CHAPTER 3 - EXPERIMENTATION

This section explains the material and methods used in the experiment, experimental set-up for three studies viz. natural cooling and forced cooling during laser bending process and electromagnetic force assisted laser bending of mild steel. Details of the measurement methods, workpiece geometries and laser parameters are discussed.

3.1. Material

The mild steel sheet having 2 mm thickness is used for the experimentation. The chemical composition of mild steel sheet used for the experimentation is described in Table 3.1. The spectroscopy test report for chemical composition of mild steel sheet is given in Appendix 3.1. It is one of the most widely used forms of steel and can be applied to a range of general-purpose applications. It is also applicable in many other fields such as ship building and shell structure construction etc. [240].

Table 3.1. Chemical composition of mild steel (%).

Component	C	Mn	S	P	S	Fe
Composition (%)	0.098	0.77	0.15	0.017	0.006	Balance

3.2. Preparation of Specimen

The specimen with dimensions of 60 mm in length, 30 mm in width, and 120 mm in length, 50 mm in width, are utilized for forced cooling-assisted laser bending and electromagnetic force-assisted laser bending, respectively as shown in Fig. 3.1. The specimens for the experimentation of the above-mentioned dimensions are cut from a bigger sheet using a precise high-power laser cutting machine. Which provides excellent dimensional accuracy and produces fine cuts. The surfaces of the samples are cleaned using emery paper.

Fig. 3.1. Experimental specimen of mild steel.

3.3. Experimental Setup

The laser bending experimentation for the three different conditions is performed on CNC controlled laser cutting machine (Model: L3015; Make: ABRO Technologies Pvt. Ltd), as shown in 3.2. It comprises a fiber laser source (Model: MFSC-1000W; Manufacturer: MAX Photonics Co., Ltd.) with a wavelength of 1075 nm and a maximum power of 1 kW. CypOne software installed in attached PC system with machine is used to parameter setup, process customizing, controlling of tool path and cutting process. The cutting head moves along Y-axis and work table moves along X-axis to define irradiation path and the laser beam travels along Z-direction. The CNC system can manage the laser power, scanning speed, and the diameter of the laser beam can be changed by adjusting the height of the laser head above surface of the workpiece. The specifications of the laser cutting machine and fiber laser source are given in Appendices 3.2 and 3.3, respectively.

Fig. 3.2. Fiber laser cutting machine.

3.4. Selection of Process Parameters

The process parameters and their levels are selected by reviewing the literature, and availability of resources. The experimental design for the laser bending process under natural cooling and forced cooling conditions is detailed in Table 3.2, while the experimental design for electromagnetic force-assisted laser bending is outlined in

Table 3.3. For the development of an electromagnet in electromagnetic force-assisted laser bending, the two additional parameters of air gap and electrical current are also considered.

Table 3.2. Experimental design for natural and forced cooling laser bending.

S. No.	Laser Power (W)	Scanning Speed (mm/min)	Beam Diameter (mm)
1	400	1000	4
2	600	1000	4
3	800	1000	4
4	1000	1000	4
5	400	2500	4
6	600	2500	4
7	800	2500	4
8	1000	2500	4
9	400	1500	4
10	400	2000	4
11	1000	1500	4
12	1000	2000	4
13	1000	1000	2
14	1000	1000	6
15	1000	1000	8
16	1000	1000	10
17	1000	2500	2
18	1000	2500	6
19	1000	2500	8
20	1000	2500	10

Table 3.3. Experimental design electromagnetic-force assisted laser bending.

Sr. No.	Laser Power (W)	Scanning Speed (mm/min)	Beam Diameter (mm)	Air Gap (mm)	Current (A)
1	400	1000	4	20	4
2	600	1000	4	20	4
3	800	1000	4	20	4
4	1000	1000	4	20	4
5	400	2500	4	20	4
6	600	2500	4	20	4
7	800	2500	4	20	4
8	1000	2500	4	20	4
9	400	1500	4	20	4
10	400	2000	4	20	4
11	1000	1500	4	20	4
12	1000	2000	4	20	4
13	1000	1000	2	20	4
14	1000	1000	6	20	4
15	1000	1000	8	20	4
16	1000	1000	10	20	4
17	1000	2500	2	20	4
18	1000	2500	6	20	4
19	1000	2500	8	20	4
20	1000	2500	10	20	4
21	1000	1000	4	10	4
22	1000	1000	4	30	4
23	1000	1000	4	40	4
24	1000	2500	4	10	4
25	1000	2500	4	30	4
26	1000	2500	4	40	4
27	1000	1000	4	20	2
28	1000	1000	4	20	6
30	1000	2500	4	20	2
31	1000	2500	4	20	6

3.5. Experimental Conditions

In this study, the different levels of laser process parameters i.e., laser power, scanning speed, and beam diameter are used for the experimentation, as listed in Table 3.4. Each experiment is performed for five scans under different conditions. To ensure repeatability, all tests are repeated thrice and the average value is considered.

Table 3.4. Experiment conditions.

