Welding of stainless steel with pure copper by Nd:YAG laser, optimizing the tensile strength

A thesis submitted to the National Institute of Technology , Rourkela in partial fulfillment of the requirements of

Bachelor of technology(mechanical engineering)

by

SUJIT KUMAR SAHOO,Roll no. 108ME083

Under the guidance

Of

PROF. SUSANTA KUMAR SAHOO

Department of Mechanical Engineering,

National Institute of Technology,Rourkela,Odisha769008

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CERTIFICATE

This is to certify that the project entitled, “Welding of stainless steel with pure copper by Nd:YAG laser, optimizing the tensile strength,” submitted by Mr. SUJIT KUMAR SAHOO in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance, and the information contained in this report is true to the best of my knowledge.

DATE: 9/5/12

PLACE: Rourkela

PROF. S.K. SAHOO
Mechanical Engineering Department
National Institute of Technology
Rourkela

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DATE:9/5/12 **Sujit kumar sahoo(108ME083)**

PLACE: Rourkela

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ABSTRACT

Welded joints of copper and stainless steel has very important applications in the industries. In this project, laser welding of copper and stainless steel was carried out at different values of beam power, speed of the beam and pulse duration. A 9 kW ALPHALASER AL200 Nd:YAG was used to weld 1.5mm thick stainless steel plates and 1.6mm thick copper plates. Tensile testing of the specimen was done using universal testing machine(UTM) to find out the peak load at which the specimen breaks. The results were analysed using signal to noise ratio and multiple regression analysis for optimum parameters and degree to which each factor contributes respectively. Equation is found out to depict the relation between tensile strength, beam power, speed of the beam and pulse duration. Results indicate that tensile strength increases with increase in beam power and pulse duration, and decreases with increase in laser speed.

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CHAPTER ONE

INTRODUCTION

1.INRODUCTION

1.1 Background

Light amplification by stimulated emission of radiation (LASER) is a mechanism which emits electromagnetic radiation, by the process of simulated emission. The laser's beam of coherent light differentiates it from light sources that emit incoherent light beams, random phase varying with time and position whereas the laser light is a narrow-wavelength electromagnetic spectrum monochromatic light yet, there are lasers that emit a broad spectrum light, or simultaneously at different wavelength. Laser welding is one of the nonconventional and non-traditional methods to join materials. Laser beam welding has high power density, high heating and cooling rates that result in small heat affected zones(HAZ). Laser beam welding (LBW) is a unique welding technique to join metals through the heating effect of a concentrated beam of coherent monochromatic light known as LASER. LASER light is generally a spatially coherent, narrow-wavelength electromagnetic spectrum monochromatic light. An inert gas, such as helium or argon is used to protect the weld bead from contamination and to reduce the formation of absorbing plasma. Industrial lasers are used for welding, cutting, drilling and surface treatment of a wide range of engineering materials. Depending upon the type of weld required a continuous or pulsed laser beam might be used[1]. LBW is a very versatile process, which is capable of welding a variety of materials like stainless steels, carbon steels, aluminum, copper, tool steels etc. The weld quality is high although some cracking may occur in the weld region. The speed of welding is proportional to the amount of power supplied but also depends on the type and thickness of the work-pieces[2]. Laser welding is of particular interest in the automotive industry, laser welding has been applied for joining sheet body panels, transmission components and chassis members during production. When using laser for welding purposes, energy is transferred from the laser to the work-piece via two different ways or modes. The laser welding mode may be either the conduction mode or the keyhole mode depending upon the power density. Conduction limited mode is a low energy density process, which basically heats the surface of the material being welded. The beam energy is deposited on the material surface, conducted into the material forming a hemispherical bead. The size of the weld on the surface is generally larger and the depth of penetration of the weld is generally shallower. In keyhole mode a narrow, deeply penetrating vapour cavity, or keyhole is formed due to local vaporization. The keyhole is surrounded by a thin layer of molten material. This layer is maintained by equilibrium between vapour pressure, surface tension and hydrostatic pressure[3]. Material at the leading edge melts and flows around the keyhole, solidifying to form a deep, narrow weld bead. Heat affected zones (HAZ) are very narrow.

1.2 laser welding equipment

Basically two types of laser equipment are in use- solid-state lasers and gas lasers. Solid-state lasers employ solid media like synthetic ruby, yttrium aluminum garnet crystals doped with neodymium (Nd:YAG), chromium in aluminum oxide, etc. Gas lasers use carbon dioxide, nitrogen, etc as medium. The medium when excited emits photons and forms a laser beam.

solid state laser

The most popular solid state design is a rod shaped single crystal approximately 20 mm in diameter and 200 mm long with flat grounded ends. A flash tube, containing xenon or krypton surrounds this tube. When flashed, a pulse of light lasting for about two milliseconds is emitted by the laser.

Nd:YAG lasers may be operated in both pulsed and continuous mode providing power outputs between 0.04–6000 W[4]. Solid-state lasers operate at very low wavelengths and hence cannot be operated with the naked eye. Operators must wear special eyewear or use special screens to prevent damage to the eyes[6].

Gas lasers

In gas lasers, the lasing medium (gas mixture) is excited by using high voltage, low current power sources. Power outputs for gas lasers can be much higher than solid-state lasers, and these lasers can operate both in continuous as well as pulsed mode.

