PARAMETRIC STUDY OF LASER WELDING
ON
TRANSPARENT ACRYLIC

A thesis submitted towards partial fulfillment of the requirements
for the degree of

Master of Technology in Laser Technology
Course affiliated to Faculty of Engineering and Technology and
offered by Faculty Council of Interdisciplinary Studies, Law and Management,
Jadavpur University

submitted by
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Examination Roll No. : M4LST19009
Registration No.: 141054 of 2017-2018

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India
2019

M. Tech in Laser Science & Technology
Course affiliated to
Faculty of Engineering and Technology
and offered by
Faculty Council of Interdisciplinary Studies, Law and Management
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CERTIFICATE OF APPROVAL **

This foregoing thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

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The author, hereby declares that this thesis contains original research work by the undersigned candidate, as part of his **Master of Technology in Laser Technology** studies during academic session 2018-2019.

All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

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ACKNOWLEDGEMENT

I express my sincere gratitude to my supervisor **Dr. Arunanshu Shekhar Kuar** for his invaluable guidance, whole-hearted support and encouragement for accomplishing the present investigation. His dynamism, fantastic stamina and day-to-day monitoring every minute detail were a constant source of inspiration to me.

I express my great depth of gratitude to **Dhiraj Kumar & Dr. Somnath Paul** for their inspiration and encouragement and helping me through the research work.

I would also like to express my deep sense of thankfulness to **Sri. Dipten Misra** providing me necessary atmosphere to work on.

I record my acknowledgement to **School of Laser Science and Engineering** for giving me the opportunity to pursue my research work.

Lastly but obviously not the least I would like to pay my special admiration thanks to my parents and brother for their constant support, love and faith.

My eternal gratitude goes to god.

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NANDAKISHOR MAITY

Examination Roll No.:M4LST19009

Registration No.:141054 of 2017 – 2018

Contents

Chapter1: INTRODUCTION

1.0 INTRODUCTION

Laser welding is a high energy density joining process. It has been increasingly utilized in industrial manufacturing processes. It has lots of advantages compared to the conventional welding technique (arc welding, induction welding, friction welding, solid-state welding, etc.) Due to the small heat affected zone and low distortion it has so many applications in various industries such as aerospace, automotive, electronics medical, packaging etc. [1]. The increasing demand of plastic product in our daily life, so to keep the environment clean we have to adapt new technology. The laser technology plays a vital role to fulfil the required demands for plastic processing.

There are different processes of materials joining like rivet, threads, and welding. Due to several benefits of welding over others it is regarded as most popular joining method which able to join two or more materials with or without application of heat, pressure, filler materials. Welding can also be performed for joining of plastic materials. Sometimes the conventional processes are not suitable for environment, collateral damage of materials because of the issue of high temperature . In the case of laser welding, precision controlling of power and localized heating are the prime advantages. It may be the best possible solution for plastic welding. In this present work parametric investigation of Laser Transmission Welding of two transparent materials, Acrylic, has been performed [2].

1.1 Various type of welding process

Welding is a joining process of similar or dissimilar type of materials by using heat or without heat, applying pressure or not to join the parts together and allowing them to cool down for causing fusion. Welding process is distinct from lower temperature metal-joining techniques such as brazing and soldering, which do not melt the base metal. Welding are mostly classified in four types as follows.

a) Shielded metal arc welding (SMAW)

In case of shielded metal arc welding, the welder follows a manual process of stick welding (consumable electrode). The stick uses an electric current to form an electric arc between the stick and the metals to be joined. This type is often used in the construction of steel structures and in industrial fabrication to weld iron and steel materials.

b) Gas metal arc welding (GMAW/MIG)

Gas metal arc welding is also known as Metal Inert Gas welding. It uses a shielding gas along the wire electrode, which heats up the two metals to be joined. This method requires a constant voltage and DC power source, and is the most common industrial welding process.

c) Flux cored arc welding (FCAW)

Flux cored arc welding was developed as an alternative to shield welding. The semi-automatic arc weld is often used in construction projects, thanks to its high welding speed and portability.

d) Gas Tungsten Arc Gas Welding (GTAW/TIG)

This type of welding commonly used for thick sections of aluminium or non-ferrous metals. It is also an arc-welding process that uses a tungsten electrode (non-consumable electrode) to produce the weld. This process is much more time consuming than the other three and much more complex.

1.2 Laser beam welding process

Laser beam welding is a process to join two or more pieces of material together by using laser beam (Energy) which is act as a heat source. It is a non-contact process that requires access to the weld zone from one side of the parts being welded. The laser beam is a coherent monochromatic in nature. The laser beam has low beam divergence and high energy and thus will create heat when it strikes on the surface of materials. The laser beam welding can be applied for most of the metal and non-metal like carbon steel, stainless steel, aluminium, plastic[3] etc. The significant advantages of laser beam welding are narrow heat affected zone, no filler metals is required and it is also feasible to weld small thin components. For the above reasons laser beam welding is most popular for industrialist and researchers.

1.3 LASER (Light Amplification by Stimulated Emission of Radiation)

A laser differs from other sources of light in that it emits light coherently. Spatial coherence allows a laser to be focused to a tight spot, enabling applications such as laser cutting and lithography. Spatial coherence also allows a laser beam to stay narrow over great distances (collimation), enabling applications such as laser pointers and lidar. Lasers can also have high temporal coherence, which allows them to emit light with a very narrow spectrum, i.e., they can emit a single colour of light. Alternatively, temporal coherence can be used to produce pulses of light with a broad spectrum but durations as short as a femtosecond.

Generally Lasers are characterized according to their wavelength . The single wavelength lasers actually produce radiation in various modes with slightly different wavelength from others. Although temporal coherence implies monochromaticity, there are lasers that emit a broad spectrum of light or emit different wavelengths of light simultaneously. Some lasers are not single spatial mode and have light beams that diverge more than is required by the diffraction limit. Lasers are employed where light of the required spatial or temporal coherence cannot be produced using simpler technologies.

A laser consists of a gain medium. The gain medium is put into an excited state by an external source of energy[4]. In most lasers this medium consists of a population of atoms which have been excited into such a state by means of an outside light source, or an electrical field which supplies energy for atoms to absorb and be transformed into their excited states. The gain medium of a laser is normally a material of controlled purity, size, concentration, and shape, which amplifies the beam by the process of stimulated emission described above. This material can be of any state: gas, liquid, solid, or plasma. The gain medium absorbs pump energy, which raises some electrons into higher-energy excited quantum states. Particles can interact with light by either absorbing or emitting photons. Emission can be spontaneous or stimulated. In the latter case, the photon is emitted in the same direction as the light that is passing by. When the number of particles in one excited state exceeds the number of particles in some lower-energy state, population inversion is achieved and the amount of stimulated emission due to light that passes through is larger than the amount of absorption. Hence, the light is amplified. By itself, this makes an optical amplifier. When an optical amplifier is placed inside a resonant optical cavity, one obtains a laser oscillator.

The gain medium to amplify light, it needs to be supplied with energy in a process called pumping. The energy is typically supplied as an electric current or as light at a different wavelength. Pump light may be provided by a flash lamp or by another laser.

The most common type of laser uses feedback from an optical cavity a pair of mirrors on either end of the gain medium. Light bounces back and forth between the mirrors, passing through the gain medium and being amplified each time. Typically one of the two mirrors, the output coupler, is partially transparent. Some of the light escapes pass through this mirror. Depending on the design of the cavity (whether the mirrors are flat or curved), the light coming out of the laser may spread out or form a narrow beam. In analogy to electronic oscillators, this device is sometimes called a laser oscillator.

Most practical lasers contain additional elements that affect properties of the emitted light, such as the polarization, wavelength, and shape of the beam.

Lasers are generally used in laser printers, scanners, DNA analysis , eye surgery and skin treatments, cutting and welding, forming and bending of materials etc.[5]

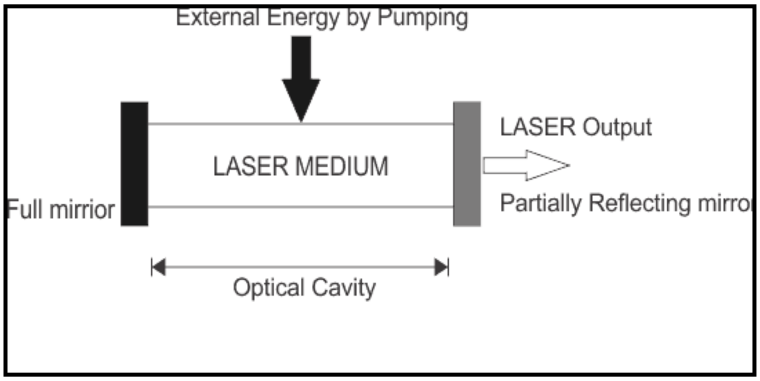

Fig.1.1: Components of LASER

1.4 Types of lasers

The lasers can be classified into four types as given in the subsequent sections given below.

a) Solid state laser

The active medium of a solid-state laser consists of crystalline or glass. The excited states of doped ions are not strongly coupled with the thermal vibrations of their crystal lattices. The most common example of solid state laser are Ruby laser, Neodymium laser, Neodymium Yttrium Aluminium Garnet (Nd: YAG) laser. For the ruby laser the rod is surrounded by a flash tube containing xenon or krypton, when flashed, a pulse of light lasting about two milliseconds is emitted by the laser. Disk shaped crystals are growing in popularity in the industry, and flash lamps are giving way to diodes laser due to their high efficiency.

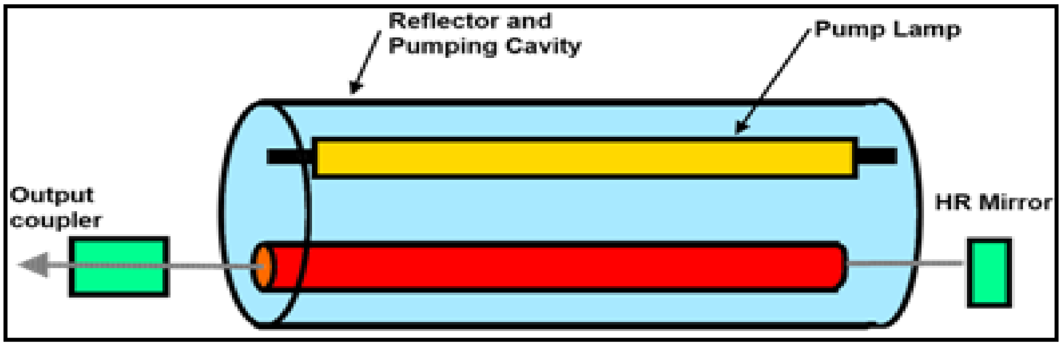

Fig.1.2: Solid state laser

b) Gas laser

A gas laser is a laser in which an electric current is discharged through a gas to produce coherent light. Example of gas laser are carbon dioxide laser, carbon monoxide laser helium neon laser etc. The main advantages of the gas laser are it is nearly impossible to damage, low cost, high production rate. But required high voltage to operate. He-Ne laser is mainly used in making holograms, reading the bar code In laser printing etc.

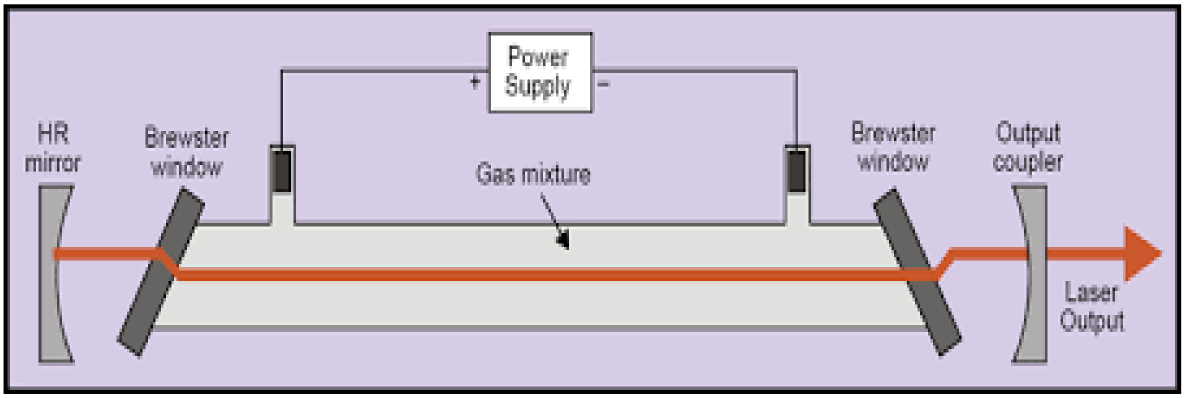

Fig.1.3: Gas Laser.

c) Dye Laser

A dye laser can usually use for a much wider range of wavelengths. The wide bandwidth makes them particularly suitable for tunable lasers and pulsed lasers. A dye laser uses a gain medium consisting of an organic dye, which is a carbon-based, soluble stain that is often fluorescent, such as the dye in a highlighter pen. The dye is mixed with a compatible solvent, allowing the molecules to diffuse evenly throughout the liquid. Dye laser has lot of medical applications, for tattoo removal, kidney stones treatment etc.

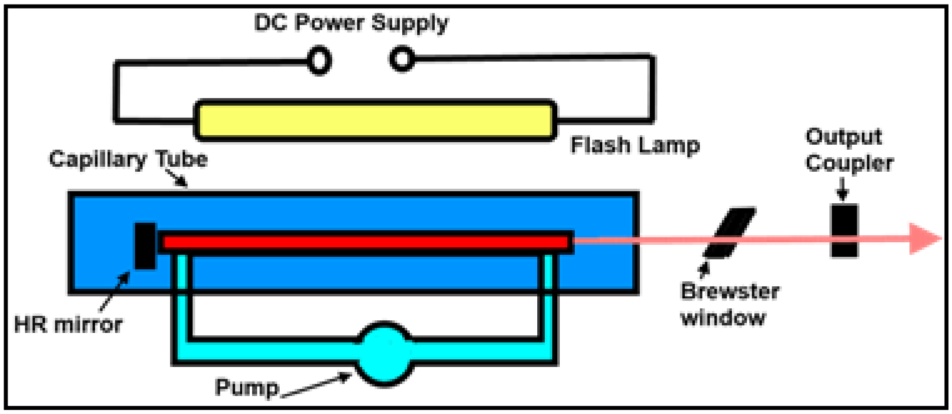

Fig.1.4: Dye Laser

d) Semiconductor Laser

Light is generated in a semiconductor laser by radiative recombination of electrons and holes. In order to generate more light by stimulated emission than is lost by absorption, the system has to be inverted, see the article on lasers. A laser is, thus, always a high carrier density system that entails many-body interactions. These cannot be taken into account exactly because of the high number of particles involved. The examples of semiconductor laser are gallium arsenide, gallium nitride, indium phosphide etc. The main application of semiconductor laser is high speed data communication.

