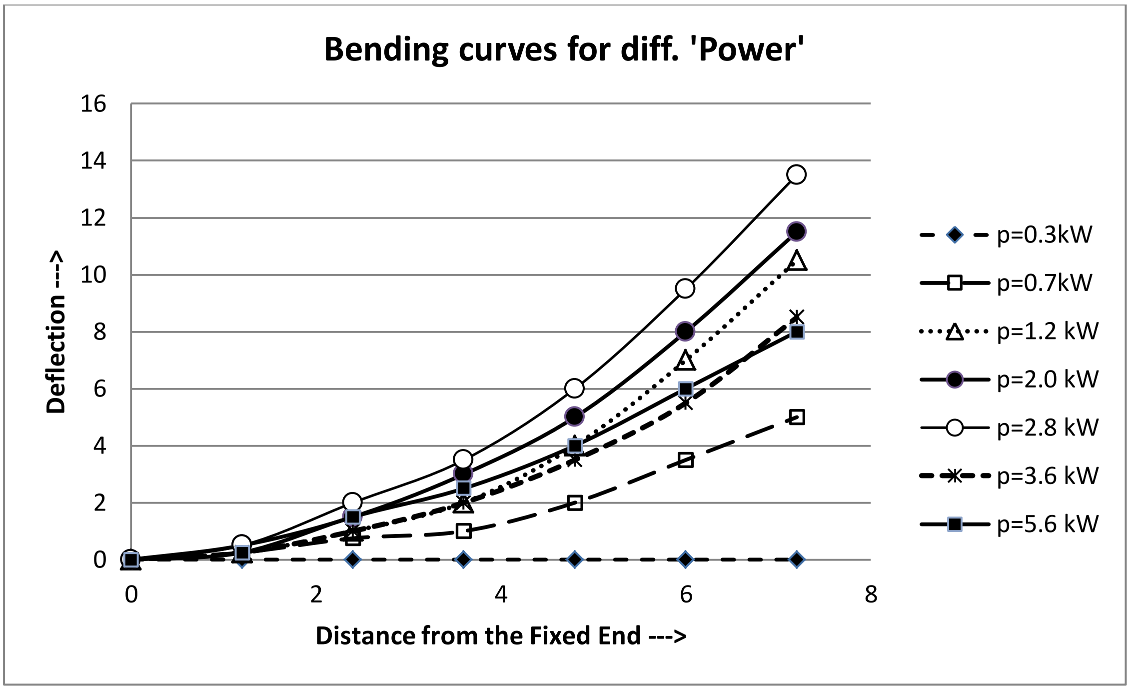

Fig. 4.2: Bending curves for different power

In the Fig,. the deflection of the w/p at various points where laser beam was passed is calculated for the same above table where other laser parameters were kept constant and only power was varied. It is observed that w/p attained different shapes with the change power. The deflection was measured at a distance of 0, 1.2, 2.4, 3.6, 4.8, 6.0, 7.2 (mm) from the fixed end where laser beam was initially passed. In some cases although the total deflection at the free end was less comparatively, but larger curvature was found.

4.1.2 Pulse Diameter Vs Deflection & Bending Angle

Constant Parameters:	Power= 2.6kW,	Variable Parameters= Pulse Diameter
	Pulse Duration= 1.5ms	Deflection
	Scanning Speed= 4mm/s	Bending Angle
	Frequency= 18 Hz	

Table 4.2: Pulse diameter V/s Deflection & Bending Angle

S. L No	**Voltage (V)**	**Pulse Diameter (mm)**	**Pulse Duration (ms)**	**Scanning Speed** (max=20mm/s)	**Frequency (Hz)**	**Energy (Joule)**	**Power (kW)**	**Deflection (mm)**	**Bending Angle (α)**
1	307	0.3	1.5	20%	18	3.9	2.6 (2.8)	7.5	5.95
2	307	0.5	1.5	20%	18	3.9	2.6	9.0	7.12
3	307	0.8	1.5	20%	18	3.9	2.6	11	8.30
4	307	1.0	1.5	20%	18	3.9	2.6	13.5	10.62
5	307	1.5	1.5	20%	18	3.9	2.6	15.5	12.15
6	307	2.0	1.5	20%	18	3.9	2.6	18.0	14.04

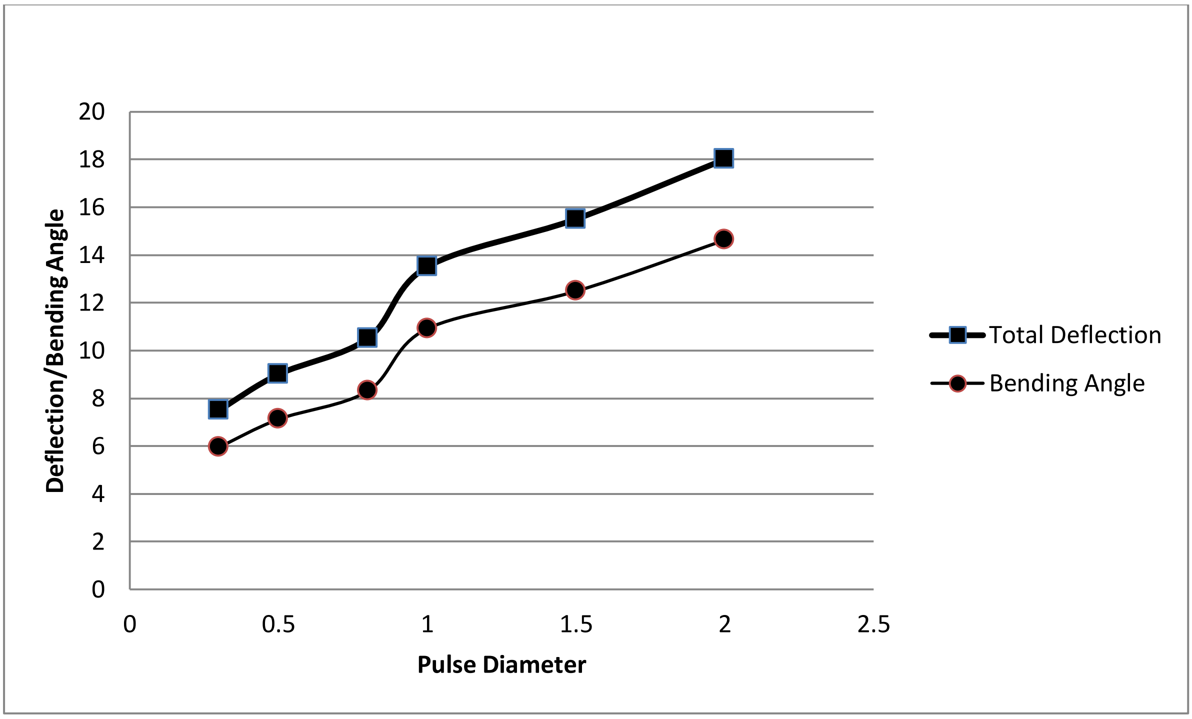

Fig. 4.3: Variation of deflection & bending angle w.r.t change in pulse diameter.

Graphs between Pulse Diameter V/s Total Deflection and Pulse Diameter Vs Bending Angle are drawn by keeping other laser parameters like Scanning velocity, pulse duration, pulse diameter, frequency constant. It is observed that with increase in pulse diameter the net bending effect was increased continuously. The maximum pulse diameter as per machine specification was 2.0 mm.

