# Residual Stress Developments during Laser Welding of Commercially Pure Titanium Sheets

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**In**
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Submitted by

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# CERTIFICATE

This is to certify that the summer report entitled, “**Residual Stress Developments during Laser Welding of Commercially Pure Titanium Sheets”** submitted by **Mr. Honey Goel** bearing **Roll No. 213MM1467**, **Department of Metallurgical and Material Engineering, National Institute of Technology Rourkela,** is an authentic work carried out by him under my supervision and guidance. I certify that the work has not been submitted elsewhere for any other report.

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# Content

Abstract I

List of figures II

List of tables IV

Chapter 1: Introduction 1

1.1. Research background of 2

1.2. Objective 3

Chapter 2: Literature review 4

2.1. Laser welding 5

2.2. Types of laser 6

  (a) Solid state laser 6

  (b) Gas laser 7

  (c) Semiconductor laser 7

2.3. Operation of laser welding 8

  (I) Energy density 8

  (II) Intensity distribution 9

  (III) Power output 10

2.4. Effect of laser welding parameter on fusion zone 11

(a) Laser power 11

(b) Welding speed 12

(c) Effect of defocusing distance 13

(d) Effect of type of shielding gas 14

(e) Beam angle 14

2.5 .Advantage of laser welding 14

2.6. Disadvantage of laser welding 15

2.7. Residual stress 16

2.8. Role of residual stress 16

2.9. Origin of residual stress 16

2.9.1 Residual stress by plastic deformation 17

2.9.2 Residual stress by thermal gradient 18

2.10. Measurement techniques for residual stress 19

2.10.1 Hole drilling method 20

2.10.2Neutron diffraction technique 20

2.10.3 X-ray diffraction technique 21

2.11. Residual stress development in fusion welding 24

Chapter 3: Experiment 27

3.1. Material and Sample Preparation 28

**3.2. Residual Stress Analysis** **29**

**Chapter 4: Result and Discussion** **31**

**Chapter 5: Summary and Future scope** **40**

**Chapter 6: References** **42**

# ABSTRACT

The laser welding of cp-ti sheet was done by using a continuous wave welding and gas laser ($CO_2$).Laser welding is operating at different conditions like laser power at 2kW & 2.5kW, range of welding speed is from 4m/min to 8m/min and laser intensity distribution by Gaussian Mode and Donut Mode. Macrostructure of weld size and fusion zone were examined by using optical microscope. It is found that weld size was decreased with increasing welding speed and increased with increasing laser power and spot diameter and weld size for donut mode is higher than the Gaussian mode. Residual stress which is developed due to thermal gradient is measured by X-Ray Diffraction Technique. These residual stress measurements were taken at a series on the top surface covering the fusion zone, heat affected zone (HAZ) and base metal. Here residual stress is compressive in nature. Residual stress at weld pool for Gaussian mode is lower compared to Donut mode.

**Keywords:** Laser welding, CP titanium, Residual stress, Gaussian mode, Donut mode.

# List of Figure

| Figure Number | Figure caption | Page number |
|---|---|---|
| 2.1 | Schematic diagram of Laser welding | 5 |
| 2.2 | Schematic diagram of Solid-state laser | 6 |
| 2.3 | Schematic diagram of Gas Laser | 7 |
| 2.4 | Schematic representation of types of weld | 8 |
| 2.5 | (a) Gaussian mode (b) Donut mode | 9 |
| 2.6 | (a) continuous welding (b) pulse wave welding | 10 |
| 2.7 | Effect of laser power on penetration depth of type 304L and type 316L steel welds | 11 |
| 2.8 | Effect of welding speed on weld depth for 304L & 316 L steels | 12 |
| 2.9 | Effect of defocusing distance on penetration depth of 304L and 316L steels | 13 |
| 2.10 | Residual stress during plastic deformation | 17 |
| 2.11 | Residual stress for three different grinding processes | 17 |
| 2.12 | Residual stress during temperature gradient | 18 |
| 2.13 | Hole drilling equipment | 20 |
| 2.14 | A line diagram of neutron diffraction technique | 21 |
| 2.15 | X-ray diffract meter | 22 |
| 3.1 | Representation of different regions where residual stress measurement was performed in the present study. | 30 |

| | | |
|---|---|---|
| 4.1 | Macrostructures of laser welding samples at different processing conditions. Refer Table 3.3 for the processing conditions adopted for the present study. | 33 |
| 4.2 | Residual stress developments of laser welded samples across the weld pool as a function of welding speed at a laser power of 2 kW and Gaussian mode of welding. Different regions, where residual stresses were measures, are indicated as follows: BM – Base Metal, IF – Interface between base metal and the weld pool, WR – Weld Region or Weld Pool. | 36 |
| 4.3 | Residual stress developments of laser welded samples across the weld pool as a function of welding speed at a laser power of 2.5 kW and Gaussian mode of welding. | 37 |
| 4.4 | Residual stress developments of laser welded samples across the weld pool as a function of welding speed at a laser power of 2.5 kW and Donut mode of welding. | 39 |

# List of table

| Table no. | Table caption | Page no. |
|---|---|---|
| 2.1 | Process that cause residual stress | 18 |
| 2.2 | Compression between the residual stress measurement techniques | 22 |
| 3.1 | Chemical composition (in wt.%) of cp-titanium used in the present study. | 28 |
| 3.2 | Weld parameters used in the present study. | 28 |
| 3.3 | Different processing conditions of laser welding investigated in the present study. | 29 |

# Chapter 1

# INTRODUCTION

# 1. INTRODUCTION

## 1.1 Research background:

Titanium and its alloys possess excellent mechanical properties like high specific strength, high strength, high corrosion and erosion resistance, high toughness, high stiffness and good sustainability at elevated temperature [1]. Use in medical instruments, implants in human body, petroleum, automobile, chemical industries, power generation and many more [2-5]. Normal fusion welding is rarely used for titanium [6]. Because large heat is required for welding of titanium during normal fusion welding .It has also many drawbacks like decreases its mechanical property during application of large heat as it induces larger HAZ, greater distortion, large residual stress and high risk of contamination [7]. For excellent mechanical property; HAZ should be a narrow, less distortion and continuous weld seam [8-10]. To minimize these difficulty that is occur during normal fusion welding laser beam welding is used now these days due to its low heat input requirement [11, 12].The welding speed is higher than normal fusion welding [3]. The width of weld pool is less than the normal fusion welding and has high aspect ratio and high welding efficiency [13].

Residual stresses have major role in the performance of engineering structure like stress corrosion, cracking, fatigue strength and other forms of cracking [14]. Therefore in designing the mechanical parts it becomes necessary to study the effect of residual stress. There are many techniques for measurement residual stress like hole drilling method, Raman spectroscopy, Neutron diffraction and X-ray Diffraction [15]. Residual stresses are directly superimposed and effect the performance of materials [16].Compressive residual stress during machining improve fatigue life creep life and resistant to crack propagation [17]. In the present work, an extensive study on residual stress development in LBW of commercially pure titanium (cp-ti) sheets is investigated.

## 1.2 Objectives

- LBW of cp-ti sheets at different process parameter – laser power at 2 & 2.5kW, welding speed from 4-8 m/min and beam focus at 0.18 & 0.36 mm.
- Analysis of residual stresses in the laser welded cp-Ti samples near the HAZ, base metal and the centre of weld pool.
- Investigation of effect of process parameters during laser welding on residual stress developments of cp-Ti samples.

## Chapter 2

# LITERATURE REVIEW

# 2. LITERATURE REVIEW

## 2.1 LASER WELDING

Laser welding is unique welding process, which is use to weld the metal through the application of heating effect of concentrated beam of coherent monochromatic light known as LASER [18]. LBW is High power density welding processes which can penetrate thicker specimen with a single pass and due to this a small HAZ, good weld quality, low heat input per unit volume obtained [19,20]. Energy required for welding in laser welding is handling by the spot size, focused area, shielding gas, laser power and speed of welding. Due to high power density of laser beam ($10^9$ W/mm$^2$) that is focused on the small spot are can melt any known materials [21].

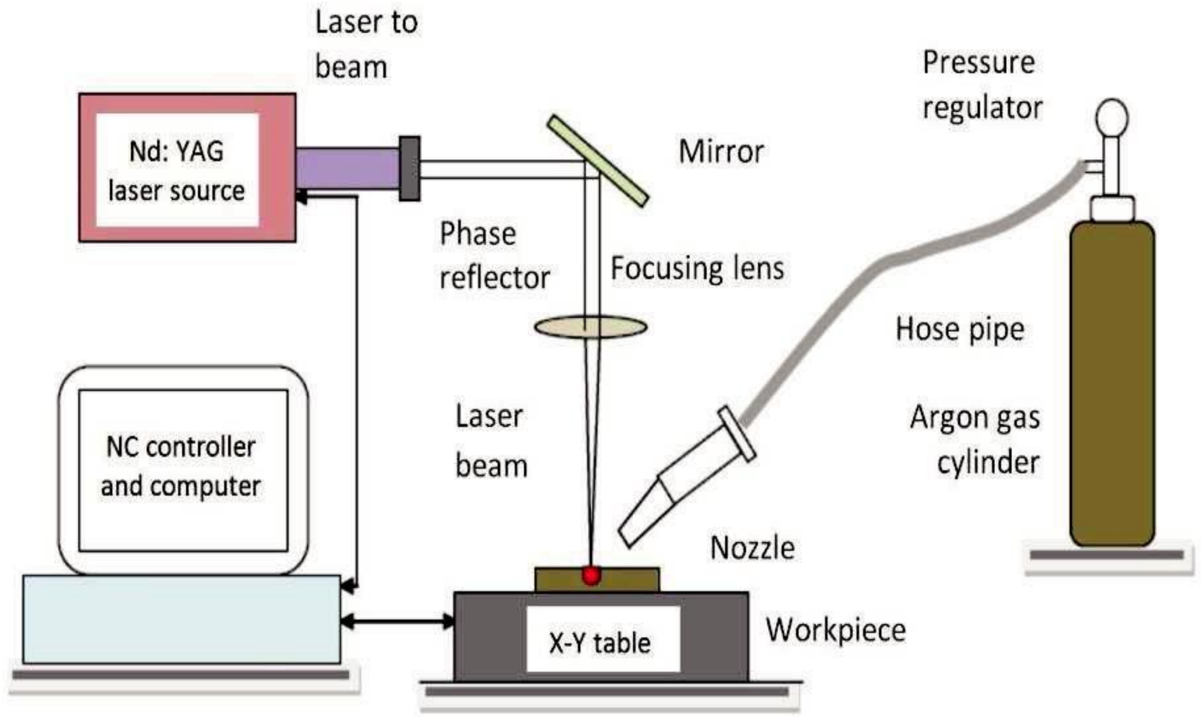


Figure 2.1-Schematic diagram of Laser welding [18]

## 2.2 TYPES OF LASER

There are two types of laser

(a) Solid state laser (b) Gas laser (c) Semi-conductor laser

### (a) Solis state laser

The active medium for solid-state laser is consisting of glass and crystalline [22].Ruby crystal, Nd:YAG crystal and artificially doped crystal are used in this laser. Its shape is cylindrical and dimension of solid-state laser is 20mm dia. and 200mm length [23]. Ruby laser is example of solid-state laser and rarely used now due to its lower power efficiency. It can works on both pulsed and continuous mode. Wavelength of laser in solid state is order of 1 mm, which is less than the gas laser. Power required for ruby laser is lies between the 10–20 W and for Nd:YAG is 0.04–6,000 W. Quality of weld is depend on the power input. Diameter of core depends on the input power and spot size.

