

Experimental and Numerical Investigations on Laser Forming of Multi-layered Clad Sheet Metal

Thesis Submitted

**in Partial Fulfilment of the Requirements for the
Degree of**

DOCTOR OF PHILOSOPHY

in

MECHANICAL ENGINEERING

by

Praveen Kumar Singh

(2K22/PhDME/504)



Under the supervision of

Prof. Vijay Gautam

DEPARTMENT OF MECHANICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Main Bawana Road, Shahabad Daultpur, Delhi-110042, India

December, 2025

ACKNOWLEDGEMENT

I want to express my sincere gratitude to the many people who have helped me during the tenure of my Ph.D. work. I take this opportunity to express my deep gratitude to all of them for their support and help during various phases of my doctoral research work. At this moment of accomplishment, first and foremost, I would like to give my utmost gratitude to my supervisors, **Prof. Vijay Gautam**. This work would not have been possible without their guidance, support, and encouragement. Under their guidance, I could overcome many difficulties and learned a lot. Despite being very busy, they reviewed my thesis progress, gave their valuable suggestions, and made corrections even during late hours. This persistent courage and opinion will always inspire me, and I can only thank them through my future work.

I am highly thankful to my colleague **Dr Rajendra Prasad Meena, Dr Ravi Dutt Yadav, Mr Rakesh Kumar, Dr Bijendra Prasad, Mr Gaurav Ranjan, and Mr Jayant Kumar** for their advice at various stages of this work. This magnificent period would have been incomplete and tasteless without the company of my colleagues and friends.

I heartily admire the support provided by technical staff, Mr Tek Chand, Mr Omprakash, and Mr Deshraj. Thank you for your help and assistance in finding the microstructure. Last but not least, I would like to thank my mother, **Mrs Girjavati** and my brother, **Dr Yogendra Kumar Singh**, for always being there when I needed them most and for their moral support that kept my spirit up during the endeavour.

Praveen Kumar Singh



MECHANICAL ENGINEERING DEPARTMENT
DELHI TECHNOLOGICAL UNIVERSITY
DELHI-110042, INDIA

DECLARATION

I certify that the work being presented in this thesis entitled “**Experimental and Numerical Investigations on Laser Forming of Multi-layered Clad Sheet Metal**”, in the partial fulfilment of the requirement for the award of the degree of Doctorate in Philosophy submitted in the Department of Mechanical Engineering at Delhi Technological University, is an authentic record of my own work carried out during a period from January 2022 to December 2025, under the supervision of **PROF. VIJAY GAUTAM**, Department of Mechanical Engineering, Delhi Technological University, Delhi. The matter presented in this thesis has not been submitted to any other University/Institute for awarding any degree or diploma.

Date:

A handwritten signature in blue ink, which appears to read "P. Singh", is shown within a rectangular box.

Praveen Kumar Singh

(2K22/PhDME/504)

Mechanical Engineering Department

Delhi Technological University



MECHANICAL ENGINEERING DEPARTMENT
DELHI TECHNOLOGICAL UNIVERSITY
DELHI-110042, INDIA

CERTIFICATE

This is to certify that the thesis entitled “**Experimental and Numerical Investigations on Laser Forming of Multi-layered Clad Sheet Metal**”, submitted to the Delhi Technological University, Delhi -110042, is a fulfilment of the requirements for the award of a degree of Doctorate in Philosophy in Mechanical Engineering embodies the original research work carried out by **Mr. Praveen Kumar Singh**, Enrolment No: 2K22/PhDME/504 under my supervision. This work has not been submitted in part or full for any other degree or diploma from this or any other university.

Prof. Vijay Gautam

Department of Mechanical Engineering

Delhi Technological University

ABSTRACT

The effectiveness of the laser forming process is strongly dependent on the interaction of thermal and mechanical properties inherent in a clad sheet comprising different layers having different properties. The present research examines how laser power, scanning speed, and number of passes at two distinct levels of maximum and minimum affect the bend angle in the samples of a two-ply clad sheet comprising SS430 and AA1050 layers. The clad sheet, was chosen because of its demand in precision manufacturing for performance attributes like as corrosion resistance, thermal conductivity, and mechanical strength. A central composite design was carried out to determine the correlation between the input variables and output response. Design-Expert software was employed to design the experiments, which gave 20 runs to conduct the tests. Response surface methodology was incorporated to optimize the results. The results obtained by analysis of variance were found to be in agreement with the results obtained by experiments. An optimized combination of 900 W laser power, with number of scans and velocity of 60 and 30 mm/s, respectively resulted in a maximum bend angle of 39° with a relative error of 2.14%. The effect of laser bending due to multiple scans on the clad sheet along the laser path in the thickness direction was also examined to understand the microstructure and texture evolution by electron backscattered diffraction technique. The irradiated surface is affected the most and the texture becomes poor whereas, the layer of AA1050 below the irradiated surface improved in texture. It is also observed that the residual stress in the innermost layer of SS430 is of compressive nature whereas the stress in the outermost layer of AA1050 is tensile in nature. The microhardness in the laser-irradiated zone of the SS430 layer ranges from 200 HV to a maximum of 272 HV, whereas the hardness in the AA1050 layer across the bent zone does not vary significantly.

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ABBREVIATIONS

AA	Aluminium Association
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BM	Base Metal
BMS	Bi-metallic Structure
CAD	Computer-Aided Design
CCD	Central Composite Design
CCFCD	Central Composite Face-Centred Design
DED	Direct Energy Deposition
DOE	Design of Experiment
DPC	Digital Processing Control
DR	Debye Ring
DSS	Duplex Stainless Steel
EBSD	Electron Backscatter Diffraction
EDM	Electric Discharge Machining
EDS	Energy Dispersive X-Ray Spectroscopy
EL	Elongation
EDAX	Energy-dispersive X-ray spectroscopy

FCAW	Flux Core Arc Welding
FCD	Face Centred Design
FGM	Functionally Graded Materials
FSOA	Fish Swarm Optimization Algorithm
GBA	Grain Boundary Austenite
GND	Geometrically Necessary Dislocations
HAGB	High angle grain boundary
IGA	Intragranular Austenite
IMC	Intermetallic Compounds
IML	Intermetallic Layer
IMP	Intermetallic Phases
IN	Inconel
KAM	Kernel Average Misorientation
LAGB	Low angle grain boundary
LBP	Laser bending process
LD	longitudinal direction
LF	Laser Forming
RSM	Response Surface Methodology
SEM	Scanning Electron Microscopy

SDSS	Super Duplex Stainless Steel
SS	Stainless Steel
TD	Travel Direction
TD	Transverse Direction
THI	Thermal Heat Input
TS	Travel Speed
UTM	Universal Testing Machine
UTS	Ultimate Tensile Strength
XRD	X-Ray Diffraction
YS	Yield Strength

CHAPTER 1

INTRODUCTION

1.1 Sheet metal deformation

Sheet metal forming is a crucial technique of contemporary manufacturing, enabling the production of high-quality sheet metal components with complex geometries at reduced costs, thereby meeting the growing demands of design and manufacturing engineers across automotive, aerospace, shipbuilding, domestic appliances, and other sectors. Sheet metal forming is a method wherein a thin sheet metal blank experiences a permanent alteration in shape through plastic deformation without fracturing. These sheet metal forming technologies generate a range of skin panels and structural components for automobiles and airplanes. The technical progress in automation and computerized control of sheet metal forming operations has led to enhancements in process capabilities and product quality. Key sheet metal forming techniques include deep drawing, stretching, and bending.

The process of sheet metal deformation involves applying force to a blank in order to change its geometry. The blank is subjected to a force that exceeds its yield strength, resulting in plastic deformation without failure. The material can be stretched or bent into many complicated shapes in this way. The broad category of production procedures wherein the material is plastically shaped to match the geometry of the die. Die and punch are among the many names given to the implements that cause this kind of deformation. Different types of sheet metal forming processes are illustrated in Fig.

1.1

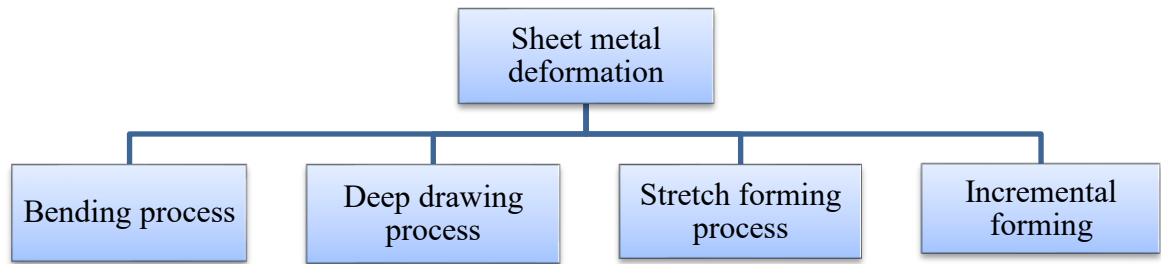


Fig. 1.1 General classification of sheet metal deformation.

- **Bending process:** In this technique, a punch applies force to the sheet material to create a bend, referred to as an angular shape, often along a straight axle.
- **Deep drawing process:** Deep drawing is a sheet metal forming technique wherein a flat blank is radially dragged into a die by the force exerted by a punch, resulting in a cup-shaped or box-shaped hollow component.
- **Stretch forming process:** Stretch forming is a sheet metal forming technique that shares similarities with deep drawing; however, unlike deep drawing, the sheet material is rigidly held between the die and the binder. This firm clamping restricts material flow, confining deformation to the area bounded by the lock beads and promoting uniform stretching. The process is well-suited for forming sheets with complex geometries, which is typically performed using hydraulic or mechanical presses and is compatible with materials such as aluminium alloys, stainless steel, low-carbon steels, and titanium alloys. The method is widely used for producing large body panels such as roofs, doors, and fenders for trucks, buses, and specialized vehicles, as well as for prototype components with significant curvature.
- **Incremental forming:** Incremental forming is a sheet metal deformation technique wherein the final configuration is achieved progressively, in a stepwise manner,

rather than being shaped simultaneously using a die. A compact instrument or energy source alters just a specific region sequentially, progressing along a predetermined trajectory until the entire configuration is realized. The laser forming is a type of incremental forming.

1.2 Introduction to laser forming

Lasers are extensively employed in the manufacturing of critical components for consumer electronics, aerospace systems, automotive applications, biomedical instruments, and shipbuilding, owing to their ability to accurately focus and efficiently manage heat. Laser forming is essential as it offers a non-contact, adaptable, and accurate technique for bending or shaping metal sheets that are challenging or impractical to shape mechanically. Metals, nonmetals, composites, and ceramics can be treated with lasers by procedures such as heat treatment, cutting, shaping, engraving, marking, joining, cladding, sintering, scribing, and drilling [1]. Forming is crucial as it provides a non-contact, versatile, and precise method for bending or shaping metal sheets that are difficult or unfeasible to manipulate mechanically. Metals, nonmetals, composites, and ceramics can undergo laser treatment through processes including heat treatment, cutting, shaping, engraving, marking, joining, cladding, sintering, scribing, and drilling [2].

A laser signifies Light Amplification by Stimulated Emission of Radiation. It is an apparatus that utilizes stimulated emission to generate a monochromatic, coherent, and narrow light beam. Lasers are classified based on the active medium utilized for light amplification, as shown in Table 1.1.

Laser forming of sheet metal is a non-contact thermomechanical technique that deforms metal sheets through laser-induced thermal stresses, rather than mechanical force or dies.

Table 1.1 Type of Laser [3]

S. No.	Type of Laser	Active Medium	Common Applications
1	Solid-state laser	Solid crystal doped with rare-earth ions (Nd: YAG)	In medical surgery, and welding works.
2	Gas laser	Gas or gas mixture	In cutting the metals, engraving, and barcode scanners.
3	Semiconductor (diode) laser	PN junction semiconductor	In Laser forming of sheet metals, communication, and pointers.
4	Fiber laser	Optical fibre fixed with rare-earth elements	In the Precision cutting process, micromachining, and laser bending techniques.
5	Excimer laser	Gas mixture of an ideal gas and a halogen	In Micro-fabrication works and eye surgery (LASIK).
6	Free-electron laser	A beam of high-speed electrons in a magnetic field	In Research, defence, and nuclear fusion-based power plants.

A concentrated laser beam is aimed onto the surface of a metal sheet, inducing localized heating and differential thermal expansion and contraction, leading to controlled plastic deformation. Laser forming is extensively utilized in sectors like aerospace, automotive, shipbuilding, and microelectronics, where its capacity to accurately change and align sheet components is very advantageous.

Deformation may be systematically generated in sheets and plates by directing the laser beam over one surface of the material. Laser bending is analogous to flame bending, a technique frequently employed in the shipbuilding sector to contour the sheet metal of a ship's hull.

The traditional forming technique requires a significant amount of man-hours and is dependent on skilled personnel. The issue can be resolved by using a laser beam to distort the metal sheets rather than a gas flame [5].

CO₂ Laser: An electric discharge within the carbon dioxide gas activates the emission of radiation in a carbon dioxide laser. The schematic diagram of the CO₂ laser is shown in Fig. 1.2.

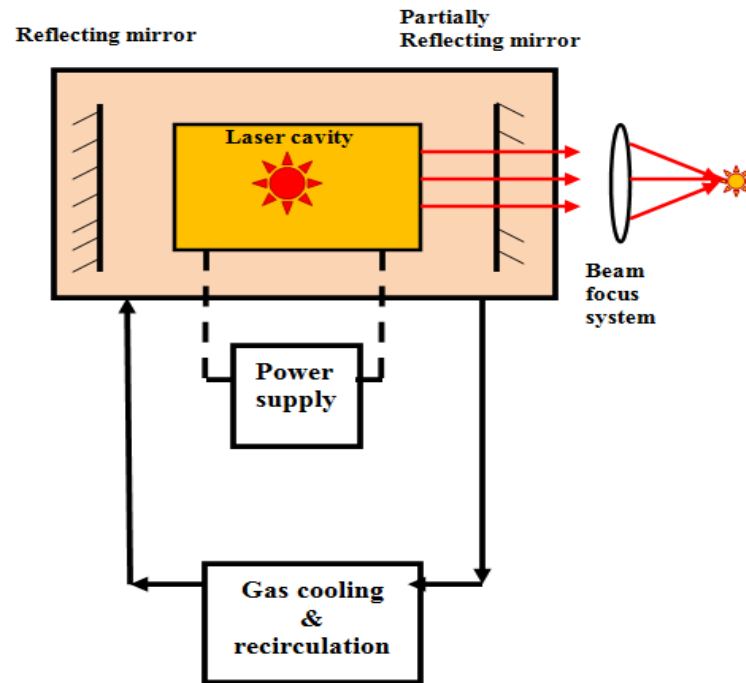


Fig. 1.2 Schematic diagram for making a CO₂ Laser

Through internal reflection, the mirrors gather the low-intensity radiation and boost its intensity. A sequence of mirrors and lenses focuses a high-power laser beam on the workpiece after it passes through a partially reflecting mirror with a wavelength of 10.6 μm . CO₂ lasers typically have an efficiency of 10% to 15%, which means they require large chillers to remove the excess heat. The absorption of plain carbon steel in CO₂ laser forming starts at 4% at room temperature, rises to 30% at the melting point, and reaches nearly 90% at the vaporisation temperature.

ND YAG laser: This technology has gained popularity due to the decreased cost of optical components and enhanced efficiency in the forming of sheet metals, attributed to its high absorption and rapid forming speed. The schematic diagram of ND YAG laser is shown in Fig. 1.3

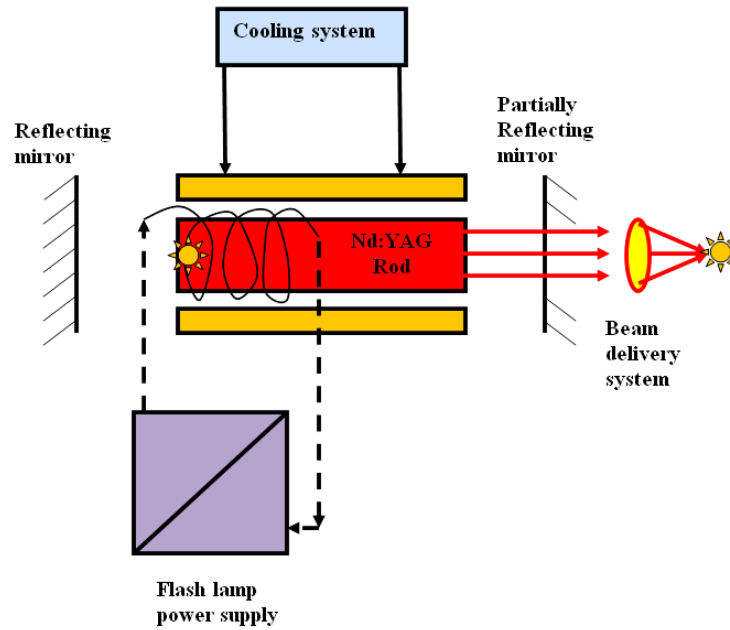


Fig. 1.3 Schematic diagram for producing Nd:YAG laser

The active material YAG in this laser is doped with neodymium (Nd). The replacement of yttrium ions with neodymium ions is referred to as doping, with a doping proportion of approximately 1-1.5%. Continuous wave output is achieved by stimulating neodymium atoms with high-power flash lasers. The laser energy is enhanced, and a beam of consistent wavelength (1064nm) is released through a partly reflective mirror.