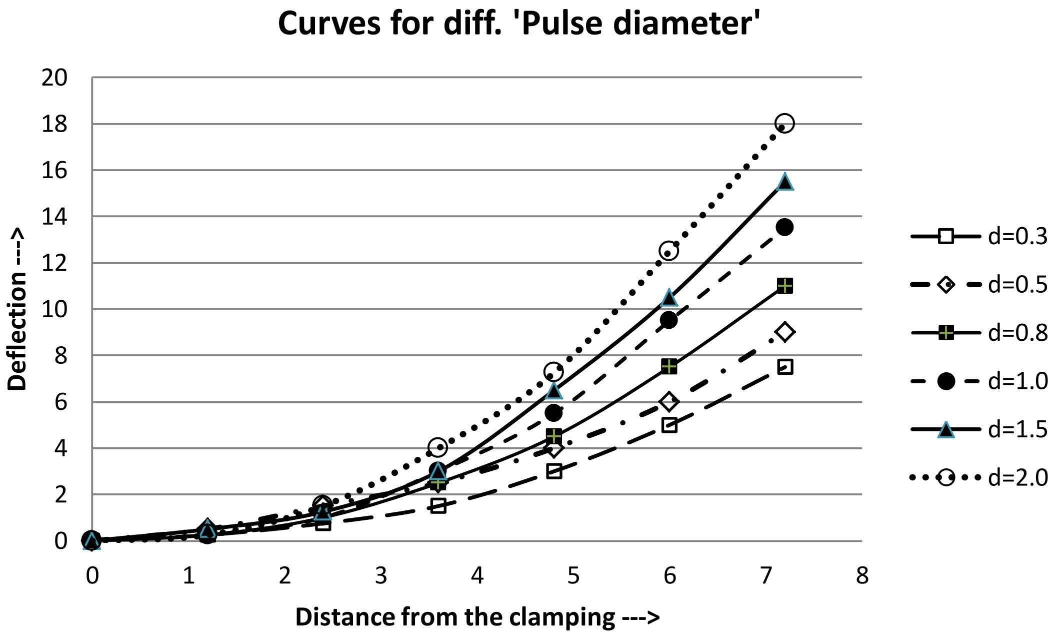

Fig. 4.4: Bending curves for different pulse diameter

In the above Fig. the deflection at some predetermined points through which laser beam was initially passed is calculated. The deflection was measured at a distance of 0, 1.2, 2.4, 3.6, 4.8, 6.0, 7.2 (mm) from the fixed end. It is observed that larger curvature is obtained as the pulse diameter is increased and normally larger curvature if observed with the increase of pulse diameter.

4.1.3 Distance between Adjacent Lines V/s Deflection & Bending Angle

Constant Parameters:	Variable Parameters= No of Lines
Pulse Diameter=1.5mm,	
Pulse Duration= 2.0ms	Deflection
Scanning Speed= 6mm/s	Bending Angle
Power=2.8kW	

Table 4.3: No. of Adjacent Lines V/s Deflection & Bending Angle

S.L No	**Voltage (V)**	**Pulse Diameter (mm)**	**Pulse Duration (ms)**	**No. of Adjacent Lines**	**Scanning Speed (max=20mm/s)**	**Frequency (Hz)**	**Energy (Joule)**	**Power (kW)**	**Deflection (mm)**	**Bending Angle (α)**
1	310	1.5	2.0	1	20%	18	5.7	2.8	4	3.18
2	310	1.5	2.0	2	20%	18	5.7	2.8	7	5.55
3	310	1.5	2.0	3	20%	18	5.7	2.8	9	7.12
4	310	1.5	2.0	4	20%	18	5.7	2.8	11	8.69
5	310	1.5	2.0	5	20%	18	5.7	2.8	11.5	9.07
6	310	1.5	2.0	7	20%	18	5.7	2.8	18	14.04
7	310	1.5	2.0	8	20%	18	5.7	2.8	19.5	15.15

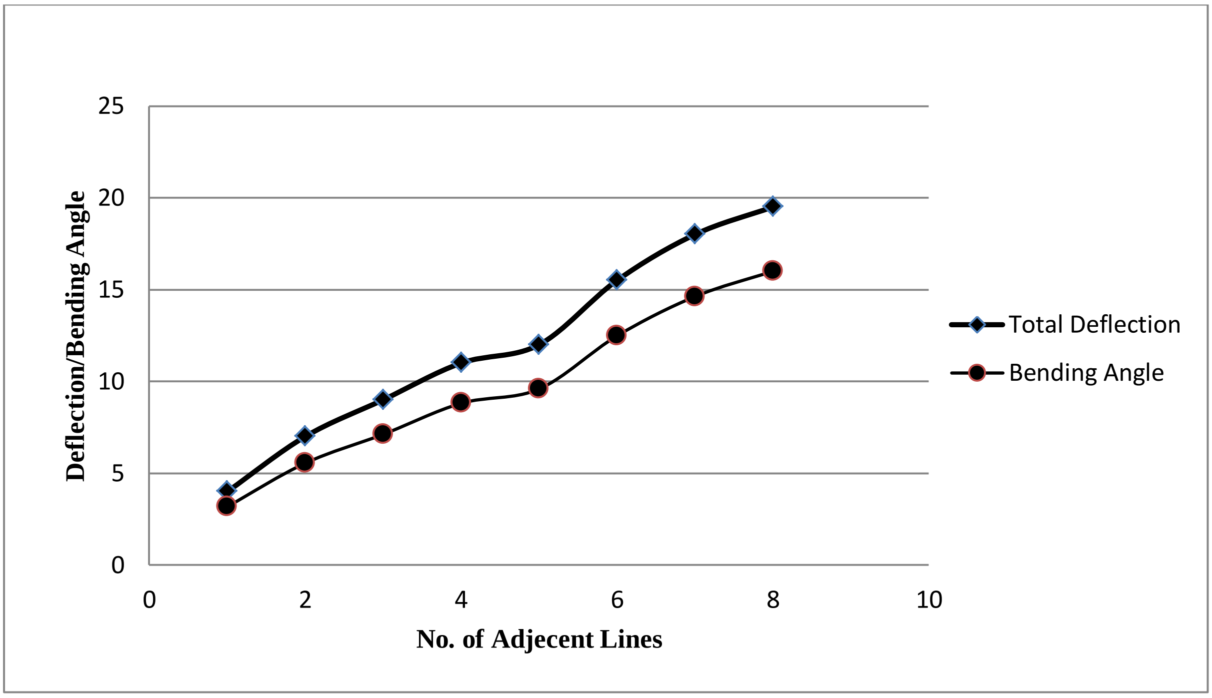

Fig.4.5: Variation of deflection & bending angle w.r.t change in No. of Adjacent Lines

