Investigations of Laser forming techniques of copper metal sheet

M.Tech Thesis

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JUNE 2020

Investigations of Laser forming techniques of copper metal sheet

A THESIS

Submitted in partial fulfillment of the requirements for the award of the degree of

Master of Technology

By

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Department of Mechanical Engineering

Indian Institute of Technology Indore

JUNE 2020

Indian Institute of Technology Indore

Candidate's Declaration

I here by certify that work which is being presented in the thesis entitled **Investigations of Laser forming techniques of copper metal sheet** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DISCIPLINE OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the time period July 2018 to May 2020 under the supervision of **Dr. I.A. Palani** of Discipline of Mechanical Engineering.

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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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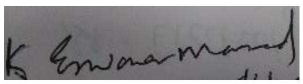
Jitendra Singh Queraly has successfully completed his M.Tech Oral Examination held on **…23-06-2020…..**

Signature of the Thesis Supervisors **Signature of Convener, DPGC**
Date: **Date:**



Signature of the PSPC Member 1 **Signature of the PSPC Member2**
Date: **Date:**

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Jitendra Singh Queraly

Dedicated to my Guide

my mother

my father

my brother

my grandparents

my teachers

and my friends

Abstract

Laser forming is an advanced manufacturing which is widely used in automotive and manufacturing industry by deforming metallic and non-metallic sheets. In this process, a continuous fiber laser is irradiated over Copper Metal sheet. As the laser beam imbibed over the sheet, a step temperature thermal gradient got induced across the thickness of the sheet. The bending moments due to uneven thermal stresses leads to the deformation of the sheet without using any external forces.

This paper shows the experiments performed on Copper Metal sheets of dimension 64mm×45mm with a maximum power of 50W. The process parameters which were varied are number of passes (10 to 30), power (30W to 45W) to get the maximum bending angle with a uniform spot diameter of 1mm.

The study between variations of the bending angle with process parameters is done. After this the characterization of the samples was done using optical microscope, XRD analysis, micro-hardness, tensile test and SEM.

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Abbreviations Used

TGM	Temprature Gradient Mechanism
UM	Upsetting Mechanism
RSRM	Residual Stress Relaxation Mechanism
BM	Buckling Mechanism
FESEM	Field Emission Scanning Electron microscope
UTL	Ultimate tensile load
BA	Bending Angle
XRD	X-Ray Diffraction

Chapter 1: Introduction

1.1Background:-

Light amplification by stimulated emission of radiation (LASER) is a coherent and monochromatic beam of electromagnetic radiation capable of generating intense heat on solid matter, which enables several types of novel and economical processing of materials, i.e., cutting, drilling, welding, forming, surface treatment etc. The applications of laser in these areas are advantageous compared to their conventional counterparts. Since then, significant interests had been created toward the use, development and improvement of laser metal forming technology among there searchers, scientists and engineers for its practical and economical applications in industries like aerospace, automotive, ship building, electronic industries etc. Laser forming is a thermal forming technique, which is a non-conventional sheet metal forming process.

The use of a laser beam in forming processes was introduced at the end of 20th century and is still under development. The laser beam makes forming technology applicable for industrial use, which formerly had to be done manually due to the lack of reproducibility or flexibility of the heat source used (e.g. straightening of distortion by heating with a gas torch). The main advantages of thermal forming processes are the fact that there's no spring-back effect and that tool and work piece are not in contact during the process. The latter fact also increases the flexibility of the processes, because no special tool is needed. Different geometries therefore, can be produced by using the same set-up and changing only the process parameters.

Laser forming has become a viable process for the shaping of metallic components, as a means of rapid prototyping and of adjusting and aligning. The laser forming process is of significant value to industries that previously relied on expensive stamping dies and presses for prototype evaluations, relevant industry sectors include aerospace, automotive, and microelectronics. In contrast with conventional forming techniques this method requires no mechanical contact and hence offers many of the advantages of process

flexibility associated with other laser manufacturing techniques such as laser cutting and marking. Laser forming can produce metallic, predetermined shapes with minimal distortion. The process is similar to the well established torch flame bending used on large sheet material in the ship building industry but a great deal more control of the final product can be achieved.

1.2 Process:-

Laser forming is a non-conventional forming process which is used for flexible manufacturing of sheet metal components of different shapes by the controlled defocused laser beam-induce thermal stresses without applying any external mechanical force. It has promising applications in rapid prototyping and shape correction in aerospace, ship building, automobile industries and microelectronics.

During laser forming, localized heating of the surface using a controlled beam without surface melting causes the expansion of the material in a confined region due to non-uniform temperature distributions. Due to the continuity of heated region with the surrounding material, the free expansion of hot region is resisted, resulting in permanent deformation of the part when the thermal stress becomes more than the temperature dependent flow stress of the material. The overall deformation in the sheet material is determined by the complete thermal cycle (heating and cooling) associated with laser processing. It is a complex thermo elastoplastic process, which depends on complex interactions of a large number of process variables. The simplest of laser forming processes is a simple straight line bending operations, as shown schematically in Fig 1.1

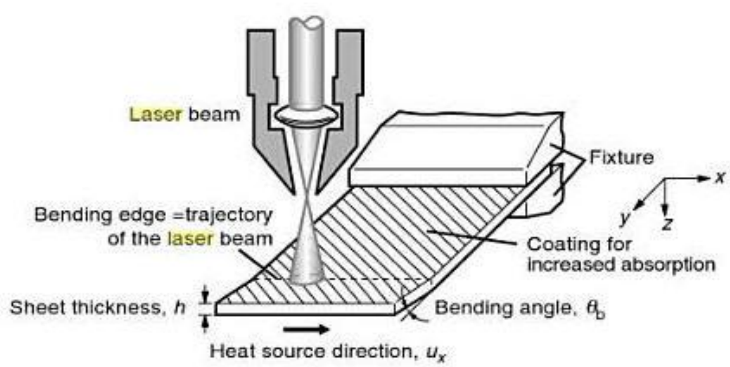


Fig. 1: Schematic view of the laser bending process.

In the laser forming arrangement shown in Fig. 1.1, one side of the sheet material is clamped in a fixture and the beam is scanned or irradiated linearly parallel to the free side of the sheet. Such a simplified arrangement is useful for typical V-shape bends in the sheet. However more complex and nonlinear scanning patterns can be used for producing complex shaped 3D parts. The final shape of the bend is determined by the actual laser processing strategy employed. This includes the consideration of three types of process parameters, i.e., parameters related to the laser source, work-piece geometry and material properties. Laser energy parameters are laser power, scan speed, spot diameter, number of laser scans, wavelength etc. The parameters related to the work-piece geometry are sheet dimensions, such as its length, width and thickness. The performance of the process also depends on the temperature dependent thermo-physical properties of the work-piece material. The related yield stress etc..thermal properties are coefficient of thermal expansion, thermal conductivity, specific heat etc. and mechanical properties are density, Young’s modulus, poisson’s ratio. Apart from these properties,the process also depends on the absorptivity of the sheet surface, method of holding the work-piece, scanning sequence in multi-scan laser forming process, cooling conditions, and others.

Generally, coatings (for example, graphite or phosphate) are used in order to improve the absorption of the laser beam energy into the surface. Without any coating, the absorption rate can be enhanced by using polarized light or using fiber laser. In general, one or two degrees of bend angle are achieved per irradiation. The bend angles may increase up to 180° with repetition of irradiations i.e. number of passes. The path of the laser is dependent on the desired shape.

1.3 Principle :-

In the traditional metal forming processes such as bending, drawing, stamping and pressing, a sheet of metal is plastically deformed when it is subjected to stress that is greater than the yield point. In the laser forming process, the plastic deformation occurs by the thermal stresses introduced into the surface of a metal sheet during the laser heating and subsequent cooling. There are various mechanisms of laser forming process depending on the processing conditions or specific combinations of the process variables, i.e., component geometries and laser processing conditions.

The mechanisms of laser forming process can be classified based on the existence of thermal gradient. The thermal forming mechanisms with the existence of temperature gradient are the Temperature Gradient Mechanism (TGM),and those without temperature gradient are the Buckling Mechanism (BM), Upsetting Mechanism (UM) and Residual Stress Relaxation Mechanism (RSRM).

Figure 1.2 shows the temperature gradient mechanism involved in the laser forming process. When a laser beam of high power density is rapidly guided across the surface of a metal sheet, the material absorbs a part of the laser energy on the surface and the thermal energy is conducted into the material in lower rate than that of the absorption on the surface, resulting in a steep temperature gradient through the thickness direction as shown in Figure 1.2(a). As a result, a differential thermal expansion occurs through the thickness direction. Initially, the material expands in the heated zone so that the whole shape of the material bends away from the beam as shown in Figure 1.3(b). This is called 'counter-bending’. This thermal expansion is converted into elastic tensile strain and compressive stress because free expansion of the heated material is restricted by surrounding material. Once the stress reaches the temperature-gradient flow stress, any additional thermal expansion is converted into a plastic strain.

The temperature gradient mechanism (TGM) is the most widely reported laser-forming mechanism, also called the bending mechanism because an out of plane bend is produced, as shown in Fig. 1.2 (a). Due to the rapid heating of the surface by the defocused laser beam and slow heat conduction into the sheet, a steep temperature gradient along the thickness sets in and thus, results in a differential thermal expansion. To create a high temperature gradient, laser beam must traverse the work-piece at such a speed that the thermal diffusion depth is small compared to the work-piece thickness.