Bending	Forced Cooling Assisted Laser Bending Process
Laser Type	Fiber Laser Cutting Machine
Process Parameters	
Laser Power (W)	400, 600, 800, 1000
Scanning Speed (mm/min)	1000, 1500, 2000, 2500
Beam Diameter (mm)	2, 4, 6, 8, 10
Cooling medium	Air and Water
Response Parameters	Bend angle, Temperature analysis, Edge Effect, Micro-hardness and Microstructure, Tensile strength
Machining Process	Bending Process
Bending	Electromagnetic Force Assisted Laser Bending Process
Laser Power (W)	400, 600, 800, 1000
Scanning Speed (mm/min)	1000, 1500, 2000, 2500
Beam Diameter (mm)	2, 4, 6, 8, 10
Air Gap (mm)	10, 20, 30, 40
Current (A)	2, 4, 6
Response Parameters	Bend angle, Edge Effect, Micro-hardness, Tensile strength and Microstructure

3.6. Experimental Procedure

The laser bending of mild steel is performed on laser cutting machine with three different conditions viz. natural cooling condition, forced cooling condition and electromagnetic force-assisted. The cooling arrangements and the developed electromagnet setup are attached to the laser cutting machine.

3.6.1. Natural and Forced Cooling Laser Bending

The mild steel worksheet is held in the fixture during the experiment as represented in Fig. 3.3 (a). The value of the bend angle is recorded using a laser displacement sensor, which was fixed at the free end of the specimen to measure the displacement as shown in Fig. 3.3 (b). An infrared thermal imaging camera is used to record the irradiated surface temperature, as presented in Fig. 3.3 (b). The laser beam is irradiated in a direction parallel to the free edge (along width) of clamped specimens, which was perpendicular to the rolling direction of the strip. The laser scanning speed can be controlled by the CNC, and the laser beam diameter can be changed by adjusting the distance between the laser head and the surface of the worksheet. Each experiment is performed for five scans under different conditions, and then specimen is placed in the environment for naturally cooling.

In forced cooling-assisted laser bending, a forced water-cooling arrangement is provided at the bottom surface of work-sheet which is represented in Fig. 3.3 (c). A pipe of 7 mm diameter with a series of holes is placed in a container that was opened at one side. The diameter of holes as well as the distance between holes was 0.75 mm. To prevent water splashing on the top surface of the worksheet, the pipe is housed in a small container that is opened from one side. To manage the water flow rate delivered by the pump, a flow control valve is installed. During the irradiation the forced water flow in the pipe which was fixed under the work sheet as shown in Fig. 3.3 (b).

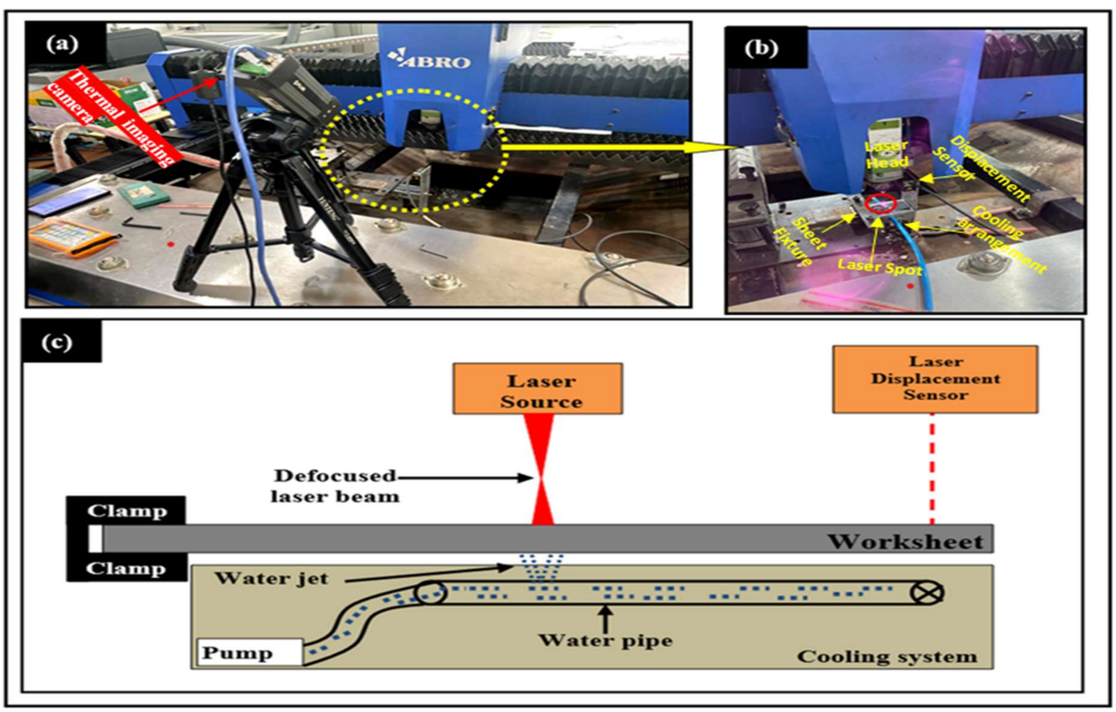

Fig. 3.3. Experimental arrangement (a) schematic of cooling arrangement (b) position of the specimen and thermal imaging camera (c) forced cooling arrangement and position of laser displacement sensor.