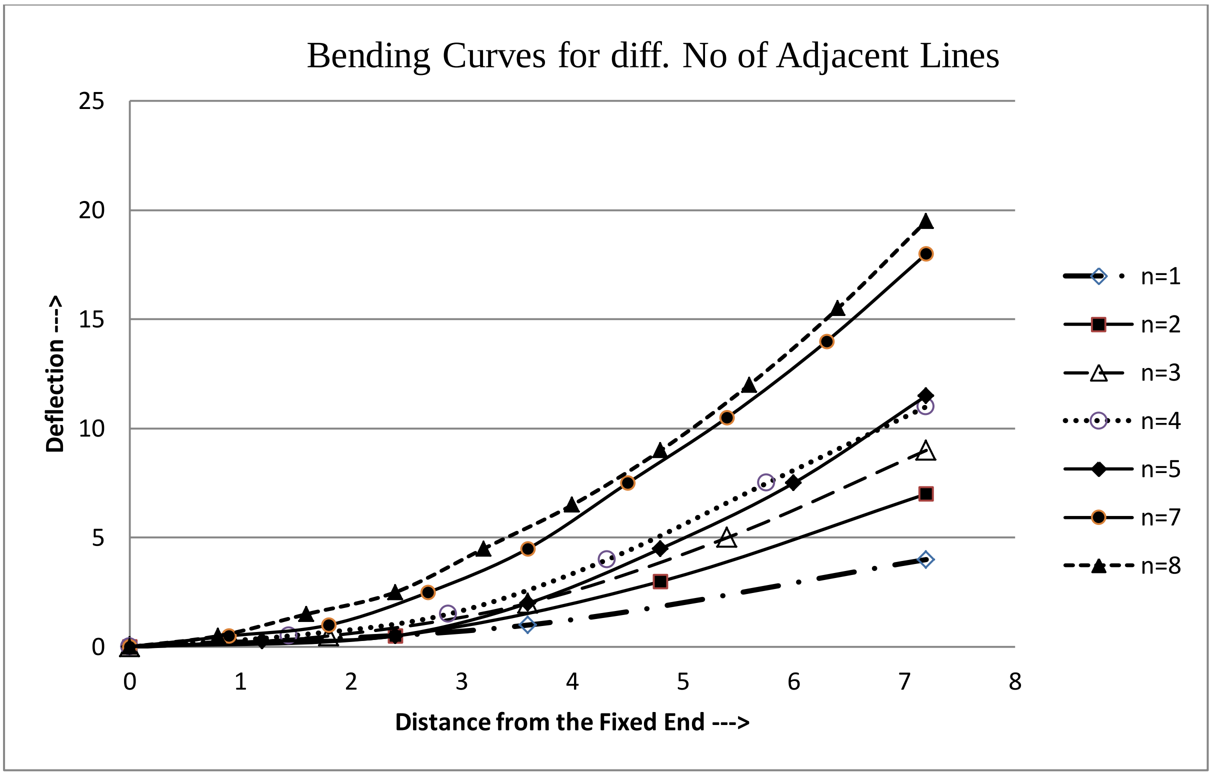

Fig. 4.6: Bending curves for different no. of adjacent lines

In the above Fig. the deflection at some predetermined points through which laser beam was initially passed is calculated. For the same w/p number of adjacent lines were varied from n=1 to n=8. The distance between two adjacent lines was kept constant for a particular number of lines. It is observed that larger curvature is found as the number of lines is increased where the total deflection at the free end is also large. So, if maximum bending and curvature is required, it can be obtained by increasing the number of lines where laser beam is to be focussed for the same w/p.

4.1.4 Scanning Velocity Vs Deflection & Bending Angle

Constant Parameters :		Variable Parameters:	
	Pulse Diameter=1.5mm,		Scanning Velocity
	Pulse Duration= 2.0ms		Deflection
	Power= 2.8kW		Bending Angle
	Frequency= 18 Hz		

Table 4.4: Scanning Speed V/s Deflection & Bending Angle

S.L No	**Voltage (V)**	**Pulse Diameter (mm)**	**Pulse Duration (ms)**	**Scanning Speed** (max=20mm/s)	**Frequency (Hz)**	**Energy (Joule)**	**Power (kW)**	**Deflection (mm)**	**Bending Angle (α)**
1	310	1.5	2.0	10%	18	5.7	2.8	10.0	7.12
2	310	1.5	2.0	20%	18	5.7	2.8	17.0	13.47
3	310	1.5	2.0	40%	18	5.7	2.8	13.0	10.23
4	310	1.5	2.0	60%	18	5.7	2.8	12.5	9.85
5	310	1.5	2.0	80%	18	5.7	2.8	11.25	8.88
6	310	1.5	2.0	100%	18	5.7	2.8	10.75	8.61

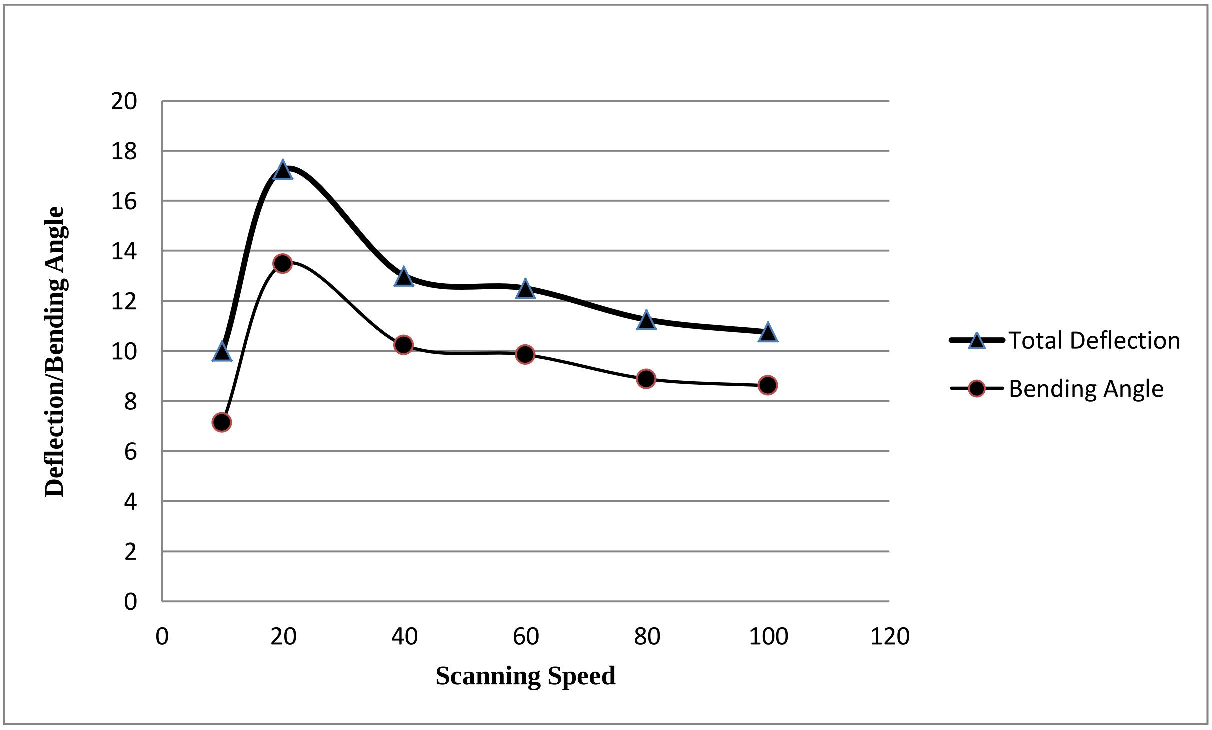

Fig.4.7: Variation of deflection & bending angle w.r.t change in Scanning speed.

Graphs between Scanning Velocity V/s Total Deflection and Scanning Velocity V/s Bending Angle are drawn by keeping other laser parameters like laser power, pulse duration, pulse diameter constant. It is observed that in the beginning, with increase in scanning velocity the bending effect increases up to a certain level. After that the bending effect decreases continuously. It is observed that optimum bending effect was observed as a scanning velocity of 20% (4mm/s). At 30%(6mm/s) of scanning velocity the bending effect was decreased to some extent but the surface finish of the w/p was better than the previous case of 4mm/s speed. With further increase in speed, the bending effect was reduced a lot as the energy of the laser beam incident on the w/p per unit area is less. The maximum scanning speed available as per machine specification is 20 mm/s.