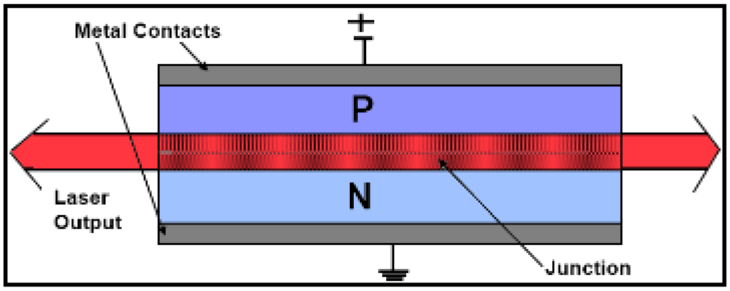

Fig.1.5: Semiconductor diode

1.5 Process fundamentals

Fundamental laws of heat transfer along with optical, mechanical, and thermal properties of solids are used in the model to understand the basics of LTW using the contour welding method. During LTW, a focused laser beam is directed at two overlapping thermoplastic parts (Acrylic).The parts contacted by the laser beam is designed to be primarily transparent, and it is called the transparent part. Likewise, the second part is designed to absorb to introduce this property we provide a absorbent layer by applying lining of black marker the laser radiation and it is also called the absorbing part.

As the laser beam strikes the surface of the transparent part, a fraction of the incident light is reflected and the remaining light energy enters the bulk of the material. While the majority of the light entering the transparent part is transmitted through the material, with the possibility of significant scattering, a portion of the energy is absorbed.

Light absorption within a solid can be described by Beers law :

$$I_z = I_O\, e^{-az} \text{ W/m}^2 \qquad \textbf{(1.1)}$$

Where I_z is the optical intensity as a function of material depth; I_O is the optical intensity at $z = 0$; 'a'is the absorption coefficient; and z is the material depth. The absorption coefficient was experimentally determined for acrylic clear at ambient temperatures and at elevated temperature.

The laser light that is transmitted through the transparent material strikes the surface of the absorbing material, where a fraction of the energy is reflected and the remaining energy enters the bulk of the material. The absorption of the laser light in the absorbing material can again be described using Beers law. De-pending on the thickness and absorption coefficient of the absorbing material, a portion of the laser energy may transmit completely through both parts[6]. Thus heat is generated and welding takes place at the line of laser.

1.6 Joining of plastic materials

The use of polymeric materials is nowadays increasingly in a many important applications including packaging, building, appliance, medical electronics, automotive, aerospace etc. There are thousands of grades of polymers are available at the market[7]. Joining is one of the critical steps in manufacturing component from plastic and polymeric composites. Various joining techniques have been developed over the years. The joining of plastic can be broadly classified in three types, chemical or adhesive, mechanical and welding. In the welding processes are also classified thermal, friction, and electromagnetic. Thermosetting plastic cannot be melt, only thermoplastics can be melts under heat. The joining is the last phase of the fabrication cycle. The efficiency of the joints play a vital role in the application field of plastic. Welding joint has so many advantages over other like light weight, less time consumption etc.

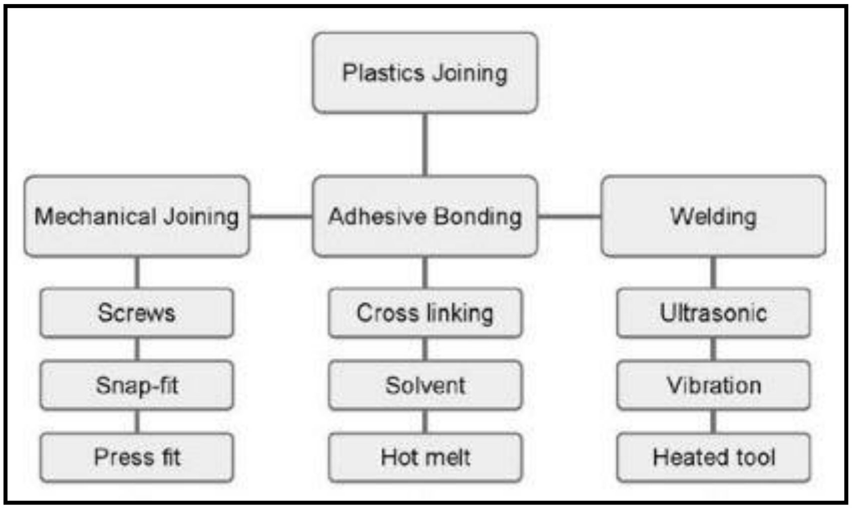

Fig.1.6: Joining method for plastic.

1.7 Plastic welding process

Plastic welding is the process of creating a molecular bond between two compatible thermoplastics. There are three main steps of any welding process, pressing, heating and cooling. Generally plastic welding are done either lap joint, butt joint or any other configurations. The thermoplastic welding can broadly be classified as:

i. Thermal bonding
ii. Friction welding
iii. Electromagnetic bonding

Thermal bonding generally includes hot gas welding, extrusion welding, Hot tool welding and infra-red welding. Friction welding generally includes spin welding, angular welding, orbital welding and ultrasonic welding and ultrasonic welding. Electromagnetic bonding includes resistance welding, induction welding, dielectric welding and microwave welding.

Brief overview of some conventional welding process that are used for plastic:

a) Rotary welding

In rotary welding process one component is stationary while other moving with high velocity and high pressure. Rotating friction has been generated in between the contact of two components, due to high velocity and pressure heat is generated and melts the both components and welding takes place. The advantages of this types of welding is low time cycle, low cost etc.

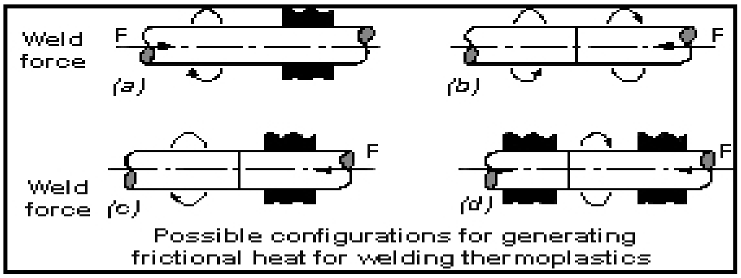

Fig.1.7: Rotary welding

b) Ultrasonic welding

In ultrasonic welding there is a transducer which convert the electrical signal to mechanical oscillation. The frequency of mechanical oscillator is 10-70 KHz. When a thermoplastic lie in between the anvil and horn due to high oscillating force plastic are melt and flow across the bond line creating a weld. . This is similar to the heating that occurs in a metal wire that is bent back and forth repeatedly, or in occurring when materials are general, to the effect subjected to cyclical loading. The heat, which is highest at the surfaces, because asperities are straining more than the bulk, is sufficient to melt the thermoplastic and to fuse the parts. Usually, a man-made asperity in the form of a triangular protrusion is molded into one of the parts to improve the consistency of heating and welding.

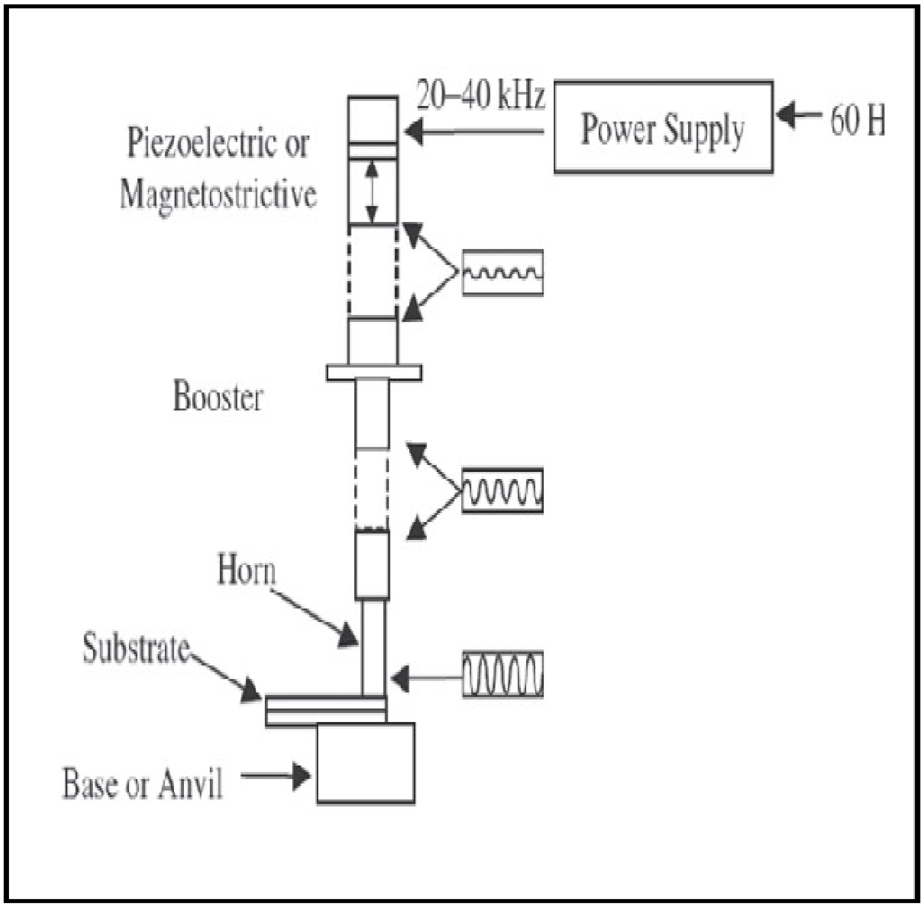

Fig.1.8: Arrangement of an ultrasonic welding device

c) Hot plate welding

This type of welding process is one of the simplest and commonly used in plastic welding. In this process one a heated tool is comes to contact of plastic then plastic are getting melt, after that by applying pressure welding are perform. This process is also known as hot tool welding. After a pre-selected heating time, the parts are retracted from the tool, the tool is quickly displaced away from the parts and the parts are brought together to allow the two molten interfaces to weld. Again, the amount of displacement during the cooling phase may be limited by mechanical stops to prevent excessive squeeze out which would force the majority of melt out of the weld zone leaving a cold weld.

d) Hot gas welding

This is usually a manual process where hot gas or hot air is usually directed simultaneously at weld joint and a filler rod is to create a weld in a similar to oxy fuel welding. To ensure good quality of welding, proper heating and pressure is required. In this process stream of hot air is directed toward the filler and the joint area using a hot air torch. A filler rod of a similar composition as the polymer being joined is gently pushed into the gap between the substrates. The round cross-section filler rod is used, but it is also available in oval, triangular and rectangular cross section. This kinds of welding is slow and function of operator dependent.

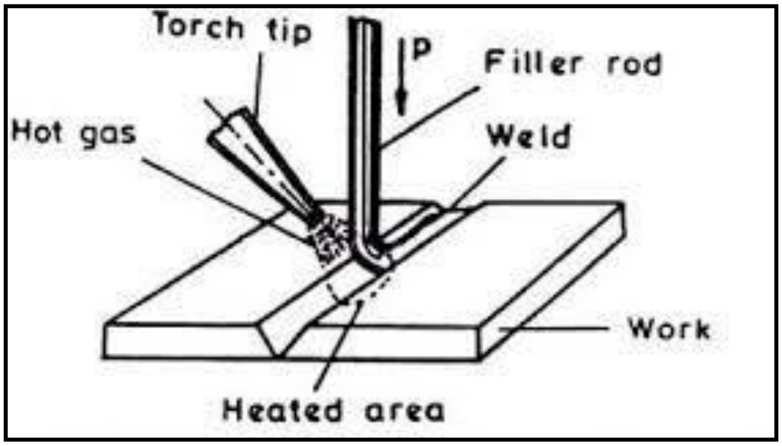

Fig.1.9: Hot gas welding

e) Laser transmission welding

Laser transmission welding process for plastic welding is more popular over others, because it is non-contact type and non-contaminant process. Laser has advantages of easy to automate and control. Its required less time, so high production rate and more reparability. Generally semiconductor diode, Nd:YAG and fiber lasers are typically used in plastic welding. Wavelengths of the specified laser must be transparent for the above layer and absorbent for the intermediate portion. The parts to be weld are placed under the laser head with clamping. There is required a clamping pressure to form the weld, which provide adequate pressure to hold the molten metal at the weld location. Melting takes place due to localized heating of the interface.

1.8 Advantages and limitations of laser welding

Advantages:

i. Aesthetically pleasing weld seams – visually better on “class A” surfaces.
ii. Ability to hold tighter tolerances in the joining process.
iii. No damage to surrounding materials or sensitive electronics.
iv. A perfectly hygienic method of bonding – no particulates generated.
v. Ability to miniaturize designs.
vi. Joining of 3D and complex shapes.
vii. Removal of costly and cumbersome part features.
viii. Eliminate consumables – fasteners, glue, etc.
ix. Drastically improve quality.
x. Bonding strength virtually as strong as the base material.

Limitations:

i. Optical surfaces of the laser are easily damaged.
ii. High capital cost for equipment.
iii. High maintenance costs.
iv. Its required more safety in process.

1.9 Application of the laser welding

1. Welding of automotive components.
2. Automotive body assembly.
3. To prepare micro channel for fluid.
4. Solenoids joining.
5. Welding of medical device under low spatter.