3.6.2. Electromagnetic Force-Assisted Laser Bending

For the experimentation, an electromagnet setup has been developed and integrated with a laser cutting machine. The components include an E-Shape electromagnet, a programmable power source, and an ammeter (ampere meter) as shown in Fig. 3.4.

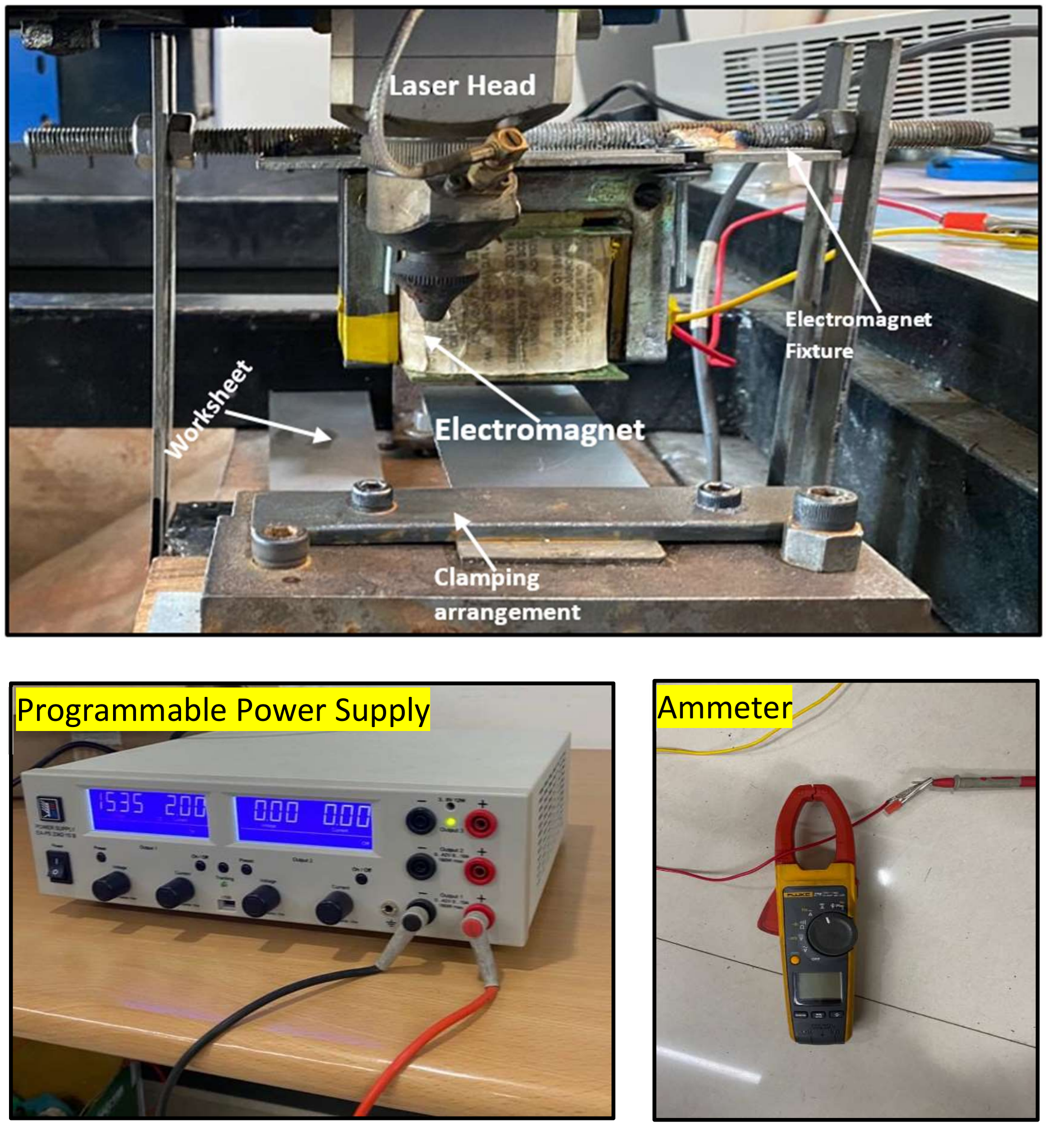

Fig. 3.4. Electromagnetic force-assisted laser bending components.

3.6.3. Development of Electromagnet

In this study, the E-shaped electromagnet has been developed, which consists of two main elements: the core and the coil. The coil is prepared using very thin-laminated sheets, which serve to protect the binding from the high heat generated during operation by minimizing the effects of eddy currents. In addition, a cooper wire of 22-gauge with 950 turns is wrapped around the core as shown in Fig. 3.5. To generate the electromagnetic field in the E-shaped electromagnet, a direct current (DC) is supplied within the range of 2-6 amps. A programmable power source is used which could provide the required DC current output. The intensity of the electromagnetic field generated by the electromagnet setup can be measured using a gauss meter. A gauss meter is a device specifically designed to measure the strength or intensity of magnetic fields. By placing the gauss meter near the electromagnet, the magnetic field strength can be quantitatively evaluated. According to the measurements taken with the gauss meter, it is revealed that the maximum intensity of the magnetic field is generated at the center of the electromagnet. This means that the magnetic field strength is strongest in the central region of the E-shaped electromagnet.