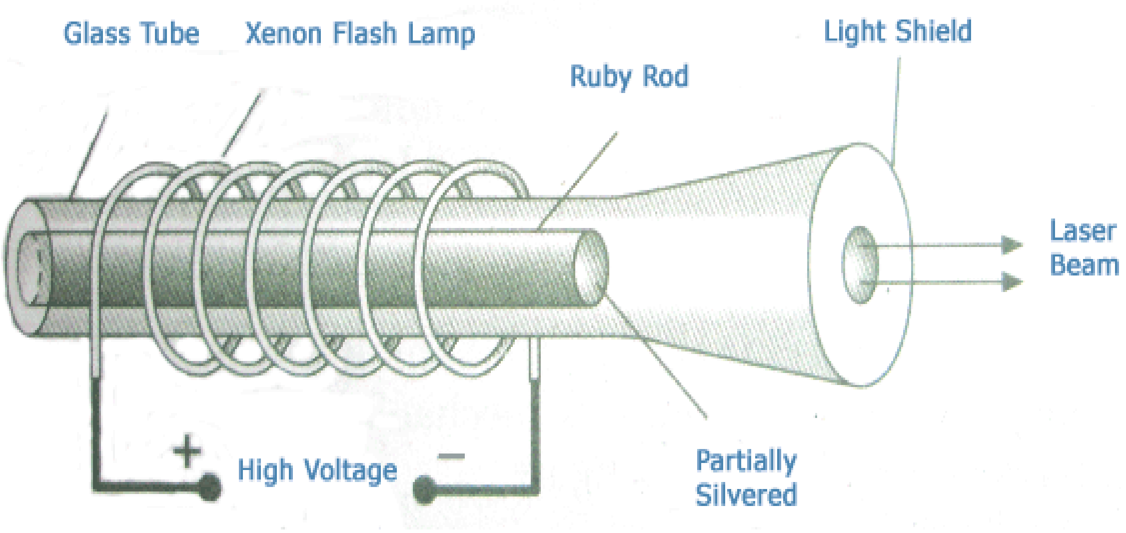


Figure 2.2-Schematic diagram of Solid-state laser [22]

### (b) Gas Laser

In the gas lasers, the lasing source is either a gas or mixture like hydrogen, nitrogen, argon and carbon dioxide [24]. In this type of laser atoms of gas mixture are excite by applying low current and high voltage. Wavelength of gas laser is order of 10.6 µm and it is use for both pulsed and continuous mode. Optical fiber is used to deliver the laser beam to weld surface is not used in gas laser whereas it is used in solid-state laser. Due to high wavelength, it destroys the optical fiber by absorption. So to remove this difficulty mirror and rigid lens are used for deliver the laser beam to weld surface. Power output in gas laser is higher than the solid-state laser.

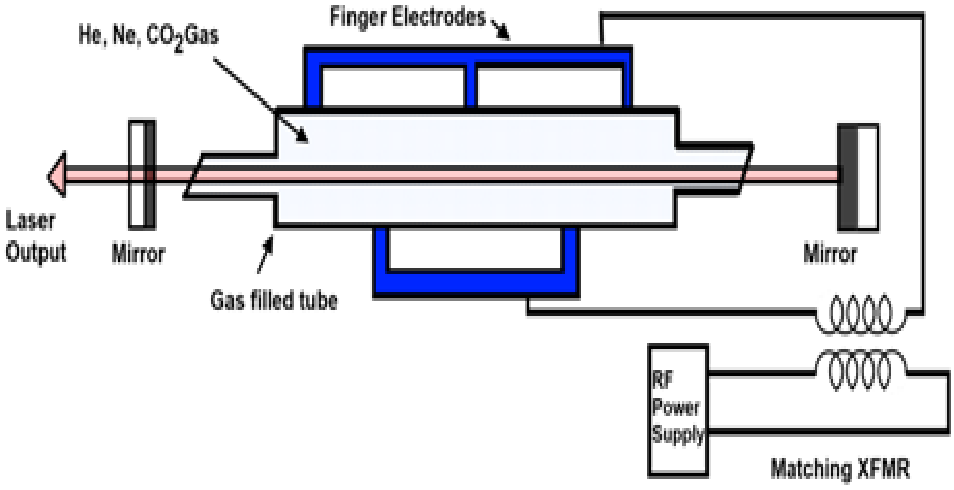


Figure-2.3 -Schematic diagram of Gas Laser [24]

### (c) Semiconductor laser

In the semiconductor lasers (also type of solid-state laser), the lasing materials are single crystals of semiconductors such as gallium and indium arsenide, alloys of cadmium, selenium and Sulphur etc.

## 2.3 OPERATION OF LASER WELDING

There are three factors in operation mode of laser welding.

- (I) Energy density
- (II) Intensity distribution
- (III) Power output

(I) **Energy density:**

There are typically three types of welds: –

- a) Conduction mode
- b) Penetration
- c) Keyhole mode

**(a) Conduction mode**

This type of welding is occurring relatively low energy density, due to this, a low depth of weld on the surface of specimen is formed as shown in figure 2.4 and specimen is heated above the melting temperature without vaporizing. It has low welding efficiency and use for thin material like foil, wires and thin tubes etc.

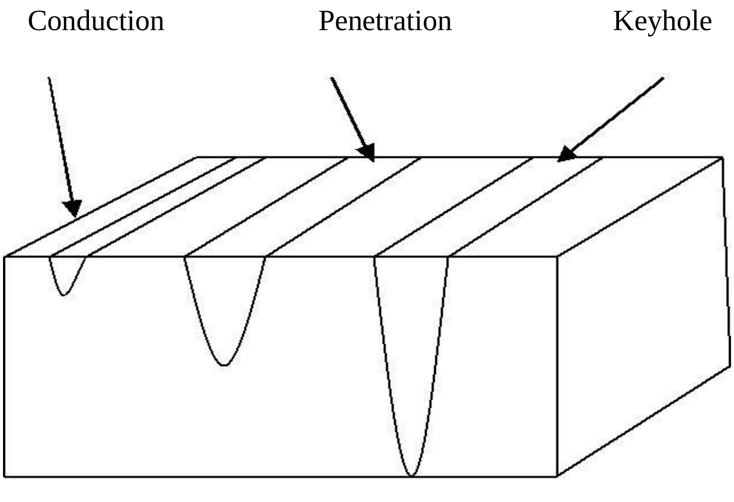


Figure-2.4 Schematic representation of types of weld [25]

(b) **Penetration mode**

This type of welding is achieve at medium energy, forming the moderate depth as shown in figure 2.4.Its efficiency is higher than the conduction welding, and specimen is heated above the vaporizing temperature. It is use for thick material like ceramic.

**(c) Keyhole welding**

This type of welding is occur at the high energy density, and formed key hole as shown in figure 2.4.This is occur at above evaporation temperature and use for hard material.

**II) Intensity distribution**

Two types of intensities is used foe welding (a) Gaussian mode (b) Donut mode

**(a) Gaussian mode**

In this mode the maximum intensity occur at the center of beam and varies the across the radius across the beam as shown in figure 2.5. In this mode, the diameter of concentrated beam is 0.18mm is appearing at the focus point.

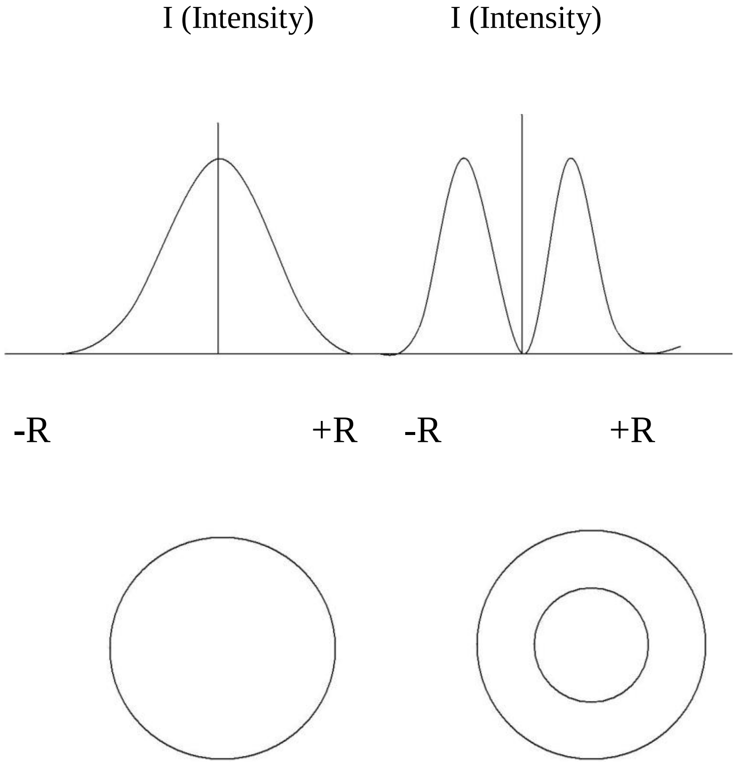


Figure –2.5(a) Gaussian mode 5(b) Donut mode [25]

### (b)Donut mode

In this mode, the intensity of laser is zero at the center, reaches increases with radius up to the certain point, and then become zero. The diameter of beam is 0.36mm with dark spot at its center is appearing at the focus point.