1.3 Process parameters of the laser bending process

The preferred method can be attained by modifying certain process parameters. The process parameters may be classified into three categories: energy parameters, material properties, and worksheet geometry. The parameters affecting the laser forming process are given in Table 1.2.

Table 1. 2 Constraints affecting the laser bending method.

S.No.	Laser parameters	Material properties	Specimen geometry
-------	------------------	---------------------	-------------------

1	Power	Coefficient of thermal expansion	Thickness
2	Scanning speed	Thermal transmission	Width
3	Number of scans	Specific heat	Length
4	Cooling conditions	Elastic modulus	
5	Scanning path	Absorption coefficient	
6	Beam size (in diameter)	Poisson ratio	

1.3.1 Laser power

The laser power influences energy absorption in the worksheet. The bending angle generally rises with laser power, reaches a maximum, and thereafter declines. Elevating the laser power enhances the peak temperature and plastic deformation at the scanned surface, therefore augmenting the bend angle. As laser power escalates, the bend angle diminishes for two primary reasons following its apex. Higher power melts the irradiation zone, and the heat energy is utilised during the phase transition instead of being dissipated through bending. Second, the peak bottom surface temperature occurs at high power. This reduces the top-bottom plastic deformation difference, reducing the bend angle at higher power.

1.3.2 Scan speed

The scan speed controls the duration of the laser beam's contact with the worksheet during scanning. Nonlinear connection between scanning velocity and bend angle. As the scanning speed increases, the bend angle decreases after reaching a peak. This is because a low scanning velocity cannot support the large temperature differential. Due

to the significant temperature differential, the bend angle is considerable at low scanning velocities. Faster speeds reduce bend angle.

1.3.3 Beam size diameter

The diameter of the irradiation point on the worksheet corresponds to the diameter of the laser beam. Modifying the standoff distance of the laser head worksheet alters the standoff distance. As the diameter of the laser beam expands, the heat flux density and temperature gradient decrease. Decreases in heat flow density and temperature gradient lead to reduced bend angles for greater beam diameters.

1.3.4 Coefficient of absorption

The absorption behaviour affects numerous laser bending process variables. Shorter-wavelength laser beams increase absorption. Additionally, the surface condition of the worksheet impacts absorption. The number of beam reflections increases as the surface roughens. Metals absorb more when coated with rust and oxides, yet their high reflectivity remains. Coating may increase surface absorption. Graphite coatings are preferred for their excellent absorption and simplicity of application. Basic black enamel paint creates a high bend angle. Lime coating boosts laser bending performance. Lime coating is affordable and eco-friendly.

1.3.5 Number of laser scan

Laser bending involving many irradiations is referred to as multi-pass. The bend angle increases with irradiation. Irradiations produce varying effects, each contributing to a decreased bend angle. The temperature differential diminishes with each irradiation due to the worksheet's preheating. Variations in worksheet thickness, strain hardening, and beam arrangement resulting from worksheet bending also diminish changes in bend angle after each irradiation [4].

1.3.6 Cooling condition

Multipass laser bending is affected by cooling. In multi-pass laser bending, the work sheet must cool for a prolonged period to create a sharp temperature gradient for the subsequent irradiation. Implementing forced cooling subsequent to each irradiation might diminish this waiting period. It inhibits surface melting during many irradiations and sustains a more pronounced temperature differential throughout each laser scan. It enhances the bend angle with each repetition. Implemented water cooling at the upper, lower, and both surfaces during single-pass laser bending of steel plates. Compared to other cases, cooling the top and bottom surfaces concurrently improved the bend angle.[5].

1.3.7 Outcome of material properties

Laser bending is a thermomechanical process; therefore, the thermal and mechanical properties of the sheet material significantly affect the operation. The key thermal parameters are thermal conductivity (k), heat capacity (C_p), density (ρ), and thermal expansion coefficient (α). The thermal impact index (R) is the proportion of the coefficient of thermal expansion and the volumetric heat capacity (representing specific heat and density) and is represented as $R = \frac{\alpha}{\rho C_p}$. Material properties are primarily associated with this index. The bend angle grows piecewise linearly with index R . Thermal conductivity affects the degree of temperature gradient and the dominant mechanism. Increased heat conductivity reduces the bend angle. Because high-conductivity materials dissipate heat quickly, peak temperature and temperature gradient diminish [4].

1.3.8 Outcome of the laser beam on the specimen geometry

Worksheet thickness, length, and breadth are critical characteristics in the laser bending process. The thickness of the sheet is a crucial element, since it directly influences the temperature gradient and material limitations. The bend angle is generally inversely proportional to the square of the sheet thickness. The counter-bending diminishes with a broader sheet due to the rigid-end effect. The bend angle escalates with an increase in sheet width. A wider dimension can be attained with a narrower worksheet, so alleviating tension in the forming zone. It significantly diminishes process efficiency. The length of the sheet has a little impact on the bending angle.

1.3.9 Impact on microstructural and mechanical characteristics

Examining the impact of laser settings on microstructural and mechanical qualities is crucial for the fabrication of defect-free, high-quality products. There has been minimal experimental study on the microstructural and mechanical properties of laser-bent specimens.

Elevated temperatures and localized distortions in the irradiation zone may alter metallurgical properties during laser bending. Laser irradiation influences the characteristics of materials. The laser-irradiated surface exhibited neither cracks nor porosity. Dispersed microcracks may develop on an irradiated surface as a result of a fast cooling rate. The phase transition refined the grains and induced significant recrystallization in the heat-affected zone. Martensite formed in significant quantities due to fast cooling following irradiation.

Laser bending is a method that operates at elevated temperatures. It includes strain hardening, as well as compressive and tensile deformations, and the generation of residual stresses in the irradiated region. These factors affect the mechanical qualities,

such as tensile strength, fatigue strength, hardness, and ductility, of the material. The fatigue life of the worksheet materials was markedly enhanced subsequent to laser beam irradiation. The endurance limit of the laser-formed specimen has also increased. The phenomena arose from the laser-hardening process and the compressive residual strains induced by laser beam irradiation. Observed enhancements in yield strength and tensile strength under bending.

1.4 Benefits of laser forming

Laser forming is necessary because it provides a non-contact, flexible, and precise method for bending or shaping metal sheets that are difficult or uneconomical to form mechanically. Laser forming is necessary due to the following points, as listed in Table 1.3.

Table 1.3 Benefits of laser forming over traditional forming

S. No.	Benefit	Description
1	Tool-less forming	No mechanical dies - ideal for small-batch or customised components.
2	Microscale precision	Achieves bending of thin sheets (≤ 2 mm) or micro-parts where press forming fails.
3	Forming of hard or brittle materials	Stainless steels, ceramics, and laminates can be formed without cracking.
4	No spring back	Complete plastically deformed.
5	Automation and flexibility	Easily integrated with CNC or robotics.

6	Applicable to dissimilar materials	Mostly suitable for clad sheets or laminates (like SS–Al), where mechanical forming would cause delamination.
7	Tool-less	No physical contact, uses a laser beam only.

1.5 Drawbacks of laser bending

Despite various advantages, laser bending has some limitations. Points are given in Table 1.4.

Table 1.4 Drawbacks of laser forming

S. No.	Limitations	Description
1	Suitable for low reflectiveness	The procedure is inappropriate for materials with high reflectivity.
2	Mass production	In the mass manufacturing of large sheet metal components, laser bending technology is less efficient than the conventional punch-and-die approach.
3	Melting may occur	Improper selection of laser parameters may result in melting. This diminishes the quality of the work surface.
4	Microstructural properties	The material and microstructural characteristics of an irradiated area may depreciate.
5	Energy consumption	The bend angle per contamination is nominal; therefore, many irradiations are necessary to

		achieve a greater bend angle. This leads to heightened energy consumption and diminished efficiency.
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1.6 Applications of laser forming

Fig. 1.4 illustrates the fundamental applications of the laser forming process, which is based on the aforementioned three laser bending mechanisms for metal sheets.



Fig. 1. 4 Basic applications of Laser forming [6]

- Laser bending is utilized throughout several industrial sectors, including automotive, aerospace, shipbuilding, medical, microelectronics, and materials processing.
- Laser bending is utilized to achieve exact and minute bend angles in small components employed in microelectromechanical systems, as well as in the chemical and sensor sectors.
- Laser bending is a precise and economical method for adjusting or aligning interface components in welded structures, the shipbuilding sector, and the correction of car body components. It is utilized in the production of intricate smooth surfaces, quick prototyping, and the modification of sheet metal designs. It is further employed for the deformation of fragile materials.

- The technology is well-established; torch flame bending is employed on huge sheet material in the shipbuilding sector; however, significantly greater control over the final product may be attained. Some Examples of laser-formed parts produced are shown in Fig. 1.5.

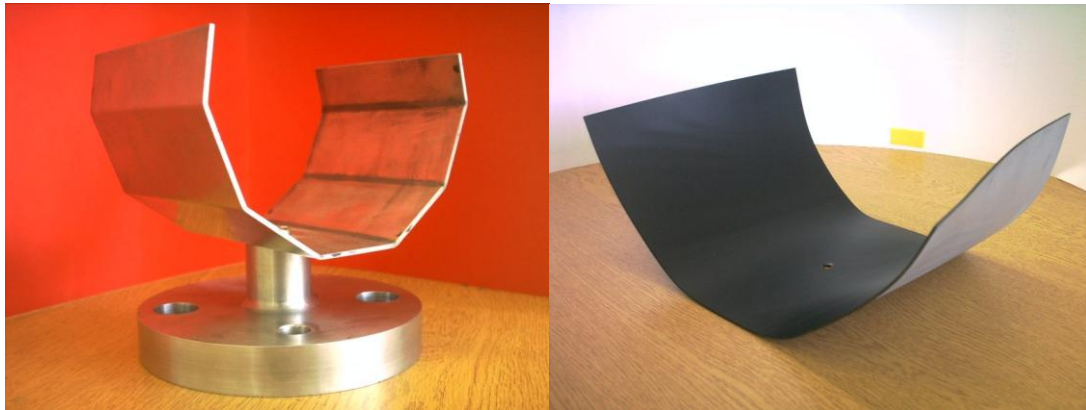


Fig. 1.5 Deformed parts produced by laser forming [7]

The process's progressive nature enables the attainment of high precision. Minor deformations can be achieved in sections of a ship that standard forming processes cannot accomplish due to the material's springback. The fundamental components of a ship, namely the bow and hull, were fabricated using a laser-assisted forming technique, as seen in Fig. 1.6.

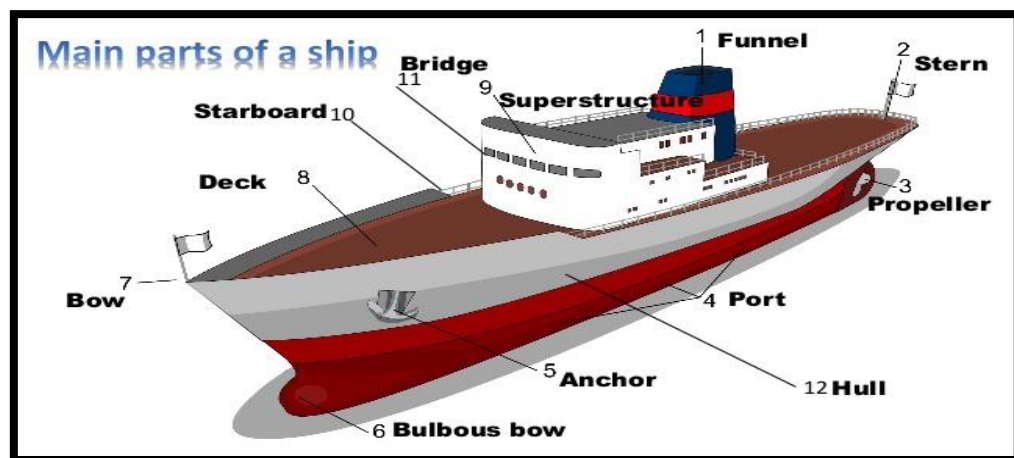


Fig. 1.6 Basic parts of a ship[8]

1.7 Clad Sheet Metals

Aluminium alloys, steel, brass, copper, titanium, tin, and nickel are used to make car and aeroplane skin panels, roofs, household appliances, cans, and other purposes. Automobile and industrial industries are embracing laminated/clad sheets. These materials can solve engineering problems requiring outstanding metal characteristics. Intermetallic bonding bonds alternating metal or metal-containing layers in metal-clad sheet composites. Various clad sheet metals are increasingly used in automotive, aeronautical, and electrical applications due to their unique mechanical qualities [9].

Clad sheet composites are unique composite materials made of inter-metal-bonded metal or metal-containing layers. Designing and creating clad composite materials with the best qualities includes stacking layers of different materials with variable thicknesses and attaching interface structures and features. Diffusion, explosive, and roll bonding have been used to generate clad sheets; however, cold roll bonding (CRB) is the most efficient and cost-effective method.[10]. CRB is a solid-phase welding method that establishes a robust connection between sheets by the plastic deformation of the metal sheets. The plastic deformation characteristics of a clad sheet are influenced by the qualities of the constituent materials, the thickness ratio, the arrangement of components in the thickness direction, surface attributes, bonding parameters, and thermal treatment [11].

1.7.1 Diffusion bonding

A process of joining layers of sheet metal together with heat and pressure, as shown in Fig. 1.7.

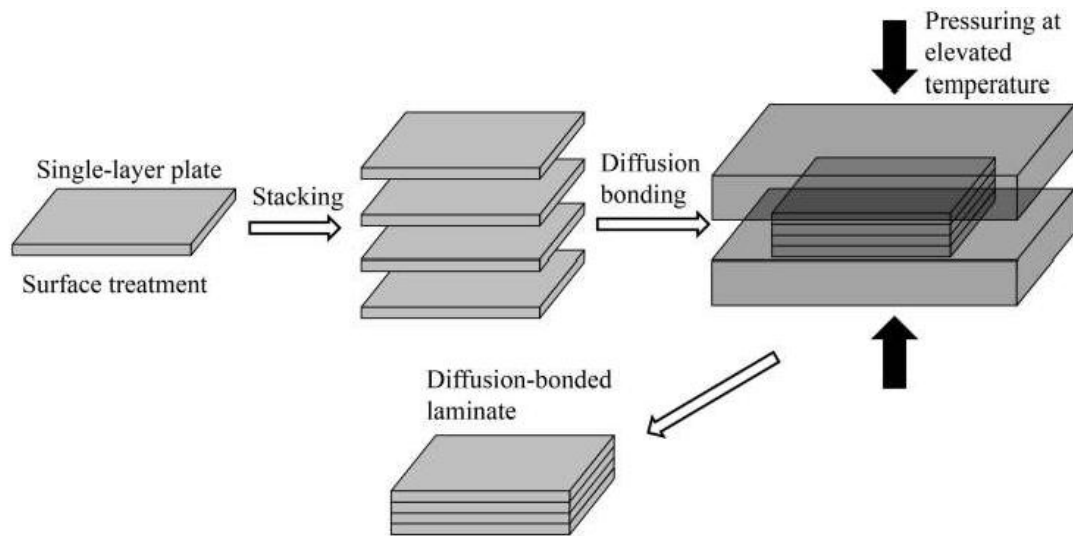


Fig. 1.7 Schematic picture of diffusion bonding [12]

This technique involves assembling thin metal sheets in a vacuum, then raising the temperature to 50-80% of the base material's melting point while applying pressure concurrently. The concurrent application of heat and pressure induces the transfer of electrons from each metal sheet to its adjacent counterpart, resulting in the formation of internal joints within the stacks. The results of diffusion bonding preserve all the characteristics of the parent metal and exhibit significant strength. There are several steps to the diffusion bonding process, including:

- 1. Part Preparation:** The pre-etched component's surface must be clean, straight and have a suggested finish of less than $0.4\mu\text{m}$ RA. This prevents the surface from being contaminated. Stainless steel, Copper, Gold, Silver, aluminium, Inconel, Moly, Nickel, Titanium, etc. can all be utilised in diffusion bonding.
- 2. Heat Applied:** Heat is applied in the form of induction, radiation, direct or indirect resistance in a controlled environment or a vacuum.
- 3. Pressure Applied:** The range of the applied pressure is 3-10 MPa in a single

direction. Pressure is applied along with the application of heat.

- 4. Part Finishing:** To confirm the surface of the final part is free from any type of residue, the part will undergo a simple cleaning process after the bonding process is complete.

1.7.2 Explosion bonding or cladding

It joins metals metallurgically via solid-state welding. Explosion bonding uses controlled explosive detonations to propel one metal into another and fuse their interfaces. Plasma is ejected via explosion-forced angular collisions. Plasma jets remove impurities from both metal surfaces before contact, leaving clean metal for joining. High pressure near the impact front makes solid metals behave like viscous fluids. The collision front pressures make solid metals behave like viscous fluids. A substantial bond line wave pattern in an explosive weld is caused by the fluid-like behaviour of solid metals. Excessive energy can cause solid metals to melt, resulting in brittle intermetallic compounds. Additionally, inadequate energy will prevent solid metal bonding. Calculating the optimum force during the connection of solid metals is one of the biggest challenges in explosive welding.