As a result, a differential thermal expansion occurs through the thickness direction. Initially, the material expands in the heated zone so that the whole shape of the material bends away from the beam as shown in Figure 1.2(b). This is called ‘counter-bending’. This thermal expansion is converted into elastic tensile strain and compressive stress because free expansion of the heated material is restricted by surrounding material. Once the stress reaches the temperature-gradient flow stress, any additional thermal expansion is converted into a plastic strain.

In TGM, as the material is heated, the thermal expansion of the top surface becomes greater than that of the bottom surface, initially. This results in a bending opposite to the laser beam, which is called counter-bending. Due to this bending moment, a small amount of plastic tensile strain occurs at the heated top surface. With further heating, the bending moment opposes the counter-bending away from the laser beam, and the yield stress of the material is reduced with the temperature rise. Once the thermal stress reaches the temperature-dependent flow stress of the material, any additional thermal expansion is converted into a plastic compressive strain, because of the fact thatthe free expansion is restricted by the surrounding material. During cooling, the material contracts again in the upper layer, and as it has been compressed, there is a local shortening of the upper layer, and a bending angle develops that finally bends the specimen towards the laser beam.

To achieve higher efficiency in the process, the thermal expansion has to be converted into more plastic than elastic strain. The amount of elastic strain may be minimized by using high temperatures.

Generally, the TGM may be used for bending thick sheets along straight lines towards the laser beam. The irradiation of the surface may be repeated in order to increase the bending angle. It remains constant for the first few passes for a given material, laser power and beam size. Thereafter, the bending angle per pass starts to fall owing to work hardening and thickening of the material at the bent edge.

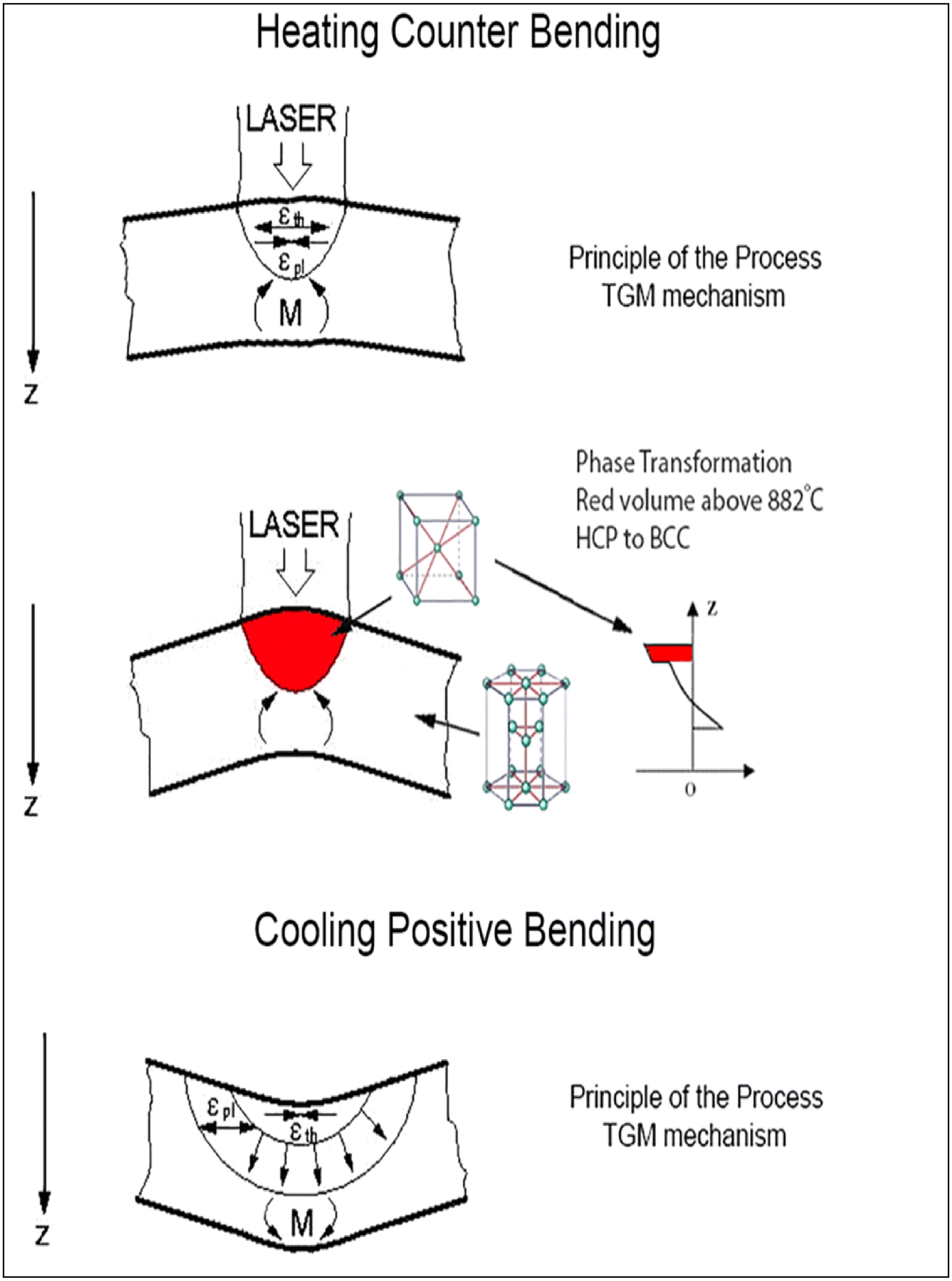

Heating Counter Bending
LASER
ε_{th}
ε_{pl}
M
Z
Principle of the Process
TGM mechanism
Phase Transformation
Red volume above 882°C
HCP to BCC
LASER
Z
z
0
Cooling Positive Bending
ε_{pl}
ε_{th}
M
Z
Principle of the Process
TGM mechanism

Figure2:- Temperature gradient mechanism involved in the laser forming process: (a) temperature gradient; (b) during heating; and (c) during cooling.

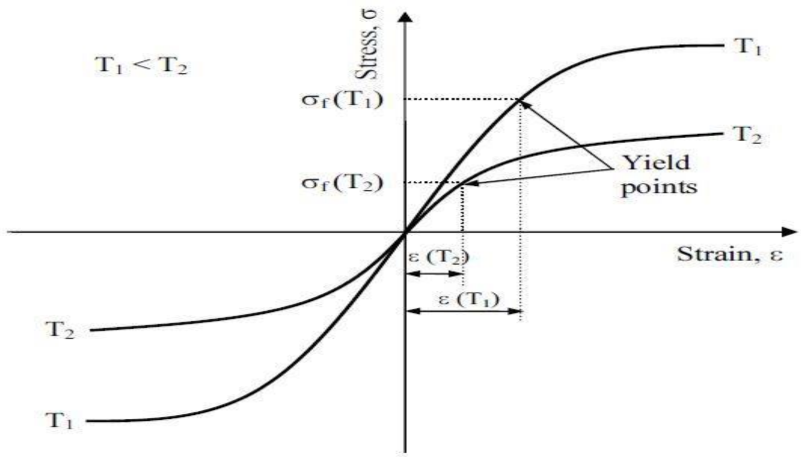


Figure3:- Stress-Strain relationships of material as a function of temperature.

As shown in Figure 1.3, the elastic strain as a function of temperature, ε(T), is determined by the elastic modulus *E* and the flow stress σf(T), ε(T) = σf(T)/*E*. During cooling mainly by the heat conduction into the material, the material contracts in the upper layer of the sheet so that the higher tensile stress occurs in the upper region. Therefore, the sheet metal is plastically bent toward the cooling laser path to relax the higher tensile stress as shown in Figure 1.3(c). A flow chart of this forming process is shown in

Heat conduction into the material in lower rate than absorption.

⇩

Rapid laser beam heating.