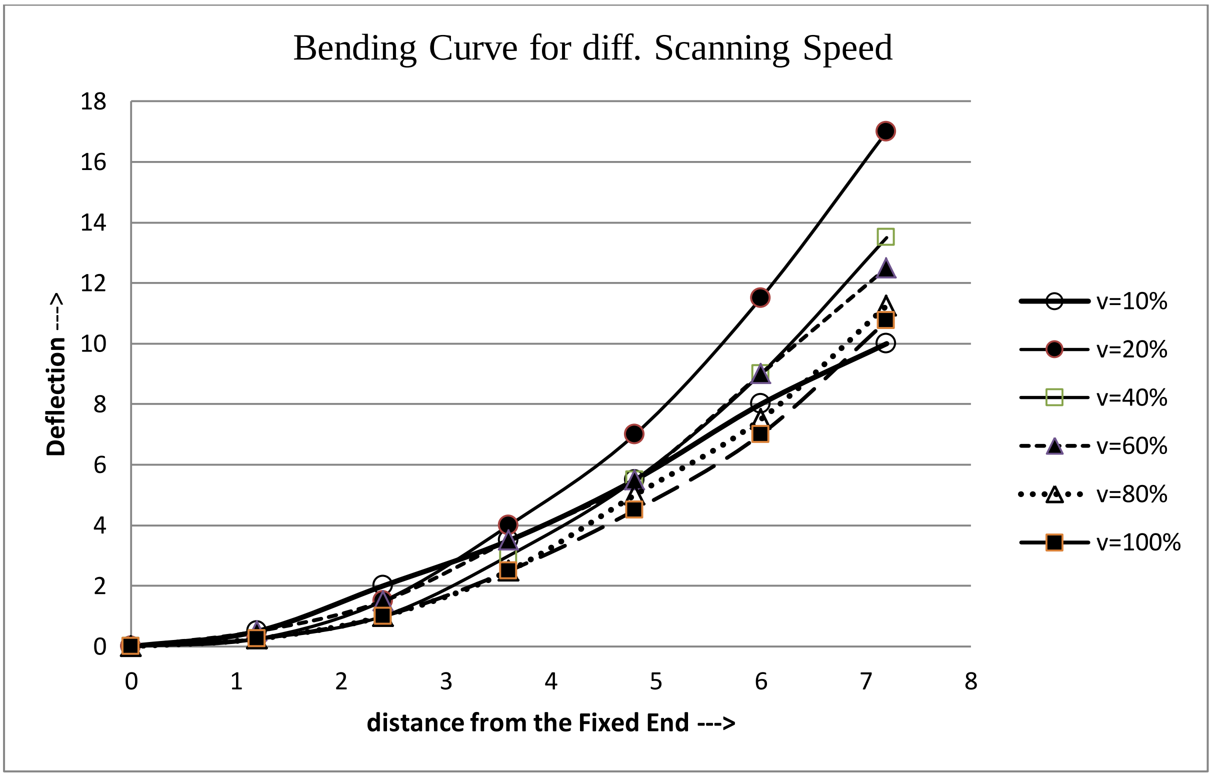

Fig 4.8: Bending curves for different scanning speed

The same procedure is followed in finding the deflection at points measured at a distance of 0, 1.2, 2.4, 3.6, 4.8, 6.0, 7.2 (mm) from the fixed end. As the scan velocity was changed, it is observed that largest curvature was found for 20% of the scanning speed i.e, 4mm/s.

4.2 Experimental Analysis for Total Deflection

4.2.1 Experimental Layout for Total Deflection

Table 4.5: Experimental Layout for Total deflection using Taguchi Method

SL No.	Power	Pulse Diameter	Scanning Velocity	No. of Lines	Total Deflection	SNRA1
1	1	1	1	1	0.75	-2.4988
2	1	2	2	2	4.5	13.0643
3	1	3	3	3	7.5	17.5012
4	1	4	4	4	5.5	14.8073
5	2	1	2	3	6.5	16.2583
6	2	2	1	4	12	21.5836
7	2	3	4	1	4	12.0412
8	2	4	3	2	5.5	13.9794
9	3	1	3	4	6.25	15.9176
10	3	2	4	3	9	19.0849
11	3	3	1	2	9.25	19.3228
12	3	4	2	1	4	12.0412
13	4	1	4	2	3	9.5424
14	4	2	3	1	3	9.5424
15	4	3	2	4	11.75	21.4008
16	4	4	1	3	9.5	19.5545

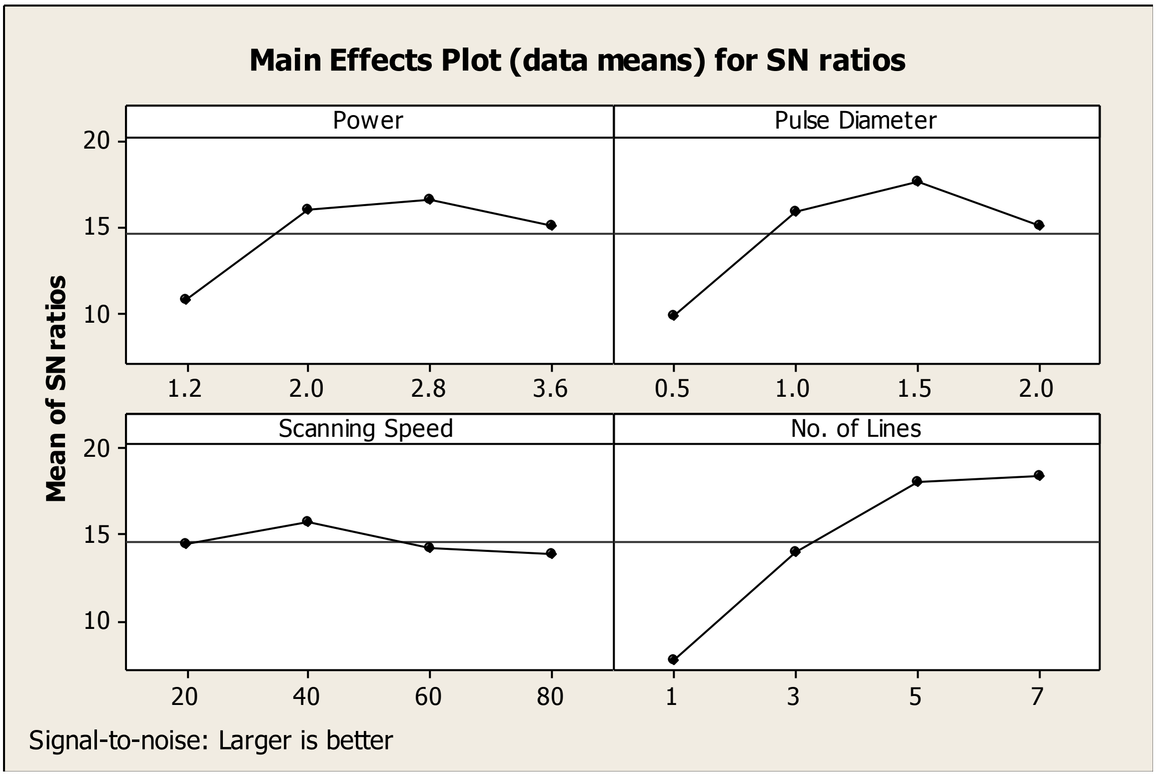

Fig 4.9: Main effect curves for S/N ratios

Response Table for Signal to Noise (S/N) Ratios
Larger is better

Table 4.6: Response table for Signal to Noise (S/N) Ratios

Level	Power	Pulse Diameter	Scanning Speed	No. of Lines
1	10.718	9.805	14.491	7.782
2	15.966	15.819	15.691	13.977
3	16.592	17.567	14.235	18.100
4	15.010	15.096	13.869	18.427
Delta	5.873	7.762	1.822	10.646
Rank	**3**	**2**	**4**	**1**