1.10 Plastic Materials

Plastic are mainly contains organic polymers of high molecular weight,[8]. Plastics are classified on the basis of density, hardness, tensile strength, resistance to heat, oxidation tendency, etc. Depending upon the light transparency plastics are again classified in three types, transparent which allow light to pass through them, opaque which do not allow light to pass through them, and last one is translucent which are combinations of both transparent and opaque plastic. Another important classification of plastics is by the permanence or impermanence of their form, thermoplastics or thermosetting plastic.

Types of plastic:

Plastic are broadly classified into two types:

a) Thermoplastic

Thermoplastics are the plastics that, when heated, do not undergo chemical change in their composition and so can be molded again and again. Examples are polyethylene (PE),polystyrene (PS),polypropylene (PP), Acrylic, polyvinyl chloride (PVC),Polyoxymethylene (POM)[9].

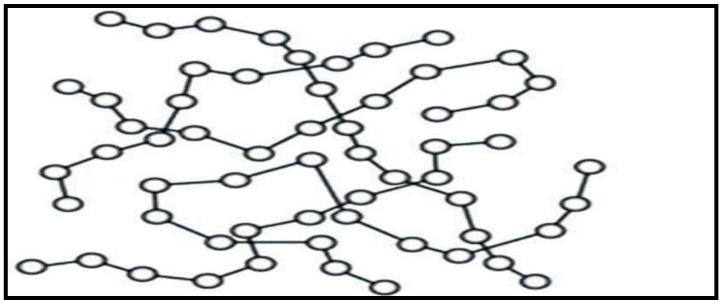

Fig.1.10: Structute of Thermoplastic

b) Thermosetting polymers

Thermosetting polymers can melt and take shape only once after they have solidified, they stay solid. In the thermosetting process, a chemical reaction occurs that is irreversible. The vulcanization of rubber is an example of a thermosetting process is before heating with sulfur, melamine, epoxy, polyester[10].

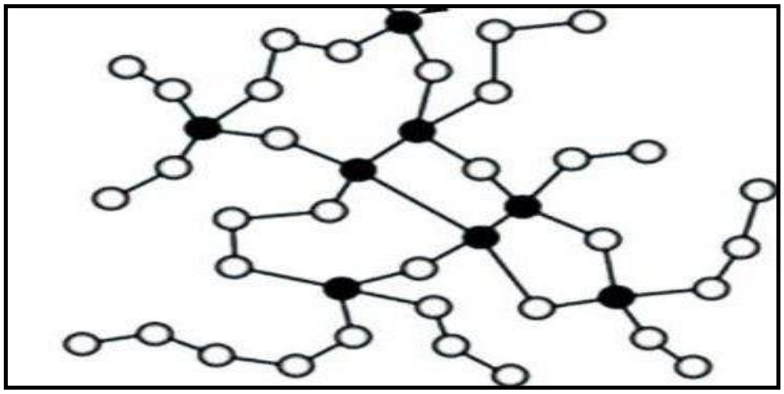

Fig.1.11: Structure of Thermosetting polymers

Some commonly known plastics materials are described below

a) Polypropylene

Polypropylene (PP) is a thermoplastic polymer similar to polyethylene, It is a white, mechanically rugged material and has a high chemical resistance. It is cheap but it is much more robust and is used in everything from plastic bottles to carpets to plastic furniture, and is heavily used in automobiles industries and packaging industry.

Fig.1.12: Polypropylene raw plastic material

b) Acrylic

Acrylics are now well known for their use in paints and synthetic fibers, such as fake furs. In sheets or slabs they are very hard and more transparent than glass and are used to replace glass and if coloured are now used to replace marble as bench and counter tops. The chemical name of acrylic is poly methyl methacrylate (PMMA).

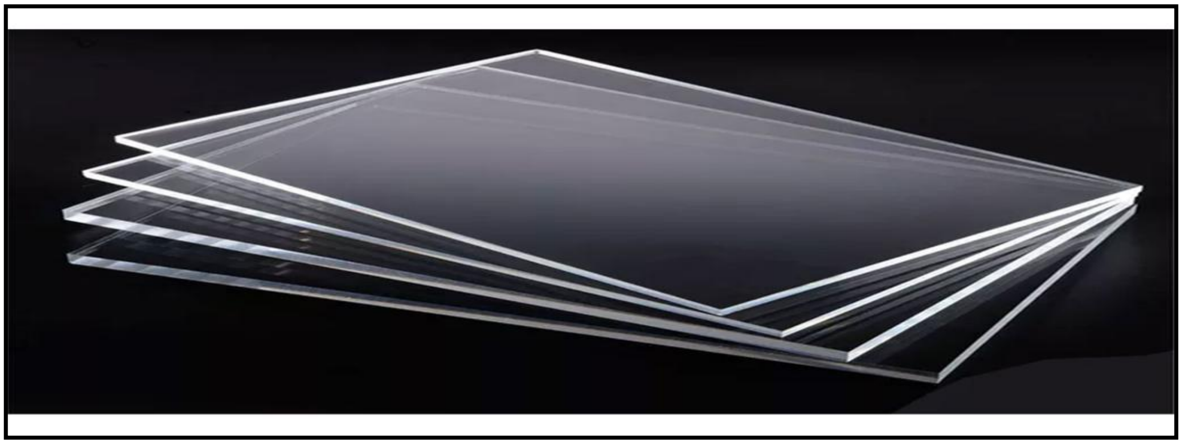

Fig.1.13: Acrylic sheet

c) Fibreglass

Fiberglass is cheaper and more flexible than carbon fiber, it is stronger than many metals by weight, can be molded into complex shapes, and is chemically inert under many circumstances. Applications include aircraft, boats, automobiles, bath tubs and enclosures, swimming pools, hot tubs, septic tanks, water tanks, roofing, pipes, and external door skins. Fiber glass covers are also widely used in the water-treatment industry to help control odors. An individual structural glass fiber is both stiff and strong in tension and compression—that is, *along* its axis. Although it might be assumed that the fiber is weak in compression, it is actually only the long aspect ratio of the fiber which makes it seem so; i.e., because a typical fiber is long and narrow, it buckles easily.

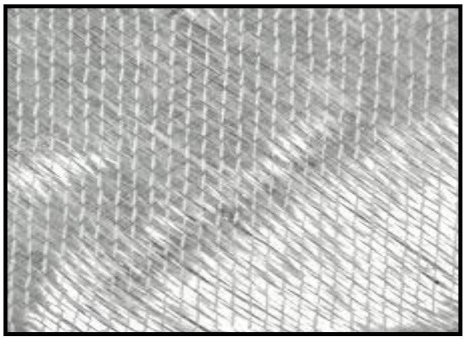

Fig.1.14: Fiberglass

d) Polycarbonate

Polycarbonate (PC) is not as hard as acrylic and can be cut easily. It is used for making protective eye wear, machine guards and riot shields. It is a thermoplastic polymer. Polycarbonates used in engineering applications due to high strength and high toughness. Polycarbonate may easily mould.

Fig.1.15: Polycarbonate

e) Nylon

Nylon invented in 1930, nylon revolutionized the clothing and fabric industries. Nylon is very strong but also very flexible. The first application was for bristles for toothbrushes but the development of fine fibers meant it could be used instead of silk and cotton. Today it is also used to build hard wearing mechanical parts like gears, bearings, bushings, parts of electrical equipment, films for good packaging [11].

Fig.1.16: Nylon 6,6

f) Polyvinyl Chloride (PVC)

PVC invented at the time of First World War polystyrene is a rigid, brittle plastic that is now used to make plastic model kits, disposable eating utensils, and a multitude of plastic pipes etc. The monomers are mainly arranged head-to-tail, meaning that there are chlorides on alternating carbon centre. PVC has mainly an atactic stereochemistry, which means that the relative stereo chemistry of the chloride centre are random. Some degree of syndiotacticity of the chain gives a few percent crystallinity that is influential on the properties of the materials [12]. PVC is brittle in nature and strong also.

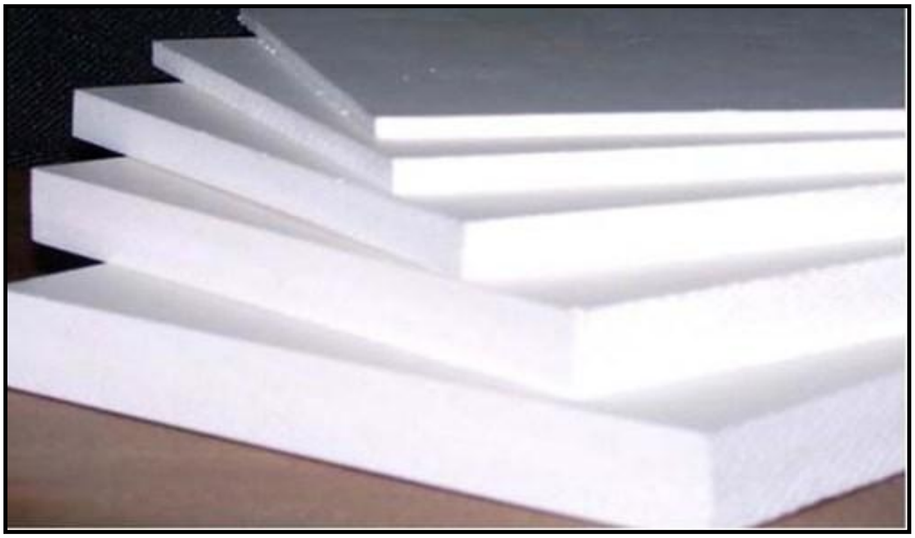

Fig.1.17: PVC sheet

g) Bakelite

Bakelite Phenol ($C6H5OH$) and formaldehyde ($HCOH$) when mixed together, they formed a sticky mass and when heated, moulded, cooled and dried it became extremely hard. Later it was worked out how to colour it. Bakelite was the first true plastic. It was cheap, strong, and durable and could be moulded into thousands of shapes like radios, telephones, clocks, light fittings etc. It had another characteristic which was brittle.

Fig.1.18: Bakelite Sheet

h) Melamine

Melamine is the organic compound with the formula $C_3H_6N_6$. It is thermosetting plastic, very tough and heat resistance. It is basically white but can be produce in others colours also. Melamine foam is used as insulation, soundproofing material and in polymeric cleaning products.

Fig.1.19: Melamine sheet

i) Epoxy resin

Epoxy resins, also known as polyepoxides. It is a polymeric or semi-polymeric materials and epoxide group content. It is two part mix which can be used as a glue or be rain forced with carbon fiber to produce a very strong and light composite materials. It has wide applications in industry for tool and composites, paint and coating, wind turbine blade composite etc.

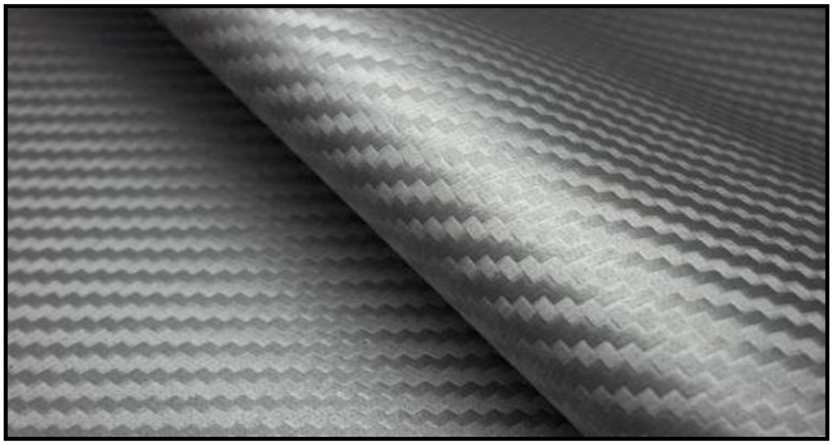

Fig.1.20: Epoxy Resin composite

1.11 **Literature review on transmission laser welding**

The literature review on progresses made in the different field of laser transmission welding of thermoplastics is presented and the literature survey given below takes into account about the research works carried out by few researchers and scientists. The literature survey also indicates that laser joining technology with “Through transmission laser welding” is an important area of research and several aspects of this area have been addressed, experimented and analyzed by the investigators through real-life application and simulation technique. Useful information in the context of the present work has been obtained from several websites as well.

Yuewei Ai *et al.*[13] worked on the laser transmission welding of polyethylene terephthalate (PET) and titanium alloy Ti6Al4V. They observed that the weld geometry predictions from the numerical simulation are in good agreement with the experimental data. The results show that the porosity consistently appears in the high temperature region due to the decomposition of PET.

Zhi Chen *et al***.**[14] observed that Fiberglass-doped polypropylene (PP) and fiberglass-doped acrylonitrile butadiene styrene (ABS) are more difficult to be laser transmission welded than other pure plastic because of its low laser transmittance, so they adapt a new hybrid heat source model is proposed to build three-dimensional finite element model for predicting temperature distribution and molten pool geometrical size by coupling Rotary-Gauss body heat source and Gauss plane heat source. By the applying simulation method to generate mathematic relationships between molten pool area, laser energy per unit of area and shear strength are fitted out to search optimal welding parameter.

Minqiu Liu *et al.* [15] presented a great method for obtaining a clean and high-quality joint between clear plastics through transmission laser welding (TLW). In the proposed method, they used the absorber likes carbon black (CB), and Fe wire, as a result higher welding strength which is associated with the thermal conductivity of the utilized metal absorber.

Xiao Wang *et al.* [16] observed that the thermal degradation of materials strongly influences the weld strength in laser transmission welding (LTW). Weld strength decreases at high temperatures because of material thermal degradation. Thermal degradation of polyamide 66 (PA66) was predicted by combining a pyrolysis kinetic model with a 3-D transient thermal model.. This study demonstrates that the predicted power at which the material starts to degrade is generally consistent with the power at which shear strength begins to decrease.