⇩

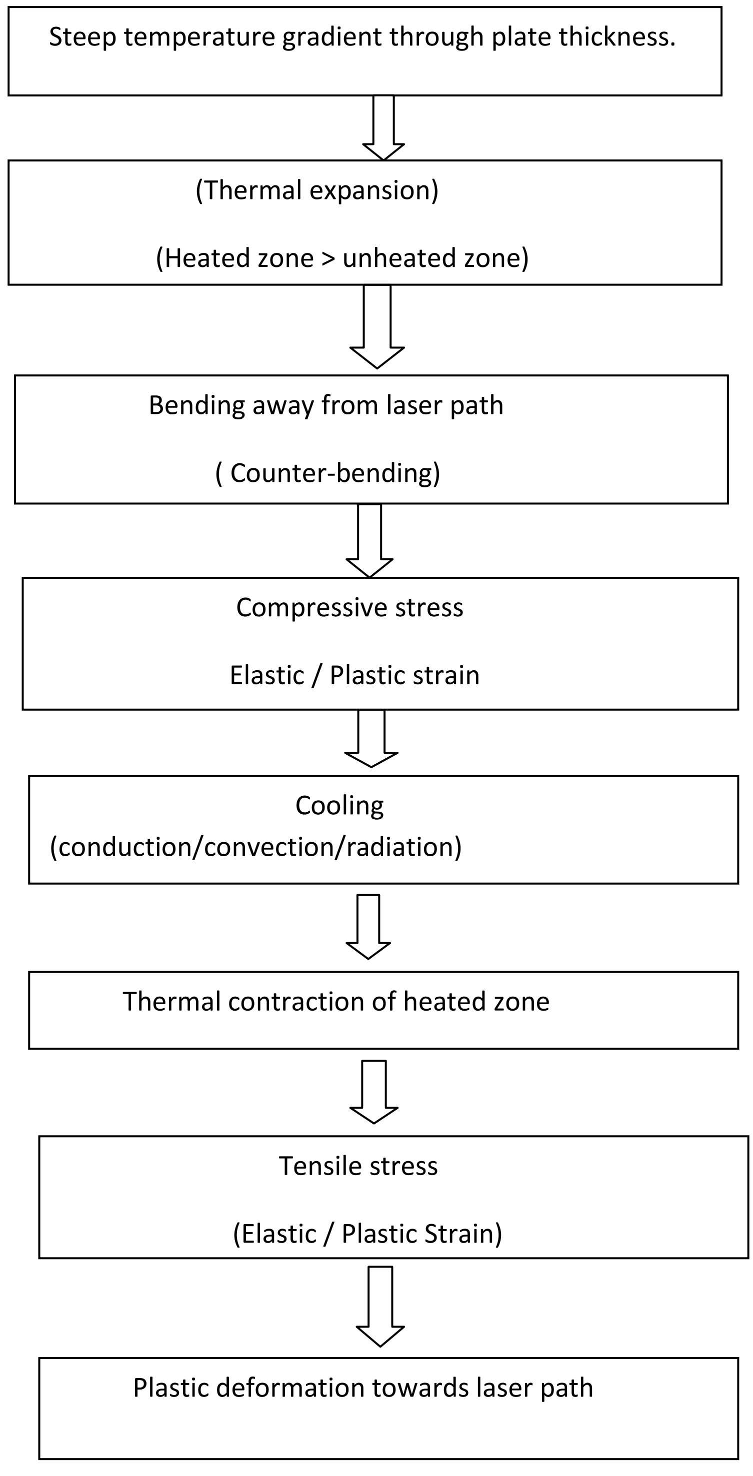


Figure 4:- A flow chart of laser forming process.

1.4Advantages and Disadvantages:

Due to the fact that the laser forming process involves thermal stresses introduced into a metal sheet by irradiation rather than external forces, which is employed in the conventional forming methods, the laser forming technique has the following advantages compared to the conventional forming operations.

• Flexible forming processes and the elimination of lead time associated with producing component for specific tooling can be realized because special hard tools are not required in this process.
• Precise deformation can be achieved because spring-back behaviors not involved which is related to the quality of product.
• Forming is available in inaccessible areas because this process is anon-contact forming process.
• Brittle, hard and thick material can be processed.
• A wide variety of complex shaped parts can be obtained through the development of new irradiation patterns.

Despite its potential advantages, the laser forming technique is not entirely free of drawbacks which may not yet be eliminated at the present development stage. Some limitations are addressed as follows:

• The forming process is somewhat slow. For some types of forming it is slower by a factor of 5, for others it may be a factor of 20 when compared to traditional methods of stamp and die.
• The process is energy consuming because of the low energy conversion factor of laser sources.

• The process requires safety protection equipment for the personnel because of multidirectional reflection of the laser beam from the metal.

1.5 Motivation:-

Laser forming has become a viable process for the shaping of metallic components. The laser forming process is of much importance to industries that previously relied on expensive stamping dies and presses for prototype evaluations on a large scale, relevant industry sectors include aerospace, automotive, and microelectronics. In contrast with conventional bending techniques this method requires no mechanical contact and hence offers many of the advantages of process flexibility and lower cycle time associated with other laser manufacturing techniques such as laser cutting and marking. Laser bending can produce metallic, predetermined shapes with minimal distortion. The process is similar to the well established torch flame bending used on large sheet material in the ship building industry but no doubt a great deal of more control of the final product can be achieved. One of the main characteristics of a laser-bending process is that it does not require use of hard tooling or external forces. Hence, a laser forming process has many advantages such as no spring-back, high process flexibility, and the capability of production of complex shapes, structures and the formation of very small parts.

Accordingly, over the years, many researchers have investigated not only the phenomena of the process, but also the realistic product applications in order to realize better achievements with the laser-bending process. Very rapid strides have been made on all fronts of science, processing, control, modeling, application developments etc. and this has made it an invaluable tool that is now being increasingly considered to be an integral part of component design. The laser beam techniques are eminently suited to modify a wide range of engineering properties. The properties that can be modified by adopting the laser technique include mechanical, thermo-mechanical, electrochemical, optical, electrical and magnetic/acoustic properties.

1.6 Research Objectives

The various research objectives of this research are as follows:-

1. Reliability:

Establish an assessment strategy of the reliability of the laser forming process, as well as evaluating the process robustness with regard to uncertainties of the input variables (e.g., laser power, feed rate, plate thickness and coefficient of thermal expansion). It is assumed that the variations of the input variables follow the Gaussian distribution.

2. Property Sensitivity:

Identify which material properties significantly affect the angular change in the straight-line process. The material properties to be investigated are confined to coefficient of thermal expansion, thermal conductivity, specific heat and modulus elasticity.

3. Characterization: The characterizations of the copper sheets were done so as to analysis the variation or change comes in the properties of the material after the irradiation of the laser.

Chapter2: Literature Review

This section provides an insight to the current technology available in the field of laser forming. It also highlights various methods used by researchers on this topic. Laser forming is a complex transient process that involves thermodynamics, elastic-plastic mechanics, metallography etc. To control the deformation of metal sheet, research of mechanics plays the major role. Forming mechanisms are governed by the temperature field which in turn is influenced by geometry of workpiece, laser power, laser spot diameter, laser pulse duration, scanning velocity, scanning path and so on.

Here we get the feel of the topic by getting to know about various mechanisms governing laser forming, influence of various parameters on the laser forming operation.

Shichun and Jinsong [9] did the experimental study to find out the changes in the bending angle with process parameters. Process parameters consist of laser energy parameters, material parameters and sheet geometry parameters. The laser energy parameters include laser power, path feed-rate, beam spot diameter and feed number. Material parameters include coefficient of thermal expansion, density and specific heat at constant pressure. Sheet geometry parameters include sheet length, width and thickness. The experiments were performed on a type of LCM408 laser machine, with a CO_2 laser source of 2 kW. Steel 08 (corresponding to AISI 1008), aluminium L3M (corresponding to ASTM 1050, annealed) and duralumin LY12CZ (corresponding to ASTM 2024, quenched and naturally aged) sheets were chosen as the working materials for the tests of laser bending. The sheet surfaces were coated with carbon black before testing in order to increase the absorption of laser power. The sheet metals after irradiation were cooled naturally. The conclusions drawn from the tests were that the bending angle varied in direct proportion to the laser power and feed number, and in inverse proportion to the path feed-rate and beam spot diameter. There was no significant influence of the strength at room temperature on the bending angle. Among the sheet geometric parameters only sheet thickness had remarkable effect on the bending angle, which decreases sharply with increase in the sheet thickness.

Shen and Yao [10] did the experimental study of mechanical properties of sheet metal after laser irradiation. Many sheet metal components formed by mechanical pressing are subjected to cyclic loading during their service life. The investigations indicated that the fatigue performance of the pressed components decreased significantly compared to the stock plate specimens of the same material. This decrease in life is attributed not only to the increase in tensile residual stress but more importantly also to the degradation of the material gains resulting from the mechanical forming process. The observed decrease in fatigue life has led to a search for an alternative manufacturing process for enhancing the fatigue performance. Laser forming is a flexible manufacturing process that forms a metal sheet by means of thermal stresses induced by external heat instead of external force. The objectives of this study are to characterize the mechanical properties of laser formed samples. The tensile properties and the low-cycle fatigue life under different laser processing parameters were investigated.

Monotonic tensile behaviour of low carbon steel specimens with different laser processing parameters was investigated. The tensile properties of specimens after laser forming changed slightly compared to the unprocessed ones. Low-cycle fatigue damage and life of the specimens were compared with that of the un scanned ones. The enhancement in fatigue life as indicated by the laser-formed specimens was encouraging. SEM analysis also revealed the reason why laser-formed low carbon steel has a longer fatigue life than before laser forming. The compressive residual strain is the most important reason why the fatigue life of low carbon steel after laser forming improves.

Shen et al. [11] proposed a new mechanism of laser forming. Laser forming is a complex thermal–mechanical process. To reveal the mechanisms dominating the forming process is essential to control accurately the deformation of metal plate. Numerous efforts had been made to understand the mechanisms of laser forming. Proposed mechanisms mainly included temperature gradient mechanism, buckling mechanism and upsetting mechanism. However, in the investigation of laser forming, it is found that the above three mechanisms cannot explain fully the process of deformation. Based on the study of thermal transfer and elastic–plastic deformation, the above three mechanisms are further explained. In addition, a new mechanism, coupling mechanism, is proposed. To verify the validity of the mechanisms proposed, numerical simulations are carried out, and simulation results are consistent with analysis of mechanisms.

Ueda et al.[12] used temperature distribution for determining the bending angle. Laser forming is a thermal process for the deformation of sheet metal by inducing localized thermal stress. Temperature distribution is the most important factor for determining the bending angle of the sheet metal. In the present study, the combined effect of the temperature of the workpiece, the temperature gradient between the two surfaces of the sheet, the size of the area irradiated with laser beam, and the thickness of the workpiece is investigated both theoretically and experimentally. The temperature at the surface irradiated with CO2 laser and at the opposite surface are simultaneously measured using two-color pyrometers with an optical fiber. The bending angle has been found to increase with the spot diameter and workpiece surface temperature and decrease with workpiece thickness.

Thomson and Pridham [13] discussed the development of a basic process monitoring and control system. Laser forming is a process that uses the energy of relatively high powered lasers to cause permanent deformation to components by inducing localized thermal stresses. This paper briefly discusses laser forming and the development of a basic process monitoring and control system used to overcome various problems due to the complex nature of the lasers and the manner in which they interact with material.