This process stacks two or more sheets, plates, or strips of metals or alloys and passes them through a well-established pair of rollers until the requisite deformation is achieved, producing a solid-state connection. Sheet metals or alloys that will be bonded must be thoroughly prepared and cleaned to remove residues, surface coatings, and other contaminants. High roller pressure in cold-rolled bonding reduces sheet metal thickness. Sheet thickness can be reduced by 50% or more in one rolling pass. A large drop in sheet thickness generates heat, which bonds the virgin surfaces of the sheet metals. To form a satisfactory metallurgical connection at the sheet metal

contact, annealing is usually done after cold rolling. Laminated/clad sheets can be produced into the desired form and size using any traditional manufacturing method after heat treatment. They may be stretched, deep-drawn, bent, roll-formed, and linked into any portion. After cold-rolled bonding, laminated composite sheets can be coil-processed. Laminated/clad sheet production is a cost-effective and productive process. The uneven surfaces of the sheets to be joined facilitate the extrusion of the softest metal into the crevices, leading to atom-to-atom contact between the base sheets.

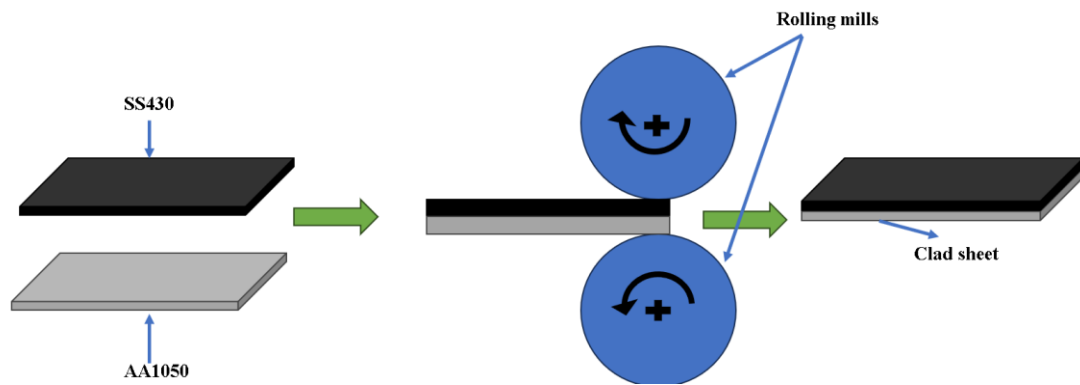


Fig. 1.8 Manufacturing process for aluminium/steel laminated sheet

Roll-bonded AlZn4SiPb/Steel laminated sheet at room temperature. An AlZn4SiPb/Steel laminated sheet was made with 2.2 mm AlZn4SiPb and 3.2 mm low-carbon steel. Al alloy and low-carbon steel sheets were 100 mm wide and 120 mm long. Heat treatment reduces roll bonding deformation resistance for AlZn4SiPb alloy and low carbon steel sheets. Using a wire brush and a flap disc with an abrasive pad, the AlZn4SiPb alloy and low-carbon steel sheets are cleaned and prepared. For 0.5 hours, both sheets were soaked in ethyl alcohol to remove oil. They employed aluminium rivets at the front ends of Aluminium alloy and low-carbon steel sheets to

prevent mismatching. The roll mill rolled these riveted sheets under normal circumstances. They reduced the thickness by 58% at a rolling speed of 12 m/min. They heat-treated the laminated sheet at 350 degrees Centigrade for 60 minutes after rolling to restore it. After heat treatment to improve mechanical properties, the laminated sheet was aged in an oil bath furnace at 120°C for one day. The Manufacturing process for AlZn4SiPb/steel laminated sheet is represented in Fig. 1.8.

Straight bonding layers and precise dimension control are key strengths of the CRB process. Researchers' growing interest in lightweight materials and the clad sheets' impressive mechanical and practical properties has led to significant advances in understanding their forming behaviour. Because clad sheet metals have different elasto-plastic properties than their parent sheets, press forming them is problematic. Clad sheet plastic deformation relies on material characteristics, thickness ratio, material arrangement in thickness direction, surface attributes, bonding parameters, and heat treatment. Due to their mechanical properties and the shift in thickness direction, Their bending and springback properties markedly differ from those of monolithic sheets. Al/ferritic stainless steel, Al/Fe, Al/Cu, Ti/ferritic stainless steel, austenitic stainless steel/Al/ferritic, Fe/Al/Fe, Al/Mg/Al, Ti/steel/Ti, and AZ31/Al/ferritic are the most often laminated sheets.

1.8 2-Ply laminate composite of aluminium and stainless steel

In this study, 2-ply laminate composites of aluminium and stainless steel (SS430/AA1050) were used in laser bending to predict deformation in the form of bend angle. These two laminated materials are manufactured by the cold roll bonding process. The composition is made to compensate for the drawbacks of each other

while also utilising each metal's advantageous properties, which together give a distinctive, sophisticated function. Fig.1.9 shows that when different metals with varied metallic properties are clad into a single sheet, the clad sheet metal becomes functional.

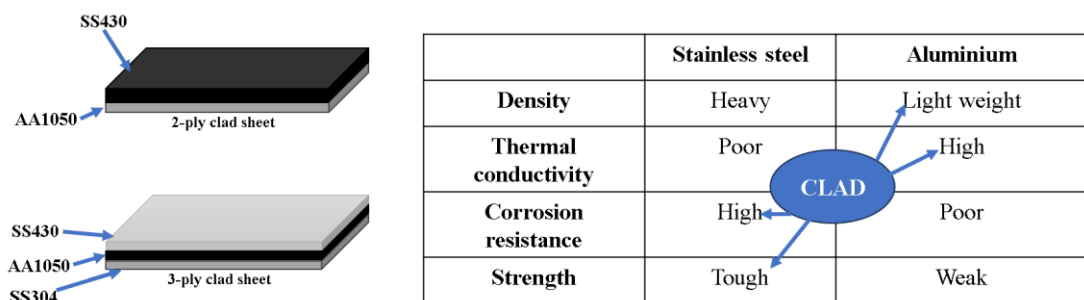


Fig. 1.9 Representation of mechanical properties by the cladding of SS and Al metal

1.9 Advantages of aluminium/ stainless steel-clad sheets

- (a) **Weight reduction:** Due to the light weight of aluminium, appreciable weight reduction is achieved in aluminium/ stainless steel clad Sheets.
- (b) **Scratch resistant:** Stainless steels are the main constituent of Aluminium/ Stainless steel-clad Sheets. They improve the scratch-resistant property of the clad sheets.
- (c) **Thermally conductive:** Aluminium/ Stainless steel-clad sheets are thermally conductive materials. Aluminium provides better heat distribution.
- (d) **Ductility:** Aluminium and stainless steel are both good in ductility. By using these materials, clad sheets give excellent ductility.
- (e) **Corrosion resistant:** By using stainless steel, clad sheets can offer resistance to corrosion.

- (f) **Electrically Conductive:** Aluminium and stainless steel are both electrically conductive materials. So clad sheets are highly electrically conductive materials.
- (g) **Strong:** Stainless steels are very strong in strength. Stainless steel gives good strength to the clad sheets.

1.10 Application of aluminium- stainless steel-clad sheets

- (a) **Automotive:** Several automotive parts are manufactured with clad sheet metals. Clad materials for disc brakes (SUS 403/Al/SUS 403). Troubles in disc brakes due to excessive heat generation can be prevented by applying a three-layer clad material, consisting of SUS/Al/SUS, to the associated sliding parts. For this purpose, a three-layer material consisting of quenched SUS 403 laminated on both surfaces of the aluminium matrix material has been developed for use as the rotor of the disc brake system for racing mountain bikes.
- (b) **Rail Transport:** stainless-aluminium transition strip allows for weight-saving, aluminium to be used on steel bodies, while the stainless steel-aluminium optimises the heat diffusion of ductwork.
- (c) **Aerospace:** The solution to current composite aircraft assemblies' aluminium composites is protected by maintenance-free stainless steel-aluminium clad sheets. These clad sheets are used in aviation applications. Many alloys and composites exhibit good heat conductivity, corrosion resistance, scratch resistance, and lightweight properties. Despite its corrosion and scratch resistance, stainless steel is unpleasant due to its limited thermal conductivity and high density. Aluminium has good heat conductivity, low density, and poor scratch resistance [13].
- (d) **Truck bumpers:** For corrosion resistance, dent and scratch resistance, bumpers

are made from aluminium-stainless steel clad sheets.

- (e) **Cookware:** Cookware made from clad sheets offers better heat distribution, which means consistent cooking performance.
- (f) **Iron soleplates:** Iron soleplates are made from aluminium-stainless steel-clad Sheets. The even heat distribution of aluminium and the scratch resistance of stainless steel make an unbeatable combination.

The application of clad metals in heat exchangers utilises heat. Clad metal application examples are shown in Fig. 1.10.

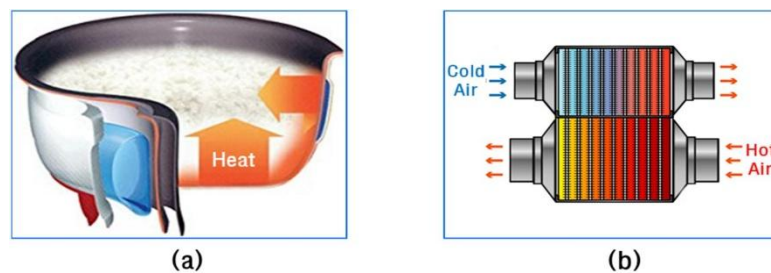


Fig. 1.10 Clad metal applications (a) container in electric cookware, (b) heat exchanger[13]

A heat exchanger is a device that effectively transfers heat from a high-temperature fluid to a low-temperature fluid. Figure 1.10(b) illustrates a conceptual schematic depicting the construction and operation principles of a heat exchanger. The heat exchanger material must possess superior formability, exceptional corrosion resistance, and good thermal conductivity. Titanium (Ti) demonstrates superior corrosion resistance; yet, its fabrication is challenging and costly. Stainless steel is cost-effective, has superior corrosion resistance and formability, yet possesses poor heat conductivity. Aluminium (Al) and copper (Cu) exhibit diminished corrosion

resistance, yet possess exceptional thermal conductivity and malleability. Consequently, clad metals may be produced by various combinations [13]

This research investigates the bending characteristics of a 2-ply laminated sheet metal made of AA1050 and SS430 by experimental and modelling methodologies. The impact of laser parameter configuration on the bending angle is analyzed. The microhardness, residual stresses, and microstructures are examined (both pre- and post-laser bending process) in the upper layer (SS430), transition zone, and bottom layer (AA1050) of the tested samples using experimental and finite element modelling techniques.

1.11 Overview of the thesis

Chapter 1 provides an introduction to metal forming, laser forming, and the classification of laser forming, as well as the mechanism and principle of the laser forming process. It also discusses clad sheets.

Chapter 2 presents a literature review on laser forming, examining the diverse results obtained by researchers using various materials with this technique. It also highlights areas where gaps exist in the study. This chapter also discussed the research goals and objectives.

Chapter 3 covers the methodology and experiments of laser bending, as well as detailing the experimental setup built for a multi-layered clad sheet of SS430 & AA1050. This section also discusses the detailed working principle of laser bending. This section elaborates on the experimental process's parameters and technique. This chapter includes the micro-hardness, microstructure, residual stresses and bend angle.

Chapter 4 presents the analysis of optimising process parameters for laser bending of clad sheet. This chapter analyses the impact of different process factors on bend angle and microstructure. The optimisation of process parameters utilised in the bend angle is achieved by the implementation of RSM, which is also discussed. The optimal parameters are determined, and a confirmation test is conducted to validate them.

Chapter 5 presents the results and discussion on the Microstructure and Mechanical Characterisation of the dissimilar SS430–AA1050 clad sheet structure before and after laser bending.

Chapter 6 presents the findings from this research work, highlights notable contributions, and identifies prospective areas for further investigation.

1.12 Summary

This chapter highlights the importance of advanced metal forming techniques in the context of the ongoing industrial revolution inspired by the principles of Industry 4.0. One technique that stands out is advanced forming, which allows the production of intricate three-dimensional finished parts by laser forming according to a finite element model. Laser bending is well-known for its efficiency in creating sheet metal structures. It offers numerous benefits, including no spring back, high precision forming, and optimal material utilisation. This makes it an ideal choice for the advanced forming process of materials, such as aluminium and stainless steel clad sheet. This makes it a highly promising method for the laser bending of 2-ply clad sheet. It also summarises the organisation of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter examines a literature study on laser shaping of diverse materials and metal sheets. This presents a summary of the microstructure and mechanical characteristics of deformed materials using laser forming. It examines the mechanical characteristics and microstructure of diverse metals and alloys generated through this process. This chapter outlines the prevalent challenges encountered in laser bending, including elevated residual stresses, delamination, and variations in mechanical characteristics. The techniques employed to minimise faults and the recent advancements in laser bending.

This chapter presents a prospective vision for enhancing forming technology to meet the requirements of the industrial sector and argues that laser forming may serve as a superior alternative technique for achieving high-quality output. The study has effectively identified research gaps and created clear objectives by meticulously reviewing the current literature. A work plan for laser forming of the samples is finally presented. It is remarkable that there is a shortage of research in India on laser forming utilising a laser heat source, as shown in Fig.2.1.

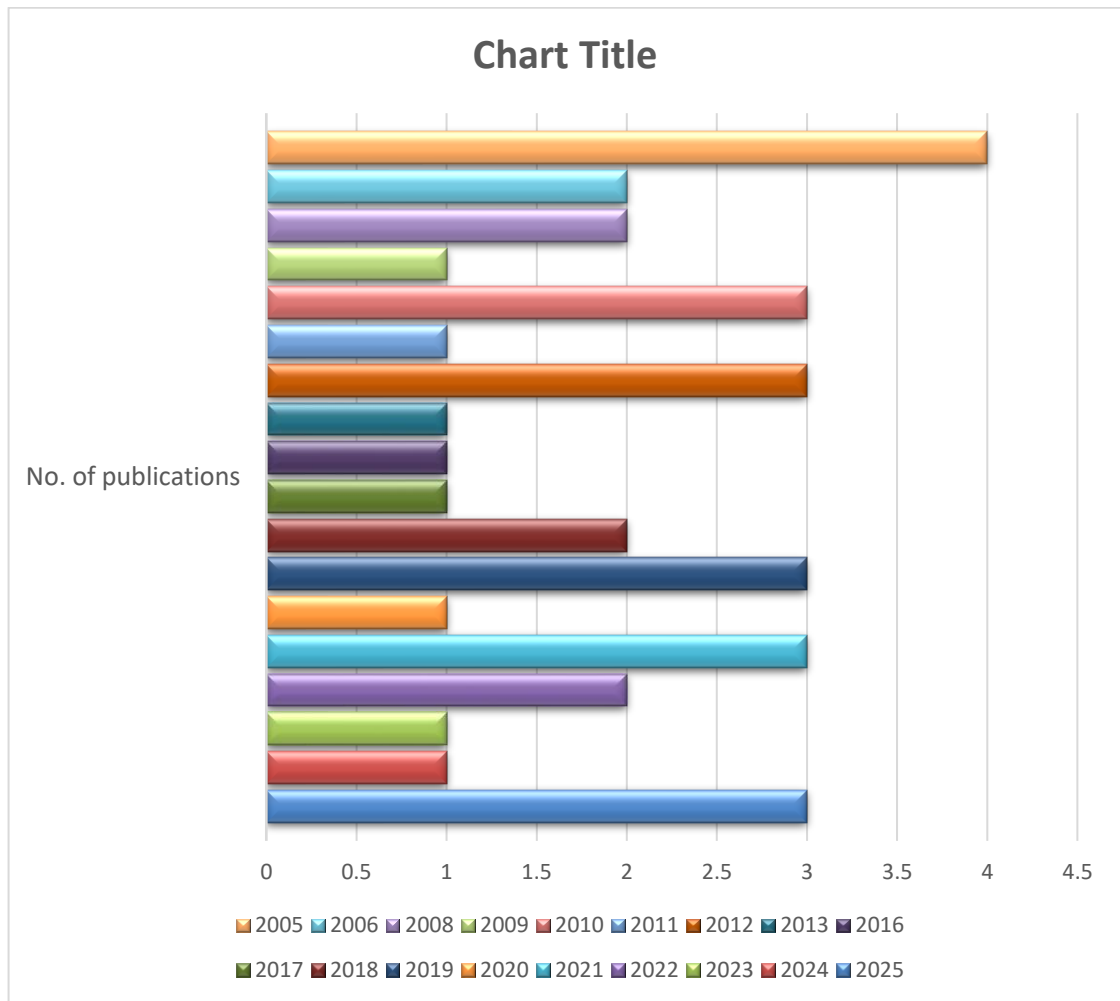


Fig. 2.1 Laser-based forming papers/ publication's year variation

The present study thoroughly evaluates the literature on laser forming of sheet metals that employs the laser technique. A comprehensive discussion is presented, encompassing recent developments and prospective paths of investigation for laser forming. Fig. 2.2, illustrates the County or regional variation in research on laser forming.