4.2.2 ANOVA TABLE

Analysis of Variance for Total Deflection

Table 4.7: ANOVA Table for Total Deflection

Source	**DF**	**Seq. SS**	**Adj. SS**	**Adj. MS**	**F**	**P**	**%age contribution**
Power	3	17.141	17.141	5.714	13.54	0.030	10.80%
Pulse Diameter	3	35.297	35.297	11.766	27.89	0.011	22.25%
Scanning Speed	3	16.891	16.891	5.630	13.35	0.031	10.65%
No. of Lines	3	88.016	88.016	29.339	69.54	0.003	55.52%
Error	3	1.266	1.266	0.422	--------	--------	
Total	15	158.609	--------	--------	--------	--------	

S = 0.649519 R^2= 99.20% R^2 (adj.) = 96.01%

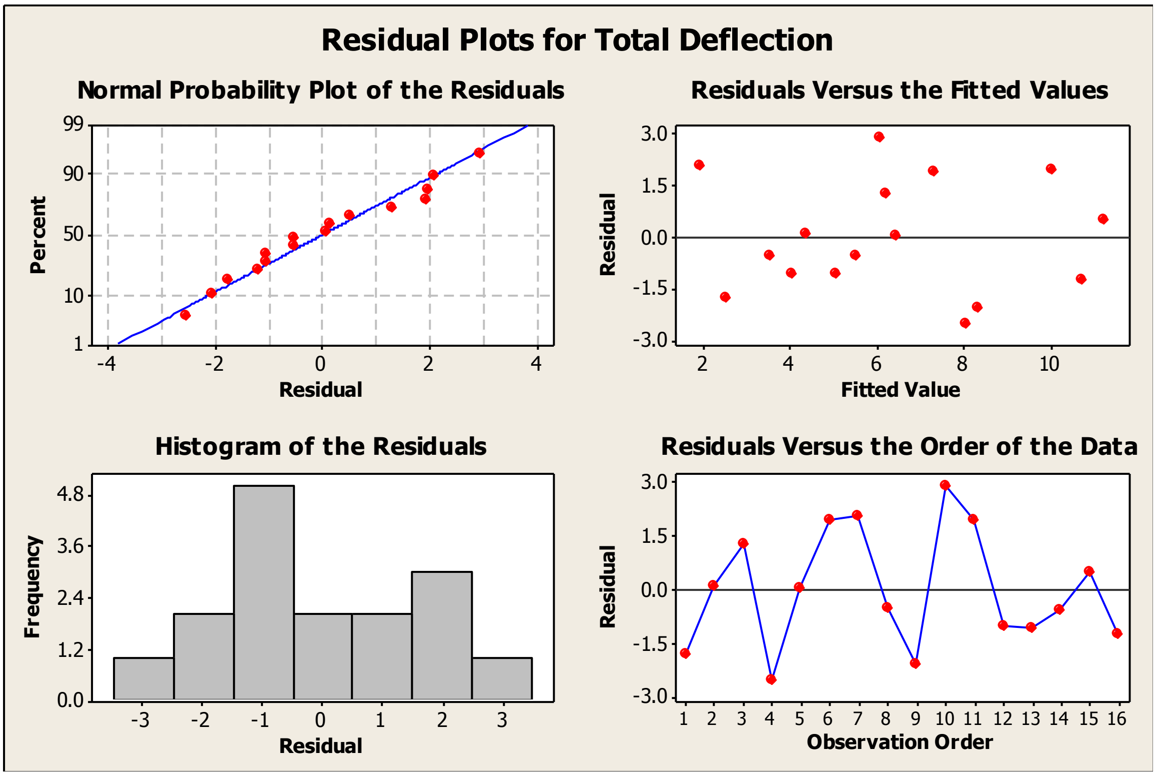

Fig 4.10: Graphs showing residual plots for Total Deflection

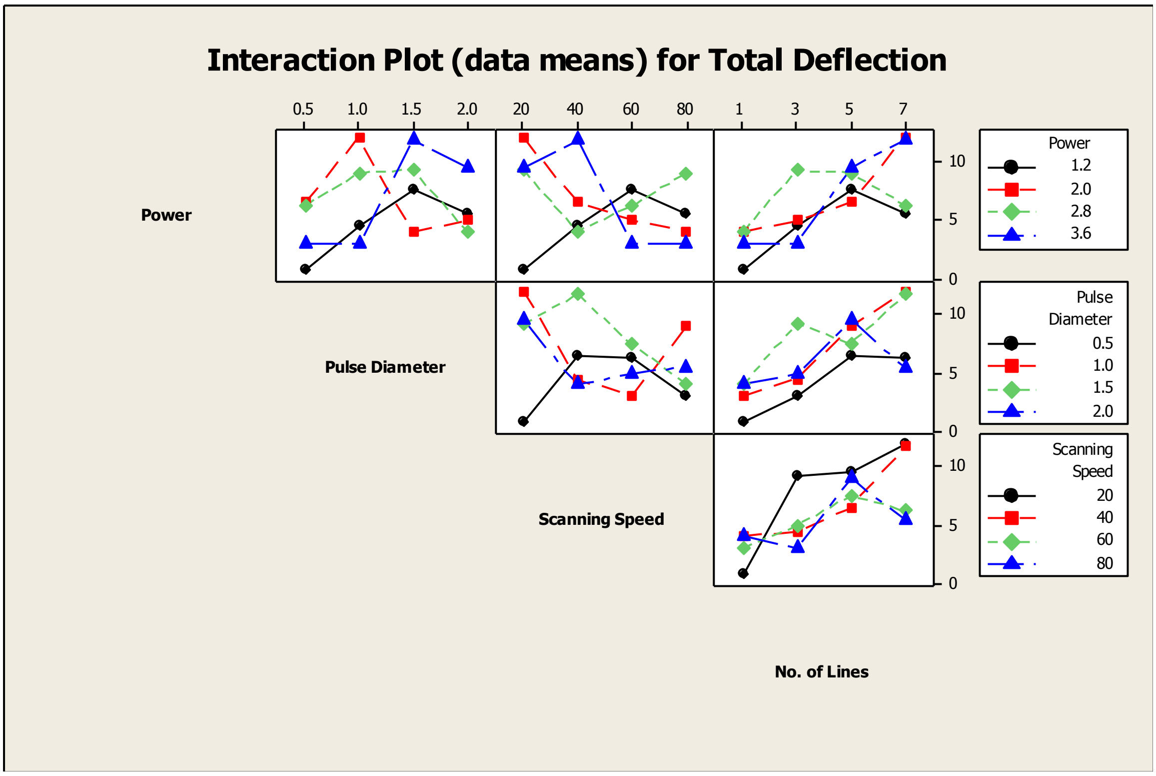

Fig 4.11: Graphs showing interaction plots for Total Deflection

4.2.3 Regression Analysis: Total Deflection versus Power, Pulse Diameter, Scanning Speed, No. of Adjacent Lines.

The regression equation is:

Total Deflection = 0.68 + 0.875 Power + 1.32 Pulse Diameter
- 0.0437 Scanning Speed + 1.03 No. of Lines