### III) Power output

There are two types of laser welding which depend on power output

a) continuous wave welding
b) pulsed wave welding

### (a) Continuous wave welding

In this type of welding steady power is supplied i.e. power is constant throughout over a period. In this, deeper penetration is achieved compared to pulse wave welding due to continuous supply of power. Different type of material can be weld together.

### (b) Pulse wave welding

In this type of welding current is switch on or off very fast. It is like a sine wave. Here average power for work piece is reduces. Those materials, which are very sensitive to heat, this welding is used to join that materials. The cycle time for complete one wave is millisecond, which is very small [25].

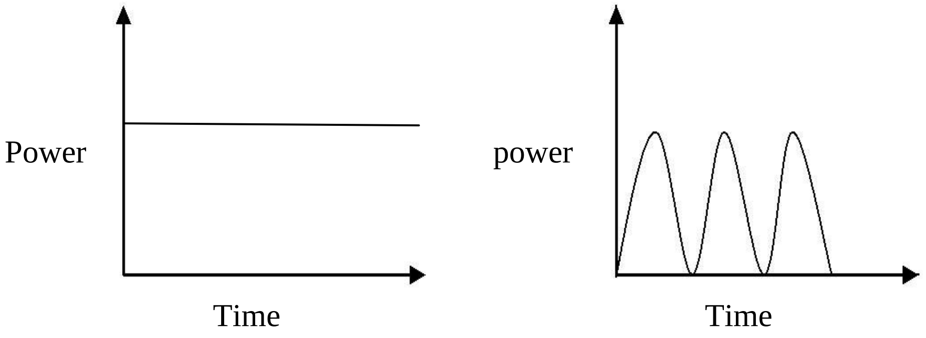


Figure-2.6 (a) continuous welding 6 (b) pulse wave welding [25]

## 2.4 EFFECT OF LASER WELDING PARAMETER ON FUSION ZONE

### (a) Laser Power

Heat input is depending on laser power. Penetration depth increasing with the increasing laser power and other parameter like welding speed and defocusing distance were kept constant [26].But this penetration depth increase between the laser power 2-3 KW for LBW of 304L austenitic steel [27]. However, with increasing in laser power, it has more effect on penetration depth and less impact on profile of weld and HAZ [28]. For complete penetration, laser power should be greater than 4KW [29].Figure shows the example of 304L austenitic steel with laser power 4KW.

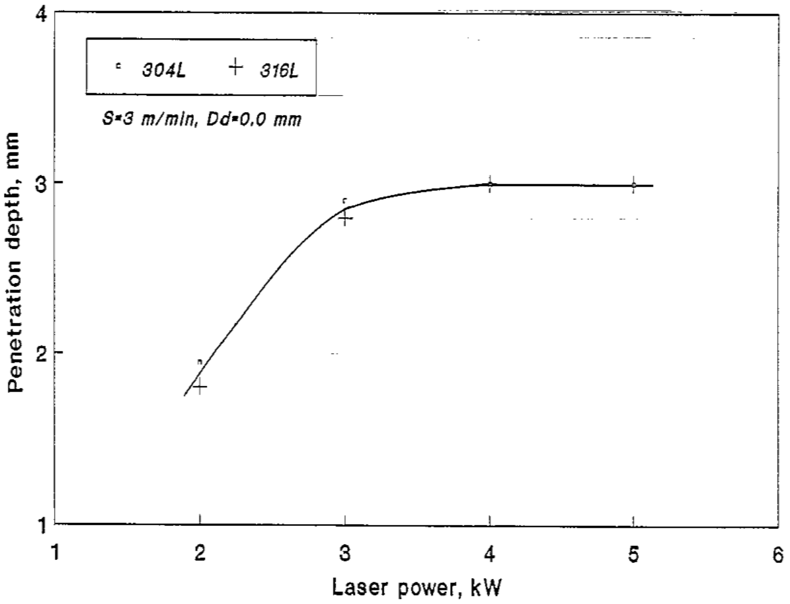


Figure-2.7 Effect of laser power on penetration depth of 304L and 316L steels welds [27]

Due to increasing in laser power ,more heat input is available for welding which results coarse grain is obtained and more precipitate concentration in fusion zone [30] for the AZ31B magnesium alloy material [31]. Moreover, increase the penetration depth in LBW of titanium alloy materials [32]. For Mg alloys, the penetration depth is also increases with increasing the laser power [33, 34].

Mechanical property such as tensile strength of austenitic stainless steel, increasing up to some instant after that decreasing [35] because due to large heat power the width of HAZ becomes wider [36]. At slow welding speed with increasing laser power, residual stresses are formed at the weld pool, which decrease the tensile strength [37].

**(b) Welding Speed**

To understand the effect of welding speed on fusion zone then laser power must be 4 kW and zero defocusing distance as shown in figure [27].The width/depth is increasing with the increasing in welding speed.

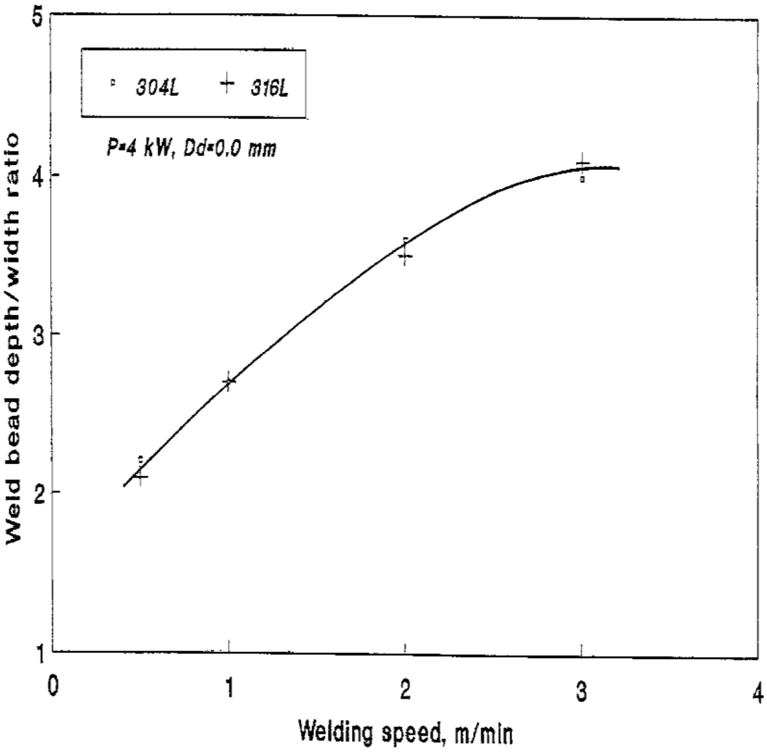


Figure-2.8 Effect of welding speed on weld depth for 304L & 316 L steels [27]

The size of fusion zone increased at the low welding speed and decreases the depth/width ratio which leading to changing defocusing distance resulting unacceptable profile [26].

In case of laser welding of stainless steel sheet, bead parameter like penetration depth , bead width, penetration area are decreasing with the increasing in welding speed however, due to less plasma blocking depth and area of penetration are increasing with higher welding speed [29]. High welding speed results, heat required for welding decreases leads to fine grains are obtained in weld zone of Mg alloy [38].For laser welding is done at higher welding speed at constant beam diameter for low carbon steel results weld width decreases

[37]. Laser welding of austenitic stainless steel, mechanical property like impact strength decreases with increasing welding speed results reduce the toughness and becomes more brittle [35]. In laser welding of titanium alloy, micro-hardness increases with increasing in welding speed [39] and heat input decrease results high cooling rate are achieve which increases the micro-hardness [40,41]

**(c) Effect of defocusing distance**

In case of laser welded 304L austenitic steel, penetration depth always decreases either the defocusing distance increase or decrease due to decrease in laser density. For obtaining the weld profile of 3mm to 5mm thickness then value of defocusing distance should be kept in range of -0.2mm and -0.4mm respectively [26].

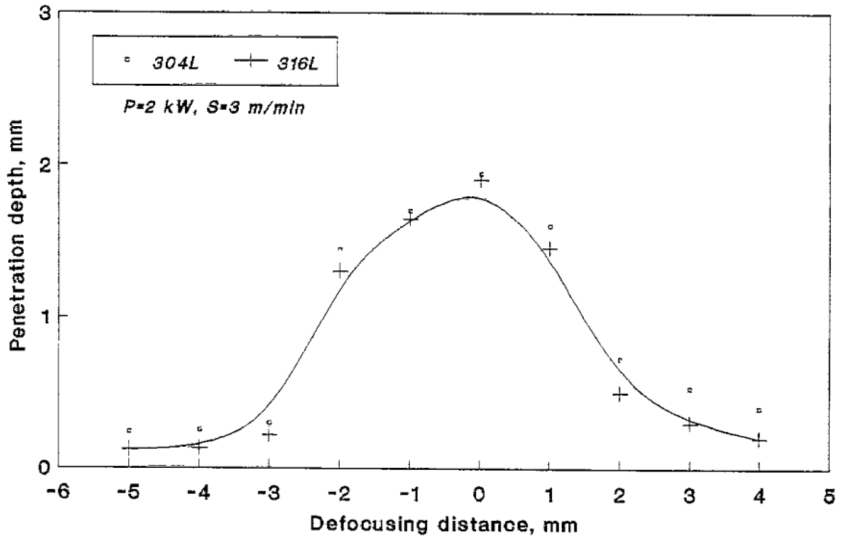


Figure-2.9 Effect of defocusing distance on penetration depth of 304L and 316L steels [27]

For an acceptable weld for LBW Mg alloys, the position of focus should be on or 1 mm below the surface of the specimen [34, 42-43] and when the focus position is on surface and power is 2.5 kW an excellent weld profile is obtained for thin plates. Whereas for thick plates (5mm to 8mm) the position of focal point 2 mm below the from surface of specimen for achieving good weld profile [44,45].There is no effect on tensile strength when LBW of austenitic stainless steel is done at low welding speed with either a focused or defocused laser beam [35].

**(d) Shielding gas**

Weld profile of laser welded austenitic steel is improved by using helium instead of Argon gas because the ionization potential of helium is more than the argon gas. Due to more ionization potential plasma, effect is reduced. Hence, weld profile is improved [26].In Nd:YAG laser welding of titanium pure argon are used to minimizing oxygen and nitrogen intake which results weld quality is improved.

**(e) Beam angle**

In LBW of stainless steel, bead width and penetration area decreases due to increasing the beam angle from 82 to 98 degree anticlockwise [29].