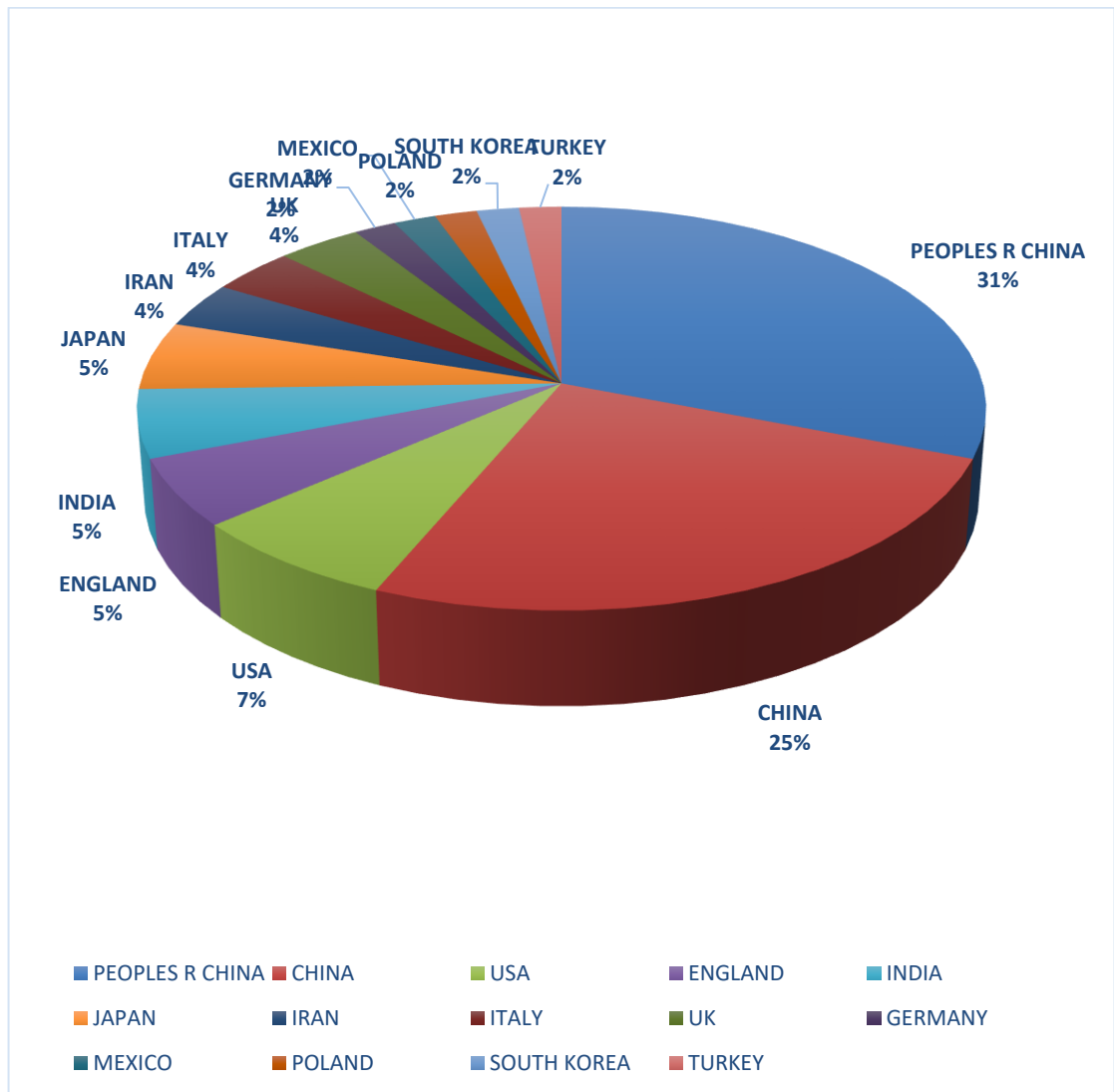


Fig. 2.2 County or region-wise variation of research on laser forming

Laser bending is comparable to flame bending, a process commonly used in the shipbuilding industry to shape the sheet metal of a ship's hull. The traditional forming technique requires a significant amount of man-hours and is dependent on skilled personnel. The issue can be resolved by using a laser beam to distort the metal sheets rather than a gas flame [5]. Deformation may be systematically generated in sheets and plates by directing the laser beam over one side of the material, as seen in Fig. 2.3.

2.2 Energy equations for laser heating

The fundamental equation for heat transmission in laser-heated metal sheets is the transient heat conduction equation, often known as the heat diffusion equation. The usual form of the equation is modified to include a heat source term that represents the energy input of the laser beam, as well as heat losses. Thermal energy is conveyed inside the sheet by conduction, while a portion is dissipated to the environment via convection and radiation.

The comprehensive three-dimensional heat conduction equation for laser heating is delineated in Equation (1) [62]

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} k \left(\frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} k \left(\frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} k \left(\frac{\partial T}{\partial z} \right) + \dot{q} \quad \text{Eq. (1)}$$

In this context, ρ , C_p , k , and $\dot{q}$ represent the density, specific heat, thermal conductivity, and the volumetric heat generation rate of the medium, respectively. The term $\rho C_p \frac{\partial T}{\partial t}$ is the rate of the thermal energy difference of the medium per unit volume. $k \frac{\partial T}{\partial x}$, $k \frac{\partial T}{\partial y}$, and $k \frac{\partial T}{\partial z}$ are the rate of heat transmission per unit area at the x , y , and z directions, respectively.

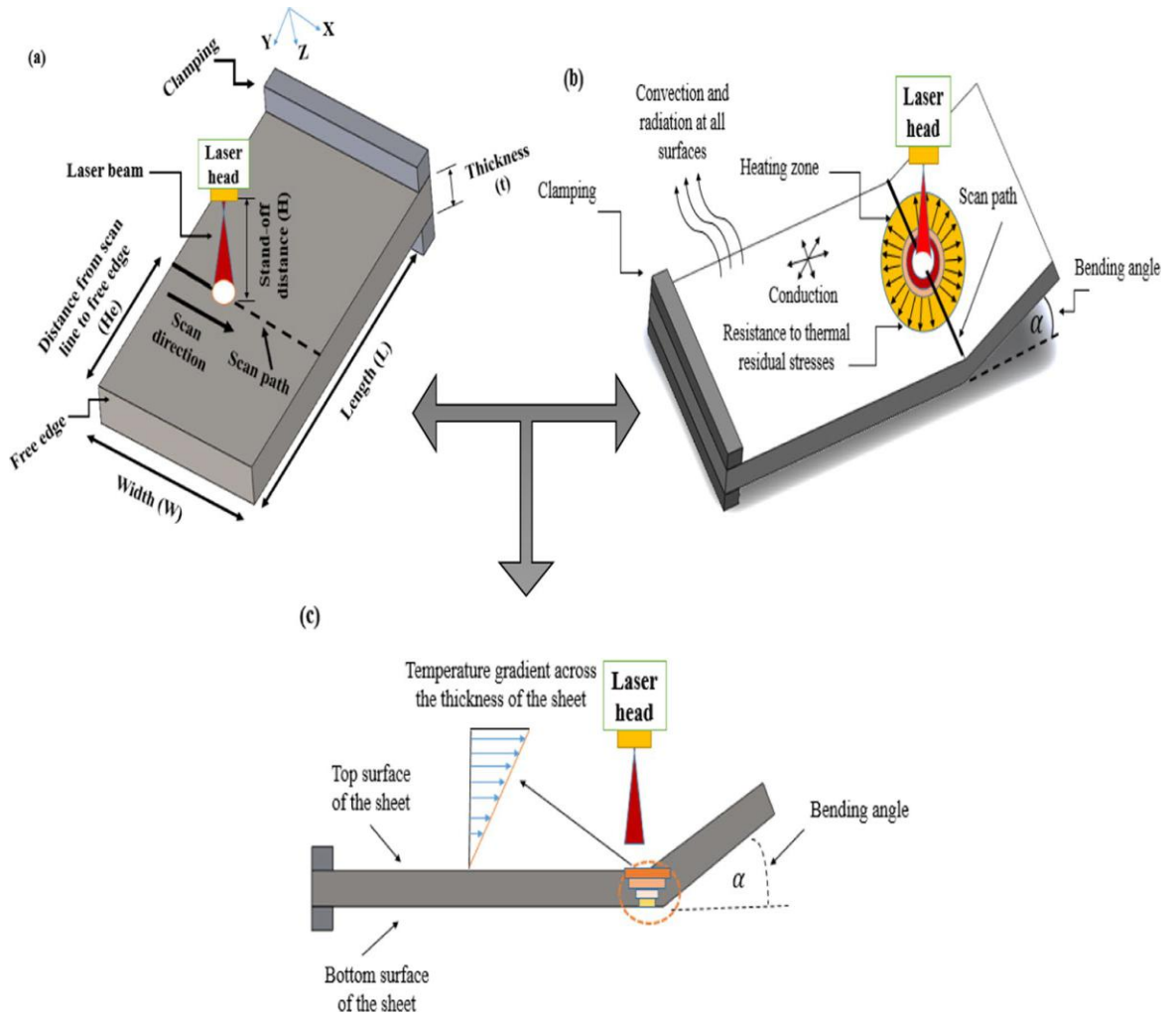


Fig. 2.3 Laser beam irradiation phenomenon [14]

Thermal energy is dissipated to the environment through the upper, lower, and lateral surfaces.

By convection: $q_{(conv)} = h(T - T_{\infty})$ **Eq.(2)**

Where h denotes the coefficient of convection and T_{∞} represents the ambient temperature.

By radiation: $q_{(rad)} = \varepsilon\sigma(T^4 - T_{\infty}^4)$ **Eq.(3)**

where ε denotes surface emissivity, and σ represents the Stefan-Boltzmann constant [6].

Laser forming works because the sheet experiences plastic strain when the temperature varies rapidly. To create something properly, there must be sufficient absorbed energy, a significant temperature differential over the thickness, and controlled heating and cooling cycles.

2.3 Mechanisms of laser forming

Laser forming is a technique that utilises the controlled application of laser radiation to deform and bend materials, typically sheet metals, by generating temperature gradients and stresses without physical contact or mechanical equipment. Figures 2.4 (a)-(c) depict the temperature gradient mechanism (TGM), buckling mechanism, and upsetting mechanism.

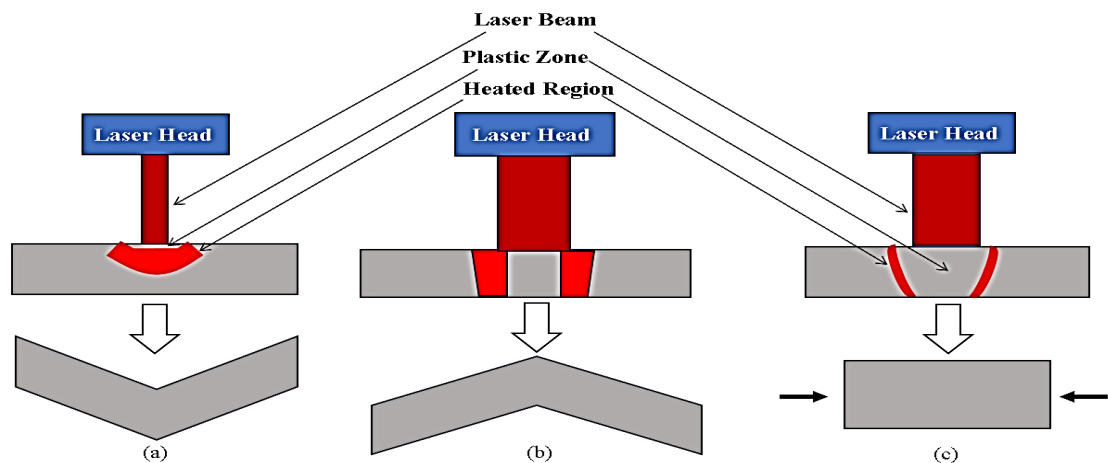


Fig. 2.4 (a) TGM (b) Buckling mechanism (c) Upsetting mechanism

Three laser forming mechanisms can be summarised as follows:

2.3.1 Temperature Gradient Mechanism (TGM)

In laser forming, the temp. gradient mechanism (TGM) is the predominant process, particularly for bending sheet metals out of plane towards the surface exposed to laser irradiation. A defocused laser beam rapidly heats the surface of TGM while keeping the remainder of its thickness at a relatively low temperature, resulting in a substantial

temperature gradient across the material. Due to the large temperature difference between the heated and cold layers, compressive stresses develop in the heated layer as surface fibres exposed to the laser try to expand but are hindered by the colder material below. The top surface experiences irreversible plastic deformation as a result of the heat pressures beyond the material's elastic limit. The residual generated plastic strain causes the object to bend toward the laser as it cools and compresses. The primary impact of TGM occurs when the thermal diffusion depth is significantly smaller than the material thickness, typically at an adequately elevated laser scan speed. The diameter of the laser spot often approximates the thickness of the workpiece, hence augmenting the through-thickness gradient. The laser power, beam width, scan velocity, and thermal conductivity of the material are process factors that affect TGM.

2.3.2 Buckling mechanism

When laser forming thin sheet metals, the buckling process typically appears as a minor temperature difference throughout the material's thickness, as the beam heats a large region. In this case, most of the heated region expands uniformly in response to heat, but the material around it stops developing. This causes significant compressive stresses that are perpendicular to the sheet's surface. When these stresses exceed the critical buckling threshold, local elastic-plastic buckling occurs, resulting in the formation of a bulge. When the bulged area cools, it bends plastically, and this may occur either toward or away from the laser's surface. In contrast to the temperature gradient mechanism, this approach usually has a homogeneous stress profile across the thickness. When the heated area is significantly greater than the thickness in thin materials, the buckling process produces intricate, out-of-plane shapes, and each pass typically results in low bend angles.

2.3.3 Upsetting mechanism

The distressing mechanism in laser forming occurs when the diameter of the laser beam is significantly smaller than the sheet's thickness, and the material's shape does not facilitate buckling. During laser irradiation, localized intense heating at a narrow spot induces plastic deformation not through bending, but by thickening the material in the irradiated region—a process known as “upsetting.” This mechanism is characterized by a reduction in the width of the workpiece and the formation of a bead or thickened zone at the point of irradiation, often achieved through multiple laser passes. This method is particularly useful when precise width reduction or localised plastic flow is required, such as in the correction or adjustment of thick plates without mechanical cutting.

2.4 Conditions for laser forming

Let the laser beam travel at a speed (v), thermal diffusion depth (t), laser beam spot diameter (d), and α is the thermal diffusivity $\alpha = \frac{k}{\rho C_p}$ (m^2/s), and worksheet thickness (s).

For the temperature gradient mechanism

$$, t < s \text{ and } t = \sqrt{(\alpha\tau)}$$

Where the interaction time (τ) depends on the laser spot diameter and scan speed.

Therefore, $\tau = \frac{d}{v}$ and $t = \sqrt{\left(\frac{d}{v}\alpha\right)}$, since $t < s$

$$\text{So, } \sqrt{\left(\frac{d}{v}\alpha\right)} < s,$$

$$\therefore \alpha \frac{d}{v} < s^2,$$

$$\boxed{\frac{\alpha d}{v s^2} < 1} \quad \text{Eq. (4)}$$

The term $\left(\frac{\alpha d}{v s^2}\right)$ is known as the Fourier number (F_o). If equation 4 is satisfied with the controlled process parameters, then the bending becomes dominant if the Fourier number is less than 1, which means heat has not penetrated deeply due to the short heating time [15].

Deformation may be systematically generated in sheets and plates by directing a laser beam over one surface of the material. Laser bending is analogous to flame bending, a technique commonly used in the shipbuilding industry. To contour the exterior metal plates of a vessel's hull. The conventional shaping method involves considerable man-hours and relies on proficient workers [4]. Materials such as stainless steel and lightweight alloys of aluminum, magnesium, and titanium have a high coefficient of thermal expansion. These sheet materials can undergo substantial deformation when subjected to laser heating, as seen in Fig. 2.5.

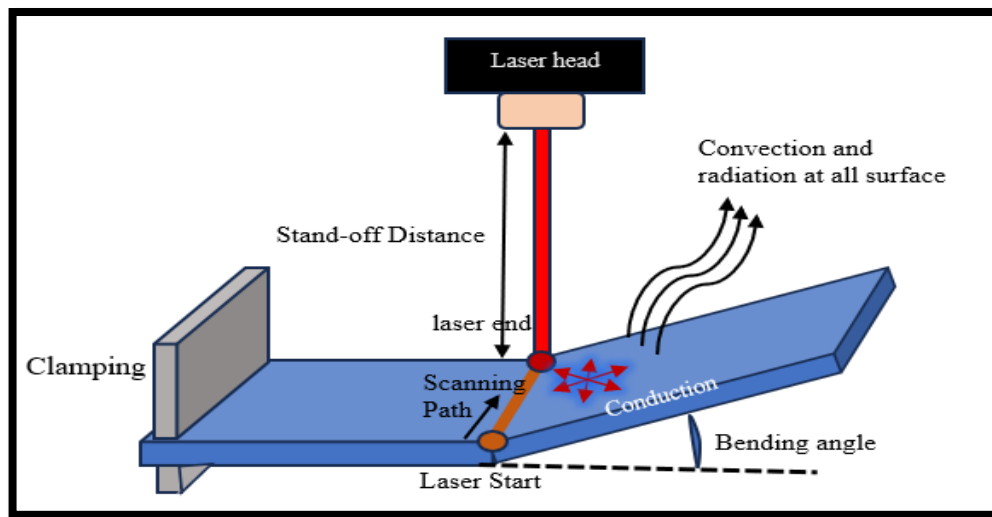


Fig. 2.5 Schematic of laser beam irradiation[4]

2.5 Recent challenges in laser forming

A literature survey concentrating on laser forming, microstructural evolution, and numerical modelling for various sheet metals. The fundamental review, experimental,

and simulation studies present a comprehensive perspective and emphasise deficiencies. Bending of the workpiece is an output result in the laser forming process; therefore, the effects of various controllable parameters are illustrated in Table 2.1.