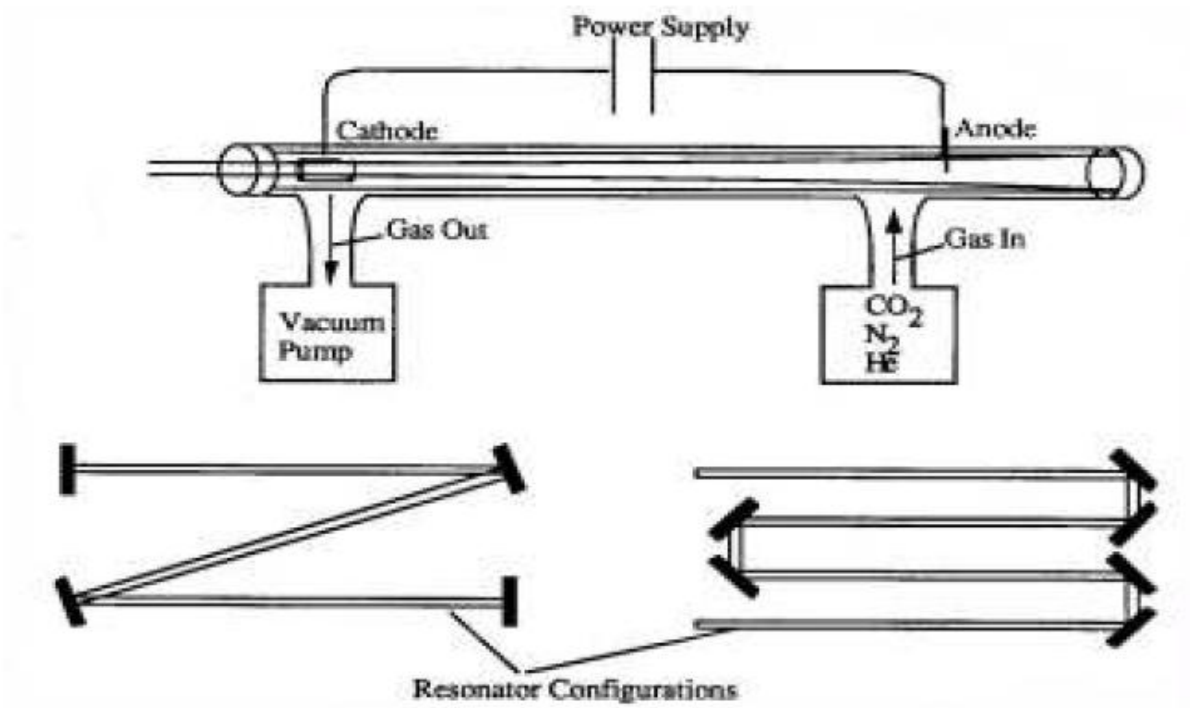

Figure 1.1 : Axial Flow CO2 laser (After Chryssolouris, 1991)

Fibre laser

In fiber lasers the gain medium is the optical fiber itself. They are capable of power up to 50 kW and are increasingly being used for robotic industrial welding.

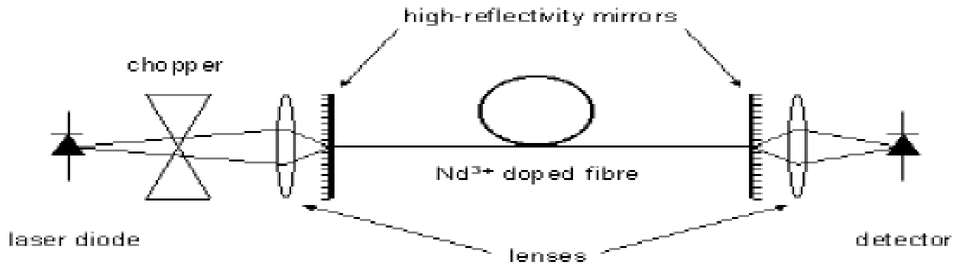

Figure 1.2 A diode-pumped Fibre laser

Nd-YAG laser

The Nd: YAG laser is an optically pumped solid state laser system that is capable of providing high power laser beam. The lasing medium here is a colorless and isotropic crystal Yttrium aluminium garnet (YAG: Y2Al5O12) having a four operational levels of energy. The yttrium aluminium garnet is doped with some amount of neodymium. When sufficient intense light is allowed to fall on this crystal, population inversion occurs and atoms in the crystal structure absorb this incident light to undergo transitions from the ground state to the absorption bands. This is often done with the help of a flash tube. The transition from the absorption bands to the upper energy laser levels is very smooth. The decays from these higher levels back to the ground state are longer in duration than the transitions to the higher levels. Due to this long lifetime, the atoms de excite back to the ground states almost spontaneously, thus producing a laser beam[5].

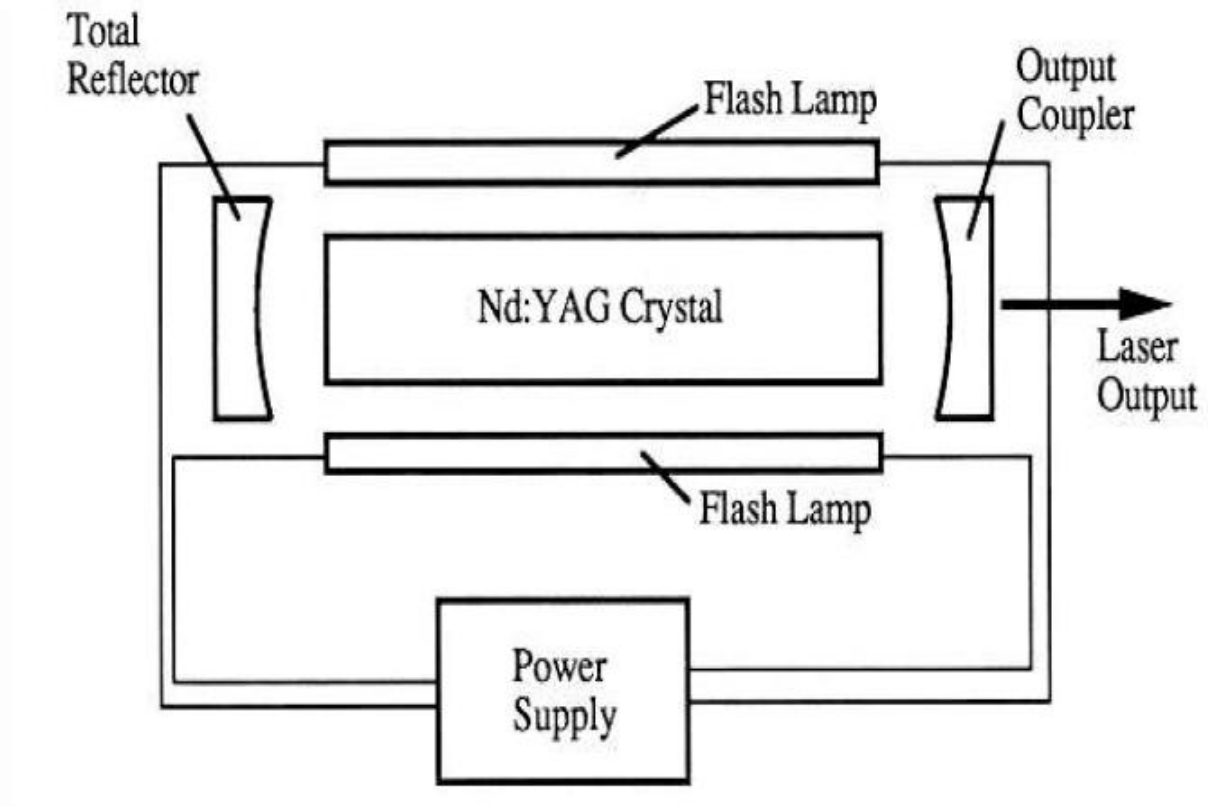

Figure 1.3 Schematic of Nd:YAG laser (After Chryssolouris, 1991)

Commercial Nd:YAG laser for welding can be operated in three modes- continuous output, pulsed pumping and Q-switched mode.