Total Deflection (x)= 0.68 + 0.875 P + 1.32 D – 0.0437 S + 1.03 N

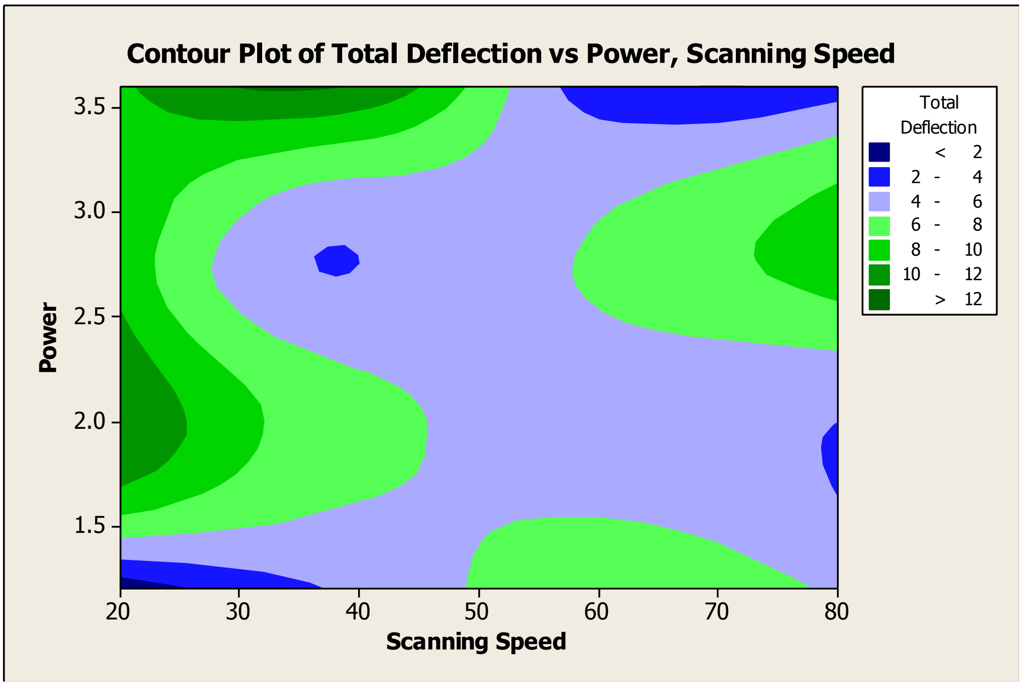

Fig 4.12: Contour plot for deflection w.r.t least effective parameters

This contour graph is drawn taking into account the least effective process parameters that affect the total deflection at the free end. Various regions of the contour graph show the effective deflection that can be achieved by mainly varying these two least effective parameters.

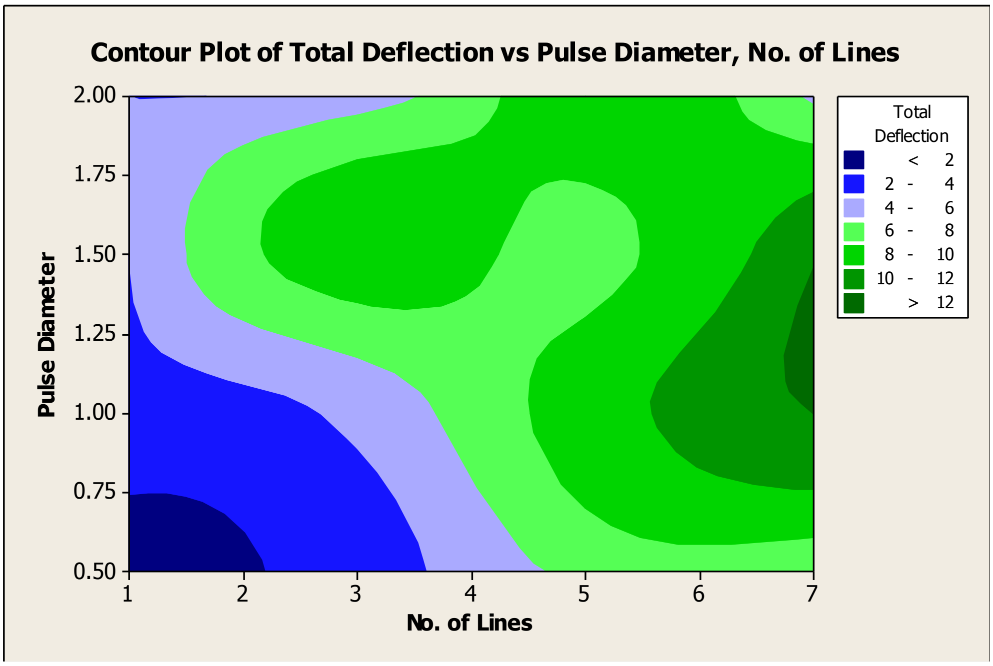

Fig 4.13: Contour plot for deflection w.r.t most effective parameters

This contour graph is drawn taking into account the most effective process parameters that affect the total deflection at the free end. The respective shaded reasons show the amount of deflection attainable considering major effect of these factors.

4.3 Experimental Analysis for Bending Angle

4.3.1 Experimental Layout for Bending Angle

Table 4.8: Experimental Layout for Bending Angle using Taguchi Method

SL No.	**Power**	**Pulse Diameter**	**Scanning Velocity**	**No. of Lines**	**Bending Angle**	**SNRA2**
1	1	1	1	1	0.597	-4.4805
2	1	2	2	2	3.576	11.0680
3	1	3	3	3	5.947	15.4860
4	1	4	4	4	4.368	12.8057
5	2	1	2	3	5.158	14.2496
6	2	2	1	4	9.462	19.5197
7	2	3	4	1	3.180	10.0485
8	2	4	3	2	3.972	11.9802
9	3	1	3	4	4.961	13.9114
10	3	2	4	3	7.125	17.0557
11	3	3	1	2	7.321	17.2914
12	3	4	2	1	3.180	10.0485
13	4	1	4	2	2.783	8.8903
14	4	2	3	1	2.386	7.5534
15	4	3	2	4	9.379	19.4598
16	4	4	1	3	7.516	17.5197