Guan et al. [14] established a three-dimensional coupled thermo-mechanical finite element model. The laser-forming process is a new flexible forming process without rigid tools and external force. The sheet metal is formed by internal localized thermal stress induced by laser. Material properties play an important role in laser forming. A three-dimensional coupled thermo-mechanical finite element model is established in this paper. The laser-bending process of a sheet blank is simulated numerically using the model. The relationship between the bending angle and material property parameters, such as Young's modulus, yield strength, coefficient of thermal expansion, specific heat, and thermal conductivity, are studied extensively by FEM simulation. The simulations show that the material with lower Young's modulus and yield strength can produce a larger bending angle. The thermal expansion coefficient is nearly in direct proportion to the bending angle. The bending angle decreases with the increase of the heat conductivity.

Hsieh and Lin [15] investigated numerically and experimentally the buckling mechanism of a thin metal tube during laser forming in this study. Metal tubes made of 304 stainless steel were heated by a CO2 Gaussian laser beam, which induced the buckling phenomenon on the tube surface due to elastic–plastic deformation. This uncoupled thermal–mechanical problem was solved using a three-dimensional finite element method and was subsequently satisfactorily verified with displacement measurements. The transient bending angle and residual stress of the thin metal tube under specific operation conditions were also studied.

Chapter 3: Experimental Setup

3.1 Laser Setup

The laser setup consists of a fiber laser (Scantech laser Pvt. Ltd) doped with rare earth elements like erbium, ytterbium, neodymium, etc. It has a rated capacity of 50 W with a galvo scanner which deflects the beam in X and Y direction with a focal length of 160mm as shown in figure below.

Figure5: - Experimental setup used for laser forming.

Controlling unit:

It consists of a controlling unit which consists of the following switches to control the laser:

a. Galvo On/Off
b. Laser On/Off
c. PC On
d. PC reset

e. Laser enable

f. Rotary enable

g. Z-axis Up

h. Z-axis Down

Figure6:- Controlling unit of the fiber laser.

Firstly the PC is turned on, after that the galvo and laser will be turned on to enable them. We can see the red spot on the surface of the worktable which indicates that the laser is properly functioning.

The Z-axis Up and Down switches are used to control the movement of the worktable in the Z direction in order to adjust the focal length of the laser. The rotary enable switch is used in case of a circular work-piece.

3.2 Work-piece Details:

Test setup is developed to perform experiments based on the medium used. It comprises of a laser source, controlling unit, work-piece holder and laser beam design software. The Scan-mark software is used to form a laser beam according to our design requirement like line, circular or ellipse, etc. Copper material is used here for the study. Following are the specifications of Copper material.

Table 1 Specifications of Cu material.

Thermal conductivity (W/m-°C)	**385**
Density (g/cm^3)	**8.96**
Specific Heat Capacity (J/g-°C)	**0.385**
Young's Modulus (G Pa)	**128**
Yield Strength (MPa)	**100**
Poisson's Ratio	**0.33**
Coefficient of thermal expansion at 20°C (/°C)	**17×10^{-6}**

Work-piece: Copper Sheet.

Dimensions of the specimen: Length: 64mm Width: 45mm Thickness: 0.40mm

Laser machine used: Fiber laser (doped with rare earth elements like erbium, ytterbium, neodymium, etc)

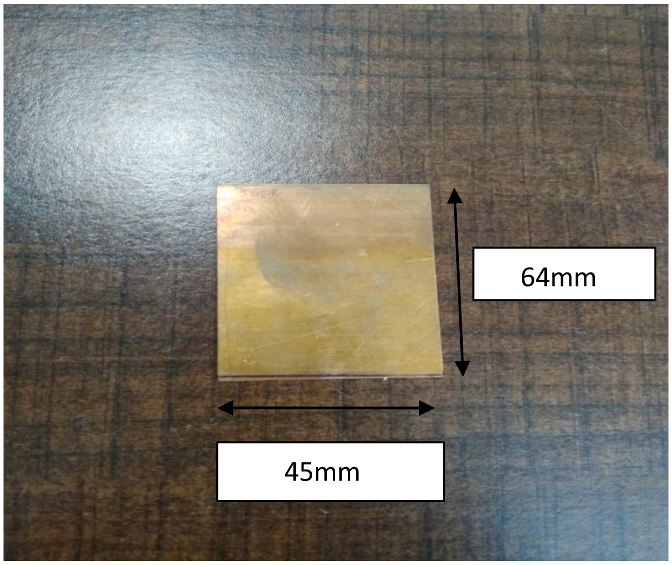


Figure7:- Copper sample used for experiment.

Ranges of various laser parameters:-

a). Laser power: 35 to 45 W

b). Spot diameter: 1 mm

c). Pulse width: 30µs

d). Number of passes: 10 to 30

e). Marking speed: 1.73 and 3.37 mm/sec

Input parameters :

a). Laser Power.

b). Spot diameter.

c). Number of passes.

d). Marking speed.

Output parameter:

a). Bending angle.

3.3 Experimental procedure:

Firstly the work-piece is fixed over the worktable at the focal length of the laser. Then with the help of scan-mark software we will make a laser line beam which will be at a distance of 22.5mm from the extreme end of the sheet. Now the parameters of laser such as power, spot diameter, marking speed and number of passes were fixed. The laser line beam is then irradiated on the surface of the Copper sheet by turning on the laser enable switch.

The forward and the backward stroke are considered as one single pass. After the completion of process the work-piece is allowed to cool for 3 to 5 minutes and then its further analysis is done. The sheets were scanned for different number of passes in order to get the maximum bending of sheets. The different laser and process parameters affect the bending angle. The parameters which were varied are: Power (35W to 45W), Number of passes (10 to 30).

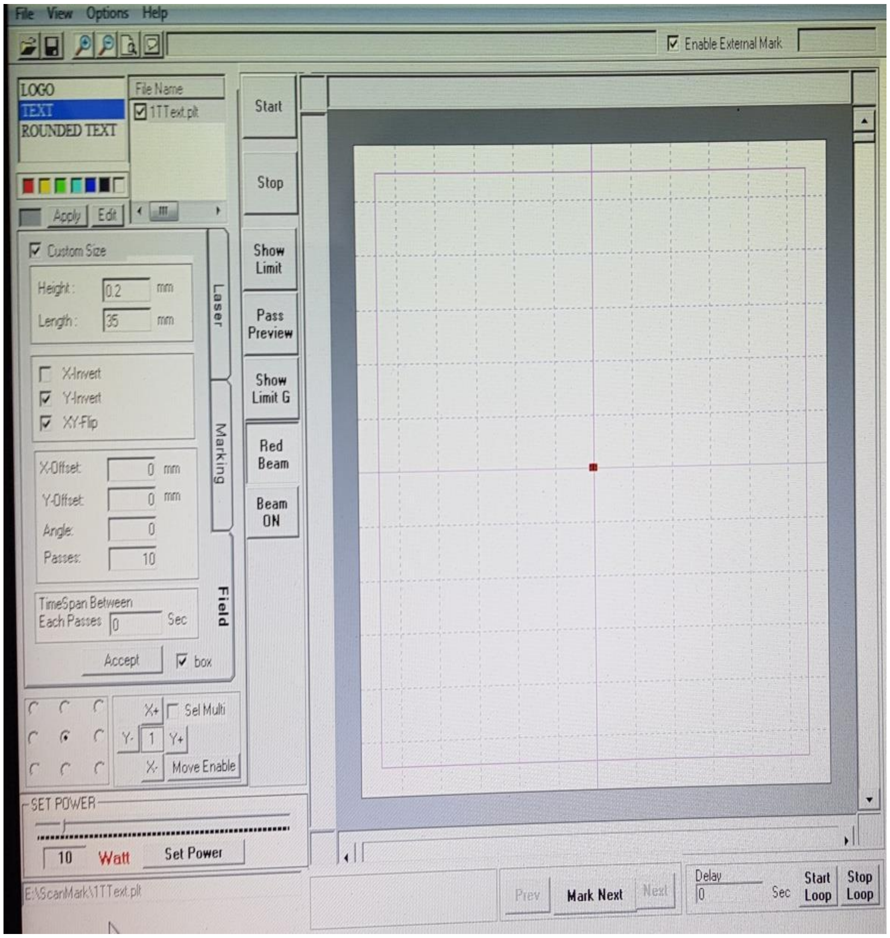


Figure 8– Forming line beam using scan-mark software.

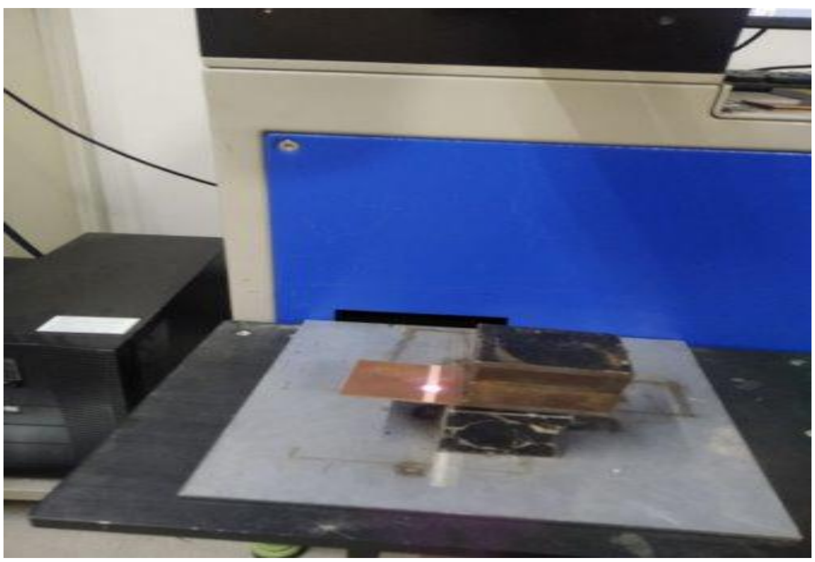


Figure 9 - Irradiation of laser on the Copper sheet.