M.Viller *et al.* [17] studied the temperature field along the thickness of the specimens has been measured during transmission laser welding. Polyetherketoneketone (PEKK) is a very high performance thermoplastic with tunable properties. They proved that this grade of PEKK can be turned to quasi-amorphous or semi-crystalline material, due to its slow kinetics of crystallization. The transmittance of quasi-amorphous PEKK is about 60% in the NIR region (wavelength range from 0.4 to 1.2 μm) whereas it is less than 3% for the semi-crystalline material. Performed welding operation under a transparent (quasi-amorphous) sample as the upper part and an opaque (semi-crystalline) one as the lower part were assembled in static conditions so upper face reached high temperature and the interface reached melting temperature before rapid cooling. This work shows that infrared thermography is an appropriate technique to improve the reliability of laser welding process of high performance thermoplastics.

Nunziante Pangano *et al.*[18] explained in this paper the feasibility of the laser transmission welding of polylactide to aluminium thin films by means of laser transmission welding through the use of a low power pulsed wave fibre laser. They achieved feasibility area is extremely narrow and possible only for the higher value of the average power. The joint tensile strength was proven to be in a proportional relationship with the effective bonded area and reached satisfactory values.

Huixia Liu *et al.* [19] observed scattering effect of laser-transparent part has significant influence on the intensity profile of heat source during laser transmission welding (LTW).The heat source considered as light scattering was modeled based on the distribution of point energy intensity. In comparison with the heat source without considering light scattering, the intensity profile of heat source considered light scattering showed a wider width and a lower peak height. It was indicated that light scattering made a significant influence on the laser intensity at the weld interface.

XinFeng *et al.* [20] discussed the way to predict and optimize the contour laser transmission welding (LTW) process. In this study, transmission measurements were made on unreinforced and glass-fiber-reinforced amorphous and semi-crystalline thermoplastics at different thicknesses. A linear relationship between the glass fiber volume fraction and the apparent absorption coefficient of reinforced polymers was observed from the outcomes. Also, similar effects were also observed for crystallinity.

V.Mamuschkin *et al.* [21], noticed that the different types of laser sources can be used for polymer welding. By the principle of laser transmission welding the wavelengths of the laser is one of the most important criteria when selecting a laser source as the optical properties of the polymers which are depending on the wavelengths. The results showed that by analysis of the optical properties, especially the absorption and the scattering coefficient and adaption of the laser wavelengths the process limits can be extended.

Stefan Berger *et al.* [22] discovered that in the automotive industry the increasing demand of lightweight construction. Especially the use of carbon fiber reinforced thermoplastics (CFRTP) plays an increasingly important role, so required adequate joining technologies. Therefore, laser transmission welding with filler material provides a way to combine two opaque joining partners by using laser transmission welding process. They successfully performed joining of PA 6 CF 42 organic sheets using natural PA 6 as filler material underlines the potential of the described joining method for lightweight design and other industrial applications.

Acharjee *et al.* [23] carried out a systematic investigation on laser transmission contour welding process using finite element analysis method and design of experiments techniques. A three-dimensional thermal model was designed to simulate the laser transmission contour welding process using ANSYS software. Four key process parameters, namely power, welding speed, beam diameter, and carbon black content in absorbing polymer were considered as independent variables, while maximum temperature at weld interface, weld width, and weld depths in transparent and absorbing polymers were considered as dependent variables.

F. Becker *et al.*[24] worked on the laser transmission welding and gained significant outcomes by displaying its specific advantages among the established welding processes for thermoplastics likes polypropylene. The numerical simulation result displayed a good level of agreement with the experimental results.

Arthur *et al.*[25] developed a model of laser transmission welding that can be used as an analytical design tool. The model created from first principles of heat transfer and utilizes contact conduction that is a function of temperature and pressure under the Gaussian laser distribution. Many material properties that changes with temperature including the absorption coefficient. The research work was carried out with two polyvinyl chloride parts by applying a diode laser.

Kawahito *et al.*[26] studied on silicon nitride ceramic and polyethylene terephthalate polymer. The joints produced with a diode laser beam were evaluated by tensile shear test. Further, the joint structure was observed through TEM. The TEM images of the joint demonstrated that the ceramic and plastic are tightly bonded on the atomic and molecular sized level.

Abreu *et al.*[27] investigated the effects of moisture content on the efficiency of laser transmission welding process and compared the weld strength of laser welded nylon specimens to those welded by vibration, hot plate and ultrasonic welding technology at different environmental conditions. It was found that absorption of moisture in plastic did not have any significant effect on the mechanical performance of the laser transmission welded parts.

Grewell, D. *et al.*[28] explored the relationship between optical characterization of coloured and non coloured polyamides and laser welding process parameters. It was observed that addition of pigments can enhance the scatter of laser radiation.

Haberstroh *et al.*[29] showed the influence of carbon black content on the formation of weld seam when joining thermoplastics in micro technology applications. It was noticed that with increase in the carbon black content, the penetration depth decreased significantly.

Peter Jaeschke *et al*.[30] investigated on the weldability of high-performance polymers and carbon fiber reinforced thermoplastics using laser transmission welding techniques. Fundamental studies of the absorption characteristics of carbon fiber reinforced thermoplastics as joining partner and the heat distribution within the surface due to laser impact was performed. The welding process was analyzed with respect to the properties of the weld seam and also lap shear strength tests were realized for different material combinations.

M.Devrient *et al.*[31] considered process parameters a geometrical joining partner design suitable for laser transmission welding and adequate clamping pressure appliance is necessary to form high quality welds. Amongst other clamping techniques Dual Clamping Devices are a promising approach to fulfill the process needs and to get to a robust and also fail safe clamping. The effect of the bars onto the spatially and temporally changing temperature field within the joining partners was monitored by the simulation method.

V.Wippo *et al.*[32] worked on Laser transmission welding to join endless fibre reinforced thermoplastics. The welding temperature is affected by the heat conduction along carbon fibresand depends on the local orientation of the fibres in the weld seam and the laser welding technique itself. They investigated that heat development during the welding with quasi-static temperature fields, which is a combination of two laser welding techniques, is evaluated and compared to welding with a homogenized intensity distribution.

Murakawa *et al*.[33] developed thermo elastic plastic simulation to study the welding distortion, the butt welding for thin rectangular plates, the result of main interest are the out of plane distortion and longitudinal residual stress. The welding deformation in the fillet welded joint using numerical simulation and comparison with experimental result.

Wehner *et al.*[34] investigated the diode laser in the manufacture of micro fluidic device. A transparent polycarbonate plate over has been welded with the polycarbonate base plate containing a different proportion of carbon black content. They have recommended the higher carbon black content due to the shallower weld seam.

Haberstroh *et al.*[35] examined the influence of carbon black content in the formation of the weld seam when joining thermoplastic in the micro technology application. The carbon black content has varied from 0.5% to 1.5%. It has been noticed that, with the increase with the carbon black content, the penetration depth decrease directly. The effect of specific nylon composition factors, such as fiberglass, mineral impact modifier content and the colour version on the near infra -red transmission.

Truckenmiller *et al.*[36] worked on a contact free method such as infrared thermography for surface temperature measurement on a typical configuration for the through transmission laser welding of polymers. The process for building up a new class of polymer fluidic micro sensors and actuators with foreign matters free, physicochemical inert flow path for application in the field of pharmaceutics, biotechnology and life sciences as well as for high temperature automotive applications.

Kumar *et al.*[37] applied orthogonal array to find best parameters setting for welding current, welding voltage welding travel speed and a number of welding pass in MIG welding process and welding parameters. The effect on residual stress and hardness of weld specimen was carried out by a statistical technique, i.e. ANOVA.

Douglass *et al.*[38] investigated laser welding of polyolefin elastomers (POE) to determine the weldability of two different POEs to thermoplastic elastomers using a fibre laser. It was seen that power and speed were the most significant effects in regard to strength and they interacted significantly. The strength increased with line energy, with the highest line energies producing the greatest strengths, even in the presence of some burning.

casalino *et a.l*[39] analyzed the keyhole and conduction welding for butt and overlap configuration. The thermo-morphologic and mechanical behaviours of moulded thermoplastic polymers during the laser welding have been simulated using finite element method.

Becker *et al.*[40] explored on laser transmission welding has gained in significance by displaying its specific advantages among the established welding processes for thermoplastics. However, a deep understanding of the developed process variants is so far missing. Useful results for temperature development were obtained in cases of high absorption constants by setting up an analytical model by analogy to single-sided heat impulse welding. This investigation was performed towards a deep and detailed insight into the heating phase of the laser transmission welding process. Experimental data for temperature progression was collected for polypropylene. In addition, an analysis of the heat transfer problem using the finite element method showed a good level of agreement with the experimental results.

Ghorbel *et al.*[41] showed that the influence of process parameters both the laser power and welding speed on the geometry and the microstructure of the polypropylene weld zone.

Ilie *et al.*[42] developed an efficient tool to determining the weld ability of polymeric materials for the reduction of time and costs with the experimental exploration.

1.12 Objective of present thesis work

Form the literature review of many researchers indicate that there different aspects in laser transmission welding is yet to be explored. The aim of this process is to understand on the laser welding and its controlled for manufacturing process. The objectives of this present research work is to achieve maximum weld strength and minimum weld width considering laser power, frequency and scanning rate are as process parameters. It is expected that the results obtained from the current study will be helpful for industrialist and researcher to get an overview about laser transmission welding of transparent materials using low power laser.

Laser welding of transparent acrylic to transparent acrylic has been considered for this present study as acrylic plastic has wide area of applications as discussed earlier. The width and strength of the weld zone have been measured and the effect of input process parameters on the quality of weld seam width and weld strength is observed. Then Response Surface Methodology (RSM) is applied to relate the input parameters (laser power, scanning speed, frequency) with the output parameters (weld width and weld strength). Finally, the optimum parameters is achieve for minimum weld width with maximum weld strength.

Chapter 2: Experimental setup and Procedure

2.0 Experimental setup and procedure

The joining of transparent to transparent materials is still a challenging task. This experiment planned by a definite orientation as described below:

i. Selecting the most efficient parameters like power, frequency, scanning rate.
ii. Through the trail set upper and lower value for each parameter.
iii. Cut the PMMA in rectangular plates of size 35mm×70 mm×3 mm and preparing them for through transmission welding(TTLW).
iv. Conducting TTLW between two PMMA in lap joint configuration and provide an absorbent layer by applying black marker in line shape, using different levels of input parameters like power, scanning speed and frequency of laser beam.
v. Identifying suitable experiment design and perform the experiment one by one.
vi. Transmitting optical microscope used for measurement the weld width.
vii. Performing the tensile tests to determine the breaking load of the welded joints by universal testing machine.

2.1 Dimensions of work specimen

In this work materials have been chosen as transparent acrylic plastic. The dimensions of the samples are 80X35X4, and lap weld configuration chosen for lapping zone of 20mm.

Fig. 2.1: Weld sample

2.2 Acrylic

Acrylic is a clear colourless polymer having high strength, toughness, heat resistance & excellent dimensional stability, which is used extensively for engineering, household, medical and optical applications.

Acrylic (PMMA) was first developed in 1928 by William Chalmers, Walter Bauer. In most popular trade name are CRYLUX, PLEXIGLAS, PERSPES. PMMA is not a type of familiar of silica based glass, it is often technically classified as a type of glass (It is a non-crystalline vitreous substance)[43]. PMMA is a good material choice in industry not only due to its characteristics but also because its processing is environmentally friendly it does not contain the potentially harmful “bisphenol-A” and also economic.

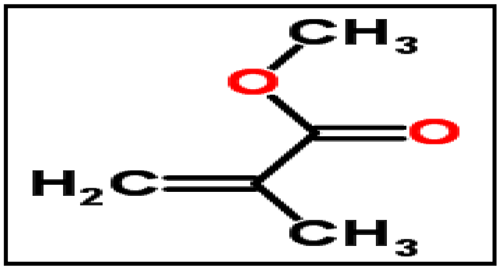

Fig.2.2: Molecular structure of Acrylic.

A. Physical properties of acrylic are given below

Table: 2.1 Physical properties of acrylic.

Density	1.18 g/cm^3
Abbe number	40.5
Refractive index	1.54
Flammability	94HB
Limiting oxygen index	(17-20)%
Water absorption –equilibrium(ASTM)	(2)%
Radiation resistance	Low
Ultraviolet resistance	Low

B. Mechanical properties of acrylic are given below

Table: 2.2 Mechanical properties of acrylic.

Young’s modulus	3.2 GPa
Tensile strength **(σt)**	70 MPa
Elongation at break	(4)%
Compressive strength	97.22-124.10 MPa
Poisson’s ratio	0.35-0.4
Hardness –Rockwell	D-875 M-94
Notch test	2.16J/m

C. Thermal properties of acrylic are given below

Table: 2.3 Thermal properties of acrylic.

Glass transition temperature	114 °C
Upper working temperature	70 °C
Lower working temperature	−40 °C
Thermal conductivity(k) at 23 **°C**	0.19 W/(m·K)
Linear thermal expansion co-efficient (α)	70×10^{-6}/K
Specific heat capacity(c)	1.47–1.50 J/(kg·K)

D. Electrical properties of acrylic are given below

Table:2.4 Electrical properties of acrylic.

Surface resistivity	$15\Omega/m^{2}$
volume resistivity	$> 10^{14}\Omega$.m

2.3 Permanent marker

In this experiment black permanent marker is used to provide absorbent layer. Here welding takes place in between the two transparent acrylic plates, so increase the absorptivity of lower plate used permanent black marker. In general, the ink comprises a main carrier solvent, a glyceride, a pyrrolidone, a resin and a colourant[44]. Glycerides, also known as acylglycerols. It is formed from glycerol and fatty acids.

2.4 Instruments used for experiments

The instruments here used for the experiments are as follows:

2.4.1. Main Laser unit

The welding experiments have been takes places in EMS 100 laser marking machine.

Specifications of the main laser unit

Maker: Electrox

Dimension of the work station:-26″ wide ×37″ deep×31″tall

Pilot laser

Laser used: Diode laser. Class: ıı
Wave length:-635-680 nm
Maximum power:-1 mW
Output:-CW (Continuous wave)

Working laser

Nd: YVO4 (Neodymium doped yttrium orthovanadate)

Class: - ı
Power: 9.28 W
Frequency: up to 500 kHz
Marking speed (0.15 to 10160) mm/s
Wavelength: - 1064 mm

Lens type: - Galvo lens (S163)

Operating temperature:-0˚C to 25 ˚ C

Spot diameter: - 50 µ

Fiber cable:-800 nm.