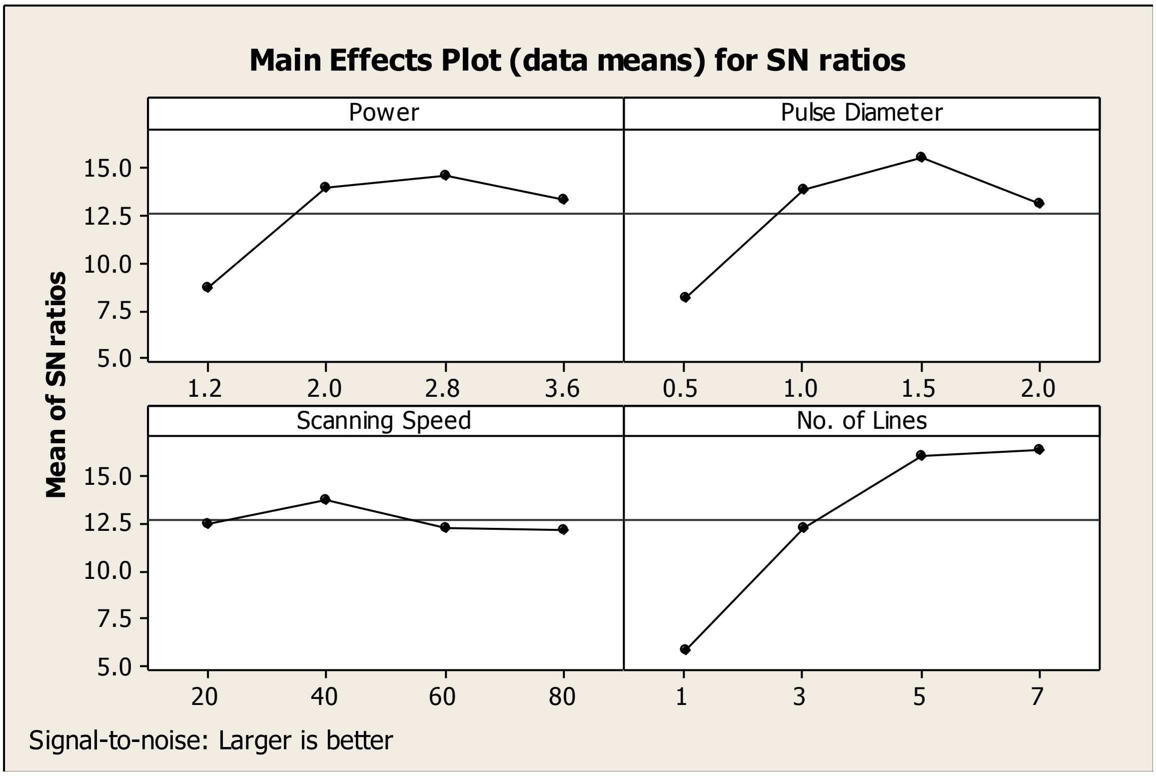

Fig 4.14: Main effect curves for S/N ratios

Response Table for Signal to Noise (S/N) Ratios
Larger is better

Table 4.9: Response table for Signal to Noise (S/N) Ratios

Level	Power	Pulse Diameter	Scanning Speed	No. of Lines
1	8.720	8.143	12.463	5.792
2	13.950	13.799	13.706	12.307
3	14.577	15.571	12.233	16.078
4	13.356	13.089	12.200	16.424
Delta	5.857	7.429	1.506	10.632
Rank	**3**	**2**	**4**	**1**

4.3.2 General Linear Model: Bending Angle versus Power, Pulse Diameter, Scanning Speed, No. of Adjacent Lines.

ANOVA TABLE

Analysis of Variance for Bending Effect

Table 4.10: ANOVA Table for Bending Angle

Source	**DF**	**Seq. SS**	**Adj. SS**	**Adj. MS**	**F**	**P**	**%age Contribution**
Power	3	11.0834	11.0834	3.6945	10.99	0.040	11.36%
Pulse Diameter	3	20.9095	20.9095	6.9698	20.74	0.017	21.43%
Scanning Speed	3	9.8551	9.8551	3.2850	9.77	0.047	10.09%
No. of Lines	3	54.7322	54.7322	18.2441	54.28	0.004	56.08%
Error	3	1.0084	1.0084	0.3361	--------	--------	
Total	15	97.5886	--------	--------	--------	--------	