## 2.5 ADVANTAGE OF LASER WELDING

**I) High power density**

In laser, welding a great concentrated beam is use for welding the material. This concentrated source of heat increases the power density [46].

**II) Narrow Heat affected zone**

HAZ is region of base metal, which is not melt but their microstructure and mechanical properties, is change by welding or other heat cutting operation.

Thermal diffusivity of the base material has the vital role in HAZ.

- Due to high thermal diffusivity, the material cooling rate becomes high and the HAZ is relatively small. On other hand, those metal have a low diffusivity show the slower cooling rate and broader HAZ.
- Size of HAZ is depending on the amount of heat required for welding. Processes like Gas welding required high heat for melting, which increases the size of the HAZ. Due to highly concentrated beam in LBW and EBW it reduces the heat required for melting and hence resulting in a small HAZ [47].

**III) Fine grains**

Due to high welding speed results, heat required for welding decreases, leads to fine grains are obtain in fusion zone [47].

### IV) High productivity

Productivity of welding is mainly depends on the welding speed. In laser welding speed of welding is range from 40 to 400 inches per minute (IPM) which much higher than other fusion welding process. Laser beam could be able to focus a small area of work- piece so, it is reliable for small size metal and internal parts [48].

### V) Deep penetration and low heat input

Laser welding can excess 1-inch thick material in a single pass of welding. Due to deep penetration, it has possibility to weld in overlap configuration. Diffusion rate is decreases with increasing the welding speed. Hence low heat input is required to weld the work piece [49]. Due to low heat input cooling rate becomes high results less residual stress, limited deformation and low thermal distortion. Whereas in TIG large heat input is required due to this cooling rate is becomes low results high residual stress [50].

### VI) Cost savings

Due to following factor cost associated with laser welding is less

- High productivity
- Low quantity of scrap from work piece is produced
- Manual labor becomes small

## 2.6 DISADVANTAGE OS LASER WELDING

- Crack may arise in some metal during rapid cooling
- Initial cost of equipment is high
- Optical surfaces are damage easily
- Maintenance cost is high
- Position of work-piece must be maintain and it should be in range of concentrated laser beam

## 2.7 RESIDUAL STRESS

Residual stress can be defined as those stresses existing within a body in the absence of external loading or thermal gradients. In other words, residual stresses in a structural material or component are those stresses, which exist in the object without the application of any service or other external loads. Residual stress can be developed in any types of metal and non- metal. Residual stress can cause of suddenly spit the metal in two or more pieces.

## 2.8 ROLE OF RESIDUAL STRESS

Residual stress has same role on the strength of metal as the mechanical stress. Mechanical stress (load per unit area) can be measured accurately. However, residual stress is difficult to measure. So, it became very important to measure the residual stress by most reliable method. Residual stresses may be desirable or undesirable which may be depending on the magnitude, distribution. For example laser peening increases the compressive residual stresses within the materials component such as blades of turbine engine. Tensile residual stress has undesirable effect on the material because it reduces the fatigue life due to increase the fatigue crack growth. While Compressive residual stress have beneficial due to lower crack growth rate increases the fatigue strength of component [51].Residual stress is more near the weld region which may increase the fatigue crack growth which may cause of brittle fracture, stress corrosion cracking [52]

## 2.9 ORIGIN OF RESIDUAL STRESS

Residual stresses are can be arise every step of manufacturing processing [53] .There are many mechanisms to produce Residual stress like plastic deformation, temperature gradient, metallurgical change [54].Residual stress could be caused by localized yielding of the material, because of a sharp notch or from certain surface treatments like shot peening or surface hardening.

### 2.9.1 Residual stress by plastic deformation

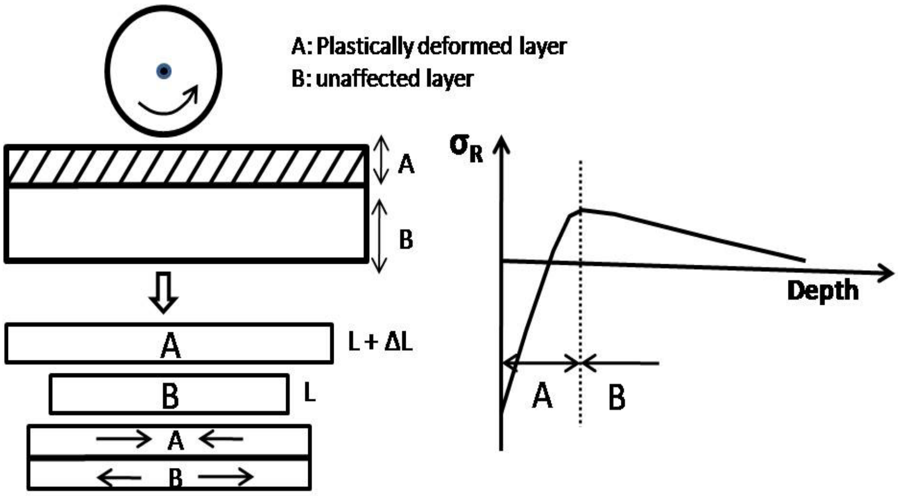


Figure 2.10-Residual stress during plastic deformation [53]

When plastic deformation is applied at the top surface in the absence of heating then layer A is elongated but layer B restraints. As the compressive residual stress is occurring at the top surface is equilibrated by the tensile stress of layer B. Example Welding, Grinding, wire drawing. Following figure show the residual stress for different grinding process.

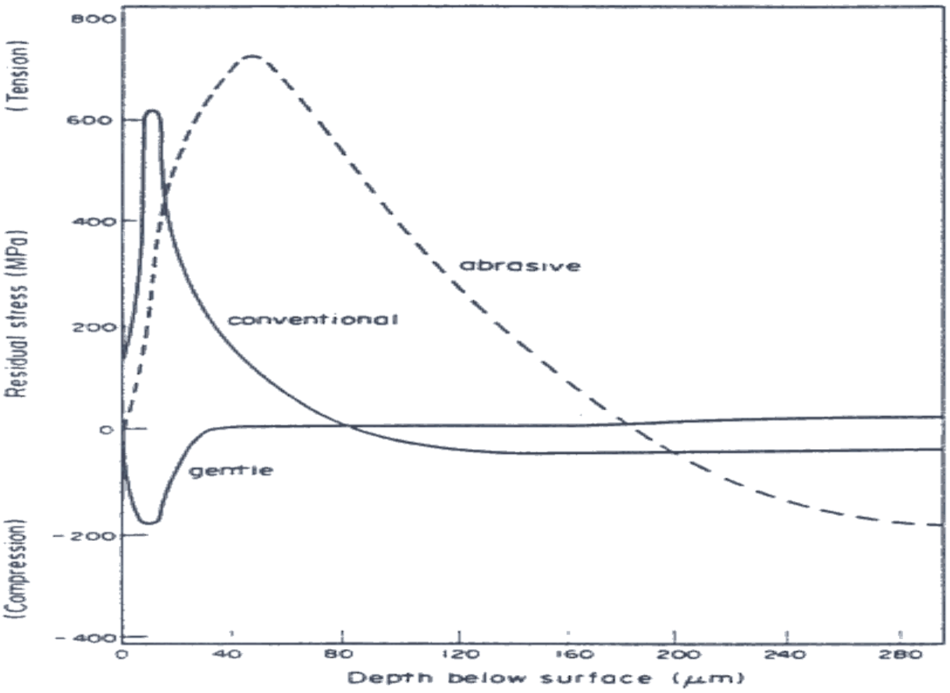


Figure 2.11-Reidual stress for three different grinding processes [53]

It has seen that tensile stress is at the surface for abrasive and conventional grinding whereas compressive stress at the surface for gentle grinding.

### 2.9.2Residual stress by thermal gradient

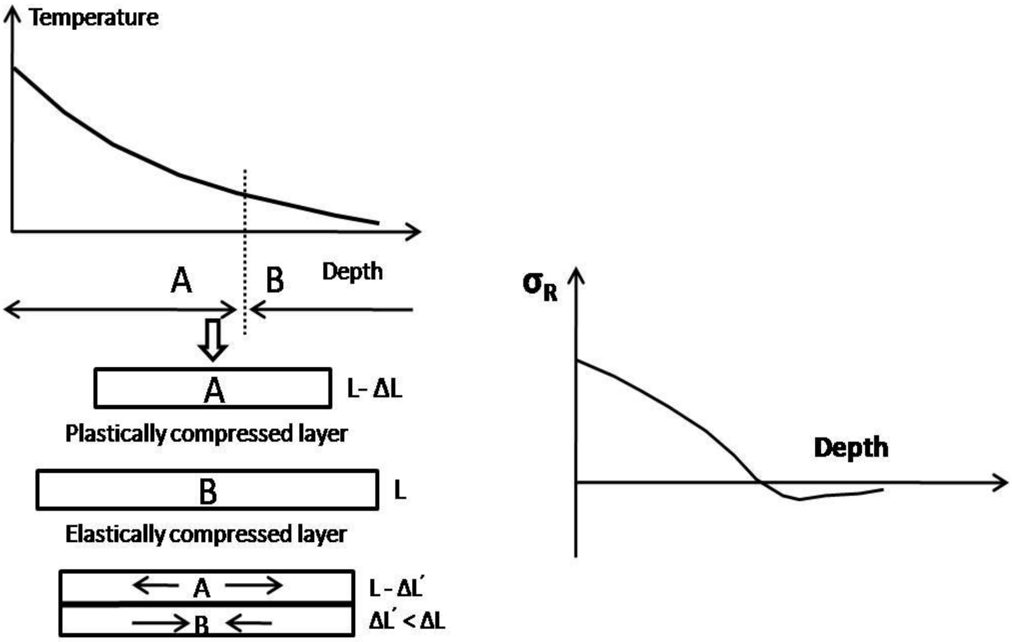


Figure 2.12-Residual stress during temperature gradient [53]

With the application of heating (temperature gradient), a tensile residual stress is developing at the heated surface (layer A) after cooling. Layer B is in compression, which equilibrated the layer A.