Working distance:-183 mm.

Field diameter:-144mm.

Nd: YVO4 Laser

In this machine Laser crystals are used to generate laser radiation. The commonly used laser crystals include Nd: YAG, Nd: YVO4 and Nd: YLF for near IR lasers, and Ti: Sapphire for tunable near IR output. Specifically, Nd: YVO4, for diode pumped solid state lasers were developed because diode pumping attracts more and more interest of both R&D and OEM customers. The laser crystals supplied include Nd: YVO4, Nd: YAG, Gr: YAG, etc. We also provide complete kits of crystals and optics for assembling your diode pumped solid state lasers.

Nd: YVO4 is one of the most efficient laser host crystal currently existing for diode laser-pumped solid-state lasers. Its large stimulated emission cross-section at lasing wavelength, high absorption coefficient and wide absorption bandwidth at pump wavelength, high laser induced damage threshold as well as good physical, optical and mechanical properties make Nd:YVO4 an excellent crystal for high power, stable and cost-effective diode pumped solid-state lasers. Developments have shown that Nd: YVO4 can produce powerful and stable IR, green, blue lasers with the design of Nd: YVO4 and frequency doubling crystals.

Compared with Nd: YAG and Nd: YLF for diode laser pumping, Nd:YVO4 lasers possess the advantages of lower dependency on pump wavelength and temperature control of a diode laser, wide absorption band, higher slope efficiency, lower lasing threshold, linearly polarized emission and single mode output. For the applications in which more compact design and the single-longitudinal-mode output are needed, Nd: YVO4 shows its particular advantages over other commonly used laser crystals. The diode laser-pumped Nd:YVO4 compact laser and its frequency-doubled green, red or blue laser light will be the ideal laser tools of machining, material processing, spectroscopy, wafer inspection, light show, medical diagnostics, laser printing and the most widespread applications.

Fig.2.3: Laser welding machines.

System specifications

An IBM PC or compatible, 1GHz CPU (AMD, Intel), 128 Mega Bytes of RAM, 16 Mega bytes of video RAM CD ROM drive. SVGA monitor set to 1024×768 resolutions free serial port, free USB port (version 1.0 or later) (32 bit PCs only),free Ethernet port. Free space on hard disk-Minimum of 12Mbytes. Operating system: Windows98, ME, 2000,XP9home or professional or Windows 7 operating system installed-Windows XP is preferred.

Software specifications

Program: Electrox Scriba 3 Laser marking program.

Written in: - C++ (copyright Borland International Inc).

Communication port with the laser marker:-RS232 serial port, a USB port (VERSION 1.0 or later) Oran Ethernet port.

Computer interface

The digital control signal can be generated locally, using the front panel keyboard or remotely using a personal computer or device capable of sending and receiving ASCII via RS-232 interface.

2.4.2 Optical transmissive microscope

An optical transmission microscope has been used to measure the weld width of welded samples. Here the microscope used for measurement purpose is **LEICA DMLM** optical microscope. The many different configuration options, based on a tailored system for all industrial microscope applications, make the **LEICA DMLM** the all-purpose microscope in every factory laboratory. The wide choice of objectives enables brilliant imaging quality for all customary imaging techniques.

Specifications of microscope

i. Maker name: Diwinter
ii. Microscope Type: Compound
iii. Objective lens: N PLAN achromat 5x, 20x,100x
iv. Techniques: Bright field, Dark field, DIC, Phase, Oblique
v. Working distance: 14 mm – 3.5mm
vi. Stage dimension: 20 mm x 13.5 mm
vii. Max sample height: 50 mm
viii. Automatic voltage adaptation and stabilization.
ix. Rotatable, ceramic-coat edstage.
x. Flexible stage height settings (up to 100 mm) for large objects.

2.4.3 Universal testing machine

The universal testing machine has been used to establish the pool test to determine the quality of the weld samples. A pictorial view of UTM machine is shown below.

Fig 2.4:Universal testing machine.

Specifications

Maker: Instron

Maximum capacity: 100 kN

Accuracy: ±0.4

Microprocessor controlled.

2.5 Experimental procedure

Two acrylic sheet are cut according to the specification then cleaning and preparing the samples for welding. The Electrox EMS 100 laser marking machine has been prepared for welding operation. The suitable clamping pressure is required for the experiment that has been given by a binder clip. The overlap length has taken as 20 mm average. The laser beam has been scanned through the middle of the overlap zone just above the marker line. For the welding purpose Neodymium-doped yttrium orthovanadate (Nd:YVO$_4$) having wavelength of 1064 nm has been used. Pictorial view of welded sample in lap joint configuration is shown in **Fig. 2.7.** Twenty experiments have been conducted as per RSM design matrix. The number of repetition is 20 for each experiment. The selected process parameters and their notations, units, and levels are given in **Table: 2.5.** Trial runs have been conducted by varying one of the process parameters at a time while keeping the rest of the parameters. The weld width is measured by optical microscope. Breaking load determined by Universal testing machine (UTM).

2.6 Design of experiment

The design of experiments is an organized way to conduct and analyzing controlled test to evaluate the factor affecting response variable. It is one of the phase of experiment work where participating factors along with their level are decided. The design specification are the particular setting level of the combination of factors at which the individual run in the experiment have to be conducted. It is a multivariable testing method where simultaneous variations of factors are performed and as the factors are varied independently of each other, a causal predictive model can be determined. Modern computer based DOE tool can quickly build a design for any predictive model and they do it virtually for any real world combination of factors type, additional constraint, and special model. It controls of the input factors in such a way as to deduce the relationship with the output.

The design of experiments has been invented by Ronald A. Fisher in the 1920's and it specifies the particular setting levels of the combination of factors at which the individual runs in the experiments are to be conducted[45]. The fundamental principles in design of experiments are solutions to the problem in experimentation posed by the types of nuisance factors and serve to improve the efficiency of experiments.

2.6.1. Response surface methodology (RSM) approach to design the experiment and analysis

Response surface methodology is a collection of mathematical and statistical techniques that are use full for analysis of problems in which a response of interest is influenced by several variables and objective is to optimize the response.

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

$$y= (x_{1,} x_{2} \ldots\ldots\ldots\ldots x_{k}) +\epsilon \qquad \textbf{(2.1)}$$

Where, y is the response of the system x_i are the variable of the action called factors and ϵ represent the noise. Error observed in the response y. If we denote the expected response by (y) = f ($x_{1,}$ x_2) =σ, then the surface represented by

σ= ($x_{1,}$ x_2) and is called response surface.

In the practical application of RSM it is necessary to develop an approximating model for the true response surface. The approximating model is based on observed data from the process or system and is an empirical model. Multiple regression analysis is a collection of statistical technique use full for building the types of empirical models required in RSM. If the response is well modeled by a linear function of the independent variables, then the approximating function is the first order model.

$$Y= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots\ldots\ldots + \beta_4 x_4 + \epsilon \qquad \textbf{(2.2)}$$

If there is curvature in the response system, then usually following second order polynomial **Eq.** is used in RSM.

$$Y= \beta_0 + \sum_{i=1}^{k} \beta i\, xi + \sum_{i=1}^{k} \beta ij\, xi\hat{}2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta ij x_{ij} + \epsilon \qquad \textbf{(2.3)}$$

Where parameters β_{ij}=0,1……k are called the regression coefficients.

RSM was developed to model experimental responses (Box and Draper, 1987), and then migrated into the modeling of numerical experiments. The difference is in the type of error generated by the response. In physical experiments, inaccuracy can be due, for example, to measurement errors while, in computer experiments, numerical noise is a result of incomplete convergence of iterative processes, round-off errors or the discrete representation of continuous physical phenomena (Giuntaet al., 1996; van Campen et al., 1990, Toropov et al., 1996). In RSM, the errors are assumed to berandom.

Central Composite Design (CCD)

Each factors varies over five levels.

Typically smaller than Box Behnken designs.
Built upon two level factorials or fractional factors of resolution V or greater.
Can be done in stage :factorial +centre points + axial points.

General structure of CCD

i.2kfactorials + 2k star or axial points + nc points

ii. The star or axial points in junction with the factorial and centre points allows the quadratic terms to be estimated.

iii. The factorial part can be a fractional factorial as long as it is of resolution V or greater so that the two factor interaction terms are not aliased with each other 2 factors interaction terms.

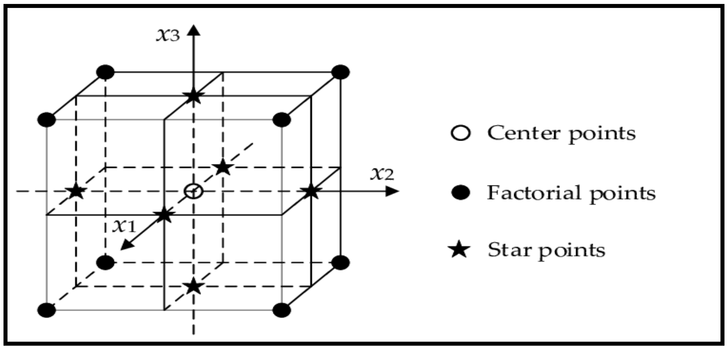

Fig.2.5: central composite design for 3 design variables

2.6.2. Desirability analysis function

The desirability function analysis method is first proposed by Derringer andSuichin1980.Thismethod makes use of a technique for combining multiple responses into a dimensionless measure of performance called the composite desirability function. The general approach of desirability function is to transfer each response y_i into an unit less desirability function d_i bounded by $0 \le d_i \le 1$ where ,the desirable ranges are from zero to one ,as least to most desirable, respectively.

For the goal of maximum, the desirability function will be defined by

$$d_{1=}\begin{cases} 0 & \text{If response (yi)} \le \text{lower value (Li)} \\ (\mathrm{yi} - \mathrm{Li}/\mathrm{Hi} - \mathrm{Li})^{w\mathrm{ti}} & \text{response (yi) varies from low (Li) to high (Hi)} \\ 1 & \text{If response (yi)} \ge \text{higher value(hi)} \end{cases} \tag{2.4}$$

For the goal of minimum, the desirability function will be defined by

$$d_{1=}\begin{cases} 1 & \text{If response (yi)} \le \text{lower value (Li)} \\ (\mathrm{Hi} - \mathrm{yi}/\mathrm{Hi} - \mathrm{Li})^{w\mathrm{ti}} & \text{response (yi) varies from low (Li) to high (Hi)} \\ 0 & \text{If response (yi)} \ge \text{higher value (Hi)} \end{cases} \tag{2.5}$$

A weight (wt.) can be assigned to a goal to emphasize the particular desirability function. Weights can be ranged between 0.1 and10.Aweight greater than1 gives more emphasis to the goal, while weights less than 1 give less emphasis. The simultaneous objective function, D is a geometric mean of all transformed responses:

$$D = (\mathrm{d1}^{\mathrm{r1}} \times \mathrm{d1}^{\mathrm{r2}} \times \mathrm{d1}^{\mathrm{r3}} \times \mathrm{d1}^{\mathrm{r4}} \times \ldots\ldots\ldots..\times \mathrm{d1}^{\mathrm{rn}})\frac{1}{\sum \mathrm{r1}} = \frac{(\prod \mathrm{i}=1^{\mathrm{n}}\, \mathrm{di}^{\mathrm{ri}})}{\sum \mathrm{ri}} \tag{2.6}$$

Where n is the number of responses in the measure. Each response can be assigned an importance, relative to the other responses. Importance (ri) values varies from1, the least important, to 5, the most important.

2.6.3 Application procedure of RSM

Generally RSM is applied in the following ways:

a) Selection of process parameters.

b) Finding the limits of process parameters.

c) Developing the design matrix.

d) Run the experiment based on the design matrix.

e) Measure the output response and put it to the design matrix.

f) Analysis of the output results and find out the relationship between input and output parameters.

g) Finally the optimum values of output response identify.

In the selection of process parameters three independently controllable process parameters

2.7. Developing the design of matrix

Power, frequency, and speed are considered as input parameters to carry out the experiments. In case of finding the limits of process parameters Trial runs are conducted by varying one of the process parameters at a time while keeping the rest of them at constant value. The working range is decided by inspecting the weld seam for a smooth appearance and the absence of any visible effects .The upper and lower limits are coded as +2 and -2 respectively. The selected design matrix shown in **Table: 2.5** is a three factors five level central composite rotatable design with full replications consisting of 20sets of coded conditions and consists of full replication of 2^3 cube points and 6 axial points and 6 centre points. Next is to run the experiment based on the design matrix's individual experiment no. After the experiment the response output measure and put it to the design matrix and analyses the result and finally the optimum criteria achieved.

The experiment is designed, based on three factors three level central composite rotatable design.

The design matrix is given in the **Table: 2.5** The CCD comprises of $2^3 = 8$ factorial design plus 6 centre points in cube and 6 axial or star point. In this transmission laser welding process, the maximum power of working laser is 9.28 watt.

Table 2.5:Design matrix for experiment

Experiment no.	**Power , P (w) (%)**	**Frequency ,f (kHz)**	**Scanning speed ,S (mm/s)**
1	**90**	**30**	**1**
2	**85**	**15**	**3.5**
3	**85**	**45**	**3.5**
4	**85**	**45**	**1.5**
5	**90**	**30**	**6**
6	**85**	**45**	**8.5**
7	**80**	**30**	**1**
8	**95**	**45**	**3.5**
9	**75**	**45**	**3.5**
10	**85**	**75**	**3.5**
11	**80**	**60**	**1**
12	**85**	**45**	**3.5**
13	**85**	**45**	**3.5**
14	**85**	**45**	**3.5**
15	**80**	**30**	**6**
16	**90**	**60**	**6**
17	**90**	**60**	**1**
18	**85**	**45**	**3.5**
19	**85**	**45**	**3.5**
20	**80**	**60**	**6**

Chapter 3: Result and discussion

3.0 Result and discussion

According to the experimental plant the experiments was conducted. The lap joints are made by using laser welding process and results of welding strength and welding width have been presented in **Table: 3.1**.The mathematical model of each response has been developed, also response surface plots and contour plots have been generated.