Chapter 4: Result and Discussion

4.1 Bending Angle Analysis

The Bending angle analysis of copper sheet with respect to power and number of passes was done.

4.1. a) Bending angle vs Number of passes (at different powers)

The deviation of bending angle with respect to power and number of passes are discussed in this chapter. Also the phase transformational behavior as well as the optical microstructure and the hardness of the Copper samples with respect to the change in process parameters were analyzed and studied.
Laser is applied at three different powers i.e. 35W, 40W and 45W on the Copper samples. A non-linear relationship can be seen between the bending angle and power. As the power is increased, the bending angle also gets increased due to generation of more thermal compressive stresses on the irradiated area.

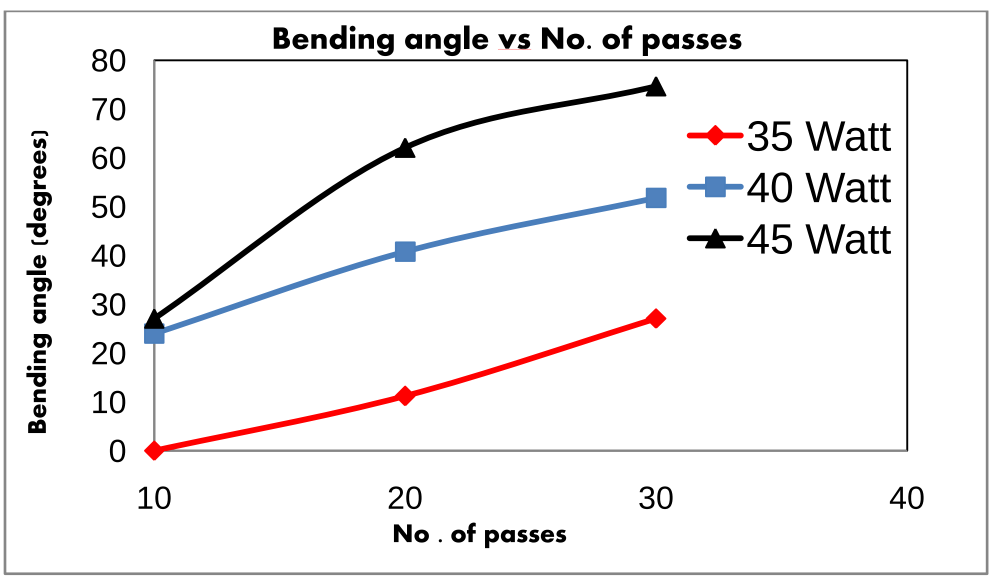
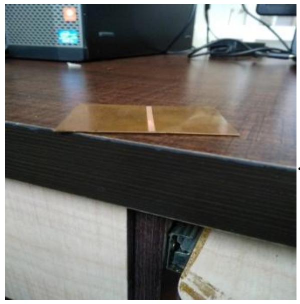


Figure10- Bending angle variation with number of passes

Experimental Details :



- Power-35 watt
- Number of passes-10
- No forming

Figure -11

- Power-35 watt
- Number of passes-20
- Bending angle –11.2 degrees

Figure -12

- Power-40 watt
- Number of passes-10
- Bending angle-24 degree

Figure-13

- Power-40 watt
- Number of passes-20
- Bending angle-40.8 degree

Figure -14

- Power-45 watt
- Number of passes-10
- Bending angle-27.1 degree

Figure-15

- Power-45 watt
- Number of passes-20
- Bending Angle-62.1 degrees

Figure-16

With the increase of laser power and number of passes the thermal compressive stresses will increase and leads to thermo-mechanical effects over the sheets due to which the bending angle increases.

Table 2 Variation of bending angle with changing number of passes (at different powers).

S. No.	Power	No. of Passes	Bending Angle (Degrees)
1.	35	10	No forming
2.	35	20	11.2
3.	35	30	20.1
4.	40	10	24
5.	40	20	40.8
6.	40	30	52.2
7.	45	10	27.1
8.	45	20	62.1
9.	45	30	71.2

4.2 Bending angle Vs Scanning Speed

Figure18 shows the variations in the bending angle with reference to scanning speed for different laser powers 10W, 20W, 30W, 35W, 40Wand 45W. Whereas figure 18 shows the change in the bending angle with reference to power at two different scanning speed i.e. 1.73(mm/sec) and 3.37(mm/sec). It can be noticed that power and scanning speed are the two important parameters which are affecting the bending angle of sheet. Here number of passes are 30.

Table 3 Variation of bending angle with changing scanning speed.

S. No.	Power(watt)	Marking Speed(mm/sec)	Bending Angles(Degrees)
1	35	1.73	19.4
2	35	3.37	7.5
3	40	1.73	66.6
4	40	3.37	42.2
5	45	1.73	68.1
6	45	3.37	60.2

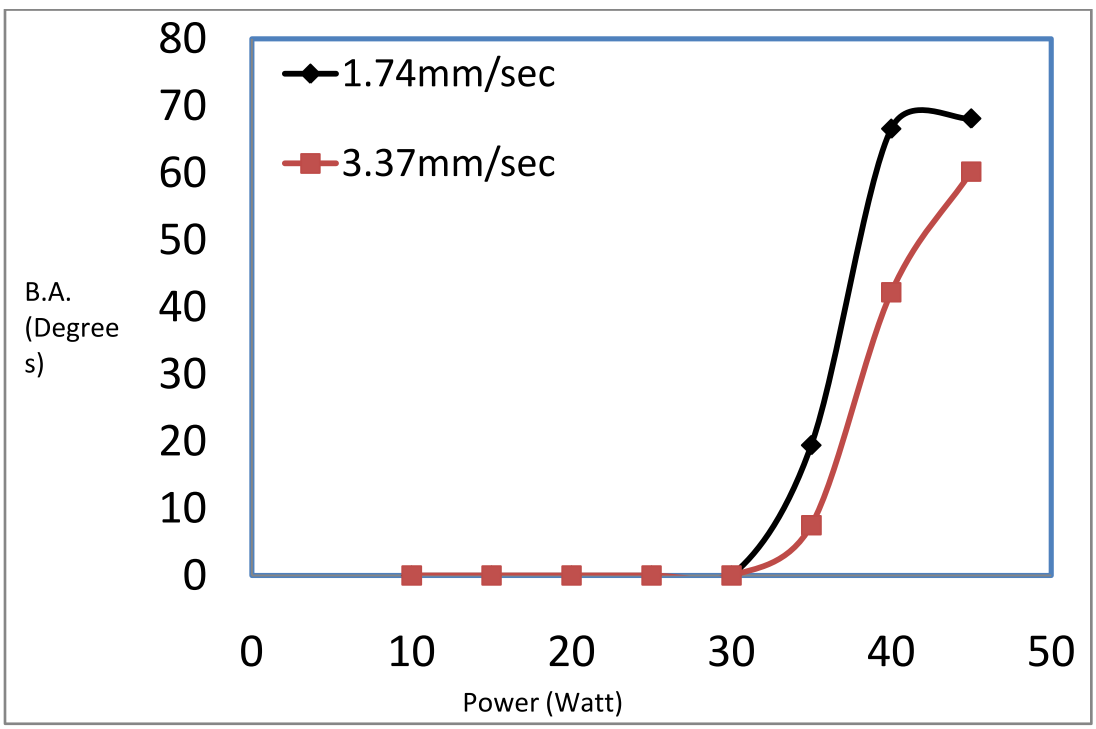


Figure17- Bending angle variations with scanning speed

With the increase of scanning speed thermal energy per unit time will decreases the thermal compressive stresses will decrease and leads to thermo-mechanical effects over the sheets due to which the bending angle decreases .