Table 2.1 The Laser forming process effects on the bending of the workpiece

Authors	Machine and Materials	Process parameters	Output results
Mazdak, Siamak, et al. (2023)	CO ₂ laser used. Cu alloy and AISI 1010 steel. Specimen Size = 200×100×0.5 mm ³	Power (W) = 500, 1000, 1500 Scan speed (mm/s) = 10, 15, 20; Number of passes = 15, 20, 25	The optimum parameters are 1000W, 20 passes and 10mm/s for max. bending angle= 11.2°.
Guo et al. (2023)	Continuous fibre laser YLR – 1010. titanium alloy TC2 Specimen Size= 40×20×2 mm ³	Laser Power P=150-300 W, Scan Speed=6mm/s, preload F = 10 N Scanning and position=10 mm	When the laser power P is 150 W, the angle difference is 1.4°; when the P is 350, the angle difference is 0.5°
Qiuyu Miao (2023)	kW Nd: YAG continuous laser. thermoplastic composites Specimen Size= 40×20×2 mm ³	The influence of laser power (70 W, 80 W, 90 W, 100 W) and Consolidation force (26 N, 48 N, 68 N, 92 N,	A laser power of 80 W, the speed of 800 mm/min, and the consolidation force of 68 N. It decreases with the increase of laser power and the number of layers.

		109 N) on angle deviation is studied.	And the angle deviation is larger when angled laminates are manufactured.
Sharma et al. (2023)	Fibre laser machine. mild steel Specimen Size= $150 \times 70 \times 2 \text{ mm}^3$	laser power (400, 600, 800, 1000 W), beam diameter (2, 4, 6, 8, 10 mm) and scan speed (1000, 1500, 2000, 2500 mm/min).	Bend angle (20.37°) obtained at 1000 W and 1000 mm/min, respectively. And the high micro-hardness (179 HV) and fine grain structure obtained at 1000 W and 1000 mm/min.
Mehdi Safari (2022)	CO2 Laser Steel sheets Specimen Size= $60 \times 40 \times 0.7 \text{ mm}^3$	Start point of scan= 1/2, Irradiating method= 1/2/3, Beam diameter = 4/5/6 mm, power=300/400/500 W & Number of passes= 1/2/3	At 1, 1, 6mm, 500W & 3 passes, laser bending $\alpha = 0.9438^\circ$.
Nath et al. (2022)	Continuous-wave fibre laser, Al 6061-T6 sheets.	Power = 500/600W, Scan Velocity 1000/1500 mm/min, No. of pass 1/2/3	Maximum temp. variation (267°C to 370°C) along the sheet thickness (a),

	Specimen Size= $110 \times 50 \times 1.5 \text{ mm}^3$		temperature profile observed at (P= 500W,V= 1500 mm/min. maximum bend angle 0.8° to 1.7° at V = 1500 mm/min, N = 1 and (b) P = 600 W, V = 1500 mm/min.
Sharma, Pankaj et al. (2022)	Clad sheet metal SS430 and SS304 with AA1050 150 mm x 25 mm Specimen Size= $150 \times 25 \times 2/2.6 \text{ mm}^3$	Tensile Strength (MPa) 0.2% Yield Strength (MPa) % Elongation	Spring back was controlled by taking the optimal bending radius/punch profile radius value.
Wang et al. 2022	MFSC-2000 optical fibre laser stainless steel composite plate (06Cr19Ni10/ 1Cr17Mn6Ni5N/06Cr 19Ni10) Specimen Size circular plate with 100 mm diameter, 12 mm	laser power heating line length Scanning speed 06Cr19Ni10(t=0.8mm)/ 1Cr17Mn6Ni5N(t=1.04 mm)/06Cr19Ni10 (t=0.8mm) The plate was a circular plate with a 100 mm	Optimum P = 500W, V = 10 mm/s, L = 20 mm, N = 7. The plate deformation increased with the increase in laser power (P), then decreased with the increase in heating line length (L), and decreased

	diameter hole at its centre and thickness 2.64 mm	diameter and a 12 mm diameter hole at its centre.	with the increase in scanning speed.
Shi et al. (2022)	ND-Yag Laser DP980 high-strength steel Specimen Size= $80 \times 40 \times 2 \text{ mm}^3$	laser power(P), and the radius of the laser spot (R) P = 300 W, R = 3 mm and v= 2 mm/s Line force F(N/m)= 3125 Scan Number= 1	Investigate the temperature distributions and bending angles at different positions along the scan line of the steel sheet.
Nath et al. (2021)	AM30 magnesium alloy sheet. Specimen Size= $80 \times 40 \times 2 \text{ mm}^3$	Power(W)= 450/500/600 Scan Speed(mm/min)= 1500/2000/2500/3000 Beam Dia (mm)= 2/3/4/6	Achieved maximum bending angle 3.56 ° at 500W, 1500 mm/min and 2 mm in a single pass.
Guo et al. (2021)	IPG YLR-1010 LASER titanium alloy plate Ti-10V-2Fe-3Al. Specimen Size= $110 \times 50 \times 1 \text{ mm}^3$	Process parameters in the experiment. F/N= 20, 30, 40, 50, 60, 40 P/W= 200, 100, 150, 200, 250	The average error of the laser bending angle obtained by the analytical model is less than 4.57%

		$v = 1 \text{ mm} \cdot \text{s}^{-1}$ $d = 4 \text{ mm}$	(different pressure) and 4.11% (different laser power).
Kulkarni et al. (2021)	ND: YAG laser. A356-alloy. Specimen Size= $25 \times 15 \times 6 \text{ mm}^3$	Stand-off distance =30 cm Frequency=10 Hz Spot dia = 0.5 mm Spot area =0.2 mm ² Laser fluence =510 mJ/mm ² , 1020 mJ/mm ² and 1530 mJ/mm ² Scan speed= 1 mm/s N ₂ gas pressure=5 bar	The optimized hardness (2.8 GPa, at 25 °C) and fretting wear resistance (1307.18 mm^{-3} , at 200 °C).
Wang X et al. 2021	MFSC-2000 Fibre Laser Composite plate (06Cr19Ni10/Q235-B/06Cr19Ni10) Specimen Size= $100 \times 50 \times 3 \text{ mm}^3$	Laser power= 600 W Scanning velocity= 25 mm/s Spot diameter= 4mm mm Number of scans= 1-20 ALE (J/mm) = 24-480	ultimate tensile strength (562.4-582.9 MPa) and yield strength (395-455 MPa) are increased with an increased number of scans. When ALE reaches 480J/mm then, a molten pool is created.
Reza Masoudi Nejad (2021)	Fibre laser (max. power 100W)	Parameters include laser beam power (50,	The optimal parameters were a laser beam power

	2-ply Al-Cu Clad sheet Specimen Size= $50 \times 50 \times 0.5 \text{ mm}^3$	75, and 100 W), beam diameter (0.50, 0.75, and 1 mm), and scanning speed (3, 6, and 9 mm/s).	of 100 W, a scanning speed of 3 mm/s, and a laser diameter. 0.75 mm. Optimum bend angle 210.
Zhang et al. (2021)	PRC-1500 laser system. DP980 high-strength steel. The Specimen Size= $80 \times 80 \times 2 \text{ mm}^3$	Power=1000W, scan velocity = 3 m/min, and laser spot radius = 2.6 mm.	When the velocity is 3 m/min, the bend angle variation increases with the increasing scan speed. When $v > 3 \text{ m/min}$, then the bending angle variation reduces with the growing scan velocity.
Ponticelli et al. (2020)	AA 6082 T6 aluminium alloy. Specimen Size= $19 \times 69 \times 2 \text{ mm}^3$	Laser power Scan Speed Number of passes Defocusing distance	spring back effect
Wang et al. (2020)	a three-layer stainless steel composite plate, 06Cr19Ni10/1Cr17Mn6Ni5N/06Cr19Ni10.	Laser power scanning velocity number of passes	The bend angle gradually increased with the laser power. It did not increase any longer after the laser power exceeded 700 W.

Behera et al, (2020)	Nd: YAG laser Al metal sheet Sample Size= 60×20×0.5 mm ³	Scanning Speed=1-5 mm/min Frequency = 0.5-20 Hz Laser power=50-200 W Pulse Duration = 0.5 20 μs.	Optimal parameters are: Scanning Speed 3 mm/min Frequency 0.5 Hz Laser power 100 W Pulse Duration = 0.5 μs Final bending angle 20°.
Rattan A et al, (2020)	Laser Power = 1.0 kW, the radius of the Gaussian heat source = 2 mm, scanning speed=25mm/s, Initial temperature was 20 °C.	The bending angle obtained from the present analysis was 25°.	The bending angle was inversely proportional to the coating thickness. The increase in power increases the bending angle, whereas the bending angle decreases with the increase in the scanning velocity.
Kotobi et al, (2019)	titanium-steel double- layered sheet	Laser power= 1.6/1.8/2.2/2.4 kW, scanning velocity= 65/72/79/86/93 mm/s, number of passes=1/2/3/4/5, beam diameter= 2.75/3/3.25/3.5/3.75	The bending angle increases with increasing power and number of scan passes. The bending angle was also inversely proportional to the scanning velocity and the beam diameter.

		mm and sheet thickness= 1.3/1.5/1.7/1.9/2 mm	
Safari et al, (2018)	Different thickness tailor-made blanks of mild steel	start point of scan path, laser irradiating method, laser beam diameter, laser output power and the number of radiation passes	The measured value of the bending angle was observed.
Pankaj et al, (2018)	3-ply clad sheet metal SS430 and SS304 with AA1050	bending force and punch displacement	The spring back is observed
Fetene et al, (2018)	CO ₂ Laser used AH36 steel strips Sample Size= 200×20/30/40×1/1.5/2 mm ³	input parameters for experiments are: laser power (P)=500/600/700 W, scan speed (v)= 800/900/1000 mm/min, laser beam (spot) diameter (D)= 7.6/9.4/11.4 mm, number of passes (N)= 1/3/5, thickness of strip	The max. bend angle of 2.3°/2.2°/2.1°/3°/2.1°/ 2.35 ° was obtained at the following combination of parameters: 700 W power, 1 mm thickness, 40 mm width, 5 passes, 800 mm/min scan speed, and 7.6 mm beam diameter.

		(t)= 1/1.5/2 mm and width (w)= 20/30/40 mm.	
Kumar et al, (2018)	CO2 Laser was used. AH36 Steel Sample Size= 200×40×2 mm ³	Power= 500 W Spot Dia. 11.4 mm Passes= 1/3/5	$\alpha=0.13^\circ$ & VHN=141 at N=1, $\alpha=0.35^\circ$ & VHN=170 at N= 3, $\alpha=1.06^\circ$ & VHN=202 at N= 5.
Kant et al, (2016)	CO2 Laser used Magnesium M1A alloy sheets. Sample Size= 70×40×1.9 mm ³	Laser power P= 300/400/500(W) Scan speed V= 1000/2000/3000 (mm/min) Beam diameter, D= 3.87/5.81/7.74 (mm	obtain large bend angle= 17.09° at 500W, 3000mm/min & 3.87 mm.
X Wang et al, (2016)	ND YAG Laser was used. 3ply stainless steel(0Cr18Ni9Ti)/car bon steel(Q235A)/SS(0Cr 18Ni9Ti) laminated	laser power, scanning speed, scan times, power density and sheet thickness	The bending angle increases with the number of scan times.

	plate (SCLP) Sample Size= 100×30×0.82 mm ³		
Hossein et al, (2016)	Ytterbium fibre laser (IPG YLR-200) 3-Ply Clad Sheet SUS430/C11000/SUS 430 Sample Size= 100×44×0.5 mm ³	Scanning Speed=3.82, 7.66, 11.62 mm/s Beam Dia =0.5, 0.7, 0.9 mm Laser power= 160,180,200 W Delay Time = 1-120 s N= 1-40	A bending angle of 64o was obtain at P=200W, v=3.82mm/s D= 0.5mm
Chakraborty et al, (2015)	austenitic AISI 304 stainless steel sheet	Fourier number and laser spot diameter	bending angle and thickness increment induced by laser scans
Zhang et al, (2015)	The material was a quenching and artificial ageing of LY12CZ aluminium alloy	laser pulse laser wavelength laser energy	A residual stress state exists on both side surfaces of the deformed region.

Shitanshu et al, (2015)	Stainless steel sheet of AISI 304	Fourier numbers and laser spot diameters	The change in bent angle was found to be significantly larger when the laser was scanned on the convex side than on the concave side.
Agnel et al, (2015)	CO2 Laser with maximum energy of 3000W. FE410 plates.	power (2KW to 3KW), number of passes (1to 210), scan speed (10 to 30 mm/s), laser spot diameter (9mm to 13mm) and frequency(500Hz to 20000Hz)	Obtained bending angle $\alpha=60^\circ$ power in the range of 2400W-2600W, scan speed of 0.9m/min and spot diameter of 11mm.
Sivankutty et al (2014)	A solid-state Nd: YAG pulsed laser rectangular sheet metal of AISI 304 Stainless steel with a length of 50 mm and a width of 18 mm is used	Power 20/35/50 W, feed rate 100/150/200 mm/min and the number of scans= 2/4/6	Maximum bend angle of 34.7 ° at 50 W, 100 mm/min, N=6 and minimum bend angle of 3.5 ° at 20 W, 200 mm/min, N=2.

Maji et al, (2013)	YLR- fibre laser, AISI 304 stainless steel sheet, Sample Size= 120×40×0.5 mm ³	laser power(W)= 450/500/550 beam diameter (mm)= 1/1.25/1.5 scanning speed (mm/s) = 60/65/70 pulse duration = 4/7/10 (micro sec.)	Bending angle (2.2°) increase with power= 540W, spot dia= 1.18 mm and pulse duration-1.1 μs and scanning speed= 63.5mm/s
Hu et al, (2013)	Laser 1.0 kW defocused diode ROFIN. ANSI 304 stainless steel Sample Size= 60× 60×2 mm ³	laser power 1 kW, laser spot diameter 3 mm, sheet plate 60 mm × 60 mm × 2 mm, absorption coefficient 0.6, scanning velocity 30 mm/s.	The average bending angle was 2.07° with the old strategy and 1.9350° with the new strategy
Lambiase et al, (2012)	A diode laser with a maximum output power of 1,055 kW, operating over a minimum spot size of 3.6 × 0.8 mm ² , is used. AISI304 Steel	Scanning Speed=15-50 mm/s spot area =2.90 mm ² Laser power=370,420,475,55 0 W Thickness 1 and 2 mm	Angular Distortion minimum measured bending angle α=0.3 ° for each pass at P=475W V=50mm/s and t=2 mm

	Sample size= $80 \times 40 \times 1 \text{ mm}^3$ And $80 \times 40 \times 2 \text{ mm}^3$		
Liu et al, (2010)	CO2 Laser, Stainless steel foils AISI 304 & Sample Size= $10 \times 5 \times 0.1 \text{ mm}^3$	laser power(W)= 10.7-27.2 beam diameter (mm)= 0.7-1.6 scanning speed (mm/s)= 15	In BM, a larger beam diameter, lower scanning speed, and higher laser power benefit the negative bending angle of 12° produced at 17.7W, 15mm/s & 0.7mm.
Shen et al, (2010)	CO2 Laser, low carbon steel, ST12. The plates are sprayed with a graphite coating.& Sample Size= $80 \times 80 \times 2 \text{ mm}^3$	laser power(W)= 1000 beam diameter (mm)= 6 scanning speed (mm/s)= 20-60 Focal Dis.(mm)= 10-50	Bending angle increases 1.29% with the power increase
Chao et al, (2010)	Nd: yttrium aluminium garnet (YAG) laser with a wavelength of 1064	Laser energies of 200, 300, and 400 mJ were used, along with the die diameter. The pulse	The maximum deformation- depth of the laser bulge at the centre is 158 mm. Laser bulge forming employs the

	nm was used. pure copper foils	duration is 11 ns and the laser beam diameter is 1 mm.	shock wave pressure induced by a laser pulse to deform thin metals.
Shen H et al; (2010)	HJ-3000 CO2 laser system, with a maximum output power of 3000 W. low carbon steel. The plates 200×200×2 mm ³ were used.	Laser power= 1000 W, Scan velocity= 20-60, Distance away from the free edge of the plate 10-50 mm, Laser beam diameter= 6 mm	Bending angle was found to be 1.29° at laser power of 1000 W, scan velocity 30 mm/s and laser beam diameter of 6 mm.
Paunoiu et al, (2008)	CO2 Laser was used. AISI304 Steel Sample Size= 100×35×1.2 mm ³	Power 100/150/200 /250/300 W Speed= 4/8 mm/s Passes= 2/4/6	When laser power exceeds 200W, melting begins. Maximum angle 21.40° achieved at 150W, 8mm/s and 6 passes.
Dubey et al, (2008)	A 200W pulsed Nd: YAG laser beam machining system. SUPERNI 718 sheet of 0.7mm thickness (a	The input parameters considered are assist gas pressure, pulse width, pulse frequency, and cutting speed.	The optimum value of control factors for overall improvement in MQC is gas pressure 2 kg/cm ² , pulse width 0.6 ms, pulse frequency 23 Hz, and

	Ni-based superalloy) sheet metal.	The focal length of the lens used is 50.0 mm. Nozzle diameter (1.0 mm), nozzle tip distance (1.0 mm), and sheet material thickness (0.7 mm) were kept constant throughout the experiments.	cutting speed 20 mm/min. The value of kerf width, kerf deviation, and kerf taper at the optimum parameter level is 0.246 mm, 0.01 mm, and 0.27281.
Labeas et al, (2008)	A 2024-T351 plate of thickness $t = 10\text{mm}$. Al 6013-T4 plate of thickness $t = 3.2\text{mm}$.	For 2024-T351 Laser power (W)= 2750/1000/2000, Velocity(mm/s)= 0.6/17.5/17.5, Specimen thickness (mm)= 10/5/1.5 For 6013-T4 Laser power (W)= 1500/2500/2000, Velocity(mm/s)= 12.5/7.5/10, Specimen thickness (mm)= 3.2/5/2	It is shown that increasing the laser power or decreasing forming speed leads to higher bending angles, as well as that increasing plate thickness results in lower achieved bending angles.