For the measurements of weld width, the optical microscope has been used. To measure the average weld width, for each sample measurements have been taken from three-four different locations. Maximum weld width for sample 418 µm. and minimum weld width for sample 205.57 µm. From the **Table: 2.5** it can be noted that the average weld width varies from 418 µm to 205.57 µm. Like weld width, it is also noted from table that weld strength varies from 2.9836 N/mm to 28.5872 N/mm.

Failure analysis plays a important role and is significant in the manufacturing of mechanical parts. Through the failure analysis, it is helpful to formulate the process parameters reasonably and improve the adaptability of the application.

There are two main types of failure: interfacial and substrate. The failure of the interface is mainly due to the tensile strength of the welded joint, which is smaller than that of the base plate. When the welding intensity is getting larger, the fracture will generate along the weld seam and even the centre of base plate.

Table 3.1: Result obtained of the weld width & weld strength of each welded sample.

Experiment no.	Power, p (W)(%)	Frequency, f (kHz)	Scanning speed ,S (mm/s)	Weld width(WW) (μm)	Weld strength,(WS) (N/mm)
1	90	30	1	418	27.9
2	85	15	3.5	276	10.78
3	85	45	3.5	295	12.859
4	85	45	1.5	372	22.514
5	90	30	6	205.57	6.9721
6	85	45	8.5	253.451	6.7583
7	80	30	1	406	25.846
8	95	45	3.5	279	16.213
9	75	45	3.5	334	14.351
10	85	75	3.5	285	16.613
11	80	60	1	362	28.5872
12	85	45	3.5	300	12.5376
13	85	45	3.5	296	12.6394
14	85	45	3.5	298	12.6132
15	80	30	6	263	2.9836
16	90	60	6	230	9.1261
17	90	60	1	375	26.7852
18	85	45	3.5	287	12.9174
19	85	45	3.5	297	12.9217
20	80	60	6	302	9.8251

3.1 Analysis of variance (ANOVA)

To investigate the influence of process parameters on weld width and weld strength, RSM based analysis has been made and mathematical model for each response parameters has been developed. The main aim is to correlate mathematical relationship between the process parameters and the response. A second order quadratic polynomial **Eq.** is applied to develop the regression **Eq.** (mathematical model). MINITAB 17 SOFTWARE is used for the analysis of the responses and the mathematical models with best fit. The effect of each parameter is studied on the basis of the developed mathematical models.

3.1.1 ANOVA for weld strength

The ANOVA table of the quadratic model for weld width is given in **Table3.2**. The associated p- value of less than 0.05 for the model indicates that the model terms are statistically significant. P- Value of most of the terms is less than 0.05.So most of the terms is statistically significant. The ANOVA result shows that the main effects of the laser power (P), welding frequency(F) , welding speed(S), the quadratic effect of the power (P^2), welding speed (S^2) along with the interaction effect of power and welding frequency (PF) , Power and speed (PS) are the significant model terms associated with the weld seam width. The other adequacy measure R^2, adjusted $R^2$and predicted R^2, are in reasonable agreement and is closed to 1,which indicate adequate model. The lack of fit p-value is 0.114

Regression **Eq.** for weld strength (WS) using data in un coded units is shown in **Eq. (3.1)**

$$WS = 174.1 - 3.882\ P + 1.111\ F - 11.646\ S + 0.02651\ P * P + 0.001184\ F * F + 0.5655\ S * S - 0.01424\ P * F + 0.0303\ F * S + 0.02456\ F * S \qquad \mathbf{(3.1)}$$

Table: 3.2: Analysis of variance for weld strength model

Source	DF	Adj. SS	Adj. MS	F-value	P-value
Model	**9**	**1054.17**	**117.130**	**1920.96**	**0.000**
Linear	**3**	**467.66**	**155.888**	**2556.59**	**0.000**
Power	**1**	**4.42**	**4.243**	**72.54**	**0.000**
Frequency	**1**	**36.65**	**36.647**	**601.02**	**0.000**
Speed	**1**	**426.59**	**426.593**	**6996.21**	**0.000**
Square	**3**	**161.73**	**53.911**	**884.15**	**0.000**
P^2	**1**	**11.41**	**11.410**	**187.13**	**0.000**
F^2	**1**	**1.84**	**1.884**	**30.24**	**0.000**
S^2	**1**	**157.24**	**157.241**	**2578.78**	**0.000**
2- Way Interaction	**3**	**17.07**	**5.688**	**93.29**	**0.000**
P*F	**1**	**9.12**	**9.124**	**149.63**	**0.000**
P*S	**1**	**1.15**	**1.153**	**18.91**	**0.001**
f*S	**1**	**6.79**	**6.788**	**111.32**	**0.000**
Error	**10**	**0.61**	**0.061**		
Lack-of-fit	**5**	**0.46**	**0.093**	**3.19**	**0.114**
Pure error	**5**	**0.15**	**0.029**		
Total	**19**	**1054.78**			

S = 0.246931R^2 =99.94Predicted R^2 =99.70%   Adjusted R^2 = 98.89%

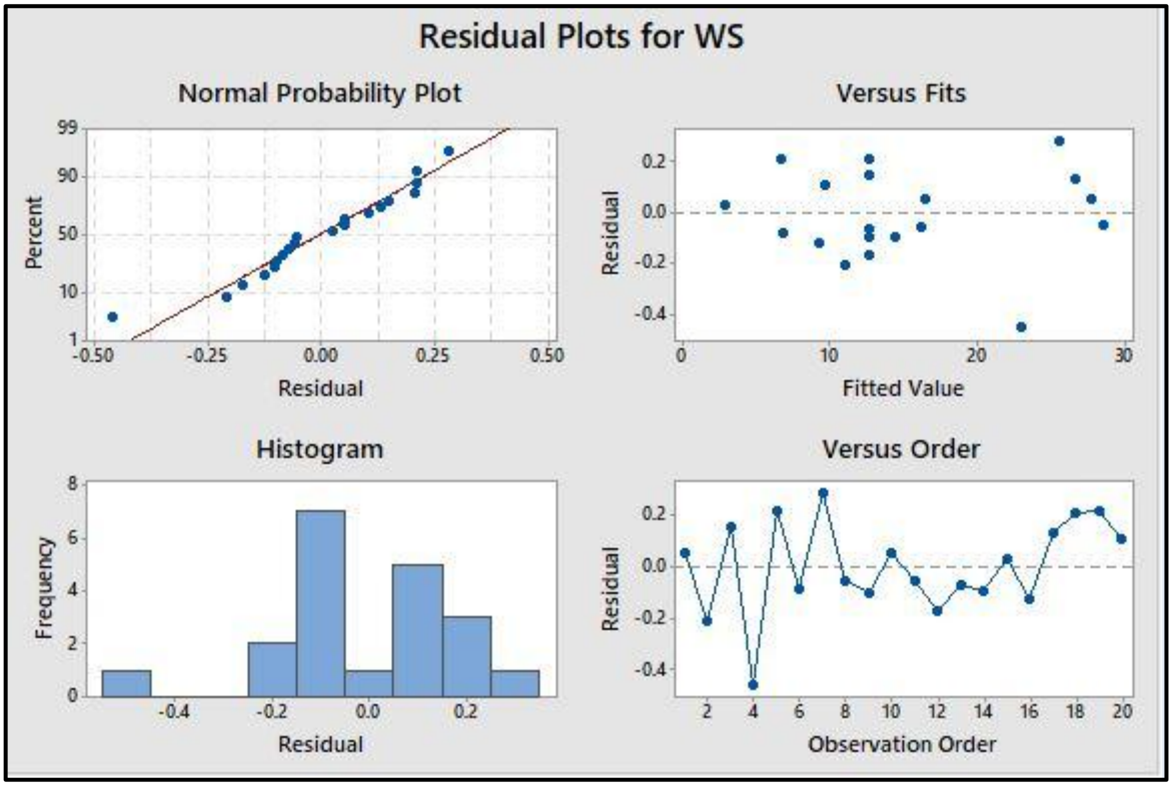

Fig.3.1: Residual plots for weld strength

3.1.2 ANOVA for weld width

The ANOVA table of the quadratic model for weld width is given in **Table:3.3**.The associated p-value of less than 0.05 for the model indicates that the model terms are statistically significant. P-Value of most of the terms is less than 0.05.So most of the terms is statistically significant. The ANOVA result shows that the main effects of the laser power (P), welding frequency(F) ,welding speed(S),the quadratic effect of the power (P^2),welding speed (S^2) along with the interaction effect of power and welding frequency (Pf) , Power and speed (PS) are the significant model terms associated with the weld seam width. The other adequacy measure R^2, adjusted R^2,and predicted R^2,are in reasonable agreement and is closed to 1,which indicate adequate model. The lack of fit p-value is 0.371

Regression **Eq.** for weld width (WW) using data in un coded units is shown in **Eq. (3.2)**

$$WW = 946 - 14.48\,P + 1.67\,F + 52.5\,S + 0.1072\,P * P - 0.01698\,F * F + 3.995\,S * S - 0.226\,P * F - 1.544\,P * S + 0.5014\,F * S \qquad \mathbf{(3.2)}$$

Table: 3.3: Analysis of variance for weld width model

Source	DF	Adj. SS	Adj. MS	F-value	P-value
Model	**9**	**58632.0**	**6514.7**	**249.83**	**0.000**
Linear	**3**	**27853.3**	**9284.4**	**356.05**	**0.000**
Power	**1**	**5669.1**	**5669.1**	**217.40**	**0.000**
Frequency	**1**	**874.4**	**874.4**	**33.53**	**0.000**
Speed	**1**	**21309.9**	**21309.9**	**817.21**	**0.000**
Square	**3**	**8771.1**	**2923.7**	**112.12**	**0.000**
P^2	**1**	**186.5**	**186.5**	**7.15**	**0.023**
F^2	**1**	**379.0**	**379.0**	**14.53**	**0.003**
S^2	**1**	**7846.6**	**7846.6**	**300.91**	**0.000**
2-way Interaction	**3**	**5832.7**	**1944.2**	**74.56**	**0.000**
P*F	**1**	**23.0**	**23.0**	**0.88**	**0.370**
P*S	**1**	**2981.1**	**2981.1**	**114.32**	**0.407**
F*S	**1**	**2828.6**	**2828.6**	**108.48**	**0.000**
Error	**10**	**260.8**	**26.1**		
Lack-of-fit	**5**	**159.3**	**31.9**	**1.57**	**0.317**
Pure error	**5**	**101.5**	**20.3**		
Total	**19**	**58892.8**			

S = 5.10651 R^2 =99.56% Predicted R^2 =97.23% Adjusted R^2 = 99.16%

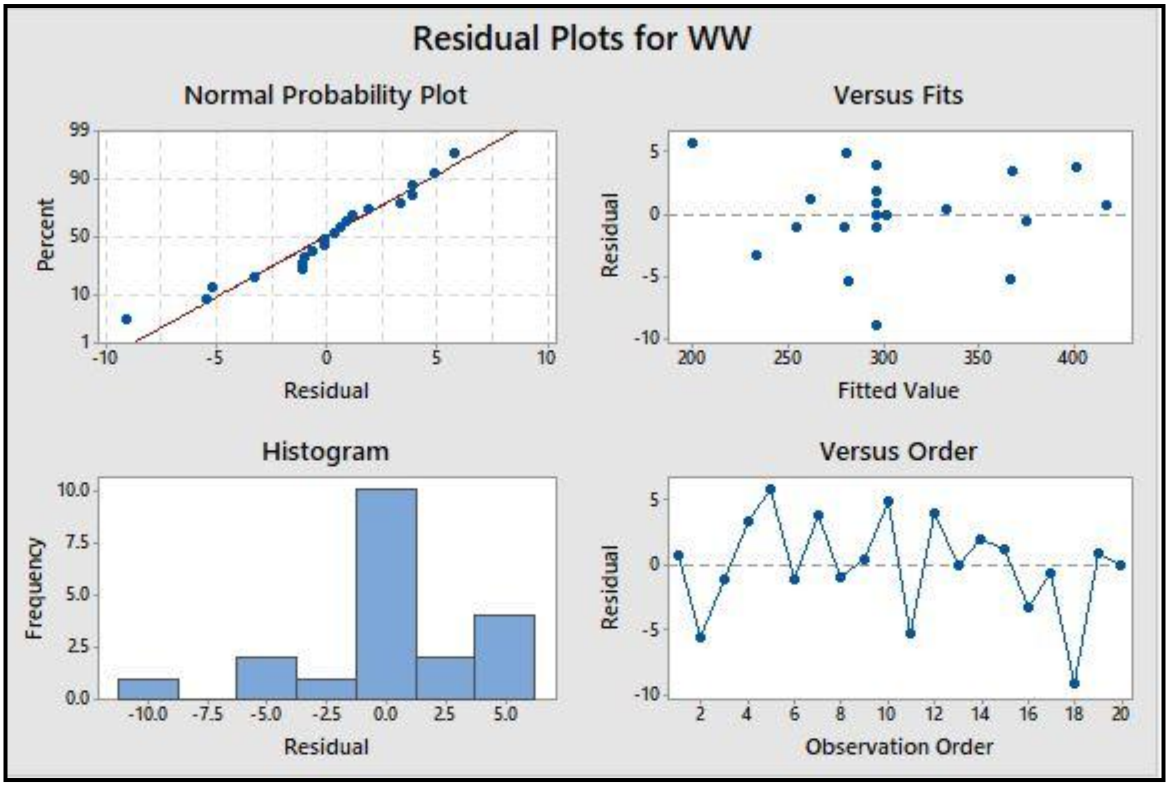

Fig.3.2: Residual plots for weld width

3.2 Effects of process parameters on response

The effect of process parameters on weld-seam width and weld strength of the welded sample is studied and discuss here in, with in the factors limits considered in this study and for the specified materials. Factors interactions plots are used to present the results in graphical form. All the significant interaction terms related to weld-seam width and weld strength models are plotted and their effect trends are explained in details.