4.3 Micro-structure analysis

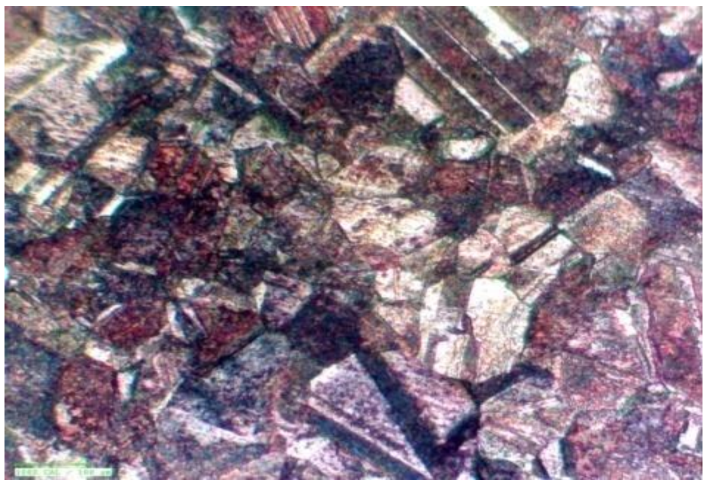


Figure 18- Before Forming

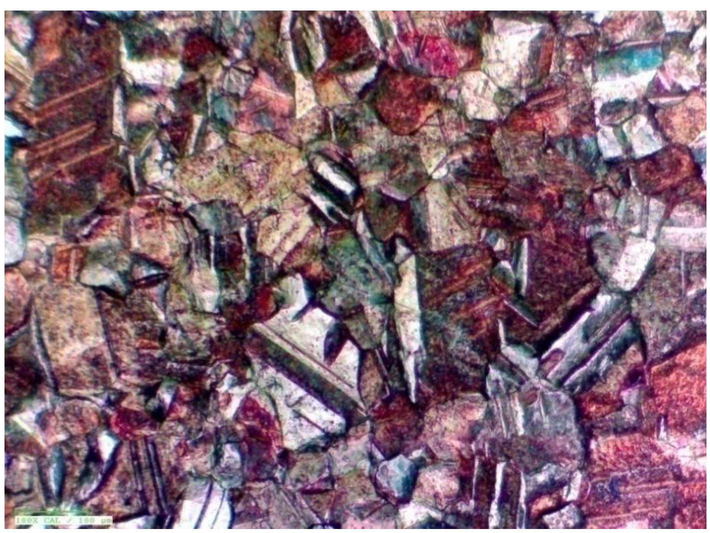


Figure 19-Heat Affected zone, 40 watt

These are the micro-structural images of Copper Sheet and heat affected zone of Copper sheet at 40 Watt, by analyzing these micro-structural images we will calculate the grain size of copper sheet metal before and after forming.

4.4 Grain Size Calculation before and after forming.

Sr. No.	L(length in microns)		D (diameter in microns)	
	Σ(l/n)/x	Σl / Σn		
Before forming	90.55	88.33	102.18	99.67
35 watt	80.34	78.15	89.98	86.35
40 watt	81.13	78.22	91.55	88.27
45 watt	97.01	91.98	109.47	103.79

Table 4 : Size of grains before and after forming at different powers

Here the size of grains is first decreasing at 35 Watt and 40 Watt and increasing at 45 Watt. Grain Size is calculated by using line intersection method in microstructure images of formed sheets at different powers.

4.5 Hardness analysis

The laser is applied at different power which leads to change in the hardness of the material. Since the thickness of the sheet was very less i.e. 0.4mm. Thus Vickers micro-hardness test was done for all the samples.

4.5.1 Hardness at different powers with 20 passes.

Hardness is one of the most important parameter for a material which helps us in determining its life. From the below table we can see that with the increase in power, the hardness of the material is getting increased for (35 Watt and 40 Watt) and decreased for (45Watt) in heat affected zone.

Table 5:- Micro-hardness at different power with 20 passes.

POWER	MICROHARDNESS (HV) AVERAGE VALUE OF THREE INDENTS	VALUE OF EACH INDENT (HV)
Before forming	107	110,109,102
35 Watt	109	109,107,111
40 Watt	110.66	109,111,112
45 Watt	105	107,103,105

Based on the above values a graph is plotted between the hardness and the different powers. This variation in the hardness of the copper sheet occurs because of the wear of the material from the surface of the work-piece.

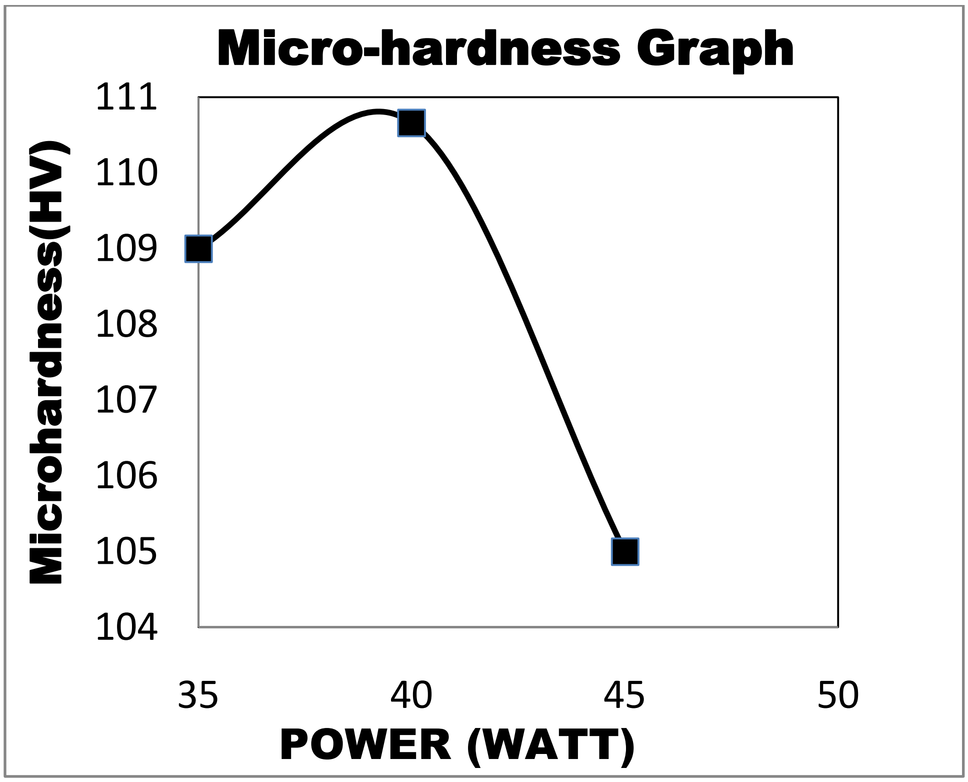


Figure 20- Graph (Micro-hardness vs power)

Here variation of hardness is non linear at different powers (30, 35 and 40 watt) with 20 passes first hardness is increasing and then decreasing because average grain size is decreasing at 35 and 40 watt and then it is increasing at 45 Watt.

4.6 XRD Analysis.

XRD analysis of copper sheet is done before and after forming at different powers to obtain the peaks in XRD graph for the verification of oxide and other elements if present in copper sheet after forming as here in experimental set up forming is done on open atmosphere that's why it is necessary to verify the amount of oxide and other elements present in copper sheet after forming because it will affect its material characterization properties.

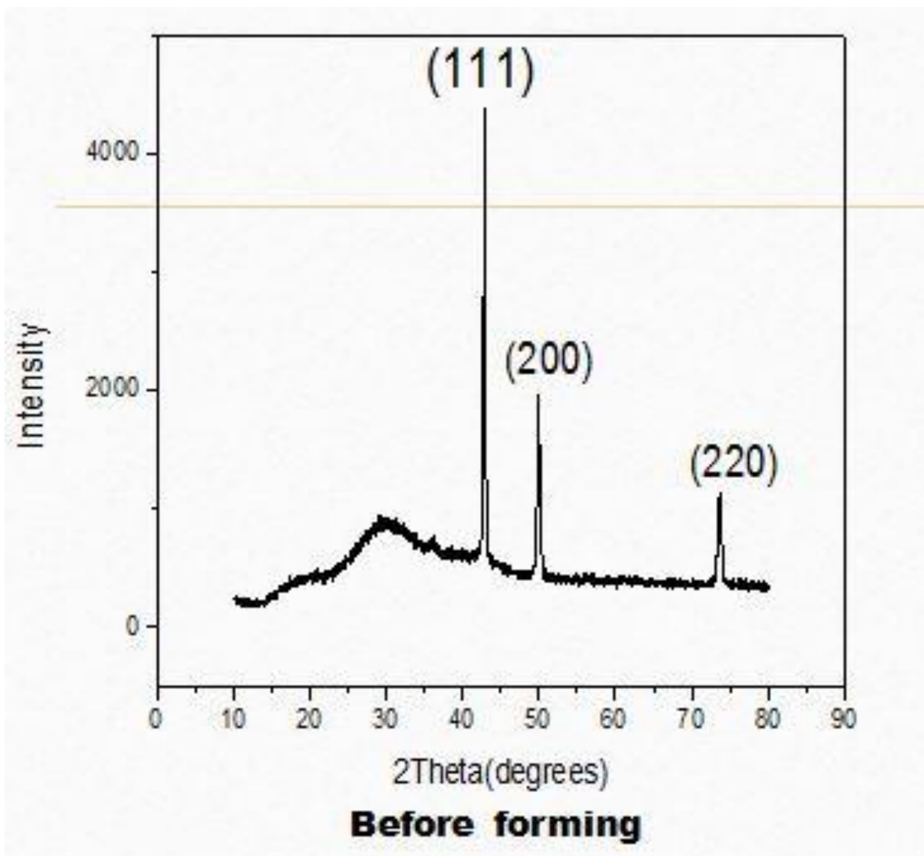


Figure 21- XRD graph of copper sheet before forming

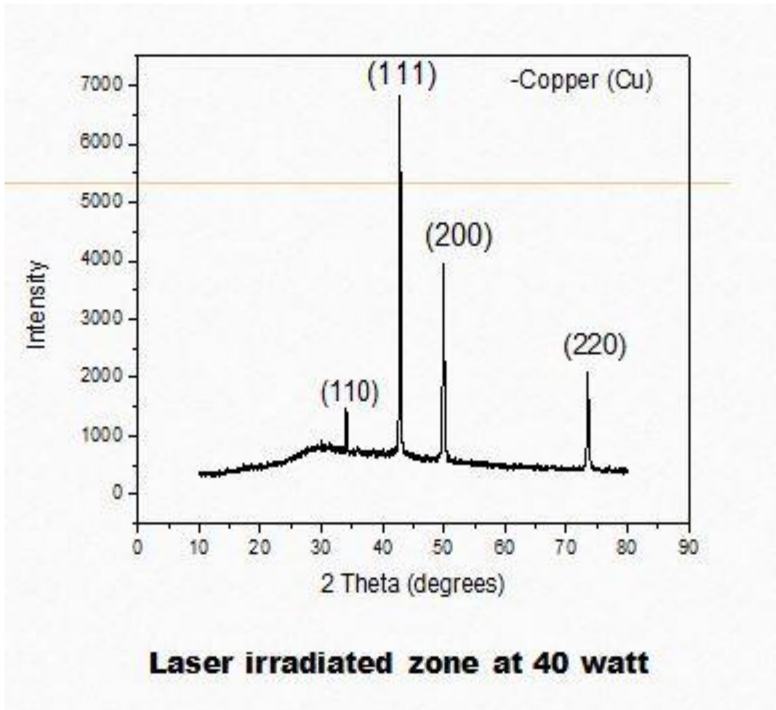


Figure 22- XRD graph of laser irradiated zone at 40 watt.