**Table -2.1 There are many process that cause residual stress as shown in table**

| **ORIGIN** | **MECHANICAL** | **THERMAL** | **METALLURGICAL** |
|---|---|---|---|
| **PROCESS** | | | |
| Smelting<br>Casting | No | Temperature gradient | Phase change |
| Quenching without a phase change | No | Temperature gradient | No |

| | | | |
|---|---|---|---|
| Case hardening, Nitriding | None | Thermal incompatibility | New chemical component with DV |
| Welding | Flanging | Temperature gradient | Micro structural change (HAZ) |
| Brazing | Mechanical incompatibility | Thermal incompatibility | New phase at inter phase |
| Electroplating | Mechanical incompatibility | Thermal incompatibility | Composition of plating depending on bath used |
| Composite | Mechanical incompatibility | Mechanical incompatibility | No |

## 2.10 MEASUREMENT TECHNIQUE FOR RESIDUAL STRESS

There are wide ranges of technique to measure the residual stress in the metal [55].These technique can be categorized based on metal damage: destructive and nondestructive techniques. In both techniques residual stress are measured by the measuring the elastic strain [56-57]. X-ray diffraction technique fall under the nondestructive are used to measure the stress on the metal surface [58]. Hole drilling and ring core technique falls under the destructive technique. However, measurement of internal stress within the thick metal is difficult .To remove this difficulty hole drilling technique is used [59]. A brief description of each technique is described in this section .But emphasis will be given to X-ray diffraction technique in this thesis.

### 2.10.1Hole drilling technique

In this technique, a small hole is drilled. The range of diameter of hole is 1to 4mm.A hole is drilled at the center of strain gauge with an air-pressured drilling machine. By controlling the depth setting, the residual stress is measured [60].

Figure -2.13 Hole drilling equipment [60]

### 2.10.2Neutron diffraction technique

It is a nondestructive technique for residual stress measurement for crystalline material**.** For this technique, a monochromatic neutron beam was employed with a wavelength of 1.65 Å. Neutron diffraction gives the value of elastic strain and measure the strain from the changes in crystal lattice spacing [61].

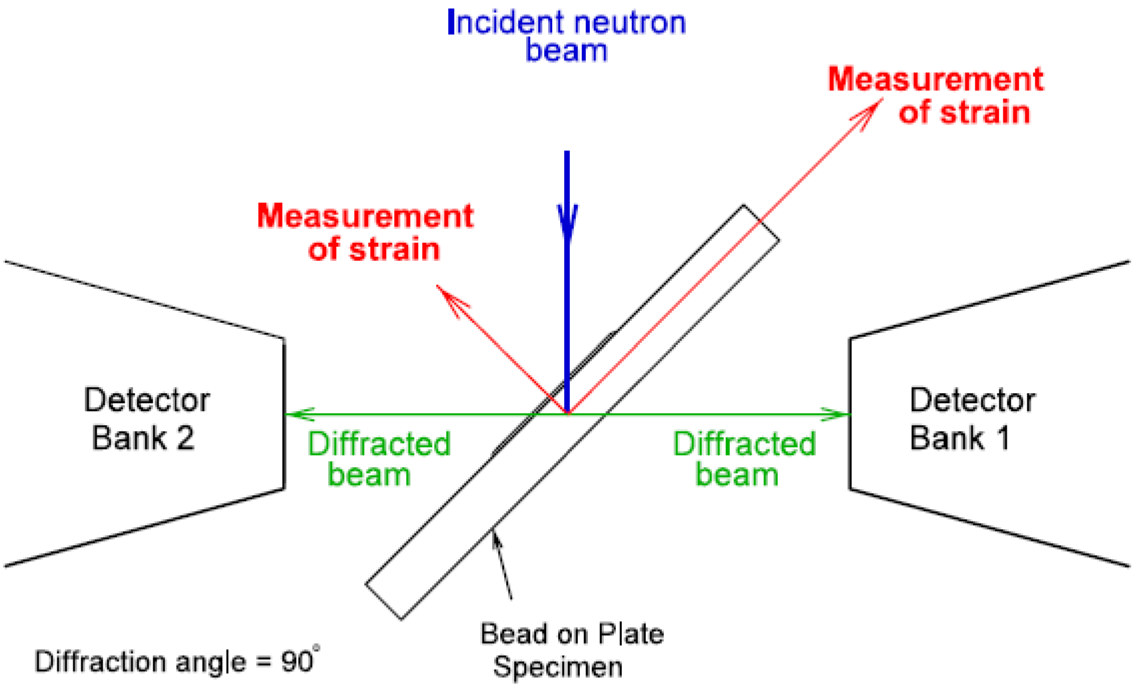


Figure 2.14 –A line diagram of neutron diffraction technique [61]

### 2.10.3 X-ray diffraction technique

XRD technique is widely regarded as an effective way to detect stress for the surface of crystalline material [62] .Principle behind the diffraction of x-ray is Bragg's law

$$n\lambda=2d\sin\theta$$

Where n is an integer, $\theta$ is diffraction angle, d is inter-planar spacing of two crystal lattice sand $\lambda$ is the wavelength.

To perform strain measurement the sample is placed in the X-ray diffract meter. A X-ray beam is impinge on the specimen which cause for the diffraction patterns. There is a clear relationship between the diffraction pattern and inter planar spacing. By the changing in inter planar spacing and wave length of X-ray a different diffraction patterns will be obtained. Inter planar spacing initially strain free will produce a characteristic diffraction pattern for that material. When the material is strained there will be a change in inter planar spacing of lattice planes. Due to change in inter planar spacing will cause the change of diffraction pattern. By the precise measuring of this change in inter planar spacing thus the strain within the material deduced. And then stress can be measured by following relation [63]

$$\sigma_y = -\frac{\dot{E}}{\nu}\left(\frac{d_n - d_0}{d_0}\right)$$

Where dn is the spacing of the planes reflecting at normal incidence under stress, and do is the spacing of the same planes in the absence of stress [64]

Figure 2.15-X-ray diffract meter [63]

**Table-2.2Comparison between the residual stress measurement techniques**

| Technique | Description | Limitation |
|---|---|---|
| X Ray Diffraction | Versatile, widely available<br>Variety of materials<br>Portable systems | Lab-based<br>For small specimen |

| | | |
|---|---|---|
| Hole Drilling | Quick process<br>Widely available<br>Variety of materials<br>Deep hole drilling for thick section components | Destructive technique<br>Limited strain sensitivity and resolution |
| Neutron Diffraction | Deep penetration<br>High resolution | Specialist facility only<br>Lab-based |
| Ultrasonic | Generally available<br>Very fast<br>Low cost<br>Portable | Limited resolution<br>Bulk measurements over whole volume |
| Raman/Fluorescence | High resolution<br>Easy available | Surface measurements<br>Interpretation<br>Limited range of materials |
| Synchrotron | Improved penetration<br>Quick process | Specialist facility only<br>Lab-based technique |

## 2.11 Residual stress development in fusion welding

Residual stresses are produce by the local plastic deformation through the rapid heating and subsequent cooling phase in fusion welding. Tungsten inert arc welding now days is preferred fusion welding for aerospace and structural alloy. Hot cracking is the main problem, which arise fusion welding is carried out for high strength alloy [65]. During welding surface area of metal gets heated quickly, compare to surrounding area. The heated surface is surface is fused. Due to heating effect material get expand. The expansion of material is restrained by the surrounding cool area. Consequently the weld surface area is plastically deform and produce tensile residual stress after the cooling which is equilibrate by the surrounding compressive residual stress[66]. Welding creates much undesirable effects like distortion, residual stress and microstructure. Residual stress can influence the fatigue life of weld metal and arise due to non-uniform cooling. There are many weld defects like slag inclusion, incomplete fusion and misalignment etc. and then weld should be repaired. Generally, weld is repaired by grinding [67]. It is believed that repaired weld has more residual stress and may cause for failures.

Filler material of has significant role on the residual stress pattern. As the angular distortion is vary with the contraction force developed in fusion zone .Furthermore, at the region of weld tensile residual stress field is developed and due to this increases the longitudinal contraction forces results bow or buckle the weld. The longitudinal contraction force is mainly depends on the volumetric changes which is due to phase transformation .By changes the metallurgical transformation and filler material at the welded region and HAZ may rises the compressive residual stress [68].And significant reduction in distortion can be achieved by the altering the chemical composition of welding wire.

Previously there is no information about the magnitude and distribution of the residual stress for repaired welds. Repairer welding shows the unfavorable effect on residual stress field .This is due to high temperature gradient and non-uniform cooling of weld during welding process [67].

Most of welding joint works on cyclic loading, so fatigue failure becomes important criteria in weldments and residual stress is the main factor that influences the fatigue performance [69]. Under the field of residual stress the growth of crack is poor [70].Residual stress have been recognized as the major cause of weld failure [71].Residual stress may be important when assessing the risk of static failure containing metal with brittle fracture behavior [72].

It is observe that distortions, which induced during welding, are highly sensitive to weld pool, thermal conductivity, heat source configuration and cross-sectional area at solidus temperature. Temperature distribution profile near the weld region is influence by the thermal conductivity of material. Armentani et al. found that welding residual stress is decreased by 15% when the thermal conductivity of material increases from 30 W/m K to 75 W/m K [73].

It also known that tensile residual stress in weld region reduces the fatigue life and increases the crack growth rate. However, compressive residual stress has increased the fatigue life and reduces crack propagation rates. There are several method are available to reduce the tensile residual stress and produce the compressive residual stress. Localized heat treatment is more effective method. Vibration is also effective method to reduce tensile residual stress near the weld pool during welding [74].One of the easiest method for reducing the residual stress is by controlling sequencing the welding.

Gas tungsten metal arc welding is preferred for very thin section of stainless steel and nonferrous material like aluminium, magnesium and copper and its alloy. Butt joint is the common type joint used in engineering application like nuclear, thermal power plant, chemical industries etc. The base metal and weld region both are in thermal cycle and due to present of thermal cycle base metal and weld region experience the plastic deformation which results induced the residual stress in weld region. As tensile residual stress, increase the stress corrosion cracking and fracture. These residual stresses create a problem during the manufacturing of thin component and it has become too difficult to achieve dimensional accuracy. Therefore, it becomes necessary to avoid the effect of residual stress and their distribution to achieve dimension stability.

To avoid the residual stress and their effect first knows the mechanism of development and effect of welding parameter like welding speed and welding power etc. on the generation and distribution of residual stress. Temperature distribution has plays major role for understanding the effect of welding process parameter on residual stress distribution near the weld region. It is well known that industries have to complete their fabrication so; it is use high welding speed by giving high welding power. This high welding speed and high input power and intransient temperature behavior are encountered during the welding. Many authors have present to understand the behavior of residual stress near the weld region by numerical analysis. Due to high concentrated beam of heat source which generates the residual stress in the weld region in longitudinal as well as circumferential direction [75]. Malik et al. [76] have analyzed the behavior of residual stress for different welding speed with different heat power and found that both have strong influence on the residual stress.