3.2.1 Effects of process parameters on weld strength

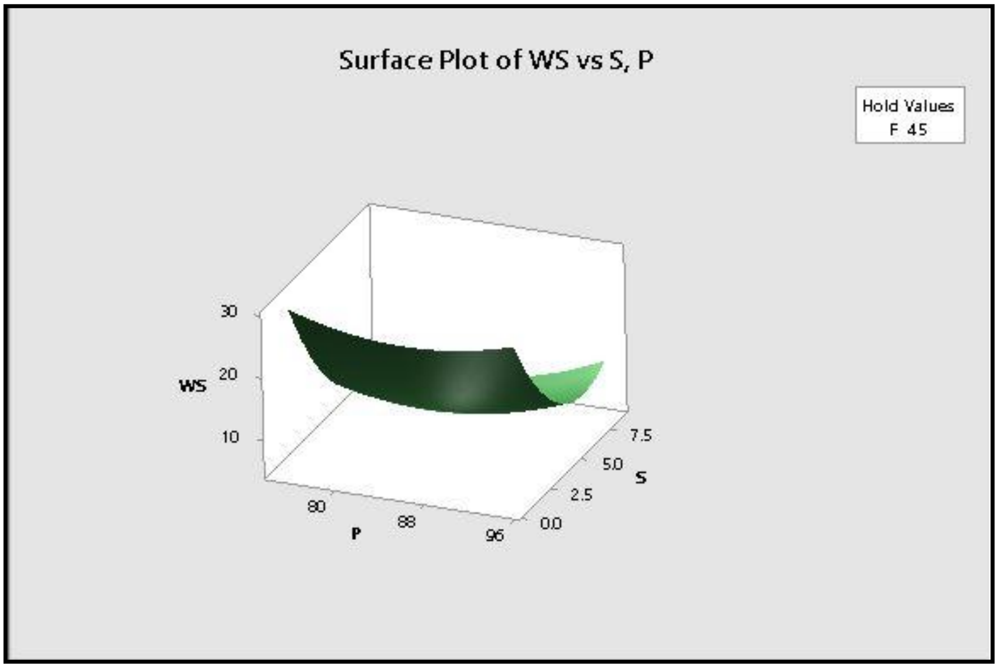

Fig. 3.3: 3D response surface plot of welding power and welding speed on weld strength

It is observed from the above **Fig. 3.3** that increasing the laser power weld strength started to decreases after a certain value and there after increases. With the decreasing speed the weld strength increases and reaches to maximum for minimum value of weld speed. In general weld strength has direct relation with power but here with increasing power above a certain value of power weld strength decreases due to high amount of heat results in evaporation of weld materials before the welding takes place. At the low speed the weld materials get sufficient time to melt that leads to higher weld strength.

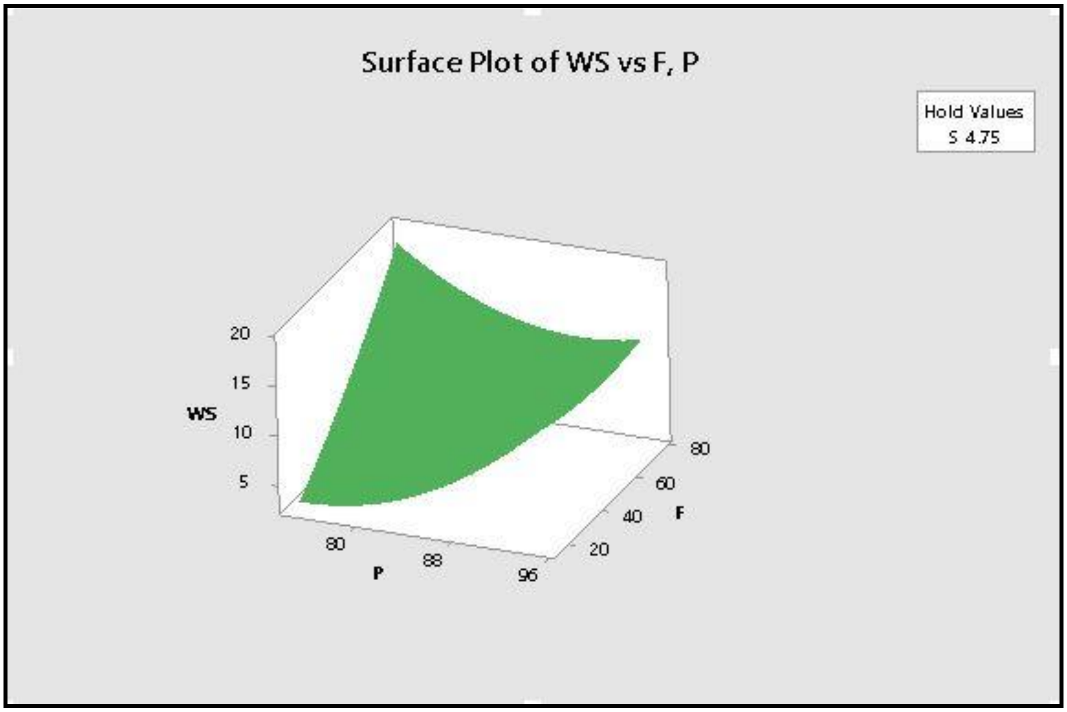

Fig. 3.4: 3-D response surface plot of welding power and frequency on weld strength

It is observed from **Fig. 3.4** that with increasing of power weld strength increases. With the increase of frequency the weld strength also increases. This is due to reason that for a particular speed with increasing power and frequency melting of base material will be increased and it will make a strong bond between two parents material. As a result after solidification, stronger joint will produce. It is also observed from the above picture that for a middle value of power and frequency weld strength is maximum.

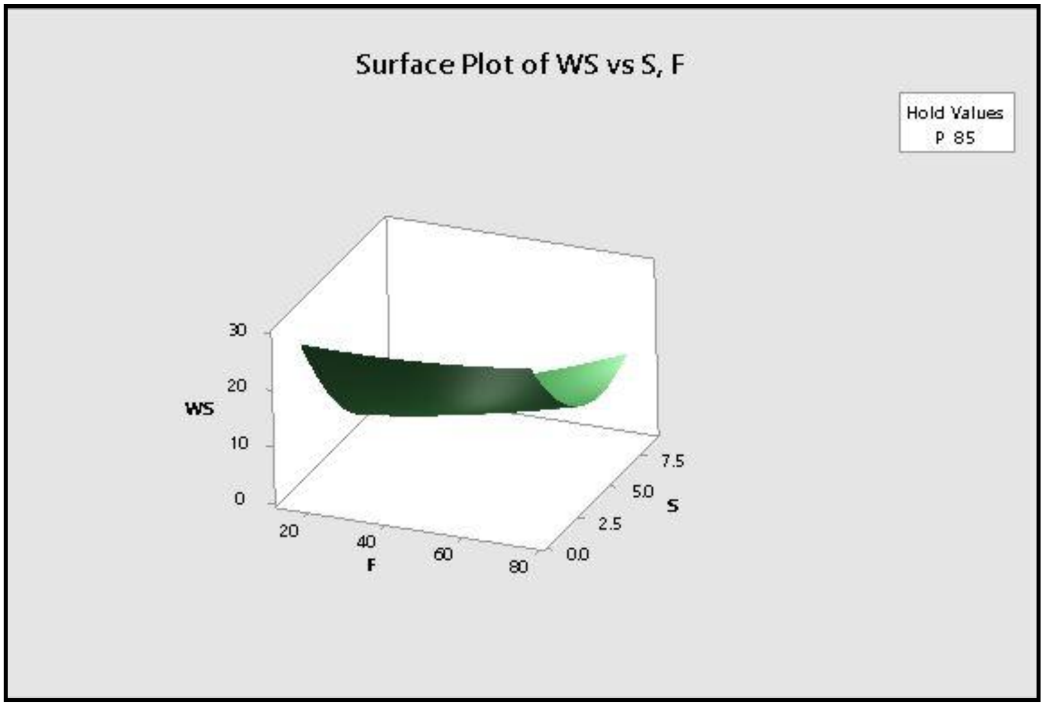

Fig.3.5: 3-D response surface plot of frequency and welding speed on weld strength

It is observed from the above **Fig. 3.5** that with increasing frequency weld strength decrease slightly and with decreasing speed strength decrease first after that increases. The strength decreased because with decreasing speed interaction time also increased but for higher frequency temperature of the material will go above the melting will happened up to the materials melting point after that it will vaporized. At minimum freq. and maximum speed strength also minimum because due to high speed less interaction time between base material and laser power and as a result less material will melt and will solidify that leads to weak joint.

3.2.2 Effects of process parameters on weld width

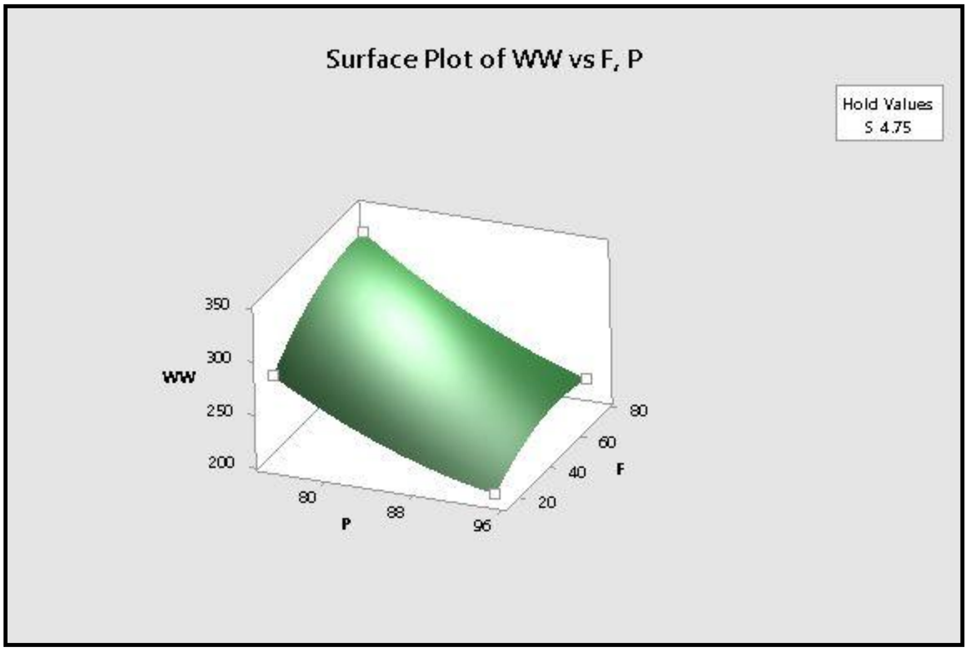

Fig. 3.6: 3-D response surface plot of frequency and power on weld width

It is observed from the above **Fig. 3.6** parameters with increasing power weld width is decrease and with the decreasing frequency weld width also decreased. This is due to for high energy and for lower frequency penetrate deeper than wider. As a result less weld width achieve here. At low power and low higher frequency weld width is moderate. In case of low frequency and maximum power it exceeds plastic's melting temperature and after melting vaporization happened. Due to less weld width achieved.

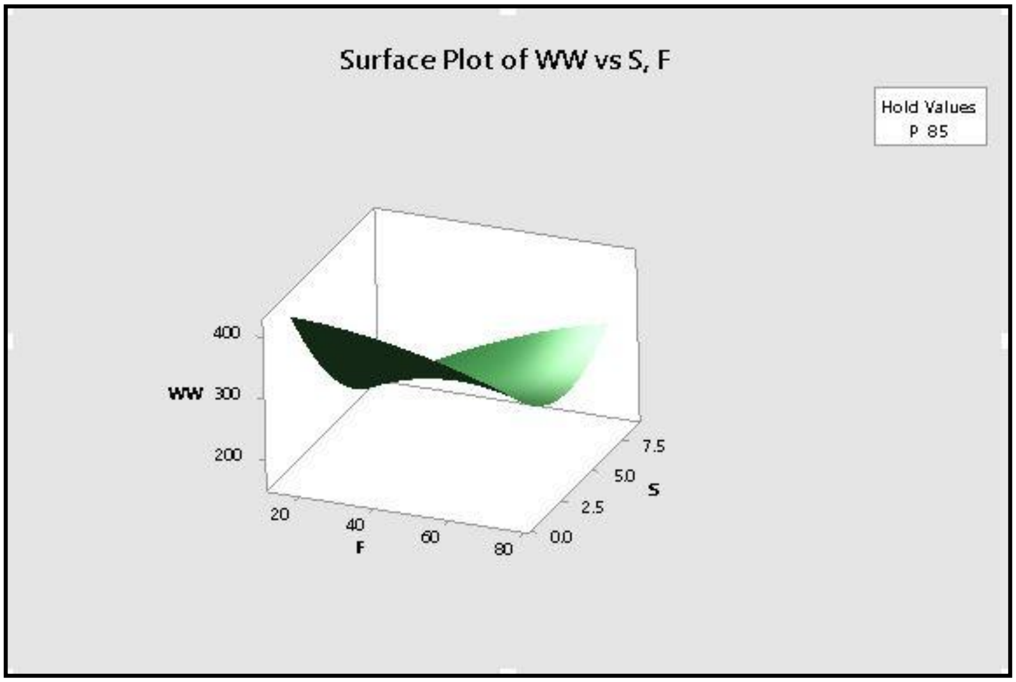

Fig. 3.7: 3-D response surface plot of frequency and welding speed on weld width

It is observed from the above **Fig. 3.7** parameters that with the increasing frequency weld width also decreases. This is due to for high energy and for higher freq. more base material will melt and make a strong chemical bond between two parent plastics. As a result strong joint achieve. Here power is dominating factor. At low power and low frequency width is moderate. In case of low frequency and maximum power it exceeds plastic’s melting temperature and after melting vaporization happened. Hence, it result in lesser weld width.