Here the peak of planes are (1 1 0) which denotes the formation of copper oxide in laser irradiated zone.

4.7 Surface Morphology

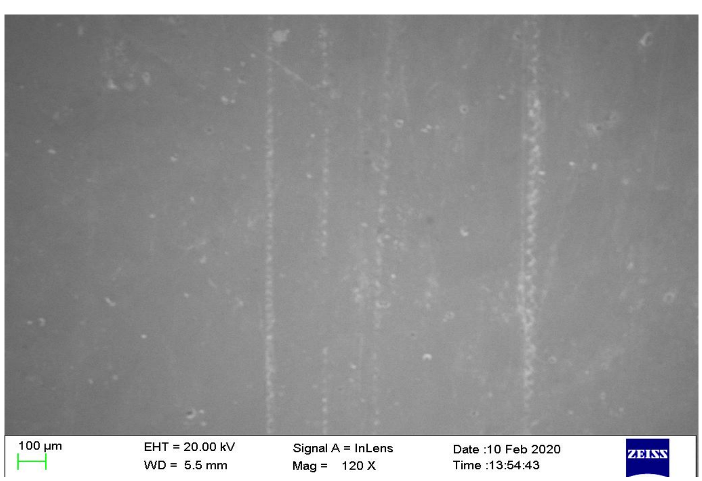


Figure 23- FESEM images of normal copper sheet.

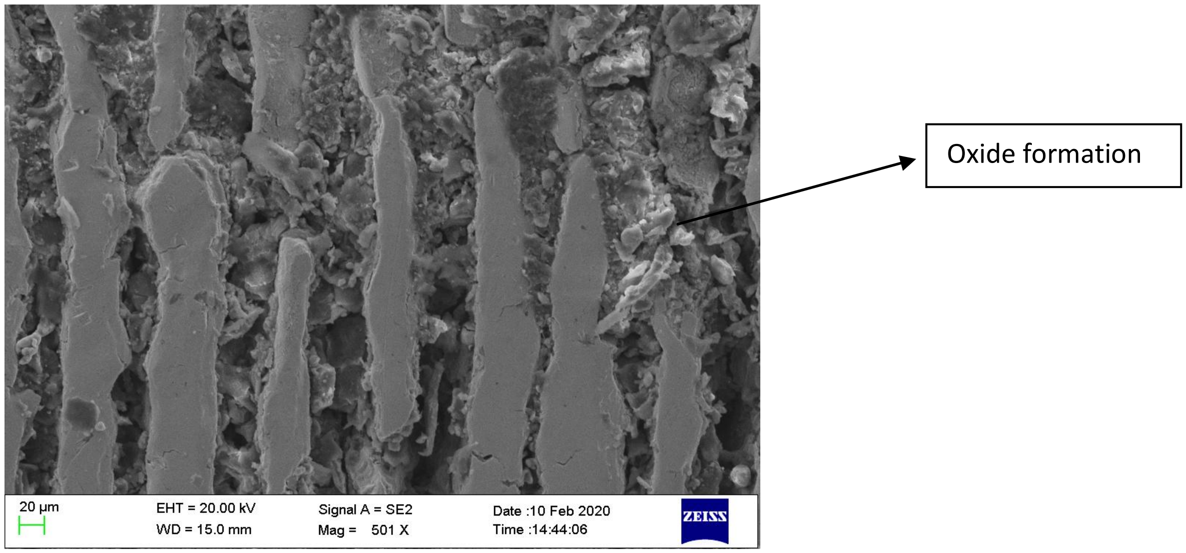


Figure 24- FESEM IMAGE OF LASER IRRIDIATED ZONE AT 40 WATT POWER

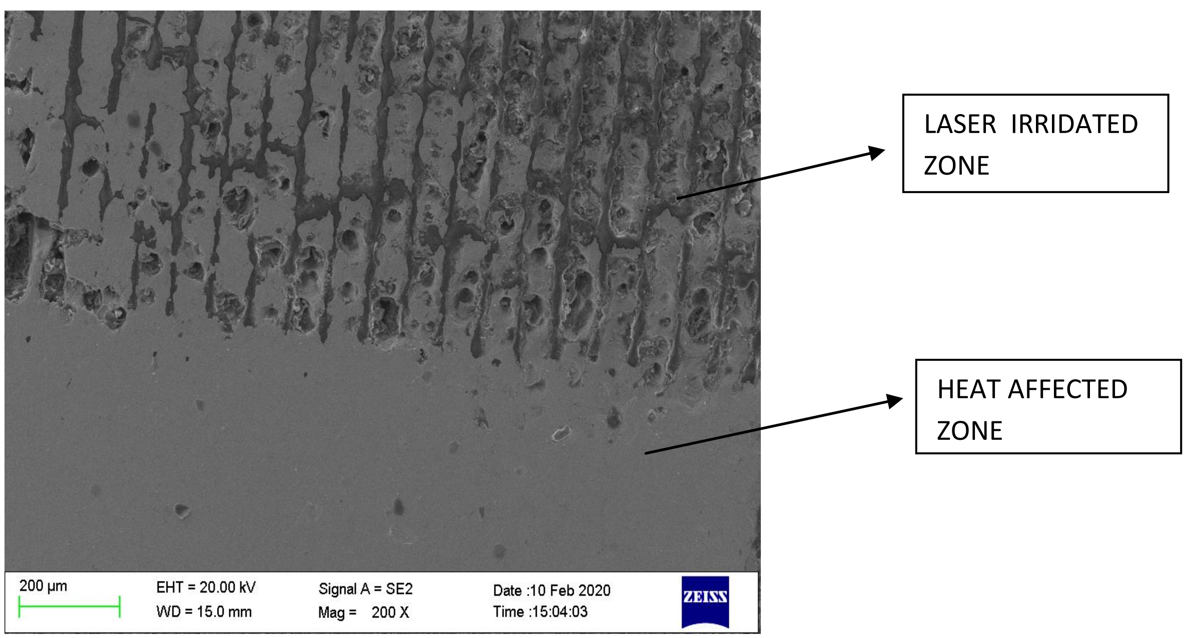


Figure 25- LASER IRRIDATED ZONE AND HEAT AFFECTED ZONE AT 40 WATT POWER.

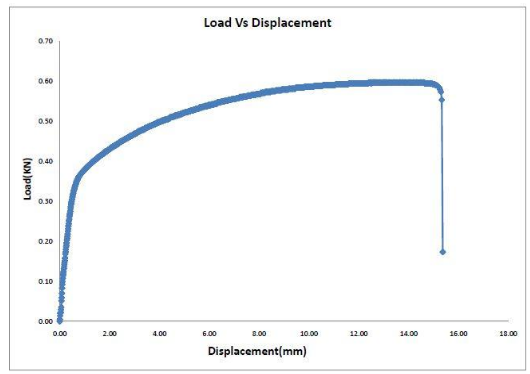
Here FESEM Images of normal copper sheet and laser formed copper sheet at 40 watt power, at laser irradiated zone we can see the formation of oxide which will somehow affect its material characterization properties.

4.8 Tensile Testing.

In this testing we will measure the ultimate tensile strength, maximum displacement and reduction in area. This testing will give result related to young's modulus, strain hardening characteristics.