Lie Zaho, Jun Liang [77] investigate the effect of welding parameter on residual stress for T92 steel and S30432 steel and found that maximum temperature is occur in centre of weld pool around 2055°C which is larger for S30432 steel compared to T92 steel and the profile of temperature distribution is unsymmetrical. The size of HAZ of T92 steel is larger than the S30432 steel. Welding power is plays a main role during welding. Because it can influence the cooling rate, which affects the HAZ, residual stress etc. Three different heat input were taken (0.8Q,Q and 1.5Q) and observed that the peak value of residual stress is not alter while heat input increase. In addition, due to increase in heat input brings a larger compressive residual stress in S30432 Steel. On the other hand when the heat input decreases from Q to 0.8 Q peak value of residual stress for T92 steel changes small and the peal value of residual stress for S30432 steel change from 106 MPa to 163 Mpa. As the heat input decreases, reduction in residual stress for S30432 steel is more than the reduction in reduction for T92 steel. It is due to that decreasing in temperature for S30432 steel is more than the T92 steel.

K.H.Tseng, C.P Chou [78] analysed the effect of pulse GTA welding on the residual stress for stainless steel. After experiment results shows that residual stress dependent on frequency. And found that residual stress is decreases with increasing the frequency and this increased frequency may increase the weld width ratio, reduce the HAZ, and represent the source of concentrated beam of light source .Therefore due to great concentration of heat it reduce the residual stress for austenitic stainless steel.

## Chapter 3

# EXPERIMENTAL PROCEDURE

## Experimental Details

### 3.1 Material and Sample Preparation:

Commercially pure titanium (cp-ti) sheets of 1 mm thick were obtained from the market. The chemical composition of cp-ti is shown on the table 3.1. The size of cp-ti sheets obtained was approx. 250mm × 200mm. For laser welding eighteen numbers of specimens of size 50mm × 50mmwere prepared. Before laser welding, all the specimens were mechanically brushed and cleaned to take out the contamination of the surface to produce defect-free joint. The specimens were cleaned properly with isopropyl alcohol then immersed with 5% NaOH at room temperature for 5minute followed by washing with running water. Subsequently specimens were dried and immersed with 5% turco acid (40%HNO3+4%HF+56% DM water) for 5minute followed by washing with running water and dried. The specimens were then welded by using a $CO_2$CW laser welding (ML 2000) at ARCI, Hyderabad, India. The laser welding was carried out at different process parameters, shown in table 3.2. Nine different conditions, shown in table 3.3, were designed by varying the process parameters for their effect on laser welding of cp-ti.

Table 3.1 Chemical composition (in wt.%) of cp-titanium used in the present study.

| Fe | C | N | H | O | Ti |
|---|---|---|---|---|---|
| 0.034 | 0.004 | 0.004 | 0.0004 | 0.134 | Balance |

Table 3.2 Weld parameters used in the present study.

| Welding Parameters | Value |
|---|---|
| Power in kW | 2 & 2.5 |
| Welding speed in m/min | 4, 5, 6, 7 & 8 |
| Beam diameter | Gaussian Mode<br>(beam focus diameter 0.18 mm)<br>Donut Mode<br>(beam focus diameter 0.36 mm) |

| | |
|---|---|
| Wave length in μm | 10.6 |
| Focal position | At the surface |
| Gas flow rate in $m^2$/min | 35 |
| Beam angle in degree | 90 |
| Focal length in mm | 300 |

Table 3.3 Different processing conditions of laser welding investigated in the present study.

| Process Conditions | Power in kW | Welding speed in m/min | Beam diameter at focus in mm |
|---|---|---|---|
| 1 | 2.0 | 5 | 0.18 |
| 2 | 2.0 | 6 | 0.18 |
| 3 | 2.0 | 7 | 0.18 |
| 4 | 2.5 | 6 | 0.18 |
| 5 | 2.5 | 7 | 0.18 |
| 6 | 2.5 | 8 | 0.18 |
| 7 | 2.5 | 4 | 0.36 |
| 8 | 2.5 | 5 | 0.36 |
| 9 | 2.5 | 6 | 0.36 |

## 3.2 Residual Stress Analysis:

Residual stresses were measured at different regions of the sample across the weld pool. The regions namely base metal (BM), weld pool (WR), interface between base metal and weld pool (IF) were considered for residual stress measurements. Figure 3.1 shows the representation of regions considered for the present investigation.

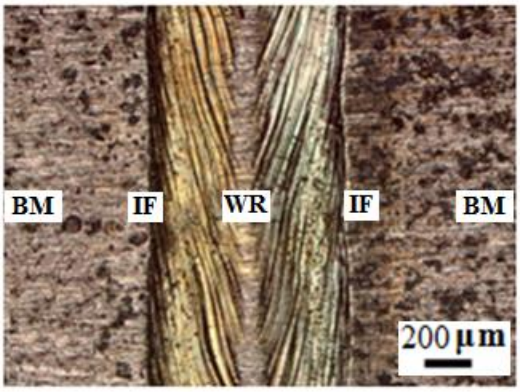


**Figure 3.1** Representation of different regions where residual stress measurement was performed in the present study.

Standard Sin$^2\psi$[ref] method was used for determining residual stress developments across the weld-pool of different LBW samples. A Bruker micro focus XRD (X-Ray Diffractometer) was used for determining the residual stresses. Inter-planar spacing, for a *(hkl)* pole, can be expressed as:

$$d_{hkl}(\psi,\varphi)=d_0[1+s_1(\sigma_{11}+\sigma_{22})+1/2s_2\sigma_{\varphi}\sin^2\psi]\text{--------------------(1)}$$

Where, $\psi$ is the inclination angle and $\varphi$ is the rotation angle of the goniometer. $D_0$ is the inter planar spacing of the stress free material. $S_1$ and $s_2$are the X-ray elastic constants (XECs), $\sigma_{11}$ and $\sigma_{22}$ are the stresses expressed in sample reference and $\sigma_{\varphi}$ is the residual stress of the material. Using appropriate continuum approach to elasticity (Reuss[ref] was used in the present study) and the material inputs, the residual stress values can be estimated from the slope of $d_{hkl}(\psi, \varphi)$ vs. Sin$^2\psi$.

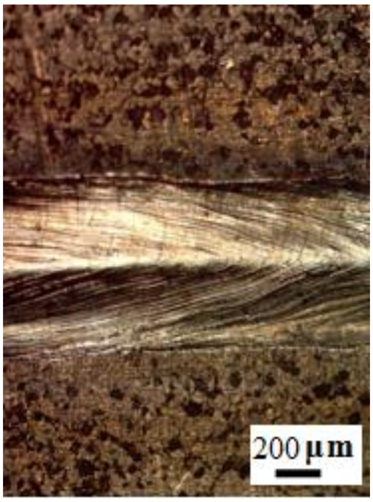
## Chapter 4

# RESULT AND DISCUSSION

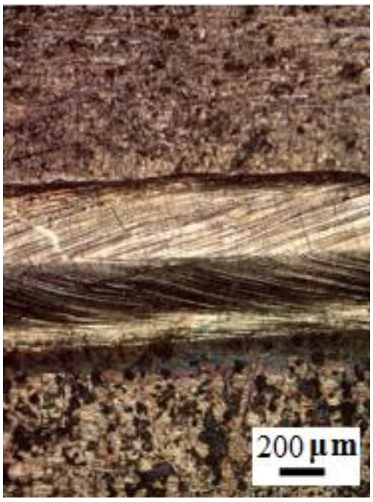
**Results and Discussion:**

Macrostructures of different laser welding samples w.r.t the processing conditions are shown in Figure 4.1. The figure clearly shows a wider weld pool in Donut mode of welding under the processing conditions adopted in the present study. A larger power density is the reason for such wider weld pool in Donut mode of welding compared to Gaussian mode of welding.