1.3 Advantages of laser welding

The heat influence zone is very small because of a very short pulse duration (welding time, 5-10 ms) and a relatively slow sequence of the individual welding pulses (up to 10Hz)[6]. One of the main advantages of laser welding is its versatility. Another important fact is that laser systems can be made completely automatic in order to have high accuracy welds. Improvements in welding speed, productivity and accuracy are achieved at the same time. Very high finish welds are obtained, that do not require further processing. These qualities make lasers a good choice for welding a variety of parts like transmission components, antilock-brake valves, pace-makers, and stainless steel tubes. Lasers provide a high heat concentration that is obtained when the beam is focused to a metal surface, resulting in deep, narrow welds with a minimum of melted metal, which reduce undesirable effects such as distortion and large heat-affected zones (HAZs)[7]. The high welding speeds and low scrap rates achieved with the laser process make it cost-effective for stainless steel applications.

i. Weld lines may be as narrow as 0.4mm

ii. Tensile strength of the weld bead is always more than base metal.

iii. Three-dimensional geometries can be welded

iv. Laser welding can produces a very narrow heat affected zone (HAZ) with low residual stress and small welding defects in the base metal.

v. The high cooling rate favors the formation of a fine microstructure so it can improve the mechanical properties.

vi. There is no requirement of the filler material because of ability to create welds that are full penetrating and improved material strength without undergoing any finishing operations.

vii. Laser welding is extremely advantageous in automotive application due to high density, high degree of automation and high production rate and repeatability of the process.

1.4 Disadvantages of laser welding

The major disadvantages of laser welding are its associated high costs, difficult operating expertise requiring highly skilled labor and high maintenance costs. Apart from that, there are some other disadvantages also, one of them being the tendency of magnesium to vaporize and create severe voids on the surface, when subjected to laser welding. The slow welding speeds (25 to 250 mm/min.), resulting from the pulse rate and puddle sizes at the fusion point also prove to be major disadvantages. Also, laser welding is efficient only up to depths of 1.5 mm[8]. Any additional energy only tends to create gas voids and undercuts in the work.

i. Initial cost is very high.

ii. Requires highly skilled operator and high maintenance cost.

iii. Slow welding speed

1.5 Behaviour of various materials to laser welding

Joints between low-carbon and high-strength low-alloy steels are required in many industries. These metals are readily laser-weldable, but two main problems are martensite formation in the weld bead or low alloy HAZ, which promotes cold cracking and the hot cracking observed in fully austenitic metal. High levels of sulphur and phosphorus, in combination with a coarse solidification microstructure and restraint, can lead to solidification cracking. Austenitic stainless steels can be laser welded with the exception of free machining grades which are susceptible to solidification cracking due to high sulphur content.

Ferritic stainless steels with low carbon and chromium contents are also readily laser weldable. Aluminum and copper: They are difficult to melt with lasers due to their high reflectivity and high thermal conductivity. There is also a large difference in melting temperatures, as well as brittle inter-metallic phases are formed. However, by using Nd:YAG laser welding, sound weld beads have been obtained. Good mechanical properties and thermal conductivities are reported. Aluminium and Steel: When attempting to weld these metals by normal fusion processes, problems result due to formation of brittle intermetallic compounds and large difference in thermal conductivities. Steel and copper: Differences in their melting temperatures and thermal conductivities, as well as compositional effects, are the main sources of difficulties in joining steel and copper. Steel and nickel: The heat resistance of the nickel component is often the determining factor in its selection. Aluminium and lead: Successful laser welding of aluminium alloys to lead, for use in instruments, through the use of a tin interlayer has been reported[9].

CHAPTER TWO

LITERATURE SURVEY

2. LITERATURE SURVEY

Serial no.	Name of the experiment	Date and author	Process specifications	summary
1	Characteristic analysis of copper steel joints.	Oct 13,2010. T.A Mai	Power:320W. Pulse duration : 5ms Welding speed:2.5mm/s Plate thickness:1mm Nd-YAG laser	Increase in welding Speed leads to decrease in no. of pores but increases their size.
2	Interface microstructure and mechanical properties of laser welding copper- steel dissimilar joints	Dec 12 2008. Chengwu Yao.	T1 Copper. E235A steel. Power: 8KW. Thickness:3mm Scarf angle:84 CO2 laser.	Welded joint with lower dilution ratio of copper in the fusion zone exhibits higher tensile strength.
3	Using Taguchi method to optimize welding pool of dissimilar laser-welded components.	2005 E.M Anawa et al	AISI316 stainless Steel and AISI 1009 low carbon steel. Power 1-1.5KW Welding speed-50cm/min. Defocussing distance 0-1mm. CO2 laser	Increase in welding velocity reduces metal vaporization. Increase in power increases weld width.
4	Characteristic of deep Penetration	2007 Xiu-bo-liu	K418 alloy and steel 42CrMo. Power 2.5-3KW	If velocity increases ,both depth and width decreases.

	laser welding of dissimilar metals		Velocity 15-20 mm/sec defocussing distance -3to+1 Nd-YAG laser	Weld depth increases with increase in weld power.
5	Dissimilar welding of carbon steel to 5754 aluminium alloy	M.J.Tarkamang et al.[1]2009	Al alloy and steel Peak power 1-2.7 KW, Pulse duration 3.7-10 ms, Velocity 5mm/sec, Pulse energy 10 J, Frequency 20/sec, Overlapping factor 40-90%, w/d ratio 1.5 mm, Power 200W,	High peak power cause mode dilution, Hardness is also increasing with increasing the peak power. Longer pulse duration cause large weld width and also penetration depth. Welding efficiency increases with overlapping factor. Ideal parameter of welding peak power is1.43KW, Pulse duration is 5 ms, Overlapping factor 80%

				Hardness value increases with increasing the penetration depth.
6	Pulse Nd-YAG laser welding of AISI 304 to AISI 420 stainless steel	Jose Rabrto Berretta et al.[2]2007	AISI 304 to AISI 420 stainless steel Energy 6 J, Average power 84 W, Pulse duration 7 ms, Pulse frequency 14 Hz, Speed 300 mm/min Pulse overlapping 30% Argon gas 10 lit/min	It can be observed that element distribution in the weld zone is homogeneous for all LASER beam position. Maximum hardness value in the HAZ of AISI 420. Tensile strength of AISI 420 is lower than AISI 304. Maximum welding efficiency get when position on the of the both specimen
7	Dissimilar material joining using	Alexandre Mathieu 2005	Aluminium to steel using zinc based	Heterogeneous steel and aluminium assemblies have

	laser (aluminium to steel using zinc-based filler wire)		filler wire Laser power 1.4 to 2 KW, Defocusing length (1 to 3), Tilt angle of the assembly with respect to the laser beam axis 35- 45 deg, Braze welding speed 2 to 3.2 mm/min, Filler wire speed 2 to 3.2 mm/min Diameter of the fiber and the laser beam shaping (one-spot or two spots)	been done by laser braze welding. Zn base alloy have low melting temperature. There is no requirement of flux. The rupture occurs in HAZ of aluminium and steel itself.
8	Modeling and optimization of tensile shear strength of Titanium/	E. M. Anawa et al.[9] 2009	Titanium / Aluminum Laser power 0.9 to 1.35 KW,	The dissimilar joint between Aluminum and titanium alloys were effectively welded by CO2 laser welding

	Aluminum dissimilar welded component		Speed 1600 to 2100, Focus -1 to 0.0 mm	with a single pass and without filler material using the overlap joint design. Tensile shear strength was almost same as the Al base metal values

Table 2.1 literature survey

CHAPTER THREE

EXPERIMENTATION

3. MATERIAL AND SPECIMEN PREPARATION

3.1 Material

The raw materials selected for this study were pure copper and stainless steel. A copper sheet of approximately 1.62mm thickness and a stainless steel sheet of approximately 1.5 mm thickness were selected for this purpose. It was seen that there was no rusting in the stainless steel and copper sheet.