S = 0.579762 R^2 = 98.97% R^2 (adj) = 94.83%

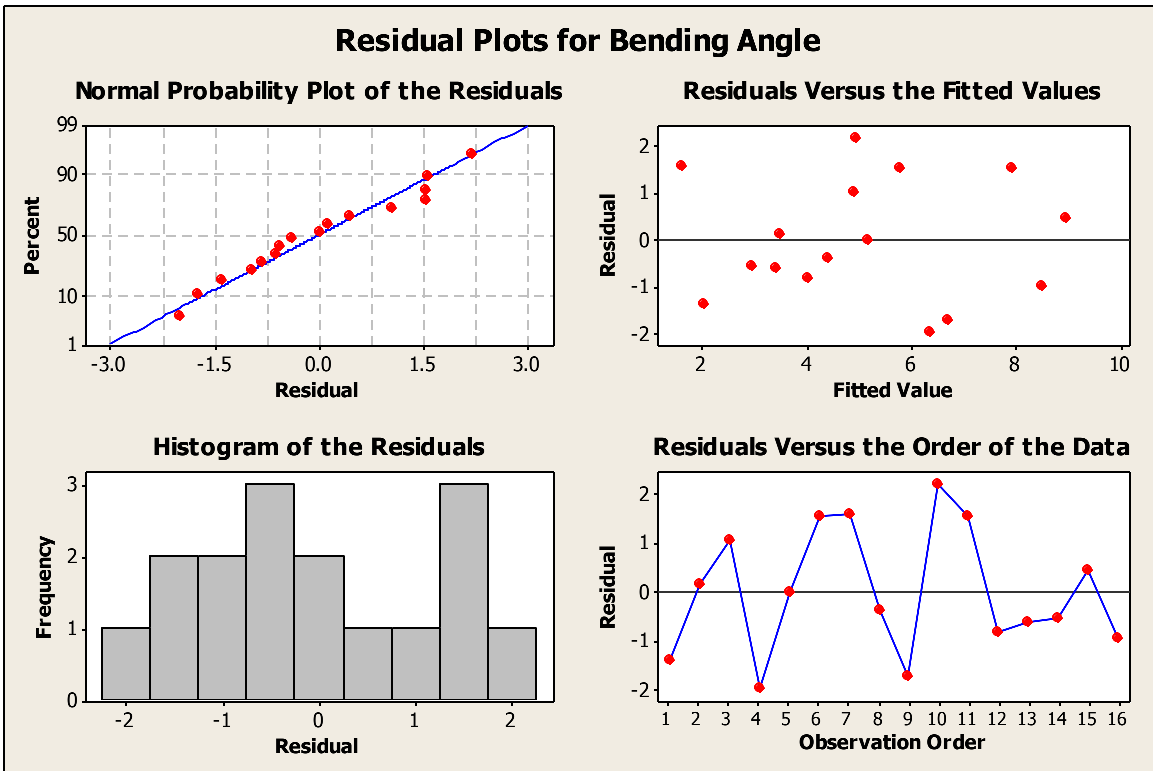

Fig 4.15: Graphs showing residual plots for Bending Angle

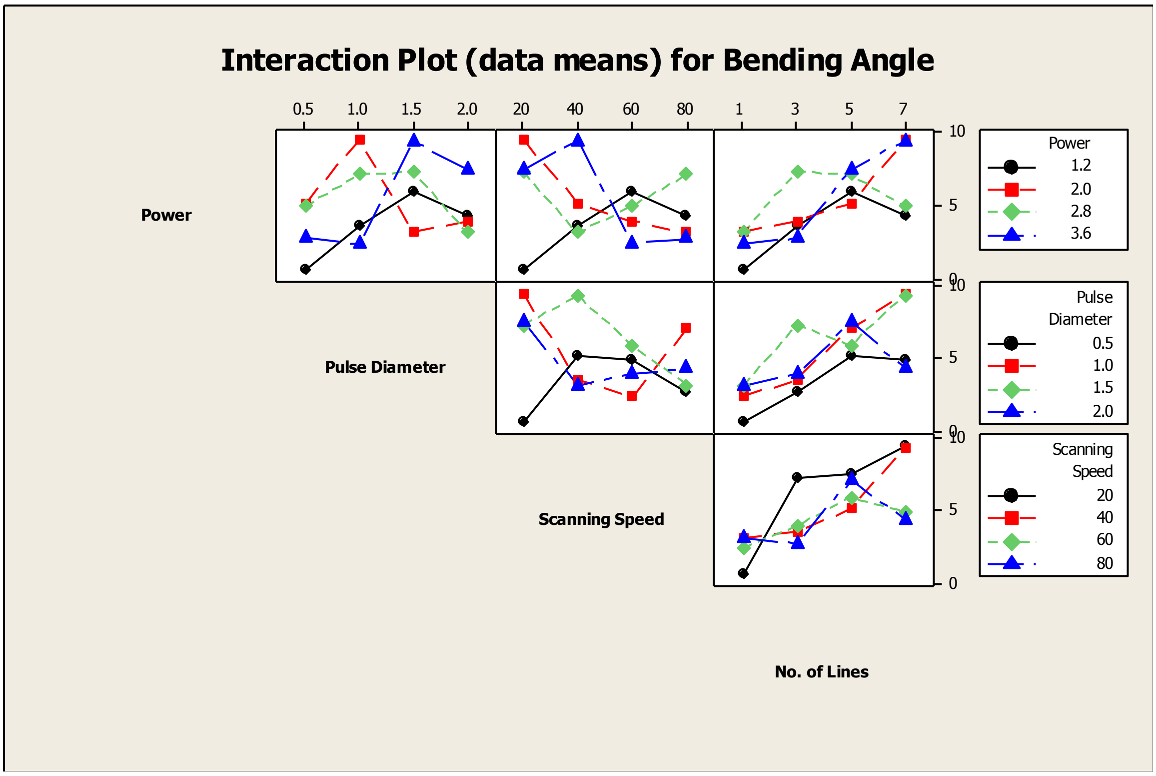

Fig 4.16: Graphs showing interaction plots for Bending Angle

4.3.3 Regression Analysis: Bending Angle versus Power, Pulse Diameter, Scanning Speed, No. of Adjacent Lines.

The regression equation is:

Bending Angle = 0.46 + 0.737 Power + 0.995 Pulse Diameter
- 0.0330 Scanning Speed + 0.808 No. of Lines

$$\textbf{Bending Angle}(\alpha) = 0.46 + 0.737\,P + 0.995\,D - 0.0330\,S + 0.808\,N$$

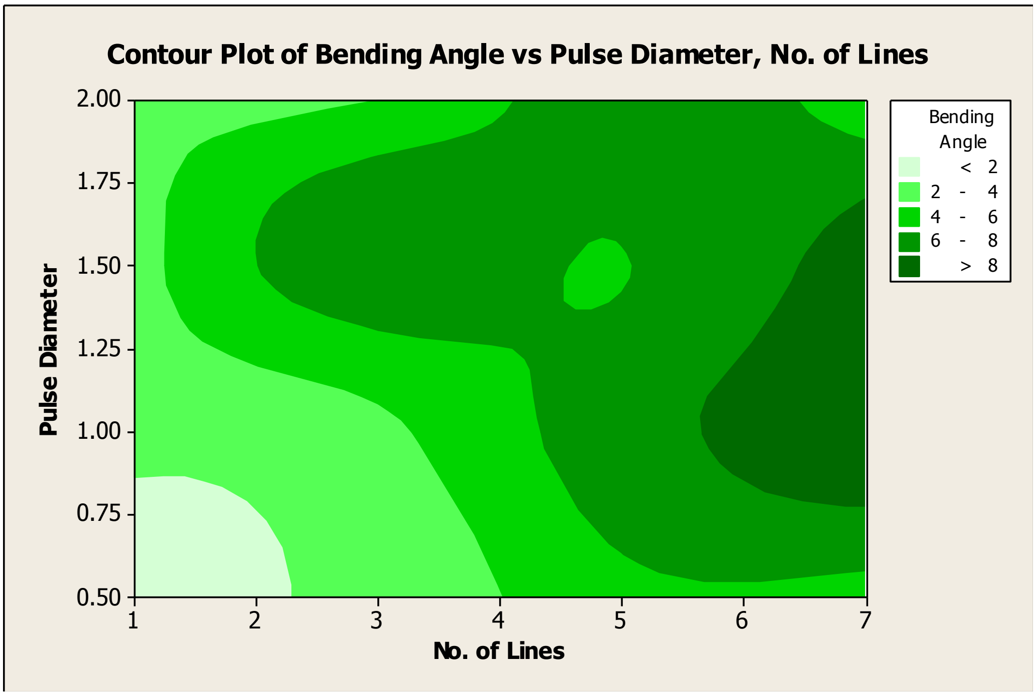

Fig 4.17: Contour plot for deflection w.r.t most effective parameters

This contour graph is drawn taking into account the most effective process parameters that affect the bending angle. The respective shaded reasons show the amount of bending angle attainable considering major effect of these factors.

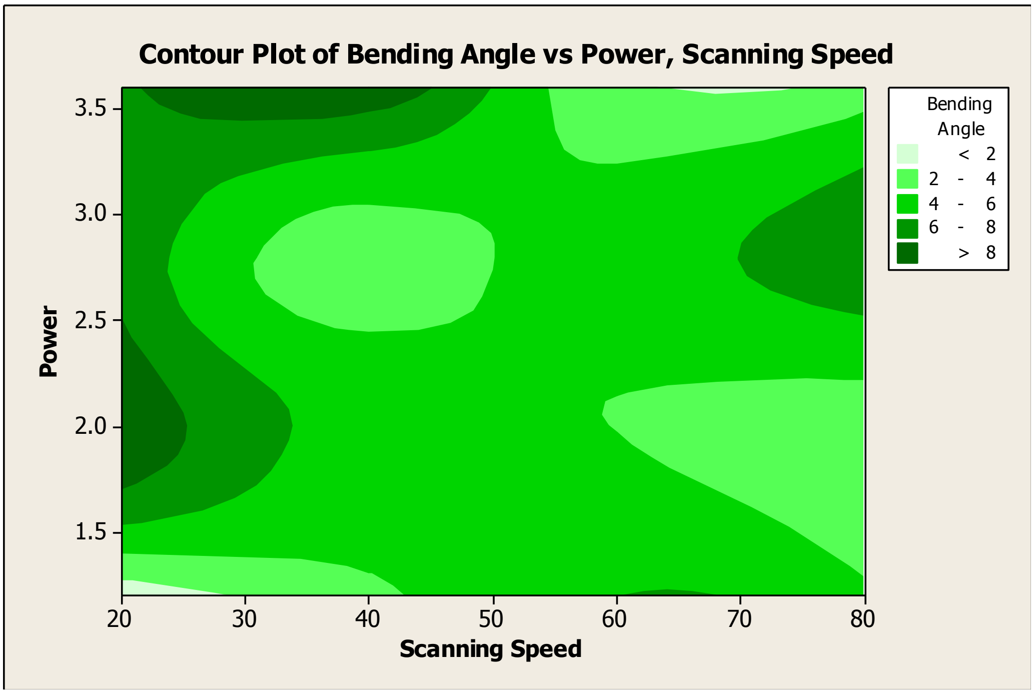

Fig 4.18: Contour plot for deflection w.r.t least effective parameters

This contour graph is drawn taking into account the least effective process parameters that affect the bending angle. Various regions of the contour graph show the effective bending angles that can be achieved by mainly varying these two least effective parameters.

chapter 5

5. CONCLUSION

Experimental investigation and analysis of the results w.r.t different process parameters led to the following conclusions:

- With increase in power the bending effect increased up to a certain level and with further increase net bending effect was decreased because of deterioration of surface of the w/p.
- With increases in pulse diameter, the bending effect continuously increased. So a better curvature and higher bending angle can be formed with increasing pulse diameter.
- For variation of scanning speed, maximum effect was found between 4-8mm/s and with further increases in speed the effect was continuously reduced.
- As the number of adjacent lines was increased, larger bending effect was observed.

The <u>most effective</u> process parameters are:

- ➢ Number of adjacent parallel lines
- ➢ Pulse diameter

(Number of adjacent parallel lines was found to be the most effective parameter.)

The <u>least effective</u> process parameters are:

- ➢ Laser power
- ➢ Scanning speed

(Scanning speed was found to be the least effective parameter.)

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