Case 1

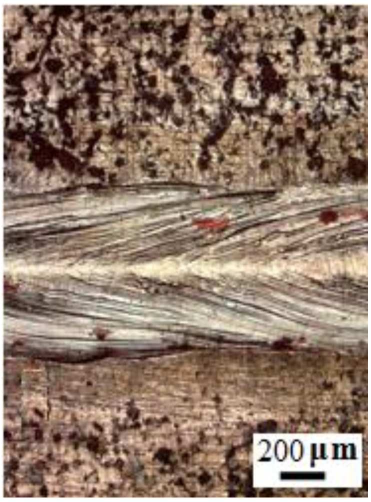


Case 2

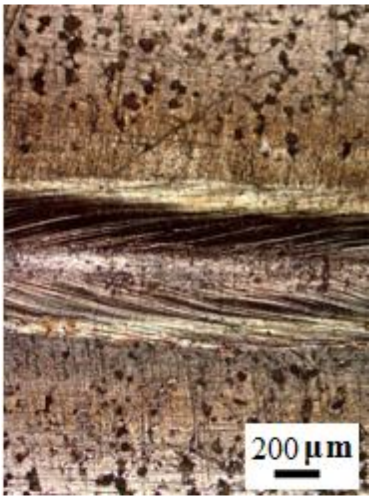


Case 3

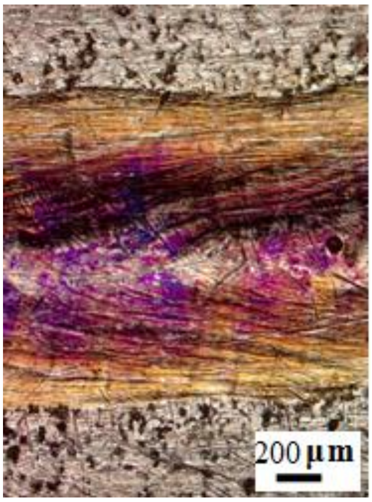
Case 4



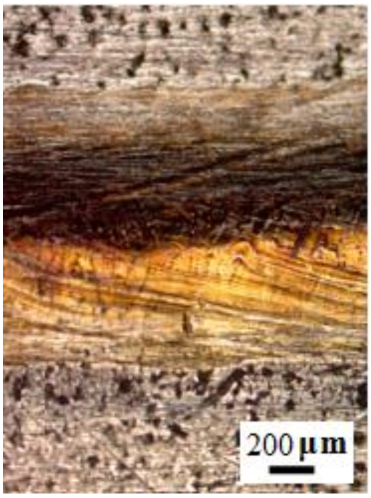
Case 5



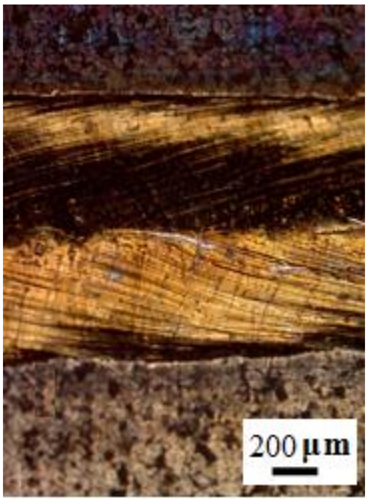
Case 6



Case 7



Case 8



Case 9

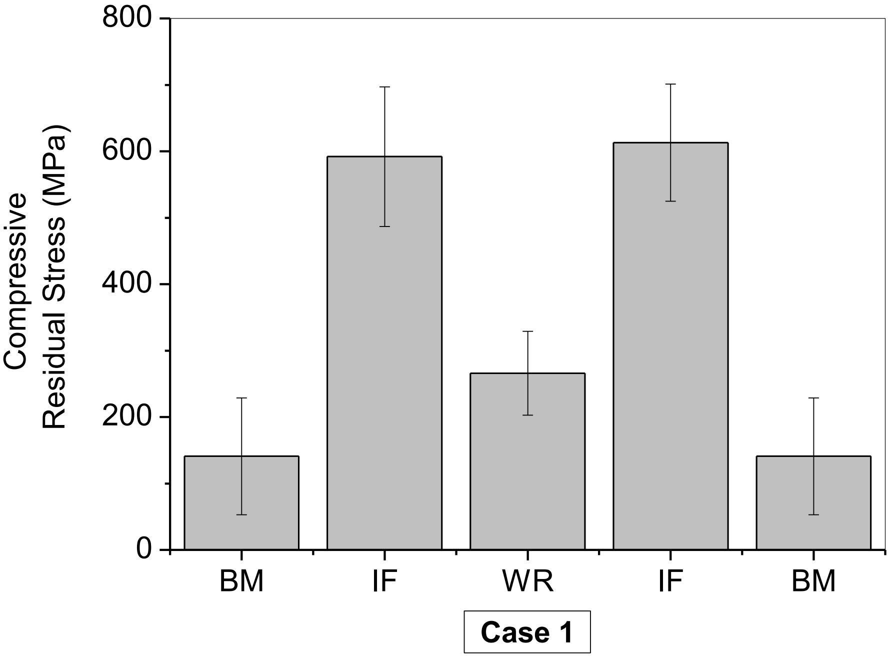
**Figure 4.1**

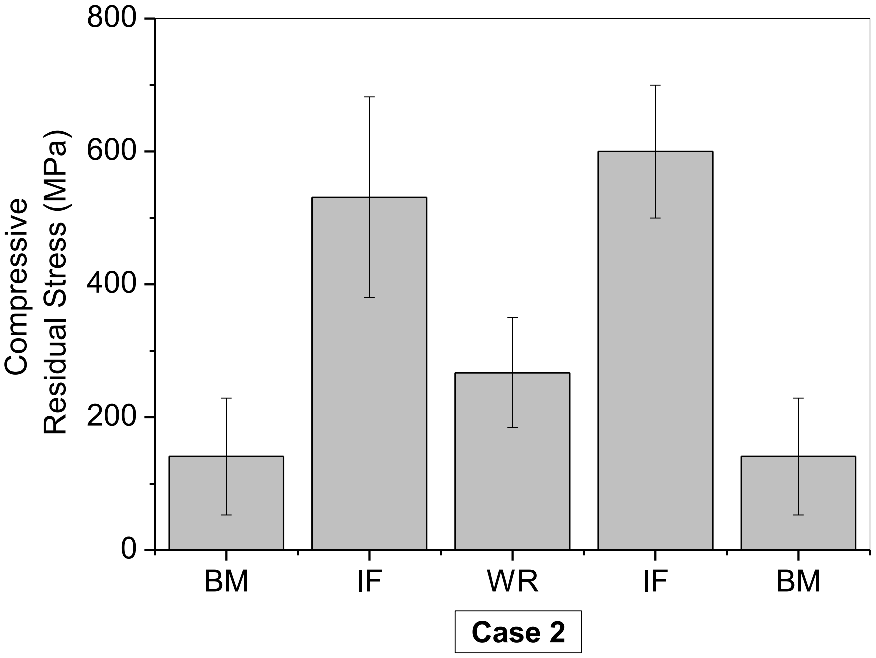
Macrostructures of laser welding samples at different processing conditions. Refer Table 3.3 for the processing conditions adopted for the present study.

The residual stress developments across the laser weld pool at different processing conditions are shown in Figure 4.2 through Figure 4.4. The following observations can be made from the figures:

- The residual stress developments in all the welded samples were found to be compressive in nature.
- In Gaussian mode of welding, the weld pools had lower residual stress compared to weld interfaces of the LBWs, whereas the weld pools had higher residual stresses in case of Donut mode of LBWs.
- The residual stresses across the weld pool (i.e. WR and IF) were found to be uniform at high speed of LBWs of Gaussian mode, at least in low laser power. However, in Donut mode of welding the residual stresses across the weld pool were uniform irrespective of any variation in welding speed.
- The residual stresses were found to be higher in Donut mode compared to Gaussian mode of welding.

It may be observed that unlike other fusion welding processes LBW showed lower residual stress developments owing to the fact that an increased supply of heat input results a slower cooling rate [13]. The residual stresses across the weld pool (between WR and IF) was found to be uniform with increasing welding speed which is in line with the literature. Heat input is inversely proportional to the welding speed and an increase in welding speed decreases in heat input rate which may normalizes the stresses across the weld pool [27]. The residual stress developments were found to be more uniform and higher in wider beam diameter. A higher beam diameter should decrease the residual stress in the weld pool, however, because of the nature of beam profile the increased residual stresses were observed.


800
600
400
200
0
Compressive
Residual Stress (MPa)
BM
IF
WR
IF
BM
Case 1


800
600
400
200
0
Compressive
Residual Stress (MPa)
BM
IF
WR
IF
BM
Case 2

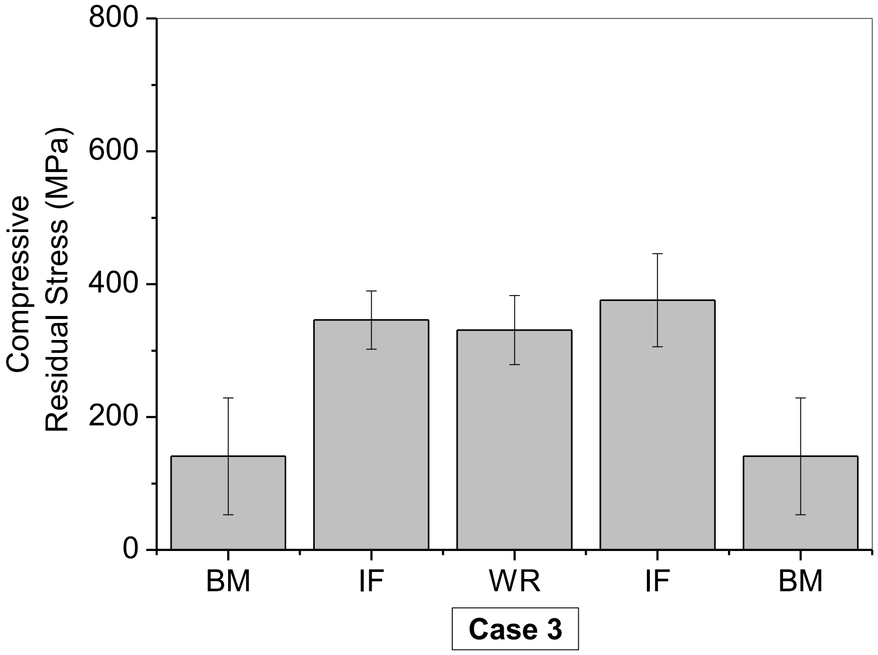
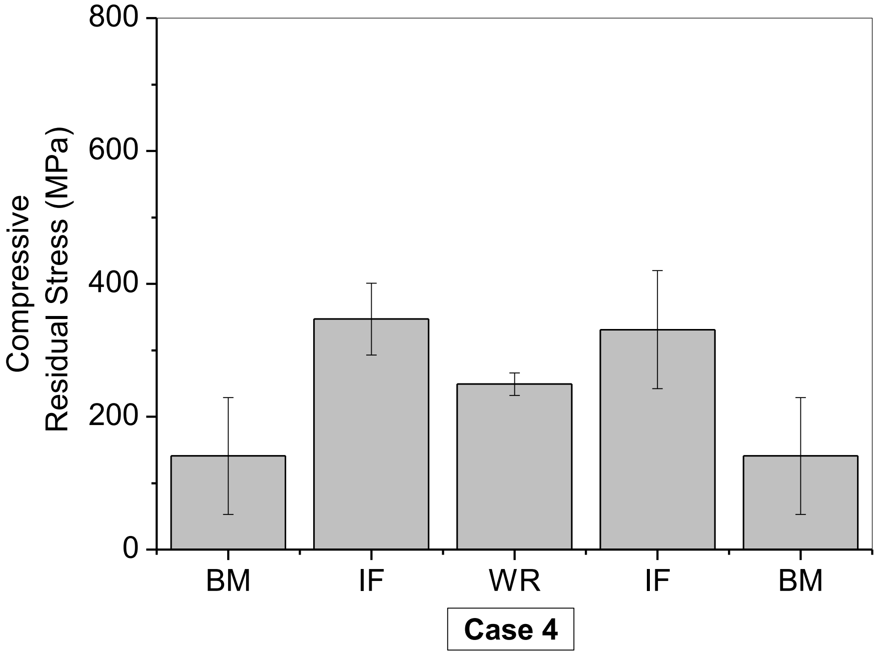
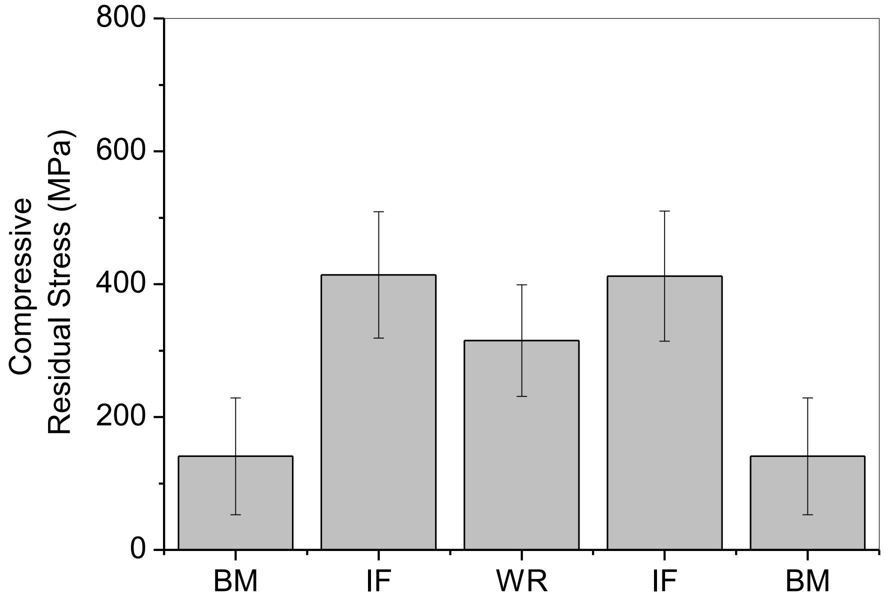
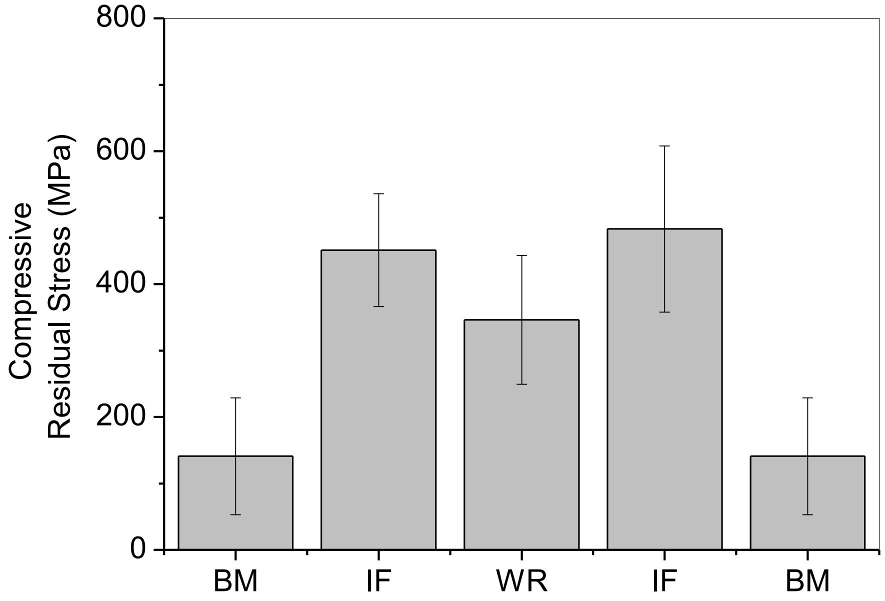