3.2 Specimen preparation

3.2.1Cutting of stainless steel by bosch jig saw

Figure 3.1 Bosch jigsaw

The stainless steel sheet was clamped in the table and then was cut with the jig saw. One of the smaller sheet of equal dimension was taken and the sheet was cut in to small strips of width 40 mm and length 640mm.

Lubricants are frequently used in order to provide better machining, keeping moving parts apart, reduce friction, transfer heat, carry away contaminants and debris and reduce wear and tear.Then these small strips are cut into small plates of dimension 70mm*40mm*1.5mm which are to be welded.

3.2.2Cutting of copper sheet by shearing machine

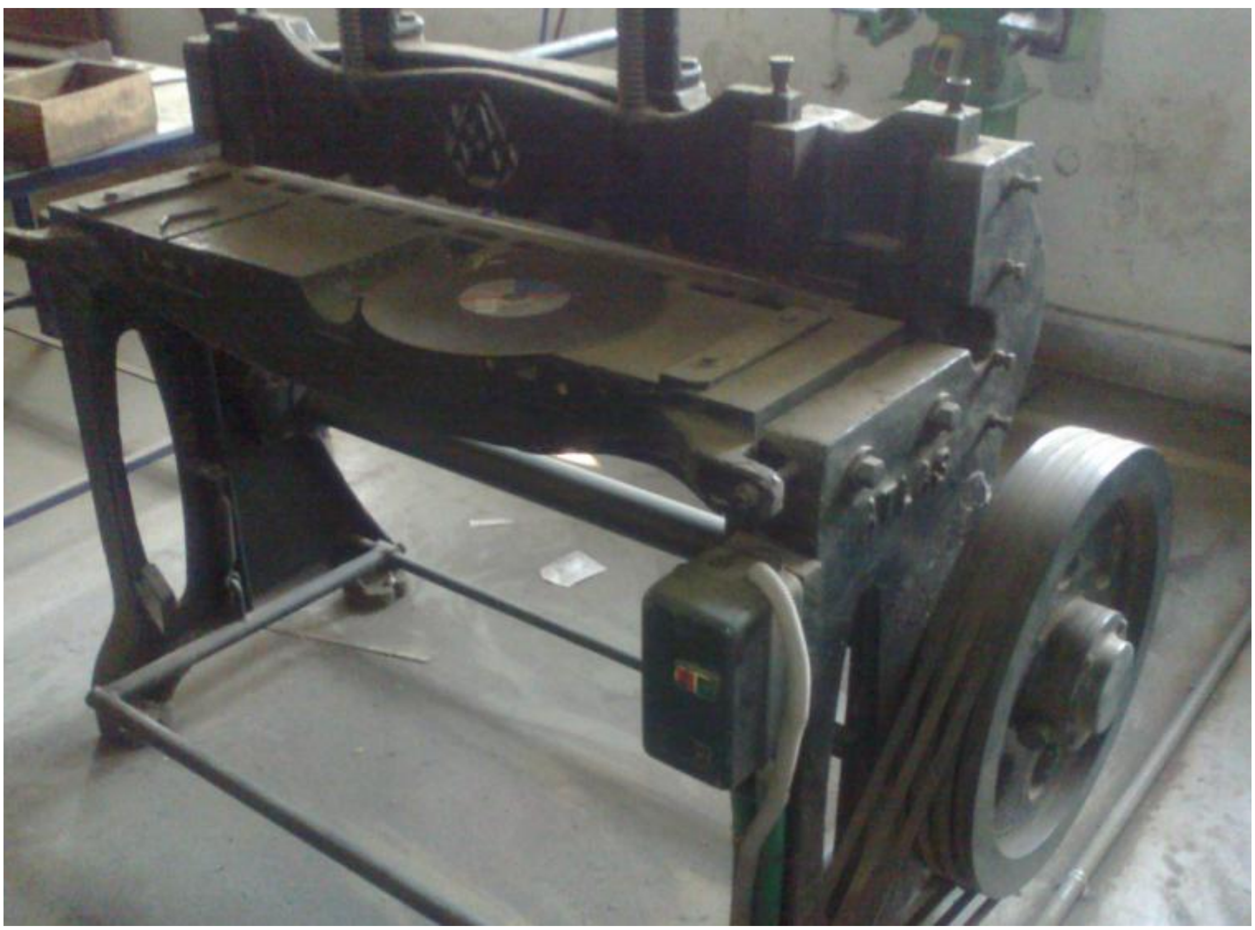

Figure 3.2 shearing machine

The copper sheet was cut into small strips of width 40mm and length 640mm by inserting the sheet along the pre marked lines. These strips were then cut into small plates of 70mm*40mm*1.62mm.

The smoothness of the edges of copper plates is high and hence do not need finishing in grinding machine.

3.2.3 surface finish in grinding machine

Fig 3.3 grinding machine

After cutting in the jigsaw the edges of the small sheets are not smooth and have burs. For welding the edges need to be perfectly smooth. So surface finish and deburring was done by the help of the grinding machine.

3.3 Laser welding

Nd:YAG Laser

The Nd:YAG laser is commonly used type of solid-state laser in many fields at present because of its good thermal properties and easy repairing. The generation of short pulse duration in laser is one of the researcher areas. Nd:YAG is chosen for most materials processing applications because of the high pulse repetition rates available . The power supply of pulsed Nd:YAG laser is designed to produce a maximum average power. The beam quality and output power are depending on length of resonator . The beam quality is important to the laser designer because the quality of a given beam profile depends on the application for which the beam is intended. The beam quality can be improved by inserting an aperture inside the resonator in order to reduce the effective radius of the gain medium . Nd:YAG laser can be used for direct energy conduction welding of metals and alloys; the absorptive of metals increases as wavelength decreases. Since conduction welding is normally used with relatively small components, the beam is delivered to the work piece via a small number of optics. Simply beam defocusing to a projected diameter that corresponding to the size of weld to be made . Argon gas is used as process gas because its high density assists in removing plasma. It has lower ionization potential then helium, it shield the welding bead pool more effectively. It is relatively cheap. The addition of argon to helium, is amount up to 50%, may improve the economics of welding, without sacrificing plasma control.