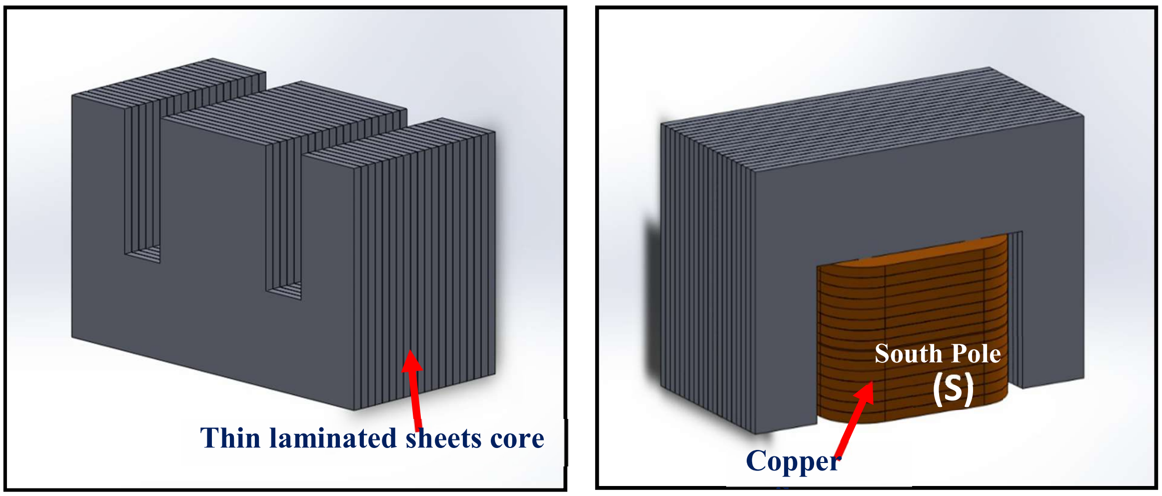

Fig. 3.5. E- Shape electromagnet with (a) core composed of laminated sheets (b) coil wrapped on core.

3.6.4. Experimentation

In the present study, the influence of various process parameters viz., laser power (P), scanning speed (v), laser beam diameter (D), number of passes, and air gap between work sheet and electromagnet, current supplied to electromagnet on the properties of bent mild steel sheet during electromagnetic assisted force assisted laser bending is examined. During the experimentation, one end of the specimen is fixed in the fixture and the other end is made free. After that, the electromagnet is placed over the free end of specimen. The electromagnet is fixed within a fixture, and it can move up and down through a groove. This movement allows for the adjustment of the distance between the worksheet and the electromagnet. The electromagnetic field is generated by switching on the programmable power source, which supplies the required DC current to the electromagnet. Once the value of the DC current is fixed, the laser beam is irradiated parallel to the free end and at 50 mm away from the free end under the influence magnetic field shown in Fig. 3.6. Bend angle after every scan is measured by laser displacement sensor.

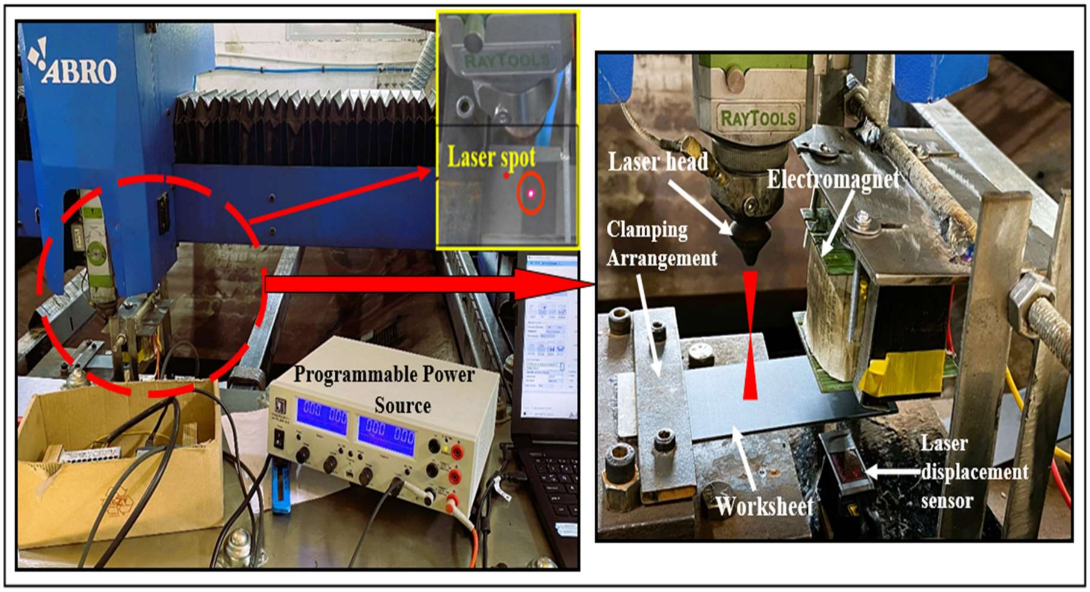

Fig. 3.6. Experimental setup of electromagnetic force assisted laser bending.