Marya et al, (2008)	1200 W Nd-YAG. titanium Ti-6Al-2Sn-4Zr-2Mo. Sample size 0.6 mm thick and 36 mm wide.	The beam diameter should be within a range of 1.4-2.3 mm, and the beam power between 240 and 300W.	The conditions provided by the 1.5 mm beam appear to yield a good result. Bending angles were measured with an estimated 0.5 °.
Majumdar J, et al; (2004)	CO2 Laser was used. AISI 304 stainless steel sheet. thin sheet (10 cm × 1 cm), and the thickness of the specimen was 1.6mm and 0.9 mm.	parameters including power density P, scan speed v, number of passes N and sheet thickness t. Bending occurs at P = 15–55 kW/cm ² ; v= 1000 –2500 mm/min (for t=1.6 mm) and P=15-55KW/cm ² ; v=4000–6000 mm/min and N= 5–40 (for t= 0.9 mm).	The bending angle was found to vary from 2° to 20° (for t = 1.6 mm) and 10° to 60° (for t = 0.9 mm), increasing with an increase in laser power, a decrease in scan speed, and an increase in the number of passes.

Shichun, Wu, et al., (2002)	08 steel sheet with depth, 1.5 mm; sheet width (along X- direction) 20 mm.	scanning velocity, 50 mm/s; spot area (A), 3×3mm ² ; laser power (P), 1000 W.	A bending angle in the direction of the laser beam. The final bending angle may be calculated to be 1.938 °.
Cheng P, et al; (2000)	CO ₂ laser with a maximum output power of 1 kW.	Scan velocity (mm/min) 1000, 3000, 5000 Power of laser 100, 300, 500 Spot dia. 0.5, 1.0 Thickness of sheet (mm)= 1.0, 1.5 Length of sheet 30, 60, 90 Width of sheet 60	The maximum bending angle was 0.462 ° at Diameter (mm)=1 Thickness (mm)= 1 Length (mm)=30 Power (W)=400 Speed(mm/min)=4000

2.6 Laser bending of monolithic sheet metals

The characterization of sheet metal pertains to the assessment of its physical characteristics by experimental methods. Mechanical testing is essential for assessing the intrinsic qualities of sheet materials, facilitating the development of novel materials, and guaranteeing material quality for design and construction applications. Assume a metal sheet has to be shaped into a certain configuration for an application that will undergo significant deformation. It is crucial to ascertain that the material possesses sufficient strength and rigidity to endure the load and deformation it will encounter during operation. The primary characterisation tests conducted are the

tensile test, peel test, and anisotropy test. This section will analyze the several research projects undertaken in this chapter.

Kumar et al. (2018) conducted research on phase fraction and hardness during laser bending of AH36 steel strip. A strong correlation was seen between the experimental and simulated findings of the Vickers hardness of the laser-scanned strip. The suggested model accounted for phase change, cooling rate, and strain hardening. Strain hardening significantly contributes to the enhancement of hardness. Disregarding this yields outcomes that contradict experimental observations. The toughness of thicker strips will be overestimated.[5].

Shi et al. (2022) showed that the bending angle was closely related to the temperature distribution. An increase in the high-temperature distribution region at a constant temperature value correlates with a greater bending angle. Consequently, an augmentation in the bending angle can be attained by altering the temperature distribution, even in the absence of a temperature rise [6].

Pankaj et al. (2018) investigated and concluded that due to its excellent tensile strength-to-weight ratio and corrosion resistance, 3-ply clad sheet metals were used in shipbuilding, residential uses, and other sectors. Spring back modifies the geometry of formed components. The spring-back phenomenon after bending a 3-ply composite-covered sheet metal was complicated by its thickness and mechanical characteristics. The paper investigates spring back in U-bending operations using experimentation and finite element analysis. A 3-ply sheet metal has AA1050 in the core and three layers of SS430 and SS304, each with varying thicknesses. Due to its rising demand in sheet metal forming, it was chosen. A universal testing equipment measured tensile strength and anisotropy of a 2.5mm 3-ply sheet. The tensile properties of each sheet in the 3-

ply configuration were separately measured using the Universal Testing Machine (UTM) and utilized in the material model for ABAQUS springback simulations of U-bending [7].

Pankaj et al. (2022) examined the influence of bending radius/punch profile radius on the spring back of SS304/Al1050/SS304 clad sheet. Bending radius/punch profile radii significantly impact the prediction of clad sheet spring back. Decrease the bending radius/punch profile radius to decrease springback. This research indicates that an ideal bending radius/punch profile radius effectively controls springback [8].

Wang et al. (2021) evaluated the HAZ's UTS, YS, and micro-hardness of the stainless steel–low carbon steel three-layer composite plate under repeated laser scanning. Laser bending in industrial production may follow theory. The bending angle escalates linearly with the scan count. The angle of plate bending rises, but the speed diminishes following the third scan. UTS and YS elevated following ten laser scans. Thermal cycling transforms the austenite at the surface of the stainless-steel layer into ferrite, hence diminishing microhardness. Following 20 scans, the superior stainless-steel substance generates a molten pool, the intermediate carbon steel layer liquefies, and the curvature of the interface amplifies; however, delamination does not transpire. [9].

Zhao et al. (2023) utilised a dataset of geometric parameters as a benchmark for developing a machine-learning GPA algorithm that trains Gaussian processes to learn geometric uncertainty, considering spatial and cross-sectional relations from accurate measurements [10].

Liu et al. (2010) experimentally studied the LBP in stainless foils to fabricate negative bending angles. They achieved this by augmenting the prestresses in the sheet, which significantly enhances the negative bending angle [11].

Shen et al. (2010) attempted to develop an understanding of the edge effect phenomenon in the LBP by performing numerical simulations and experimental tests. To mitigate the edge effect in the LBP, they devised scanning techniques that changed the velocity along the irradiation line.[12].

Maji et al. (2013) investigated the LBP of AISI 304 stainless steel and calculated the effects of process parameters on the bending angle using statistical analysis [13].

Kant et al. (2016) investigated the LBP of magnesium M1A alloy to achieve bending angles exceeding 10 degrees. Their results indicated that the quantity of laser irradiation scans significantly influences the deformation behaviour of laser-bent magnesium sheets [14].

Safari et al. (2018) predicted the bending angle in LBP of tailor-machined blanks (TMB) using an artificial neural network [15].

Wang et al. (2020) studied the mechanism of the bending process in LBP of a metal composite plate using finite element simulations. To regulate the bending behavior and mitigate the edge impact in LBP, they presented four scanning procedures and enhanced the forming precision [16].

Guo et al. (2021) examined Pressure-assisted laser forming (PALF), which represents a new research direction in laser forming. This technique has several benefits in enhancing the bending angle and regulating the bending direction. This work individually analyzes prestress and thermal stress, followed by strain coupling for both

stress types. The accuracy of this equation is refined by two experiments. Any combination of parameters (pressure, scanning location, plate length, plate width) may get any high-precision bending angle [17].

Nath et al. (2021) conducted a coupled thermo-mechanical finite element simulation to study the bending of AM30 magnesium alloy sheets using a laser beam. The primary finding they reported was that the measured bending angle in the multi-pass system was 430% more than that in the single-pass irradiating technique.[18].

Zhang et al. (2022) suggested a varying velocity scheme to reduce the edge effect in the LBP of DP-980 steel. The researchers determined that the alterations in bending angle at the free edge of the laser-bent sheet are significantly reduced when employing the variable velocity technique [19].

Racesco Lambiase (2012) assesses the bending angle in the laser shaping of metallic sheets. The model presumes elastic-bending theory, disregarding plastic deformation during the heating and cooling stages. A thermal field is initially produced, followed by the calculation of the thermal component of deformation, which is utilized in the strain balance to assess the bending angle.[20].

Long et al. (2022) suggest that reducing the thermal degradation of plastics during the laser transmission welding (LTW) process is crucial for achieving a high-quality weld seam. In this study, a model is proposed for predicting thermal degradationInitially, utilizing polymethyl methacrylate (PMMA) as a representative material, the weld seams are fabricated under varying process parameters, encompassing laser power, welding speed, and carbon black (CB) concentration. The comprehensive analysis of

the fabricated weld seams was conducted using shear testing, scanning electron microscopy, and ultra-depth-of-field microscopy [21].

Ponticelli et al. (2020) present a laser-assisted bending process. In particular, the use of this fuzzy model aims to evaluate the optimal combination of input parameters to achieve zero residual springback. The input parameters were treated as triangular fuzzy integers, and the Transformation Method was employed to manage uncertainty propagation to the residual stringback [22].

Chakraborty et al. (2015) investigated the effects of Fourier number and laser spot diameter on bending angle and thickness increment in the regime of the coupling mechanism of laser forming. A little increase in the bending angle and thickness increment values was noted for larger laser spot sizes. A novel scanning approach employing a mix of temperature gradient and coupling processes to produce low-profile surfaces has been presented [23].

Wang et al. (2006) described laser shock forming (LSF) as a new technique that utilizes an impulsive pressure generated by a laser-induced shock wave applied to the surface of a metal sheet. The titanium sample's (TM) surface quality and deformation were analyzed. ABAQUS was utilised to simulate LSF, and the centre displacement of the affected region was measured and compared with the simulation outcomes.[24].

Safari et al. (2022) showed that linear paths' bent edge displacements were far higher than the curved path's. The linear irradiating technique irradiated the plate's interior portions more than the curved one. The plastic deformations of the inner parts of the sheet significantly impact its total deformation, as their bending stiffness is larger than that of the outer sections. It was shown that the curved irradiating technique had higher

non-uniform bending in the bent edge than the linear one, owing to additional mechanical limitations in various sections of the route [25].

Zheng et al. (2010) examined the effects of laser intensity, die diameter, and sample thickness on deformation depth were examined. Results: High-speed micro-scale laser bulge formation can plastically deform copper foils to an acceptable geometry. Necking occurs at the laser spot edge and around the die entry at a certain laser intensity, limiting plastic deformation. The laser bulge-forming technique leaves compressive residual stress on the sample's bottom and a damaging tensile residual stress field on top. Process parameters must be optimized for optimal forming results. Laser energy determines deformation depth, which decreases with sample thickness [26].

Kulkarni et al. (2021) successfully examined a compound layer on the A356 alloy substrate through laser nitriding in an open atmosphere. This coating significantly improved the hardness and increased the temperature fretting wear resistance of the alloy [27].

Jun et al. (2010) Established a more precise temperature model by thoroughly analyzing the scanning process. The examination of maximum temperature distribution and limiting conditions clarifies the origins of edge effects. An improved analytical model of the bending angle with respect to the y-axis has been presented. Simulations and experiments have been conducted to validate this concept. A unique method has been developed to mitigate edge effects in laser shaping. The trial results confirmed the effectiveness of the innovative method. [28].

Hu et al. (2013) investigated by simulation a highly idealised columnar sample, showing the microstructural evolution of grains under high-strain-rate loading and revealing the formation process of nanostructures in copper foil during Laser Shock Forming. During the first phase of loading, plastic deformation is facilitated by dislocations, with slip systems in grains progressively activated. When tension is focused, secondary slip, cross-slip, and alternation of slip systems occur. Only a limited number of dislocation reactions, constrained by sample size, are seen [29].

Shichun et al. (2002) reported that when the laser beam scans along a selected line, a thermal gradient is generated between the upper and lower surfaces of the sheet, leading to thermal expansion and a small counter-bending away from the laser source. Following laser scanning, the heated zone undergoes cooling and contraction, resulting in a bending angle oriented toward the laser beam. In laser bending, a wider sheet results in a reduced counter-bending angle, thereby increasing the ultimate bending angle. The strains inside the laser's stress field are mostly attributed to variations in bending [30].

Zhang et al. (2015) examined a metal sheet that first undergoes shearing deformation along the boundary of the local shocked region, then laser shock momentum profoundly stretches it. The bulge opening eventually expands to the diameter of the die hole and remains at that diameter. The bulge depth increases, then springs back, and finally flattens to a flat bottom, exhibiting reversal deformation and a rounded tip. Both sides of the distorted area have complex residual stress. Both sides show reduced compressive residual stress and greater tensile stress [31].

Chevallier et al. (2018) provided a laser ablation simulation approach. The approach assumes the surface temperature won't climb much above the vaporisation

temperature. The energy balance equation at the solid-gas interface yields the normal velocity of the mesh for the flow of vaporised matter. With the time-dependent Energy equation resolved, the model's temperature was computed, and a Gaussian heat source represented the laser heating. Modelling the ablated matter is inadequate for accurately predicting the topography of the textured surface after a single laser hit, as the behaviour of molten material substantially influences the crater form [32].

Shen et al. (2006) provided a numerical analysis of laser plate formation employing two simultaneous laser scans along parallel lines. Results reveal that simultaneous laser scans cause more plastic deformation than sequential scans along the same lines if the distance between the scan lines is not considerable. If the scan lines are widely spaced, the plastic deformations from the concurrent laser scans and the sequential scan would be identical. The dimensions of the plastic zone generated during heating are contingent upon several elements, including the power and radius of the laser beam, as well as the material characteristics of the plate.[33].

Chakraborty et al. (2015) conducted experiments and simulations to modify the bending angle through laser forming of AISI 304 mechanically bent sheet blanks. Blanks were designed to be bent at 45° and 90° angles utilizing two die-punch combinations, each with a 4.5 mm punch radius, and to 90° angles employing an alternative die-punch with a 9 mm punch radius. The Fourier number and laser spot width were altered while keeping the peak surface temperature roughly constant. The temperature gradient mechanism was the designated method for laser formation. They regarded laser power, scan speed, spot diameter, and workpiece shape as process parameters. The dimensions of the sheet metal and its thickness were regarded as the geometry of the workpiece. [43].

Labeas et al. (2008) optimised process parameters using numerical simulation, resulting in the desired bending pattern. The simulation approach facilitated the examination of the bending limit for a specific specimen. They developed a finite element simulation method to forecast the temperature distribution and deformation profile of the aluminum foil [44].

Dubey et al. (2008) studied the multi-objective Taguchi methodology for the optimisation of pulsed Nd: YAG laser beam cutting of nickel-based superalloy. This is done to get better cut qualities [45].

Marya et al. (2008) derived a mathematical equation to optimize the process parameters of laser bending. This study uses an aluminium sheet for bending via a laser source. The process parameters, including scan speed, pulse diameter, laser power, and pulse length, are refined to get the maximum bending angle.[46].

Rattan et al. (2020) researched the effect of lime coating on the bending behaviour of plain carbon steel using a three-dimensional uncoupled thermo-mechanical finite element model. The model is verified with literature data on uncoated steel, after which the validated model is utilized for a parametric assessment of the lime coating's process and material characteristics [47].

2.7 Multi-layered Sheet metal laser forming

Wang et al. (2016) investigated the determinants affecting the bending angle of bi-layer steel-aluminium sheets. Response surface experiments were conducted to evaluate the impact of laser power, scanning velocity, and specimen passes on the bending angle following simulation validation. The ANOVA test indicated that laser power exerted the most substantial influence on the bending angle, whilst the number

of passes had the least significant effect. The key variables influencing the bending angle are power, laser scanning speed, the product of power and speed, the number of laser passes, and the product of passes and speed.[48].

Leu et al. (2018) Discovered that Cu/Ni laminated composite metal sheets exhibited increased depth with augmented laser energy, a higher frequency of laser pulses, and a reduced thickness of the soft punch. In contrast to conventional forming methods, the stacking sequence did not influence the forming depth of Cu/Ni laminated composite metal sheets. Forming caused surface roughening. Roughness increases with increasing laser energy. Under similar conditions, the copper and nickel layers exhibited identical roughness. The bottom thickness was significantly decreased, and the degree of thinning further softened from the bottom. The outermost layer deformed laminated composite metal sheets more than the interior layer because its thickness decrease was greater. Unlike typical forming techniques, the stacking sequence did not affect the thinning of the laminated composite metal sheet 49].

Shichun et al. (2002) found laser bending process may be divided into two stages: in the first stage, a small counter-bending away from the laser source appears, and in the second stage, a bending angle facing the laser source is formed [50].

Miao et al. (2021) reported that, unlike angled thermoplastic laminates manufactured by traditional methods, which exhibit spring-in deformation, those manufactured by laser-assisted forming exhibit spring-back deformation. Laser power, consolidation force, and layer count significantly influence angle deviation. It diminishes with the augmentation of laser power and the number of layers. The angle deviation increases when angled laminates are produced under a greater consolidation force [51].

Wang et al. (2021) worked on a laser as the heat source and the stainless-steel composite plate (06Cr19Ni10/1Cr17Mn6Ni5N/06Cr19Ni10) as the research object, and the forming process of the three-dimensional bowl surface was studied. The study revealed that plate deformation escalated with increasing laser power, subsequently diminished with longer heating line lengths, and further dropped with higher scanning speeds. A three-dimensional thermodynamic coupling model for a three-layer composite plate was developed and experimentally validated. [52].