3.4 Joint and fixturing

The square butt (fig 1) or I-joint is ideal for laser welding. Strength is generated from the complete weld bead penetration. However, it is the least forgiving. Air gap arise from poor fit up of part, or from the roughness of cut plate edged. Air gap must be less than about 5% of the plat thickness to avoid bead cancavity and sagging. The beam must be aligned with the joint line over its entire length.Accurate fixturing is necessary in laser welding gap along the joint line cannot be tolerated by small focused beam. Fixturing is a time-consuming and expensive manufacturing phase, but is compensated for higher quality product and a reduced need for post-welding reworking. Joint parts may be fixtured in a frame to avoid angular and bending shrinkage.

3.5 laser welding apparatus

Fig 3.4 alfa laser AL-T200

3.6 Laser parameters:

1. Average peak power (kW)
2. Pulse energy (J)
3. Pulse duration (ms)
4. Average peak power density (kW/m2)
5. Laser spot area (m2)
6. Mean laser power (kW)

7. Pulse repetition rate

8. pulse-to-pulse time (ms)

9. Duty cycle

10. Pulse frequency (in Hz

The following table gives the detailed technical specifications of the laser welding equipment used:

Wavelength	1064 nm
Average power	200 W
Peak pulse power	9 kw
Pulse energy	150mJ-80mJ
Pulse duration	0.5 ms – 20 ms
Pulse frequency	Single pulse, 20Hz – 30 Hz
Welding spot diameter	0.3 mm – 2.2 mm
Pulse shaping	Adjustable power-shaping within a laser Pulse
Control	User-specific operation with up to 128 parameter sets
Focusing lens	150 mm
VIEWING OPTICS	Leica binocular with eyepieces for spectacle users
POWER SUPPLY	
Dimensions (L*W*H)	820*400*810 mm
Weight	Approx 98 Kg

LASER BEAM SOURCE	
With focusing unit (length *diameter)	1100*120 mm
Weight	Approx 20 Kg
ELECTRICAL SUPPLY	3*400V / 3*16 A / 50-60 Hz / N, PE
COOLING	Air cooled with internal cooling watercircuit, no additional external cooling is necessary.

Table 3.1 Technical specification of laser welding machine

Software

The software used in the CNC equipment was WIN Laser NC software (NC 4-axis control).

3.7 choice of parameters

For the welding purpose, the beam diameter was fixed at 1.8 mm. welding speed was values taken were 0.6,0.8,1.0 and 1.2 mm/min; beam power values taken are 5.6,5.8,6.0 and 6.2 kW and pulse duration values taken are 13,14,15 and 16 ms.

3.8 Tensile testing

Figure 3.5 Instron universal testing machine

The tensile strength was measured using INSTRON electronic universal testing machine which has a maximum capacity of 600kN and has a measuring range between 0 to 600 kN.

CHAPTER FOUR

RESULTS,ANALYSIS AND DISCUSSION

4. RESULTS , ANALYSIS AND DISCUSSION

4.1 RESULTS

Experiments were designed by the Taguchi method using an L16 orthogonal array that was composed of three columns and 16 rows. This design was selected based on three welding parameters with four levels each. The selected welding parameters for this study were: power, speed, and pulse duration.

Experiment no.	Power(kw)	Speed(mm/min)	Pulse duration(ms)	Tensile strength(kN)
1	5.6	0.6	13	17.2
2	5.8	0.6	14	17.65
3	6.0	0.6	15	18.21
4	6.2	0.6	16	19.06
5	5.8	0.8	13	17.62
6	6.0	0.8	14	17.90
7	6.2	0.8	15	18.63
8	5.6	0.8	16	17.38
9	6.0	1	13	17.74
10	6.2	1	14	18.14
11	5.6	1	15	17.23
12	5.8	1	16	17.46

13	6.2	1.2	13	18.08
14	5.6	1.2	14	16.85
15	5.8	1.2	15	17.25
16	6.0	1.2	16	17.80

Table 4.1 Experimental inputs and response

Regression analysis was carried out for tensile strength against speed ,power and pulse duration to find out the equation of the tensile strength of the weld joint in terms of the three input variables and corresponding graphs are drawn in MINITAB®14

4.2 Regression analysis: tensile strength versus speed, power and pulse duration

The regression equation is
tensile strength = 4.31 - 0.923 speed + 2.18 power + 0.0990 pulse duration

Predictor	Coef	SE Coef	T	P
Constant	4.3100	0.9498	4.54	0.001
speed	-0.9225	0.1431	-6.45	0.000
power	2.1775	0.1431	15.22	0.000
pulse duration	0.09900	0.02861	3.46	0.005

S = 0.127955   R-Sq = 96.0%   R-Sq(adj) = 95.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	4.6700	1.5567	95.08	0.000
Residual Error	12	0.1965	0.0164		
Total	15	4.8665			

Source	DF	Seq SS
speed	1	0.6808
power	1	3.7932
pulse duration	1	0.1960

T value for all the input variables is high(absolute value greater than one). This shows that all the three experimental inputs have significant contribution in resulting in a specific tensile strength of the weld joints.

Since F value is above 95 and P value is less than .05,the experimental data can be safely said to be significant.

MINITAB - project.mpj - [Worksheet 1 ***]

File Edit Data Calc Stat Graph Editor Tools Window Help

↓	C1	C2	C3	C4	C5	C6
	power	speed	pulse duration	tensile strength	RESI1	FITS1
1	5.6	0.6	13	17.20	-0.0375	17.2375
2	5.8	0.6	14	17.65	-0.1220	17.7720
3	6.0	0.6	15	18.21	-0.0965	18.3065
4	6.2	0.6	16	19.06	0.2190	18.8410
5	5.8	0.8	13	17.62	0.1315	17.4885
6	6.0	0.8	14	17.90	-0.1230	18.0230
7	6.2	0.8	15	18.63	0.0725	18.5575
8	5.6	0.8	16	17.38	0.0300	17.3500
9	6.0	1.0	13	17.74	0.0005	17.7395
10	6.2	1.0	14	18.14	-0.1340	18.2740
11	5.6	1.0	15	17.23	0.1635	17.0665
12	5.8	1.0	16	17.46	-0.1410	17.6010
13	6.2	1.2	13	18.08	0.0895	17.9905
14	5.6	1.2	14	16.85	0.0670	16.7830
15	5.8	1.2	15	17.25	-0.0675	17.3175
16	6.0	1.2	16	17.80	-0.0520	17.8520