3.7. Testing and Analysis

The bending angle, edge effect, temperature distribution, microstructure, Vickers micro-hardness and tensile properties were evaluated to characterize the process. After experimentation, bend angles are measured after every scan pass by laser displacement sensor. The infrared thermal imaging camera was used for capturing and analyzing the temperature distribution at the scan surface.

3.7.1 Bend Angle Measurement

The laser displacement sensor (Model: ILD1320-50; Make: Micro-Epsilon Ltd.), shown in Fig. 3.7 is used to measure the bend angle. The displacement sensor has a maximum range of 50 mm and an accuracy of 5 μm. The specifications of the laser displacement sensor are given in Appendix 3.4. The sensor is positioned at a slight offset from the edge at the worksheet free end. This is due to the possibility that the laser beam sensor could exit the surface of the sheet during bending. The laser displacement sensor provides the free end displacement in the Z direction along with time. The measured value of displacement is further used to calculate the bend angle. The formula used to calculate the bend angle is shown in Equation (i).

Bend angle = ATAN(displacement/30) * (180/Pi) - (i)

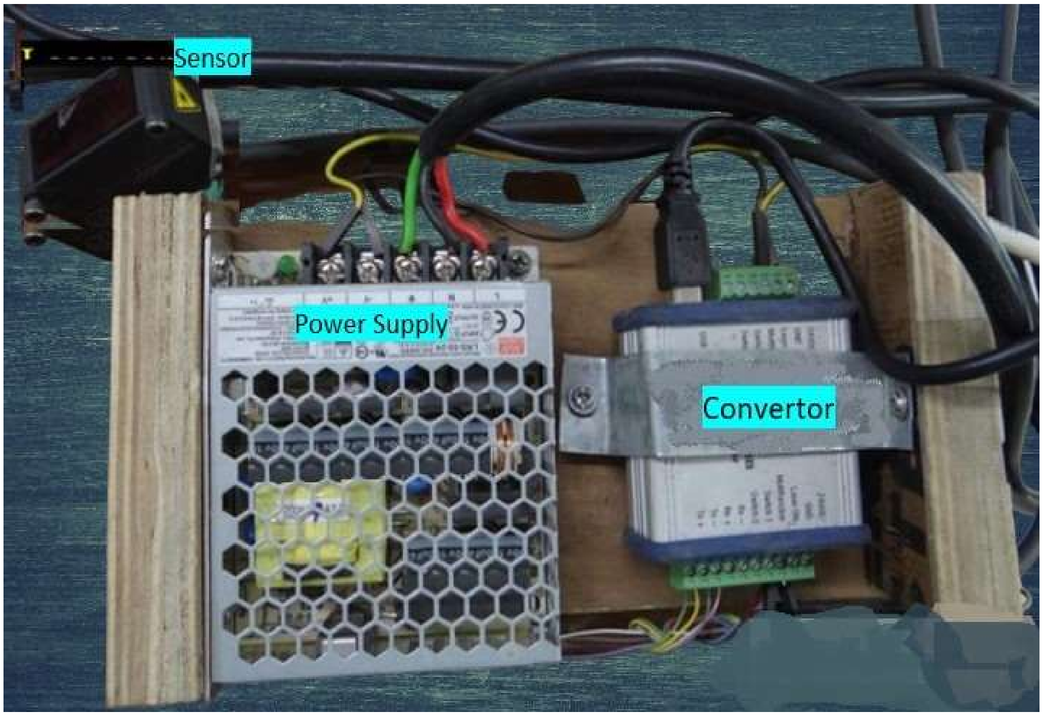

Fig. 3.7. Laser displacement sensor.

3.7.2. Temperature Measurement

An infrared thermal imaging camera (Model: A315; Make: FLIR Systems Inc.) shown in Fig. 3.8 was used to measure the upper surface temperature of specimen during laser bending of mild steel. A thermal imaging camera with a maximum range of 2000 °C at an imaging frequency of 60 Hz is used to measure the temperature of the top surface. The specifications of the thermal imaging camera are given in Appendix 3.5. For temperature measurement, the emissivity is estimated by mapping the temperature profiles of thermocouple with IR camera at different emissivity. Correlation of the temperature profile obtained from the thermocouple with the infrared camera can be found well, when the emissivity is set to 0.67 during multiple scans. Similar method to determine the emissivity of material is suggested by Goyal et al. [242] and Yadav et al. [58]. The emissivity is considered to be 0.67 for the temperature measurements throughout all five scans, considering that the emissivity does not significantly change with the number of scans for the same material. This temperature measurement is used to measure maximum temperature along the scan line at the top surface in each scan. The maximum temperature on the specimen upper surface is measured at five distinct locations along the scan line, and the average of these readings is reported in the final analysis. The average maximum temperature at the top surface (T_{avg}) is obtained by averaging the results of the three consecutive repetitions.