Wang et al. (2020) worked on a laminated stainless steel composite plate. As the laser power diminished below 700 W, the bending angle increased. Upon reaching 700 W of laser power, the bending angle no longer increased. The two extremities exhibit a slight bending angle; however, the centre displays a considerably bigger angle. With an increase in scanning velocity below 400 W, the bending angle decreased. The bending angle augmented with the scanning velocity for laser strengths of 600 W and 700 W. The bending angle ceased to increase at a scanning velocity of 30 mm/s. Modifying the laser power and scanning velocity improved the precision of plate production. Under ideal process conditions, the plate did not laminate.[53].

Hossein et al. (2016) Conducted an experimental and statistical examination of the laser bending of a three-layered SUS430/C11000/SUS430 laminated composite. Due to its corrosion resistance and the electrical superiority of copper, microelectronics may utilize this combination of linear Ytterbium fiber lasers to manipulate sheets. Three-layer laminated sheets, including steel and copper layers, are evaluated for their bending characteristics, considering variables such as the number of passes, scanning

velocity, beam diameter, laser power, and inter-pass delay time. The slender copper intermediary layer has a significant influence on per-pass bending [54].

Sharma et al. (2023) demonstrated that electromagnetic control has markedly enhanced the laser bending of mild steel. Findings indicate that input process variables influence the bend angle. The peak bend angle is 20.37° at 1000 W and 1000 mm/min, whilst the minimum is 3.17° at 400 W and 2500 mm/min. Elevated laser power and reduced scanning velocity augment peak temperature and curvature angle. The bent angle escalates following five laser scans across all studies. Laser scanning is the principal source of increased thermal levels [54].

2.8 Research gaps and objectives

2.8.1 Research gaps and motivations

After an extensive literature survey on the topic of laser-assisted forming of a multiply laminated sheet, it has been found that the following issues have not been addressed so far:

- 1.** Laser forming is a non-contact forming process that utilises the localised heating and thermal expansion of the material to achieve desired shape changes. However, when it comes to clad sheet metal with SS430, SS304, and AA1050, no research is available on the effects of laser forming on this specific combination of materials.
- 2.** Several analytical models for laser-assisted forming of sheet materials are available in the literature. Still, there is a lack of analytical models for laser bending of multi-layered clad sheet metal, including laminated sheets of SS430, SS304, and AA1050.
- 3.** The effect of laser bending on multi-layered clad sheet metal, specifically SS430, SS304, and AA1050, on the bending angle after laser forming has not been studied.

2.8.2 Research objectives

When laminated composite sheets are chosen for manufacturing automobile components, aerospace sheet metal parts, and utensils for domestic use, etc., it is essential to select the design and process variables and material properties that optimise the bending angle through laser forming operations. In view of the challenges mentioned above and the research gaps in the prediction of the bending angle of 2-ply laminated composite sheets. The objectives of the proposed research have been broadly formulated as follows:

1. Characterisation of tensile properties of multi-layered composite sheet metal.
2. Development of a numerical simulation for the prediction of the bending angle in laser bending operation.
3. To optimise the process parameters for the bending angle by the laser forming technique.
4. Microstructural characterisation of the deformed samples of the laminate composite sheet metal.
5. Experimental validation of predicted results.

2.9 Flow chart of the methodology

A flow chart offers a condensed picture of the complex activities that need to be completed. The flow chart of the current study is depicted in Fig 2.6. This flow chart illustrates the sequential technique and methodology used in this scholarly endeavour.

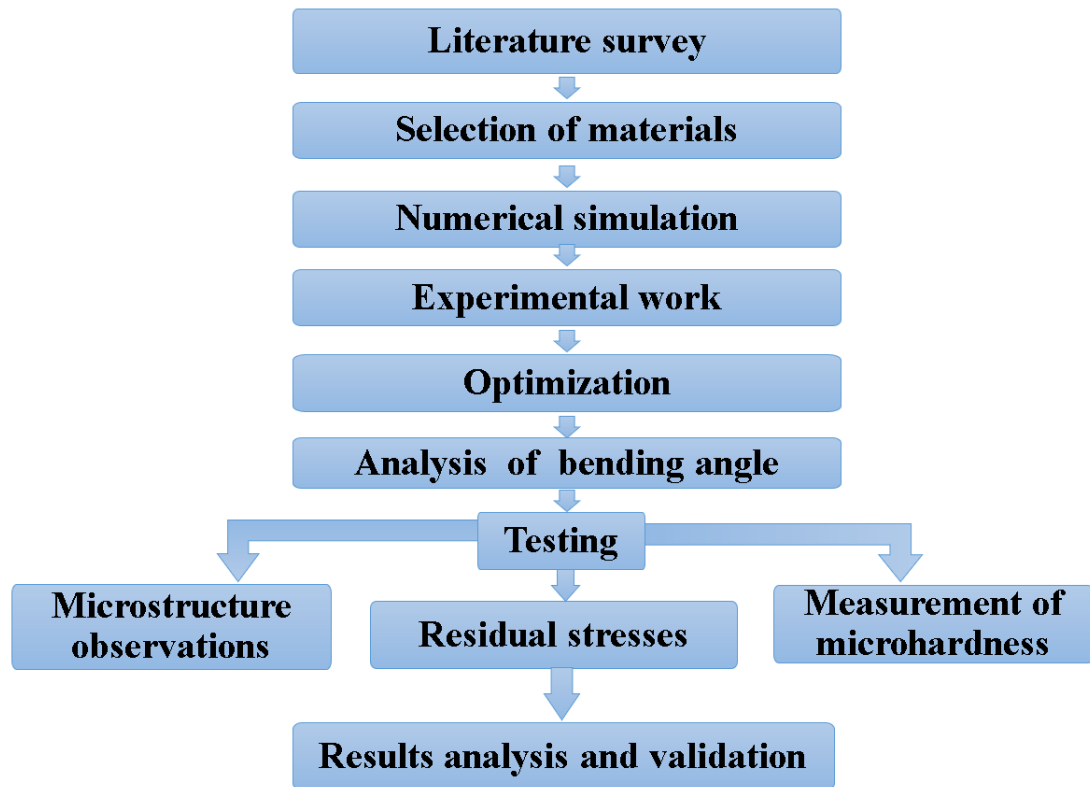


Fig. 2.6 Flow chart of research work

2.10 Summary

Within the context of the literature review chapter, a comprehensive examination of bending is presented, with a particular emphasis on techniques such as laser bending and mechanical bending. The microstructural, residual stresses and mechanical properties of materials are the primary focus of this review. In this chapter, the difficulties associated with laser bending are discussed. These difficulties include residual stresses, porosity, and delamination. Additionally, it investigates several methods that may be utilised to address these issues and reduce the number of defects. Additionally, the review highlights the scarcity of research on laser bending, despite its potential to create accurate microstructures and enhance mechanical properties.

CHAPTER 3

MATERIALS, MACHINES AND METHODOLOGY

This section presents the work material selection, machine selection, experimental setup for laser bending, and experimental methodology, along with the design of experiments.

3.1 Material

The objectives of this work are to investigate the bendability of a 2-ply clad sheet and the changes in microstructure and mechanical characteristics that occur after laser processing. The required sheet samples are sheared to a size of 120 mm x 22 mm x 2 mm using a mechanical shear machine as shown in Fig. 3.1.



Fig. 3.1 Samples of material

The chemical composition is determined by creating a spark on the different layers of the clad sample using a spectrometer. An optical emission spectrometer (Make: SPECTROMAXX) was used to determine the elemental composition of a sample by exciting its atoms with a spark and analysing the resulting light in accordance with ASTM E1251 for aluminium and E1086 for stainless steel layers, respectively. This spark excites the atoms in the sample, causing electrons to move to higher energy

levels. The produced light is then directed into a spectrometer, which divides it into component wavelengths using a diffraction grating or prism to detect the elements in the sample. Table 3.1 presents the chemical compositions of several layers of the clad composite sheet.

Table 3.1 Elemental composition of layers in wt. %

S. No.	Sheet materials	C	Mn	Si	Ni	Cr	S	P	Al	Fe
1	SS430 (Top layer-2)	0.13	0.90	0.66	0.62	17.02	0.023	0.026	0.03	80.591
2	AA1050 (Bottom layer)	0.17	0.19	0.02	0.15	0.03	0.01	0.015	99.381	0.034

3.2 Tensile properties

The mechanical characterization of the laser-cut specimens from the clad sheet and its component layers is conducted by a uniaxial tensile test, in accordance with the ASTM E8M standard, as seen in Fig. 3.2.

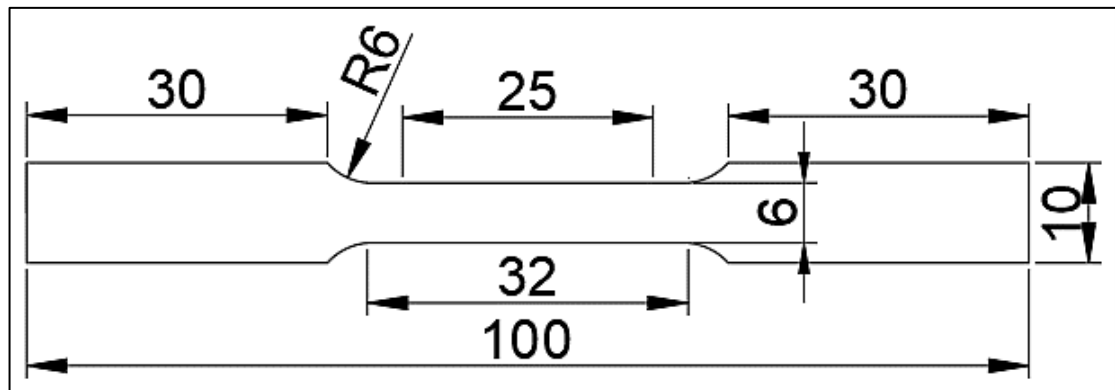


Fig. 3.2 Tensile test specimen as per ASTM E8M standard

(All dimensions are in mm)

The test is conducted at a constant crosshead speed of 2.5 mm/min using a 50 kN capacity universal testing machine. The mechanical properties are evaluated at ambient temperature.

3.2.1 Tensile testing machine

Materials for engineering purposes are selected based on their mechanical qualities, including tensile strength and percentage elongation. The tensile properties are determined using the Universal Testing Machine (UTM) of 50 kN load cell capacity.

The specimens are fabricated according to the ASTM E8 standard, as shown in Fig.

3.2.



Fig. 3.3 Tensile machine (Model: Tinius Olsen H50KS)

Tensile tests on the treated samples are performed at ambient temperature with a constant crosshead speed of 1 mm/min. The material undergoes tensile testing using a Universal Testing Machine (UTM) called Tinius Olsen H50KS, as depicted in Fig. 3.3. The standard tensile characteristics of a 2-ply clad sheet and individual sheets, derived from uniaxial tension tests conducted on specimens oriented at 0° relative to the rolling direction, are presented in Tables 3.2, 3.3, and 3.4.

Table 3.2. Tensile properties of the SS430 layer.

Temperature (°C)	Yield strength (MPa)	Tensile strength (MPa)	% elongation	Strain hardening exponent, n
Room Temperature	327 ± 4.54	464 ± 5.44	32.62 ± 1.18	0.24

Table 3.3. Tensile properties of a clad sheet.

Temperature (°C)	Yield strength (MPa)	Tensile strength (MPa)	% elongation	Strain hardening exponent, n
Room Temperature	133 ± 3.26	186 ± 3.26	30.22 ± 1.28	0.20

Table 3.4 Tensile properties of AA1050 layer.

Temperature (°C)	Yield strength (MPa)	Tensile strength (MPa)	% elongation	Strain hardening exponent, n
Room Temperature	47 ± 1.69	63 ± 2.05	13.05 ± 0.35	0.13

The 0.2% offset yield strength and ultimate tensile strength of the specimens aligned with the rolling direction, as derived from the engineering stress-strain curves, are noted to be the greatest, succeeded by the strength of the specimens oriented

transversely and parallel to the rolling direction. The strengths are ascribed to the amalgamated properties of AA1050 and SS430. All examined samples had a distinctly observable localized wrinkling and warping phenomena at the fracture zone. The average ductility of the 2-ply sheet is notably high, signifying excellent formability. The specimen aligned at 0° to the rolling direction exhibits the highest % elongation. The strain hardening exponent values are derived from the real stress-true strain curves of the tensile data. All tensile specimens of 2-ply exhibited fracture initiation from the aluminum layer, attributable to the inferior ductility of the AA1050 layer compared to that of the SS430 layer.

The tensile characteristics of the AA1050 layer extracted from the clad sheet were determined using uniaxial tension testing on specimens oriented at 0° relative to the rolling directions. This layer of aluminum is notably softer in comparison to the yield and tensile strength of the 2-ply sheet metal. The disparity between the 0.2% offset yield strength and tensile strength is approximately 11 MPa. The strain hardening exponent is determined to be 0.11 or below, signifying less uniform elongation in the tensile specimens.

The constituent layers are removed from the clad sheet to perform tensile characterisation of the individual components. The steel SS430 is isolated from the clad sheet by immersing the two-ply specimens in a sodium hydroxide solution, which dissolves the aluminum. SS430 is removed through surface facing to access the AA1050 layer from the clad sheet. The tensile specimens of the SS430 steel layers (Fig. 3.1) are extracted from a 2-ply clad sheet by dissolving the aluminum, and the requisite set of tensile samples is submerged in a glass beaker containing a sodium hydroxide solution.

The dissolution of aluminium in sodium hydroxide requires around three to four weeks, however this duration can be expedited by elevating the concentration of sodium hydroxide and applying heat to the solution, as seen in Fig. 3.4.

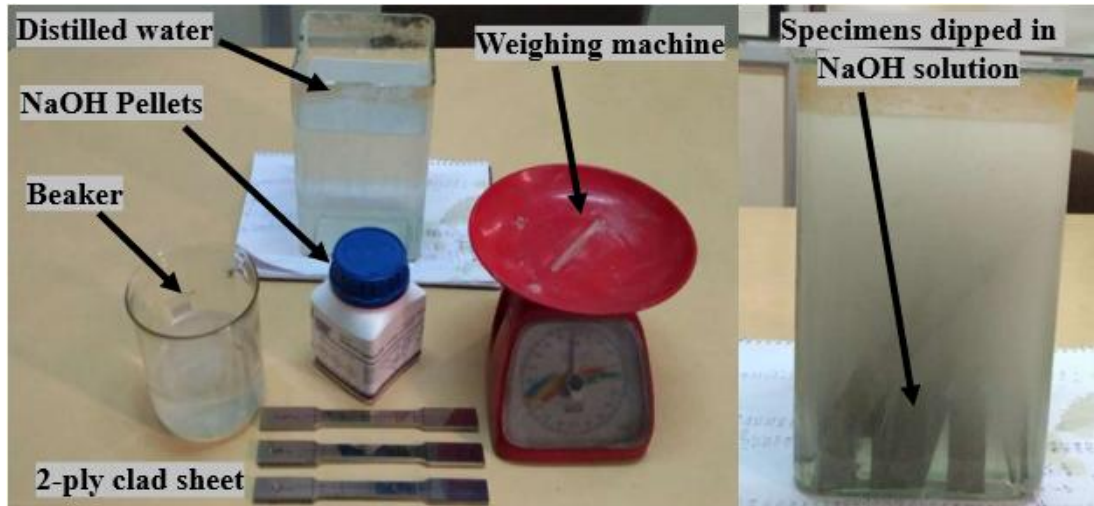


Fig. 3.4 Separation process of SS430 from a 2-ply sheet by immersing it in NaOH solution

3.3 Microhardness of 2-Ply Clad Sheet

The microhardness examination is performed utilizing a Struers Duramin-40, as seen in Fig. 3.5. In the microhardness test, a Vickers diamond indenter is pressed into the material's surface with a penetrator and a load of 500 grams. When a force is applied to a material, it produces an indentation that leads to permanent deformation on the material's surface in the form of the indenter.

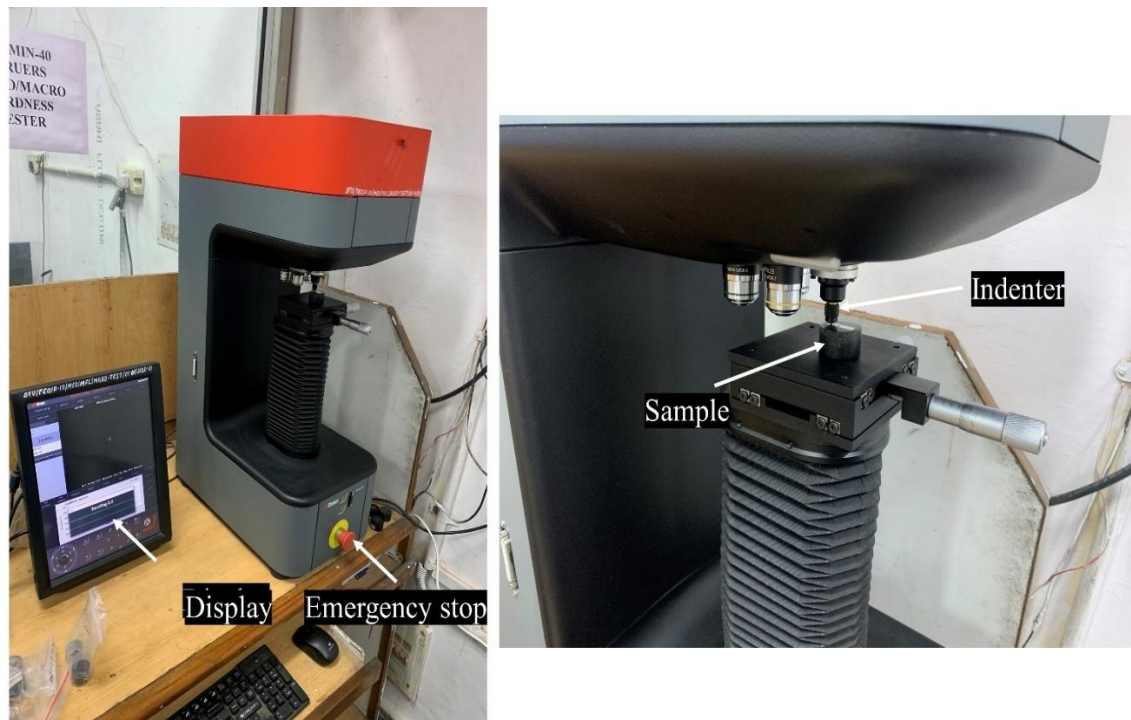


Fig. 3.5 Microhardness tester (Struers Duramin-40)

The examination is performed in a regulated setting by observing pressure for a predetermined duration, precisely 10 seconds of retention time. The diamond indenter employed for the test possesses a square configuration. The diagonal measurement resulting from the indentation on the material's surface is obtained, and the Vickers hardness value is calculated. The technical parameters of the Struers Duramin-40 are detailed in Table 3.5.