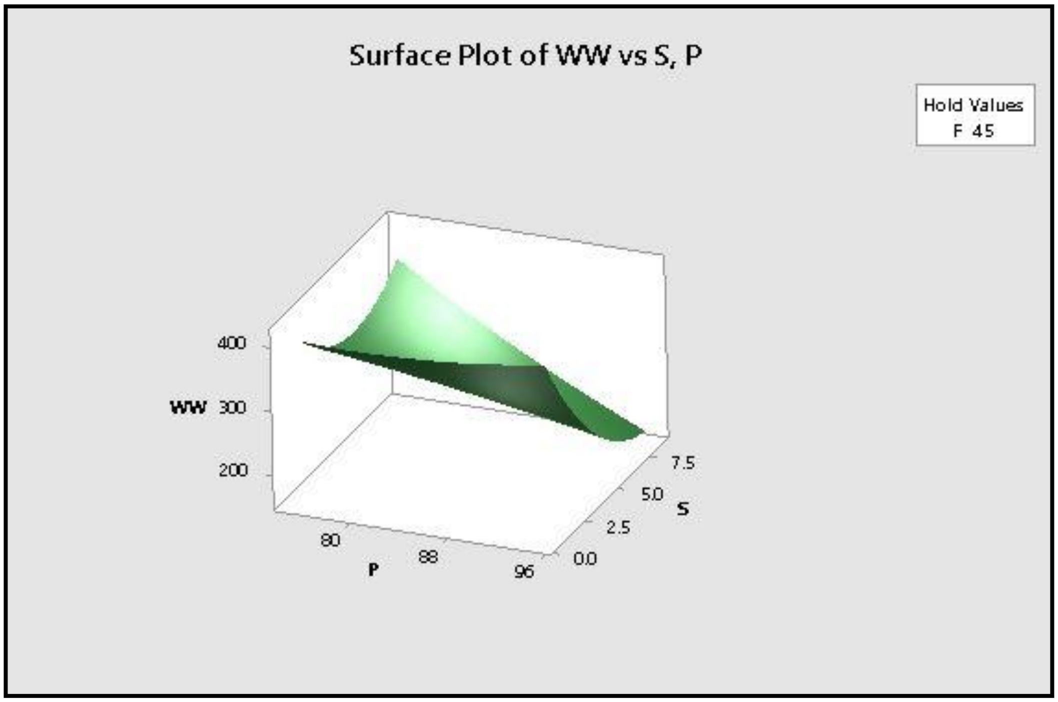

Fig. 3.8: 3D response surface plot of welding power and welding speed on weld width

It is observed from the above **Fig. 3.8** that with the increasing power weld width slightly decreases and at the lowest speed weld width is maximum. With the increasing speed up to a certain limit weld width is minimum. When speed is less the interaction time is more so weld width is high.

Chapter 4: Optimization of Parameters

4.0 Optimization

In this chapter effort is made to simultaneously optimize the weld strength and the weld width for laser transmission welding of acrylic. Therefore RSM based single objective optimization and multi objective optimizations have been done, in order to find out the optimum parametric condition. The optimum condition is identified for maximization of weld strength and minimization of weld width individually and then combination of both according to the desired optimization criteria.

4.1 Single objective optimization for maximum weld strength

Fig. 4.1 shows that optimization result for maximum weld strength based on the mathematical model developed using **Eq. (3.1).** To maximize the response, equal importance has been placed on the lower, target, and upper bound of linear desirability function. For linear desirability function, the value of the weight is considered as 1. Maximum weld strength has been obtained as 35.0299 N/mm. The required input value for the desired output is P (75%), F (75 kHz), S (1.0mm/s) respectively. The predicted setting is in the range of experimental performance indicative of the goal selection of parametric ranges. The weld strength obtained for given optimized for given optimized setting is N/mm indicates that the better result can be obtained. The optimization for welding seam width is obtained using response optimizer in MINITAB software.

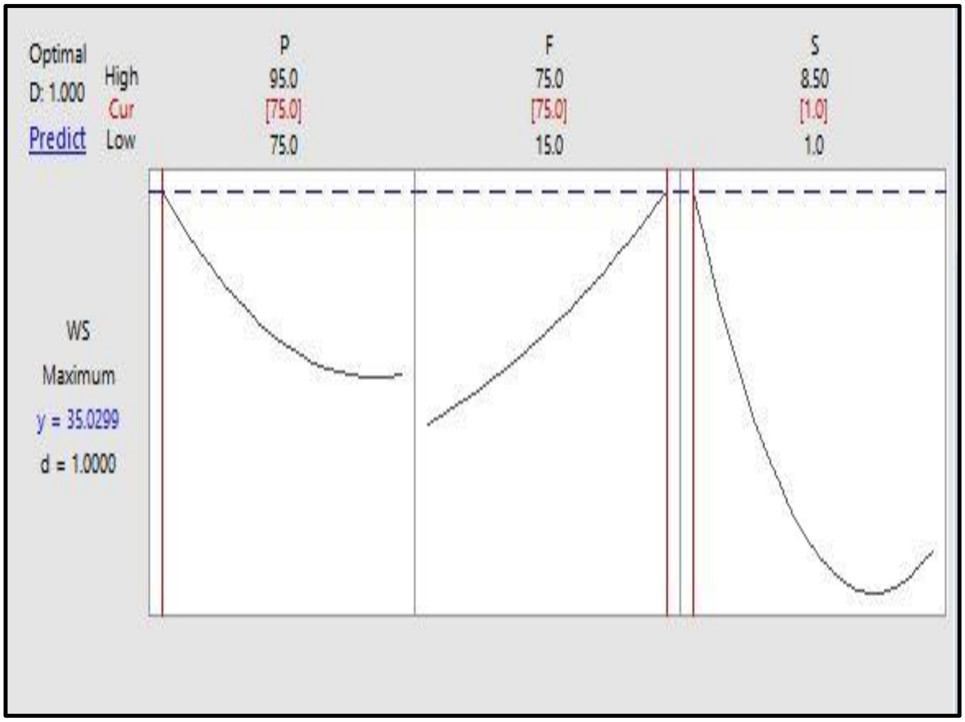

Fig.4.1: Optimization for maximum weld strength

4.2 Single objective optimization for minimum weld width

Fig. 4.2 shows the optimization results for minimum weld width based on the mathematical model developed using **Eq. (3.2)**.To minimize the response, equal importance has been placed on the lower, target, and upper bound of linear desirability function. For linear desirability function, the value of the weight is considered as 1. Minimum weld width has been obtained as 118.8497µm. The required input value for the desired output is P (90%), F (15 kHz), S (8.5mm/s) respectively.

The predicted setting is in the range of experimental performance indicative of the goal selection of parametric ranges. The weld width obtained for given optimized for given optimized setting is 118.8497µm indicates that the better result can be obtained. The optimization for welding width is obtained using response optimizer in MINITAB software.

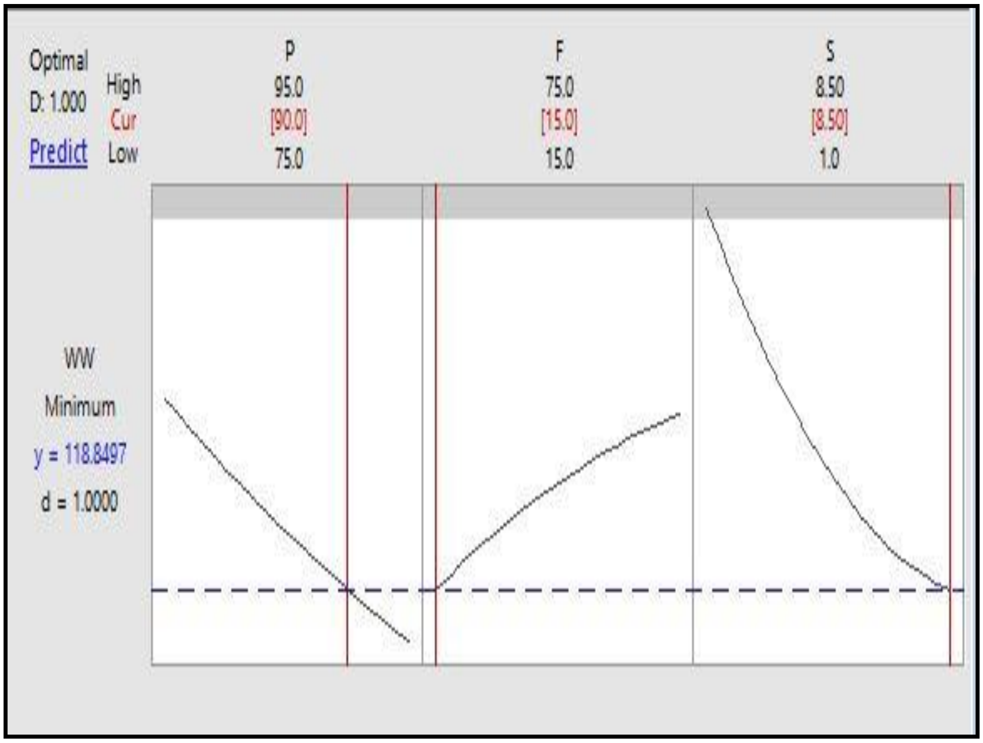

Fig.4.2: Optimization for minimum weld width

4.3 Multi-objective optimization

Fig. 4.3 shows the multi-objective optimization analysis where two responses have been analyzed together in one settings. In multi-objective optimization the goal is to maximize the weld- strength and minimize the weld seam width with a combined approach. Each row of graph corresponds to a response variable and each column corresponds to one of the parameters considered during experiment. Each cell shows the changes of response as a function of one of the process parameters inside graphs vertical red line shows the current parameters settings and blue dotted horizontal line represent the current response values. The number displayed at the top of the column shows the higher, lower and current parameters for the output response. The current parameter settings are power of 95 %, frequency of 15 kHz and speed 0f 4.333 mm/s to achieve the optimum condition for maximum weld strength 15.4407 N/mm and minimum weld width 226.0021 µm.

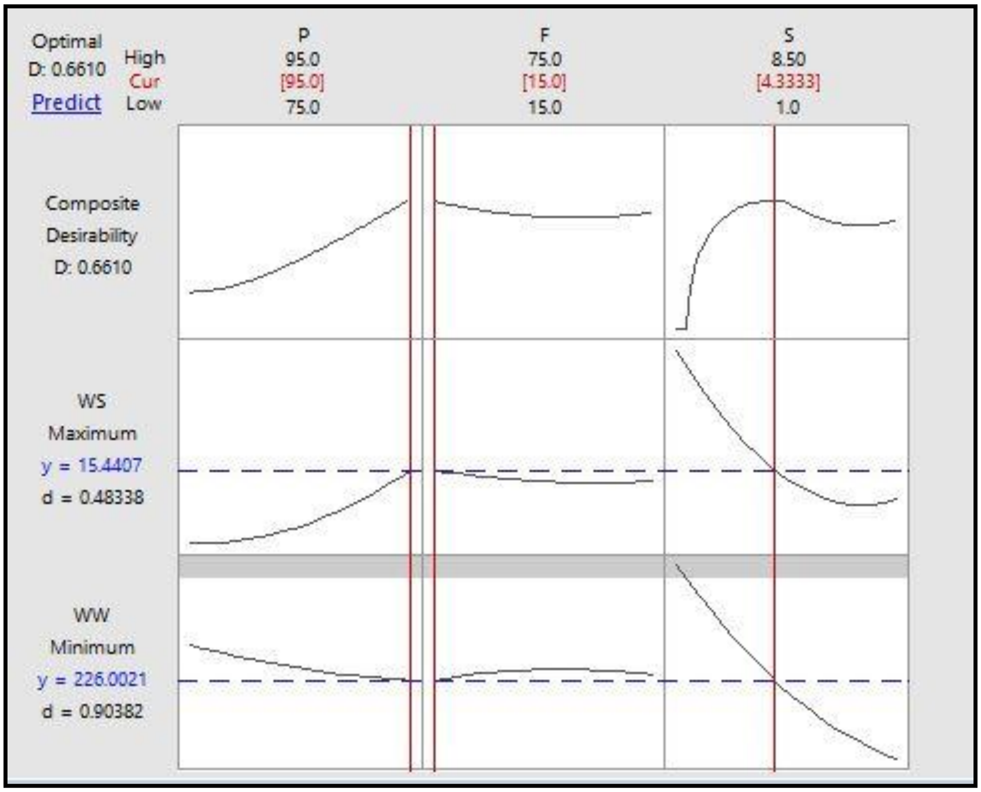

Fig. 4.3: Multi objective optimization for weld strength and weld width

Chapter 5: Conclusions and Future Scope

5.0 Conclusions

From the above experiment and analysis, following conclusions are made:

i. While increasing laser power and frequency weld strength are respectively low.
ii. High laser power and low scanning speed produce higher weld width.
iii. With the increase of power up to a certain value, moderate frequency and low scanning speed give high weld strength.
iv. Also, with the increase of scanning speed up to a certain value weld width started to decreases.
v. From the ANOVA table of weld strength, the relations among the input parameters can be obtained .
vi. From the single objective optimization and as well as multi objective optimization system gives the optimized value for maximum weld strength and minimum weld width.
vii. The maximum weld strength obtained when power is 75%, frequency is 75 KHz and scanning speed is 1 mm/s from the experimental results.
viii. The minimum weld width observed when power is 90%, frequency is 30 KHz, and scanning speed is 6 mm/s.
ix. It was evident from the multi-objective optimization process weld strength is maximum and weld width is minimum for the value of power is 95%, frequency is 15 KHz and speed is 4.33 mm/s.

5.1 Future Scope

The future scopes of the present work are given below

i. Apart from permanent marker others types of paints can be applied as intermediate absorbing layer to improve the weld quality.
ii. Clamping pressure can be treated as another process parameters other than laser Power, Frequency and Scanning speed.
iii. Numerical Simulation techniques like ABAQUS, MATLAB and COMSOL MULTIPHYSICS can be used for the verifying with the experimental results.
iv. Different types of joint configuration can be taken into consideration keeping the same process parameters (laser Power, Frequency and Scanning speed) or others.

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