Table 4.2 Fits and residuals table

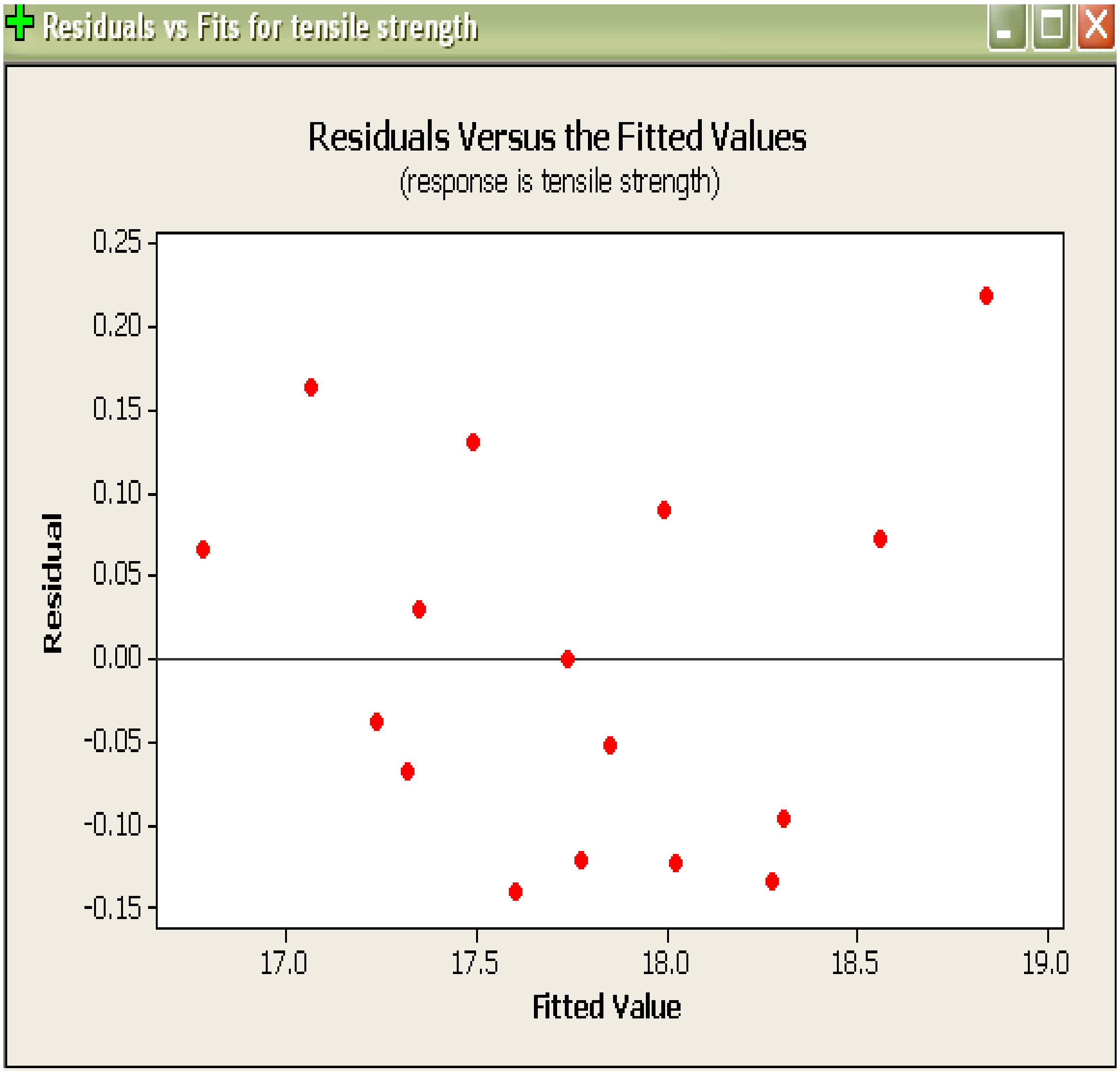

Fig 4.1 Residual vs the fitted values

It can be seen that the residuals when plotted against the fitted values do not show any visible pattern and is completely random which tells that output data is significant.