Normal copper sheet

Figure - 26



UTL- 0.597 KN

DISPLACEMENT-15.372mm

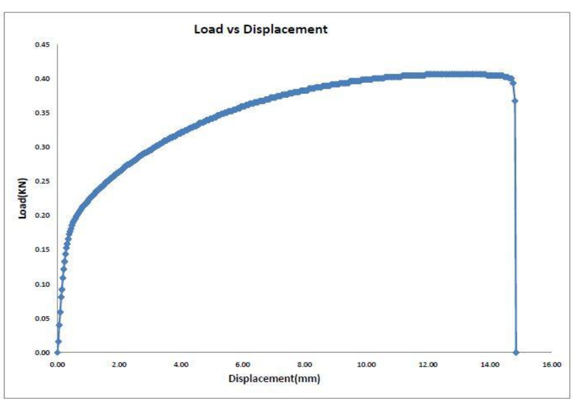


Figure-27

At 30 watt power, UTL-0.407KN

Displacement-14.849mm

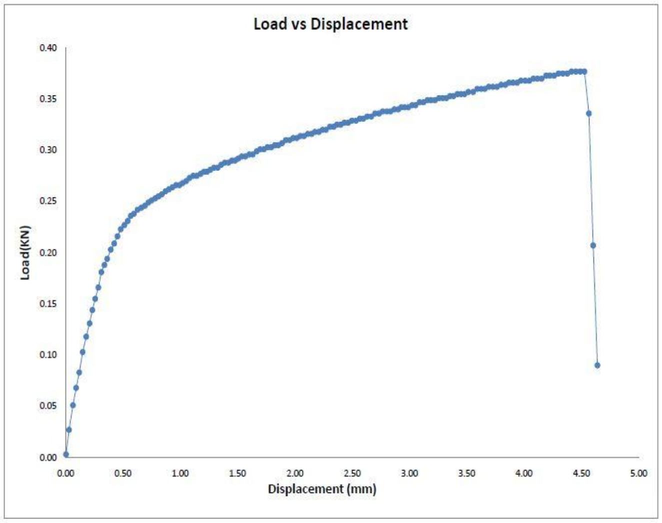


Figure- 28

35 Watt power, UTL-O.399KN

Displacement-4.64mm

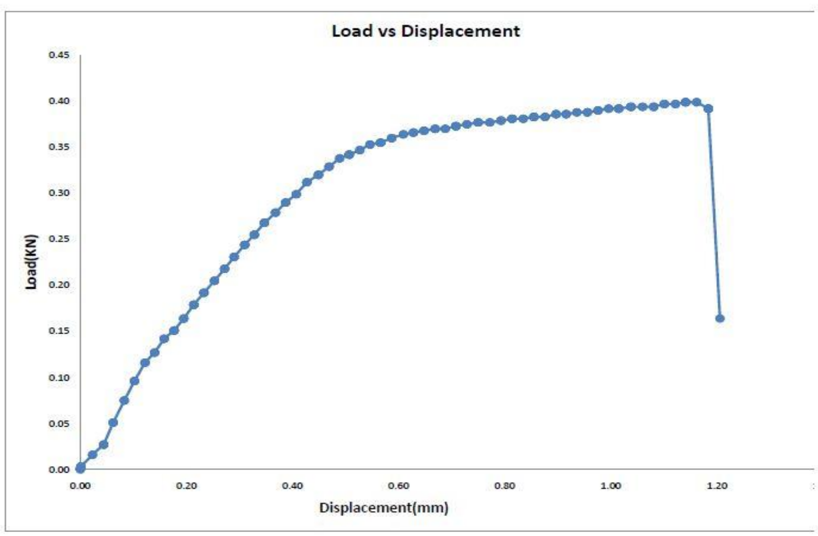


Figure 29

UTL-0.377 KN, Displacement-1.206mm

Power-40watt

Here ultimate tensile strength of the material is decreasing as the power is increasing from 30 to 35 to 40 watt due to formation of oxide in laser irradiated zone due to which copper sheet after forming becomes brittle so ultimate tensile strength will reduce as the power increases.

Chapter 5 : Application

Copper is very important material in engineering and manufacturing technology, it is used in various field of applications where electrical and thermal conductivity need to be considered . Copper is a naturally corrosion-resistant metal, while galvanized steel will eventual leak and break because of corrosion damage. Copper-based products also play a key role in meeting modern needs such as renewable energy, healthcare, more energy efficient transportation and modern communications. The purpose of this chapter is to present a brief discussion of the mechanical behavior of Copper Sheet and to describe their most promising applications in the electrical and manufacturing applications

As an electrical application we can manufacture copper bushbar with laser forming of copper sheet of appropriate dimensions of copper busbar required in junction of electrical circuit. Copper is a common conductive metal used in busbars and many electrical utilities around the world. Copper is chosen for it's resilience to higher temperatures, providing extra security during short circuit situations.

Other benefits provided by the use of copper are:

- High conductivity
- Resistance to damage
- Higher performance in clamped joints
- Lower coefficient of linear expansion
- Long lifespan
- High recovery value
- Higher modulus of elasticity

- The surface of copper naturally oxidizes forming a thin hard layer on the surface which remains conductive. Exposed aluminum surfaces also form an oxidized film. However, this film is not conductive and leads to long term reliability issues with joints.

Copper Busbar :

Figure 30

Copper Busbar

Figure31

Copper Busbar

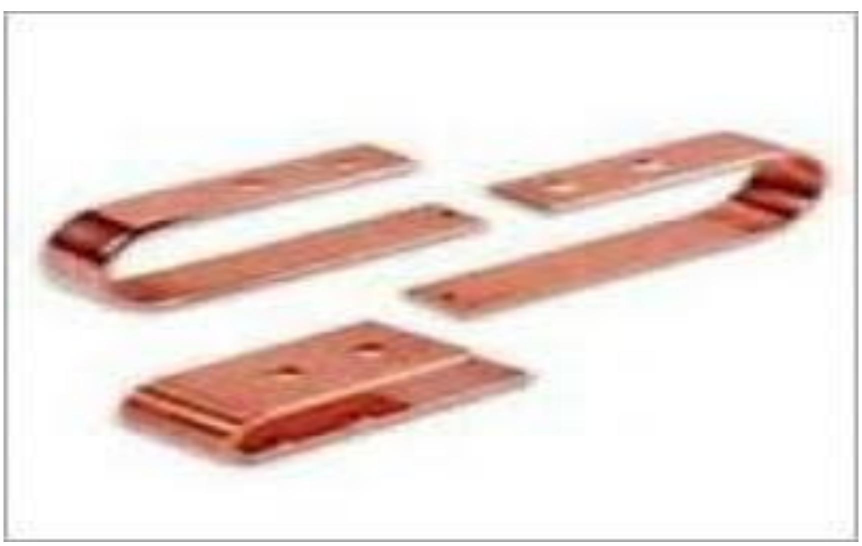


Figure 32

Copper Busbar

Busbars are used within electrical installations for distributing power from a supply point to a number of output circuits. They may be used in a variety of configurations ranging from vertical risers, carrying current to each floor of a multi-storey building, to bars used entirely within a distribution panel or within an industrial process.

The issues that need to be addressed in the design of busbar systems are

- Temperature rise due to energy losses.
- Energy efficiency and life time cost.
- Short-circuit current stresses and protection.
- Jointing methods and performance.
- Maintenance.

In any electrical circuit some electrical energy is lost as heat which, if not kept within safe limits, may impair the long term performance or the safety of the system. For Busbar systems, the maximum working current is determined primarily by the maximum tolerable working temperature, which is in turn determined by considerations such as safety, the retention of mechanical properties of the conductor, compatibility with mounting structures and cable connections. Current-Carrying Capacity of Busbar discusses how to estimate the working current and temperature.

Because of the large currents involved, short circuit protection of busbar systems needs careful consideration. The important issues are the temperature rise of the busbar during the event and the magnitude of the forces generated by the high current, which may cause deformation of the bars and the failure of mounting.

Materials for Busbars

Material Requirements

To achieve a long and reliable service life at the lowest lifetime cost, the conductor material needs the following properties:

• Low electrical and thermal resistance

• High mechanical strength in tension, compression and shear

• High resistance to fatigue failure

• Low electrical resistance of surface films

• Ease of fabrication

• High resistance to corrosion

• Competitive first cost and high eventual recovery value.

This combination of properties is best met by copper.

Mechanical Strength

The mechanical strength of the busbar material is important to ensure that the material is not deformed during transport and assembly, does not sag over an extended working life at maximum temperature, does not creep under pressure leading to loosened joints and does not permanently distort under short circuit loads. The mechanical properties are influenced by the production processes employed.

Here the production process is laser forming. Laser forming plays a very important role in this aspect as we could be able to form the sheet for complex parts of the body which could not be possible by any other conventional method. There is no spring-back effect in laser forming which is one of the biggest advantage with this method.

Chapter 6: Conclusion and Future Recommendation

The main aim of this thesis was to investigate the effect of laser forming on copper sheet so as to make them suitable for the various suitable applications such as copper busbar and electromagnetic shielding.

The laser is applied at a focal length of 280mm on all the Copper samples with a spot diameter of 1 mm at different number of passes and different powers.

In current work laser forming on Copper sheets of 0.4 mm were performed. The variation in the bending angles with respect to the process parameters were calculated and it is found that there is a certain non-linear increment in the bending angle with an increment of power and number of passes.

Also the micro-hardness test of the different samples shows that there is increase and then decrease in the hardness of the sample with the increase in number of passes and power. This increment and then decrement is due to the generation of soft phase inside the material, when there is more number of passes the material removal is more and there will be more wear in the material which leads to decrease in the strength and hardness of the material but increase in the ductility of the material.

So, finally the experimental investigations on the laser bending parameters have led to the following specific conclusions:

- Laser power is the most significant factor followed by the number of passes.

- There is a non-linear increment in the bending angle with increase in power and number of passes.

- The hardness of the sheet first increases and then decreases with increase in power and the number of passes due to the generation of soft phase because of the wear of the material.

- The ductility of the material is improved with power and passes as the hardness is decreased.

Future recommendations

The research can be extended to achieve the better hardness of the material by changing the spot diameter or number of passes of the laser. The power of the laser can be reduced in order to achieve more hardness in the material.

The problem coming in the proper variation of the bending angle with the power and the number of passes which can be optimized. It can be used to make several other shapes according to the shape of the body for the mechanical applications.

The heat input rate and the temperature range can be further controlled so that we would be able to know the exact heat input required to deform a sheet at certain angle. Thermocouple can play a vital role in this regard.

Moreover, the underwater laser study could be done by keeping the sheet in the water at different distances from the water surface in order to control the heat rate and temperature range.

Different kind of pastes such as charcoal, lime, etc could be applied so that there could be more absorption of the laser on the sheet which will be helpful in controlling the bending of sheet.

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