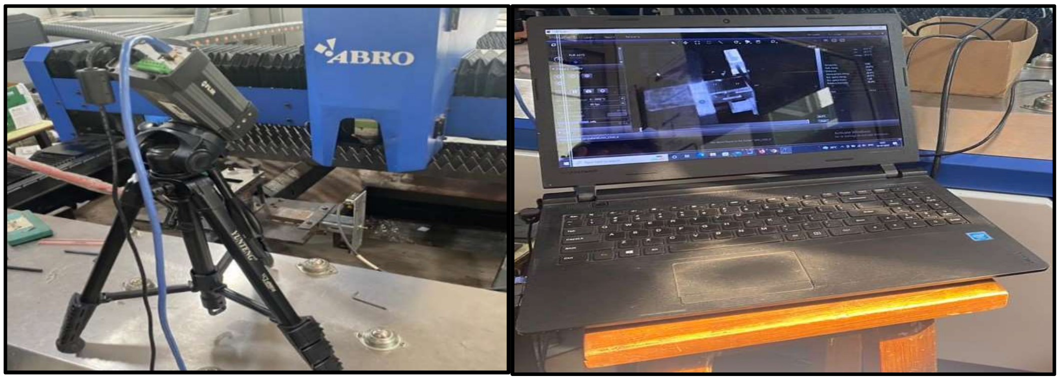

Fig. 3.8. Thermal imagining camera setup.

3.8. Study on Metallographic Sample Preparation and Examination

The basic steps followed for the preparation of samples for finding microstructure and micro-hardness as shown in Fig. 3.9. Different instruments are used in the whole operation (metallographic sample preparation and examination) explained in the following subsections.

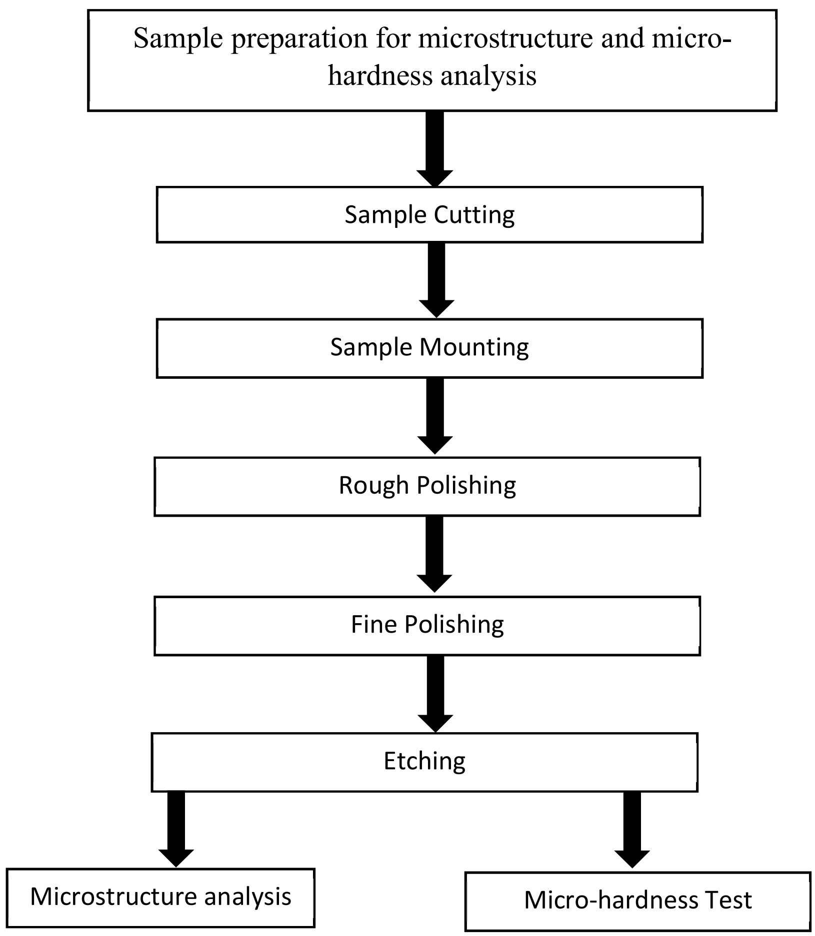

Fig. 3.9. Steps for microstructure and micro-hardness sample preparation.

3.8.1. Sample Cutting: Samples are cut with the help of fiber laser cutting machine having dimensions 20 x 20 mm as per the requirement of scanned electron microscope and micro-hardness.

3.8.2. Sample Mounting: After cutting the samples, the next step in the preparation process is mounting. The aim of mounting is indeed to handle samples, protect fragile materials, and retain the integrity of the specimen's edges. Mounting specimens to achieve a uniform size facilitates standardized processing, ensures compatibility with equipment, and enables comparability during further preparation steps. The molding machine (Make: BUEHLER; Model: Simpliment® 2) with black phenolic resin was used for encapsulating the sample as shown in Fig. 3.10. The sample was mounted under heat and pressure using an electro-hydraulic specimen-mounting machine.

Fig. 3.10. Electro-hydraulic specimen mounting machine.

3.8.3. Sample Polishing

All micro-hardness and microstructure samples are polished by using a double disc polishing machine to achieve a high-quality surface finish and precise preparation of samples for subsequent analysis and examination. The double disc polishing machine (Make: B.S. Pyrometic India (P) LTD.; Model: BSPIL– MET01008A) as shown in Fig. 3.11, is used to achieve a smooth and uniform surface on the sample, which is essential for accurate and reliable measurements and observations. It has the ability to vary the speed of the grinding wheel in a smooth and controlled manner. All samples are polished by using silicon carbide abrasive paper with a range of grit sizes from 400 to

2000 and final polishing step is performed using a velvet cloth by using alumina paste of particles of size 1 um. The polished samples are shown in Fig. 3.12.