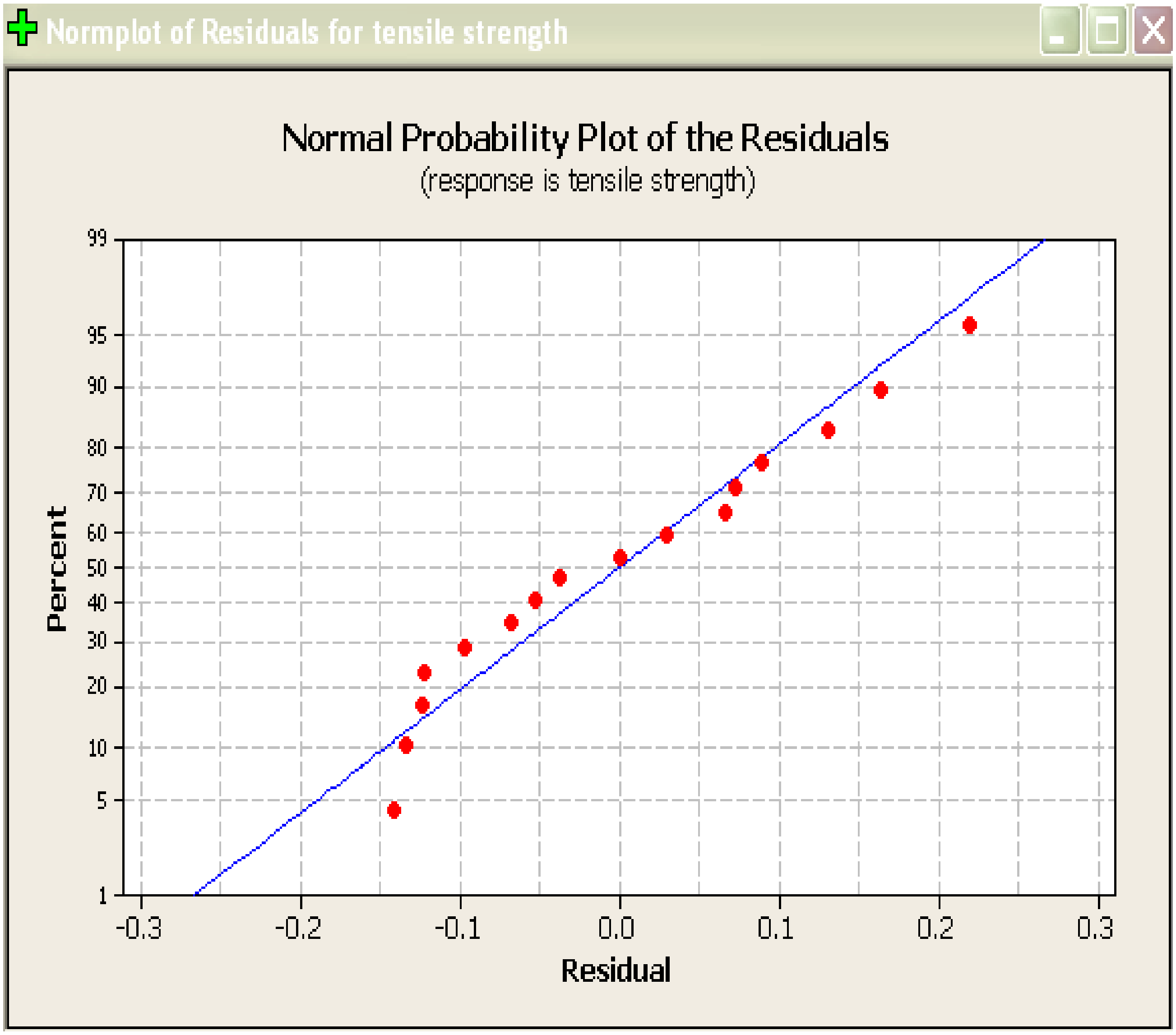

Figure 4.2 Normal probability plot of the residuals

4.3 Linear model analysis

Taguchhi analysis is carried out to find signal to noise ratio and mean values against each level of each of the input variables, i.e. speed, power and pulse duration

Linear Model Analysis: SN ratios versus speed(mm/min, power(kw), pulse durati

Estimated Model Coefficients for SN ratios

Term	Coef	SE Coef	T	P
Constant	24.9859	0.05544	450.689	0.000
speed(mm 0.6	0.1276	0.09602	1.329	0.232
speed(mm 0.8	0.0597	0.09602	0.621	0.557
speed(mm 1.0	-0.0563	0.09602	-0.587	0.579
power(kw 5.6	-0.0475	0.09602	-0.495	0.638
power(kw 5.8	-0.0618	0.09602	-0.643	0.544
power(kw 6.0	0.0320	0.09602	0.334	0.750
pulse du 13	-0.1105	0.09602	-1.151	0.294
pulse du 14	-0.1280	0.09602	-1.333	0.231
pulse du 15	-0.1064	0.09602	-1.108	0.310

S = 0.2218   R-Sq = 74.2%   R-Sq(adj) = 35.5%

Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
speed(mm/min)_1	3	0.16060	0.16060	0.05353	1.09	0.423
power(kw)	3	0.05226	0.05226	0.01742	0.35	0.788
pulse duration(ms)	3	0.63554	0.63554	0.21185	4.31	0.061
Residual Error	6	0.29506	0.29506	0.04918		
Total	15	1.14345				

Linear Model Analysis: Means versus speed(mm/min, power(kw), pulse durati

Estimated Model Coefficients for Means

Term	Coef	SE Coef	T	P
Constant	17.7625	0.1125	157.824	0.000
speed(mm 0.6	0.2675	0.1949	1.372	0.219
speed(mm 0.8	0.1200	0.1949	0.616	0.561
speed(mm 1.0	-0.1200	0.1949	-0.616	0.561
power(kw 5.6	-0.1025	0.1949	-0.526	0.618
power(kw 5.8	-0.1275	0.1949	-0.654	0.537
power(kw 6.0	0.0675	0.1949	0.346	0.741
pulse du 13	-0.2300	0.1949	-1.180	0.283
pulse du 14	-0.2675	0.1949	-1.372	0.219
pulse du 15	-0.2175	0.1949	-1.116	0.307

S = 0.4502   R-Sq = 75.0%   R-Sq(adj) = 37.5%

Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
speed(mm/min)_1	3	0.6876	0.6876	0.22922	1.13	0.409
power(kw)	3	0.2309	0.2309	0.07697	0.38	0.771
pulse duration(ms)	3	2.7319	2.7319	0.91065	4.49	0.056
Residual Error	6	1.2160	1.2160	0.20267		
Total	15	4.8665				

Response Table for Signal to Noise Ratios
Larger is better

Level	speed(mm/min)_1	power(kw)	pulse duration(ms)
1	25.11	24.94	24.88
2	25.05	24.92	24.86
3	24.93	25.02	24.88
4	24.86	25.06	25.33
Delta	0.26	0.14	0.47
Rank	2	3	1

Response Table for Means

Level	speed(mm/min)_1	power(kw)	pulse duration(ms)
1	18.03	17.66	17.53
2	17.88	17.64	17.50
3	17.64	17.83	17.55
4	17.50	17.93	18.48
Delta	0.53	0.29	0.98
Rank	2	3	1