**Figure 4.2** Residual stress developments of laser welded samples across the weld pool as a function of welding speed at a laser power of 2 kW and Gaussian mode of welding. Different regions, where residual stresses were measures, are indicated as follows: BM – Base Metal, IF – Interface between base metal and the weld pool, WR – Weld Region or Weld Pool.



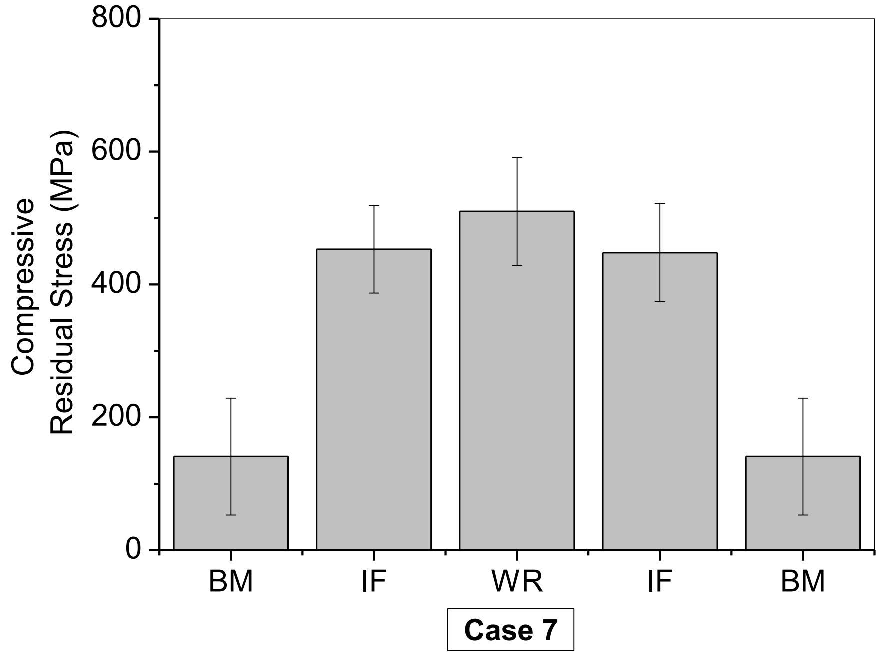


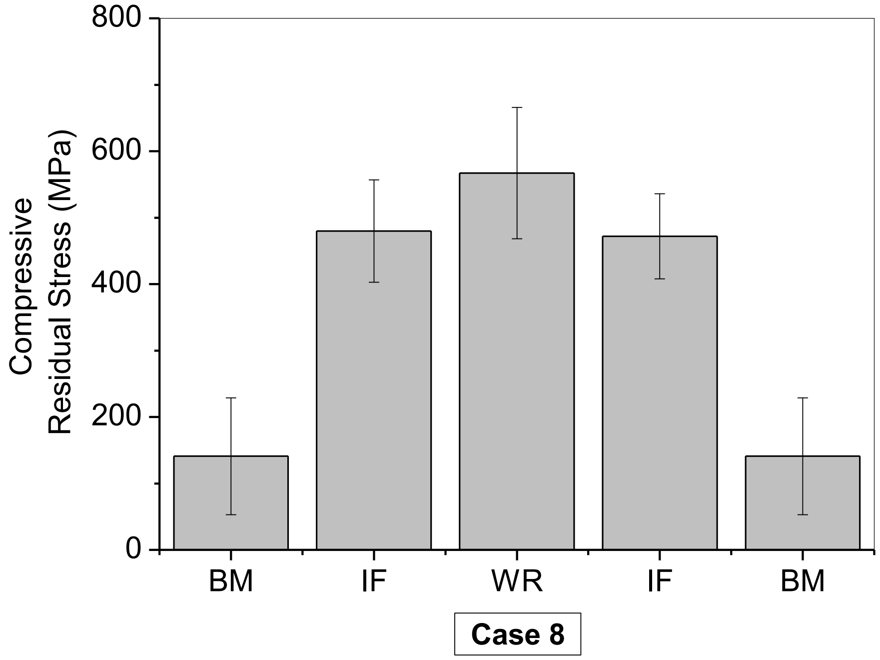
**Case 5**



**Case 6**

**Figure 4.3** Residual stress developments of laser welded samples across the weld pool as a function of welding speed at a laser power of 2.5 kW and Gaussian mode of welding.


Compressive
Residual Stress (MPa)
0
200
400
600
800
BM
IF
WR
IF
BM
Case 7


Compressive
Residual Stress (MPa)
0
200
400
600
800
BM
IF
WR
IF
BM
Case 8

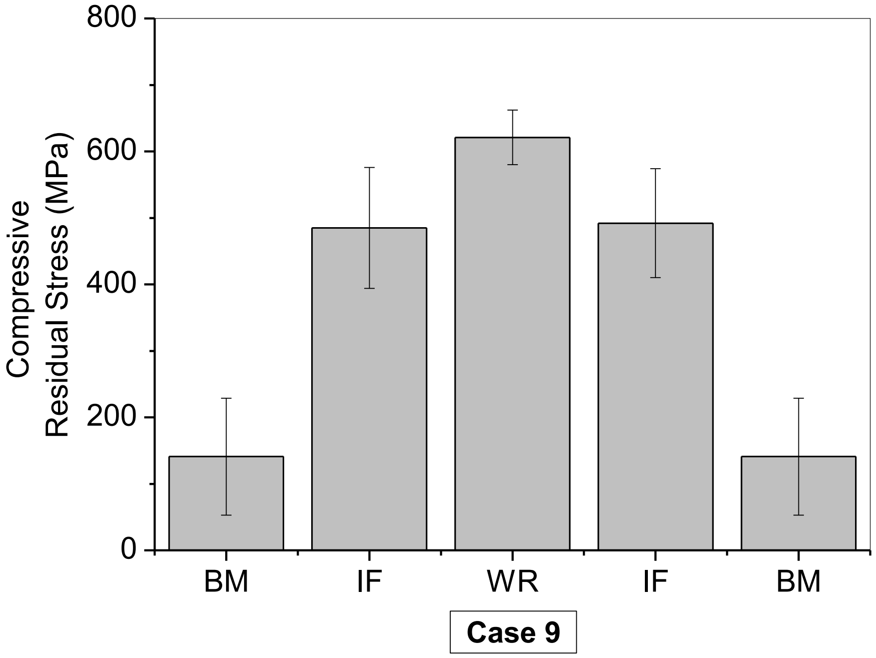


**Figure 4.4** Residual stress developments of laser welded samples across the weld pool as a function of welding speed at a laser power of 2.5 kW and Donut mode of welding.

# Chapter 5

# SUMMARY AND FUTRURE SCOPE

## Summary and Future Scope:

In the present study $CO_2$ continuous wave laser welding has been employed for the welding of cp-titanium sheets of 1mm thickness. The effect of process parameters like laser power, welding speed and beam mode on the residual stress developments across the laser welding was investigated. It was observed that the residual stress developments across the weld pool were found to be higher in Donut mode of welding. The stresses were also more uniform in Donut mode compared to Gaussian mode of welding. It was also observed that the residual stresses across the weld pool were more uniform at higher speed of welding.

The thickness of the material used in the present study, however, was very low compared to the components used for different applications. The processing conditions will significantly affect the results, if the thickness is increased. Due to unavailability of high power laser source, the present work was limited to welding of the low-thickness sheets and it will be worth investigating the residual stress developments during laser welding of higher thickness samples. Also residual stress developments during laser welding of dissimilar materials could be an important contribution to the researchers working on this area.

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