Fig. 3.11. Double disc polishing machine.

Fig. 3.12. Polished samples for micro-hardness and scanning electron microscopy analysis.

3.8.4. Scanning Electron Microscopy (SEM)

After polishing all samples are etched with 95% ethanol and 5% nitric acid for 20 s. Further Scanning Electron Microscopy (SEM) (model JSM-6610LV, make JEOL) as shown Fig. 3.13 is used to reveal the microstructure at the irradiated zone. The specifications of the SEM are given in Appendix 3.6. SEM provides high-resolution imaging and allows for detailed examination of microstructural features of the material. To conduct relevant metallographic observations and assess structural modifications and material responses, micrographs are taken specifically from the laser-irradiated region. In addition, the size of grains is measured by using ImageJ Software for better understanding. A microscopic image is marked with a line, and imageJ software is employed to determine both the length of the line and the count of intersections between the line and grain boundaries. The grain size is determined by calculating the ratio of the length of the line to the number of intersections.

Fig. 3.13. Scanning electron microscopy (SEM).

3.8.5. Micro-Hardness Testing

Vickers micro-hardness hardness tester (Make: BUEHLER; Model: Micromet-2101) as shown in Fig. 3.14 is used to measure the hardness of a laser-irradiated sample. The specifications of the micro-hardness tester are given in Appendix 3.7. In a micro-hardness testing machine, the loads of 1, 10, 50, 100, 300, 500, and 2000 grams (g) force can be applied smoothly and without impact to force the indenter into the test worksheet by using different indentation times. The proper indentation force, or the optimal load, does vary from material to material in micro-hardness testing. In the present study, the micro-hardness is examined with the help of Vickers hardness tester using 500 gm load for dwell time of 10 sec. The specimen is taken with the help of laser cutting machine from the scanning region. The hardness is tested with seven indentations on the scan line. The average value is reported as final result of micro-hardness.

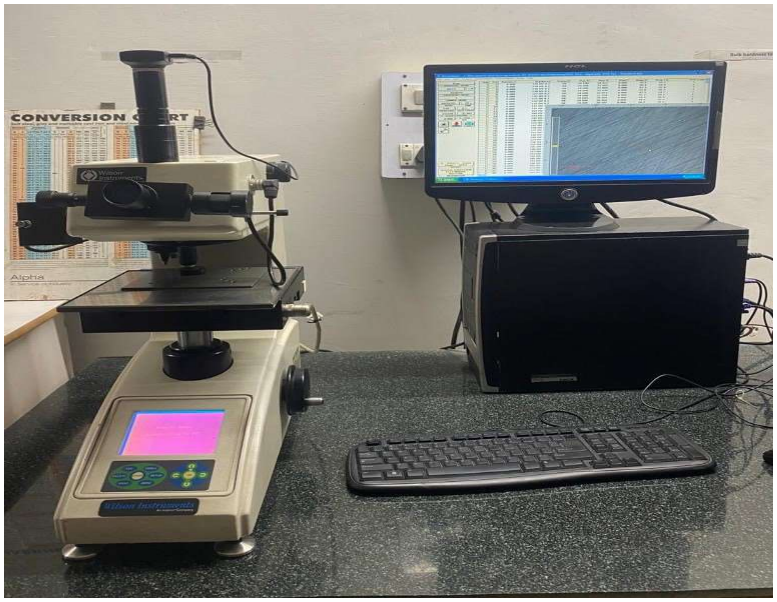

Fig 3.14. Micro-hardness tester.

3.8.6. Tensile Testing

In order to measure the mechanical properties of bent specimen of mild steel during laser bending for all three conditions tensile tests are carried out. The specimens for tensile testing are prepared on laser cutting machine. The gauge length of tensile test specimen was 10 mm and all dimensions are shown in Fig. 3.15 (a). All the samples are tested in a micro-tensile tester (Make: INSTRON, Model: 8801J4051) as shown in Fig. 3.15 (b) at a strain rate of 8 μm/s. Three tensile test specimens from each experiment condition are extracted to obtain a more comprehensive understanding of the mechanical properties of the bent specimens during laser bending. The average value of three trails is reported as a final result of tensile test.