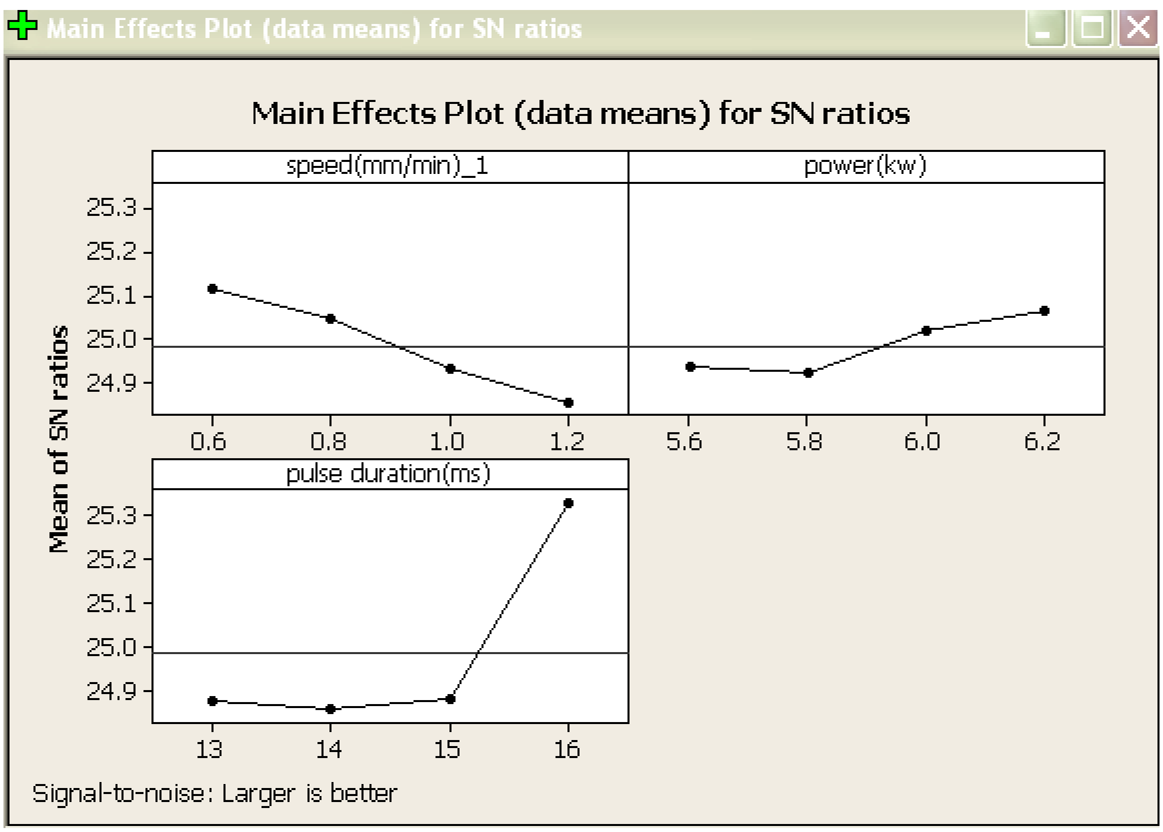

Figure 4.3 Main effect plot for Signal to noise ratio

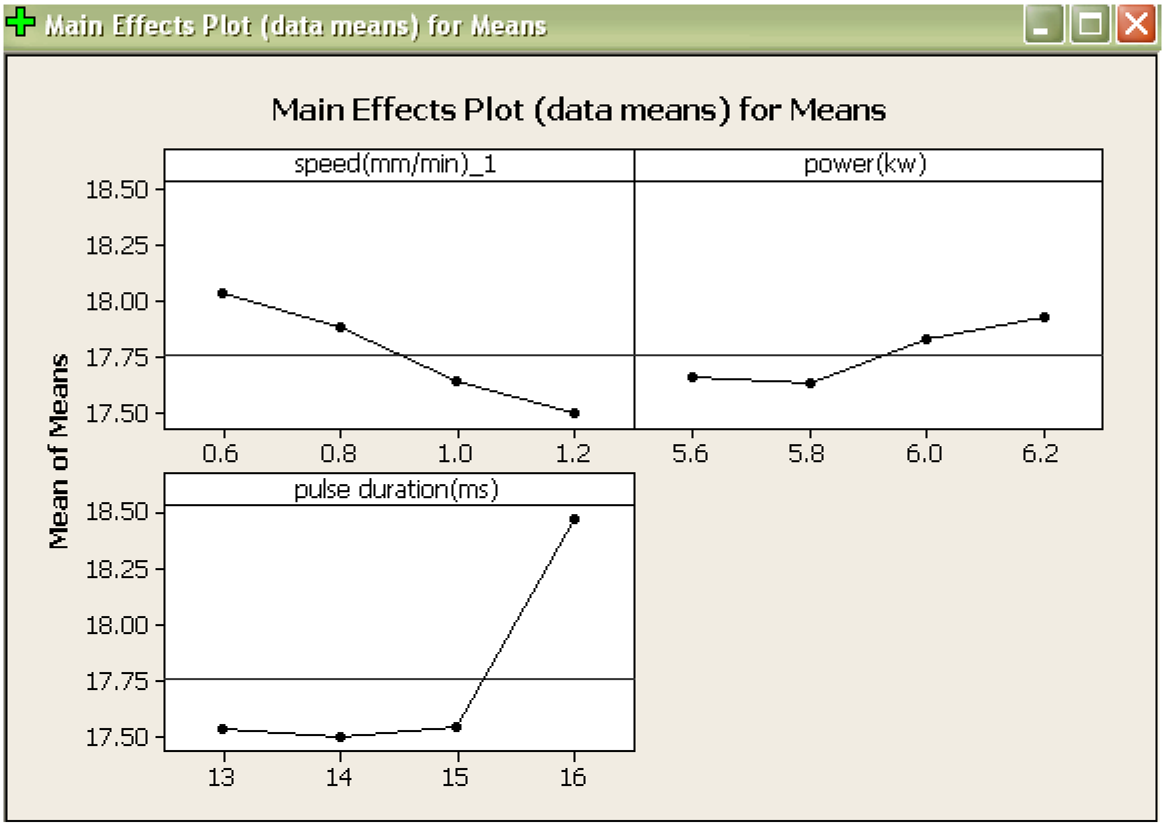

Figure 4.4 Main effect plot for means

As it can be seen from the graph 6.3 signal to noise ration are highest for speed 0.6mm/min, power 6.2Kw and pulse duration 16 milliseconds. Similarly mean of means for tensile strength is also highest at the same input values.

As linear equation of tensile tension in terms of the three input variables has been obtained, predicted values of tensile strength can be found and compared with the experimental values to find the error percentages.

MINITAB - project.mpj - [Worksheet 1 ***]

↓	C1	C2	C3	C4	C5	C6	C7	C8
	power	speed	pulse duration	tensile strength	RESI1	FITS1	predicted tensile strength	error percentage
1	5.6	0.6	13	17.20	-0.0375	17.2375	17.2512	0.29767
2	5.8	0.6	14	17.65	-0.1220	17.7720	17.7862	0.77167
3	6.0	0.6	15	18.21	-0.0965	18.3065	18.3212	0.61065
4	6.2	0.6	16	19.06	0.2190	18.8410	18.8562	-1.06925
5	5.8	0.8	13	17.62	0.1315	17.4885	17.5026	-0.66629
6	6.0	0.8	14	17.90	-0.1230	18.0230	18.0376	0.76872
7	6.2	0.8	15	18.63	0.0725	18.5575	18.5726	-0.30811
8	5.6	0.8	16	17.38	0.0300	17.3500	17.3636	-0.09436
9	6.0	1.0	13	17.74	0.0005	17.7395	17.7540	0.07892
10	6.2	1.0	14	18.14	-0.1340	18.2740	18.2890	0.82139
11	5.6	1.0	15	17.23	0.1635	17.0665	17.0800	-0.87057
12	5.8	1.0	16	17.46	-0.1410	17.6010	17.6150	0.88774
13	6.2	1.2	13	18.08	0.0895	17.9905	18.0054	-0.41261
14	5.6	1.2	14	16.85	0.0670	16.7830	16.7964	-0.31810
15	5.8	1.2	15	17.25	-0.0675	17.3175	17.3314	0.47188
16	6.0	1.2	16	17.80	-0.0520	17.8520	17.8664	0.37303

Table 4.3 Predicted tensile strength and error percentages

As error percentages are found below one percent for every reading, the linear equation for tensile strength can be said to be almost accurate.

CHAPTER FIVE

CONCLUSIONS

5. CONCLUSIONS

- AISI304L stainless steel and pure copper are laser welded successfully producing a narrow HAZ.
- Focusing diameter, frequency and welding speed are correlated. Any two of these can be used to vary the third input variable.
- Change in Laser power or voltage significantly changes the size of the fusion area.
- Within the operating range of the input variables, optimum tensile strength is found at speed 0.6mm/min, power 6.2kw and pulse duration 16 milliseconds.
- Equation for Peak tensile strength(tensile strength = 4.31- 0.93* speed + 2.18*power+0.0990*pulse duration) is proposed as it is found to be fairly accurate with low error percentages.

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