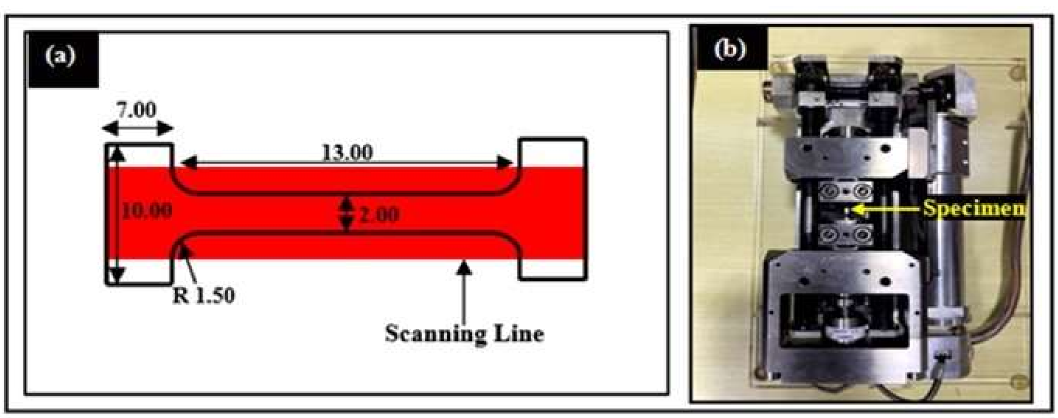

Fig 3.15. (a) Tensile sample (b) micro-tensile testing machine.

3.9. Edge Effect

The edge effect typically manifests as a deviation in the bend angle or curvature near the edges of the specimen compared to the central region. Coordinate measuring machine (CMM) (Make: ZEISS PRISMO, Model: 115330) is used to measuring the edge effect as shown in Fig. 3.16. The touch probe is typically moved along the x, y, and z-axes to obtain accurate measurements and capture the dimensional information of the worksheet. The sample's edges and the two center points are used to estimate the bending angle. The calculation of the edge effect is determined through Equation II, as illustrated [19]:

$$\text{Edge effect} = \frac{\theta \max - \theta min}{\theta avg} \quad -\text{(II)}$$

Where, Θ_{max}, Θ_{min}, and Θ_{avg} are the maximum, minimum, and the average of bend angles along the scan line (width), respectively.

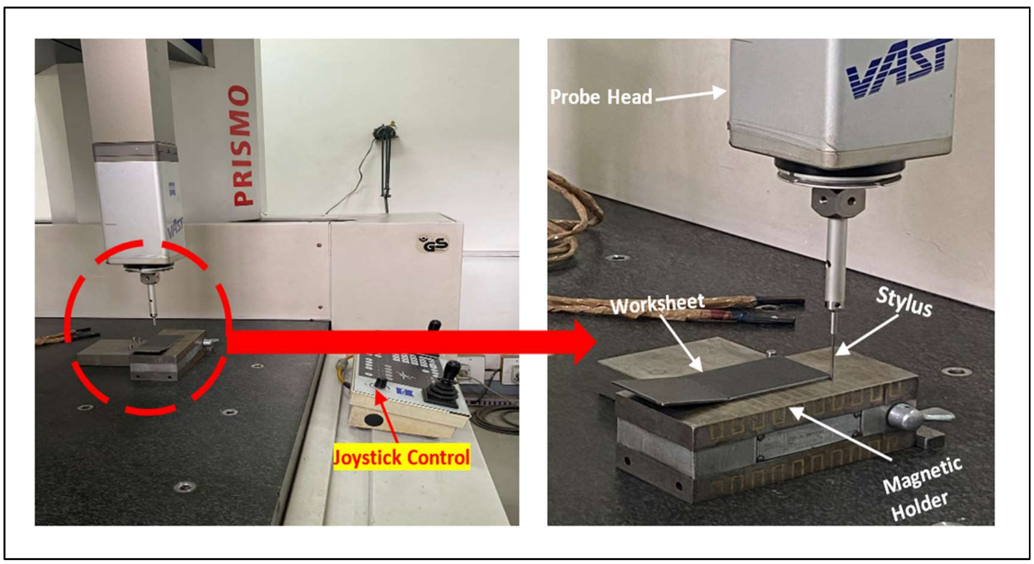

Fig. 3.16. Coordinate measuring machine.

3.10. Summary

The methodology and characteristics of the experiments performed in the study are described in this chapter. It contains information about the investigation's step-by-step method, material used, experimental conditions, output parameters measurement method and specifics about the instruments used for measurement. The chapter's executive summary is as follows:

- ❖ The chapter covers the mild steel worksheet material utilized in the investigation. It gives details about the size and condition of the worksheet's materials. The chemical composition of material is also presented.

- ❖ The chapter describes the selecting process parameters for both forced cooling condition and electromagnetic forced assisted laser bending.
- ❖ An experimental setup involving a high-power laser cutting machine equipped with a fiber laser source is described. The clamping arrangement for holding the worksheet is described.
- ❖ The cooling arrangement, which involves forced water cooling, is discussed in detail. A detailed description of the electromagnet force assisted laser bending setup is also provided.
- ❖ The measuring of the bend angle with a laser displacement sensor is described. Temperature measurement methods are detailed, including the use of a thermal imaging camera to determine the temperature of the top surface. A comparison with thermocouple data is used to explain the estimation of emissivity for temperature measurement.
- ❖ The details of edge effect measurement utilizing a coordinate measuring machine (CMM) for both forced cooling and electromagnetic force assisted laser bending are described.
- ❖ The chapter also discusses micro-hardness testing, tensile strength testing and metallurgical examination using scanning electron microscopy (SEM).

Overall, this chapter provides a complete overview of the method of experimentation, including the materials utilized, experimental setup, measurement methodologies, and mechanical and metallurgical analyses, resulting in a thorough grasp of the methods used in the study.