Table 3.5 Specification of microhardness tester (Struers duramin-40)

Model	Duramin-40 M1
Loads and applications	
Load range (main loads)	10 gf – 10 kgf
Vickers ability	Yes
Knoop ability	Yes
Brinell ability	Yes
Stages and turrets	

XY-stage	Manual
XY-stage or anvil size (mm)	90 x 90
XY-stage stroke, max (mm)	25 x 25
Vertical capacity	173
Throat depth (mm)	171
Motorized Z-axis	Yes
Motorized turret	Yes
Turret locations	6
Anti-collision protection	Yes
Machine weight	101 kg
Camera and optics	
Evaluation camera resolution	18 MP
Auto illumination	Yes
Stage illumination	Yes
Laser or LED guider	Yes
Interfaces and connectivity	
Operation	Embedded windows 10 PC featuring a 15-inch touchscreen.
Communication ports	HDMI, VGA, RJ45, WLAN, USB, RS232
Wifi	Yes
Bluetooth	Optional

To find out the Vickers micro hardness, the sample is mounted in bakelite by using a heating press machine as shown in Fig.3.6.



Fig. 3.6 Bekelite mounting

The mean microhardness of SS430 and AA1050 is 173.50 HV and 32.91 HV, respectively. The AA1050 layer is considerably more malleable than the SS430 layer.

The mean hardness of the 2-ply clad sheet is assessed at 84.03 HV (Table 3.6).

Table 3.6 Microhardness of Individual Layers of the Two-Ply Clad Sheet

S.No.	Material	Hardness (HV)	Mean Hardness (HV)
1	AA1050	36.54	32.63
2		34.41	
3		32.41	
4		31.50	
5		31.30	
6		31.23	
7		31.01	
8	SS430	176.70	173.59
9		172.95	
10		171.14	

3.4 Optical Microscope

The GX41 inverted metallographic microscope is optimal for the rapid and precise analysis of specimens to determine if their metallurgical properties conform to production standards. The device's tiny and lightweight construction facilitates effortless portability. This product is distinguished by its mobility and ergonomics, adjustable eyepoint for enhanced comfort, and superior picture clarity and resolution, facilitated by brightfield and polarized lighting. A compact and efficient physique facilitates effortless mobility and maximal comfort. A small apparatus may be effortlessly mounted in confined spaces and is also portable, rendering it appropriate for both laboratory and on-site inspection requirements in production environments.

The Olympus GX41, a tiny inverted metallurgical microscope, is shown in Fig. 3.7 and is used for optical microscopy.

The GX41 is equipped with a Tilting Binocular Observation Tube, enabling ergonomic adjustment of the eyepoint for the user. This function allows users to utilize the GX41 comfortably in both standing and seated positions, hence cultivating an atmosphere conducive to effective job execution. The exceptional picture quality and outstanding resolution in both brightfield and polarized light provide clear and vivid observation, regardless of the magnification setting used. Optimal clarity and exceptional image quality, covering the complete field of vision (F.N.22), can be attained through the utilization of infinity-corrected UIS2 lenses. This is a possibility. The objective magnifications in bright-field and clear polarizing observations may range from five to over one hundred times. The technical characteristics for this microscope are outlined in Table 3.8.



Fig. 3.7 Olympus GX41 compact inverted metallurgical microscope

Table 3.7 Specifications of Optical Microscope

Optical system		2 optical system (infinity-corrected)	
Microscope frame	Observation method		BF/KPO
Reflected/transmitted		Reflected	
Illuminator		-	
Illumination system	Reflected light		30W halogen or fibre light guide (light source:100 w)
Transmitted light		-	
Focus	Motorized/manual		Manual revolving nosepiece up/down movement (stage, stationary type)
Stroke		9 mm	
Resolution/fine adjustment sensitivity		Fine stroke per rotation 0.2 mm	
Revolving nosepiece	Motorized type		-
Manual type		Quadruple for bf	
Stage	Stroke		120(x)x78(y) mm
Observation tube	Standard field (field number 18)	Inverted image	Tilting binocular observation tube
Standard field (field number 20)	Inverted image		Binocular/trinocular/tilting binocular observation tube
Wide field (field number 22)	Inverted image		Binocular/trinocular/tilting binocular observation tube
Erect image		-	

Dimensions	236(w) x 624(d) x 407(h) mm
Weight	10 kg (in standard combination)

3.5 Electron backscatter diffraction (EBSD)

EBSD measurements are conducted to analyse the microstructural evolution of the clad sheet interface after laser forming. The three orthogonal axes of the tensile specimen, rolling direction (RD), normal direction (ND), and transverse direction (TD), are considered during the measurement. For EBSD analysis, the cross-section of the clad interface is examined at the specimen mid-length, with the TD as the viewing direction. For EBSD studies, a TSL-EDAX OIM system mounted on an FEI Quanta-3D field emission gun (FEG) scanning electron microscope (SEM) is used as shown in Fig. 3.8. The results of EBSD are described in the terms of inverse pole figure, grain boundary map, misorientation angle distribution, pole figures, kernel average misorientation, geometrically necessary dislocations, and twin boundary map.



Fig. 3.8 Field emission gun (FEG) scanning electron microscope (SEM) for EBSD

3.6 X-Ray Diffraction

Developed a more accurate temperature model by comprehensive analysis of the scanning procedure. The analysis of maximum temperature distribution and boundary conditions elucidates the sources of edge effects. An enhanced analytical model of the bending angle relative to the y-axis has been introduced. Simulations and tests have been performed to corroborate this hypothesis. A novel technique has been devised to alleviate edge effects in laser shaping. The study findings validated the efficacy of the novel technique.

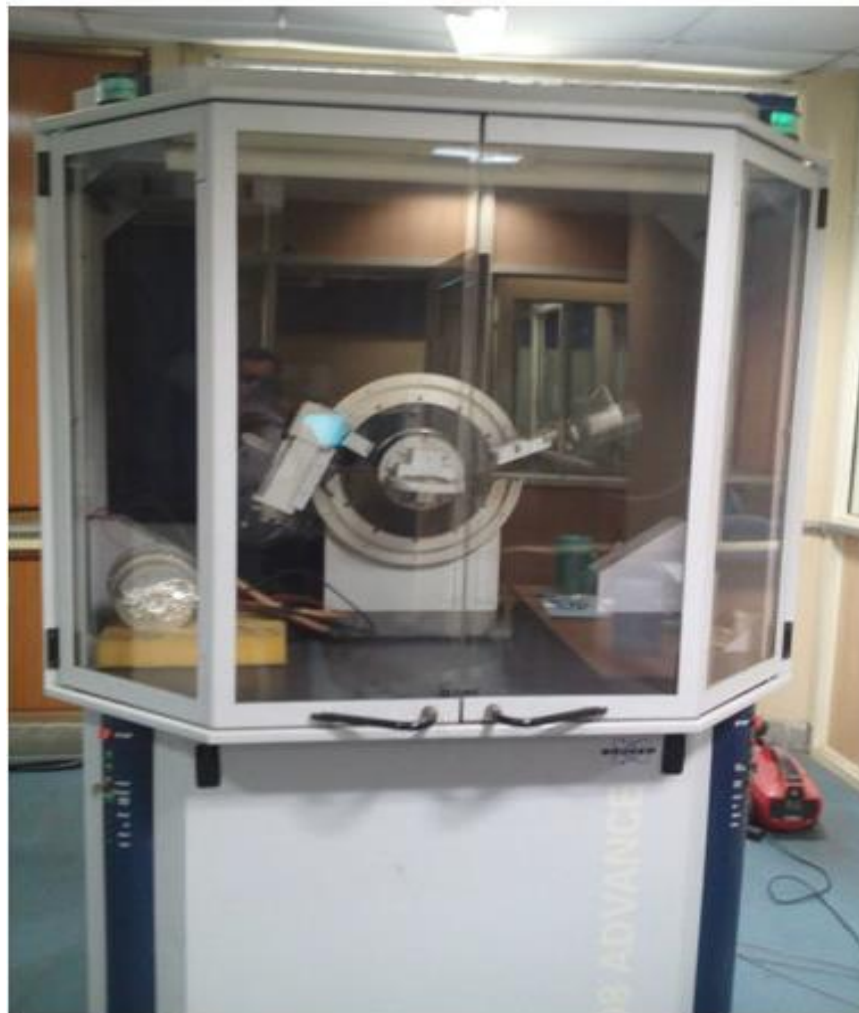


Fig. 3.9 X-Ray Diffraction (Model: BRUKER D8 ADVANCED)

The observed diffraction peaks in the XRD align with the atomic planes. The produced diffraction peaks are closely linked to the atomic planes, allowing for the analysis of atomic and microstructural properties. The position of the diffraction peaks is determined using Bragg's equation ($n \lambda = 2 d_{hkl} \sin \theta$). The term "dhkl " refers to the interplanar distance between parallel atomic planes within a crystal structure. θ represents the angle between the incident beam and the lattice normal at the reflection point. The symbol λ represents the wavelength, whereas n indicates the order of reflection, an integer value. Bragg's law facilitates the determination of the angle at which diffraction peaks occur due to the constructive interference of X-rays dispersed by the atomic planes of a crystal lattice. The intensity and position of the diffraction peaks are contingent upon the crystal structure, particularly the spatial configuration of atoms within a periodic lattice of the crystal. The Bruker D8 Advanced instrument is utilized for XRD spectrum analysis, with its technical specifications outlined in Table 3.8.

Table 3.8 Specification of XRD machine

X-ray	
Source	2.2 kW Cu anode long fine focus ceramic X-ray tube
Running Condition	40 kV and 40 mA
X-ray Beam Shaping Optics	
Beam [Cu-Ka1]	Collimated, compressed and frequency filtered by a Göbel mirror and V-Groove
Collimated beam dimensions	0.3 mm by 11 mm

Göbel mirror	60 mm multilayer X-ray mirror on a high-precision parabolic surface
Goniometer	
Maximum and minimum measurement circle diameter	250 mm & 100 mm
Smallest angular step size	0.0001°
Reproducibility	+/- 0.0001°
Maximum rotational speed	1500 °/min
Angular range (Theta)	-5° to 40°
Angular range (2Theta)	-10° to 60°
Reflectometry Sample Stage	
Samples size	200 mm in diameter and 50 mm thick
Detector	
Maximum count rate	2 x 10 ⁶ s ⁻¹ (although it should not be exposed to in excess of 5 x 10 ⁵ s ⁻¹ for periods longer than about 1 second)
Detector electronics count rate	3 x 10 ⁷ s ⁻¹

Residual stress

The residual stress induced on the surfaces of SS430 and SS304 were measured after the samples were laser formed. The experimental setup (model: μ -X360, make: PULSTEC) was utilized to determine residual stresses. It consists of a sensor unit, a power supply unit, and an adjustable table to hold the specimen, as seen in Figure 3(a). The $\text{Cos}\alpha$ method, based on X-ray diffraction, is used for assessing near-surface

residual stress before and after laser bending. This technique leverages Bragg's and Hooke's laws to measure residual strain through the inter-planar space, acting as an internal strain gauge. According to Bragg's law, when an X-ray beam is incident on a polycrystalline material, it is diffracted at an angle that is directly related to the wavelength of the X-rays and inversely proportional to the lattice spacing ($d_{\psi\phi}$) of the material. This method allows for the measurement of residual strains in a single exposure of X-rays, significantly reducing measurement time. This method uses a fundamental equation to calculate residual stresses with various diffraction vectors (n) with respect to the sample coordinate system shown in Fig 2.

The strain $\varepsilon_{\psi\phi}$, at azimuthal angle α from $-\eta$ as illustrated in Fig. 2 (b), is expressed as follows:

$$\varepsilon_{\psi\phi} = \varepsilon_{\alpha} = \frac{d_{\psi\phi} - d_0}{d_0} = n_1^2 \varepsilon_x + n_2^2 \varepsilon_y + n_3^2 \varepsilon_z + n_1 n_2 \gamma_{xy} + n_2 n_3 \gamma_{yz} + n_1 n_3 \gamma_{xz} \quad (1)$$

Incorporating the diffraction vector and Hooke's law, the above expression results as:

$$\varepsilon_{\alpha} = \frac{1+\nu}{E} n_i n_j \varepsilon_{ij} - \frac{\nu}{E} \sigma_{kk} \quad (i, j, k = 1 \text{ to } 3) \quad (2)$$

where, ν is poisson's ratio, E is Young's modulus, σ_{kk} is a stress component.

The Cos α method utilizes a specific method to determine the residual stresses by using the four strains (ε_{α} , $\varepsilon_{\alpha+\pi}$, $\varepsilon_{-\alpha}$ and $\varepsilon_{-\alpha+\pi}$) from the radius of the Debye-Scherrer ring (D-S ring) at an azimuthal angle (α) as shown in Fig 2 (b). These four strains are incorporated to calculate the strain parameter ε_{α_1} at azimuthal angle α , which is expressed as shown below:

$$\varepsilon_{\alpha_1} = \frac{1}{2} [(\varepsilon_{\alpha} - \varepsilon_{\alpha+\pi}) + (\varepsilon_{-\alpha} - \varepsilon_{-\alpha+\pi})] \quad (3)$$

Incorporating the Hooke's law (Eq 2) in the Eq 3, the residual stress σ_x is found to be related to the strain parameter ε_{α_1} as follows:

$$\varepsilon_{\alpha_1} = -\frac{1+\nu}{E} (\sin 2\eta \sin 2\psi_0 \cos \alpha) \sigma_x \quad (4)$$

The partial differentiation of strain parameter ε_{α_1} with $\cos \alpha$ gives the fundamental equation of residual stress which is expressed as below:

$$\sigma_x = -\left(\frac{E}{1+\nu}\right) \frac{1}{\sin 2\eta \sin 2\psi_0} \left(\frac{\partial \varepsilon_{\alpha_1}}{\partial \cos \alpha}\right) \quad (5)$$

The above equation could be rewritten as a product of the Elastic constant (K_α) and slope (M_α) of the (ε_{α_1} - $\cos \alpha$) plot, which is as shown below:

$$\sigma_x = K_\alpha \cdot M_\alpha \quad (6)$$

$$\text{where, } K_\alpha = -\left(\frac{E}{1+\nu}\right) \frac{1}{\sin 2\eta \sin 2\psi_0}, \text{ and } M_\alpha = \frac{\partial \varepsilon_{\alpha_1}}{\partial \cos \alpha}$$

The strain parameter ε_{α_1} is estimated as a linear function of $\cos \alpha$, and using the least-squares method the slope M_α is estimated.

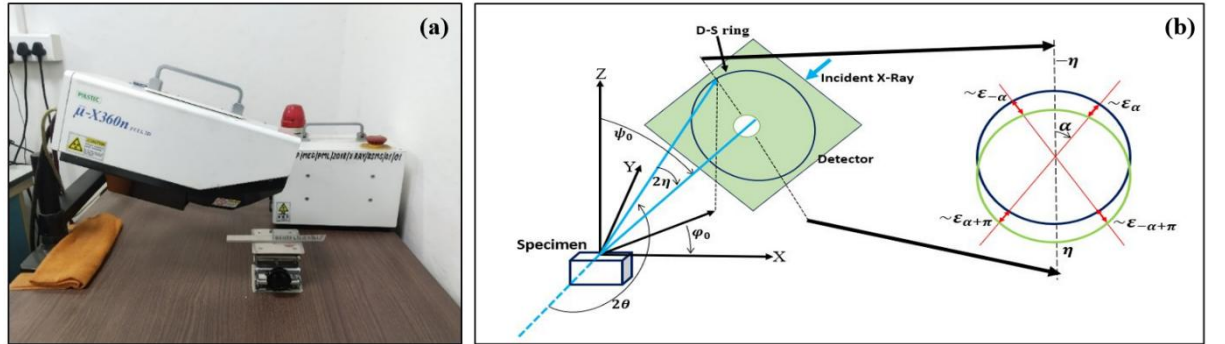


Fig. 3.10 (a) Measurement of residual stress in progress and **(b)** radius of the Debye-Scherrer ring (D-S ring) at an azimuthal angle (α)

3.7 Modelling and simulations of the bending process

In the present study, the simulations of sheet bendings are performed using ABAQUS (version 6.14-2) software. ABAQUS- An Explicit solution procedure is applied for the

bending of the loading part of the simulation, as it is faster for the complicated contact problems. The laser bending simulation is a non-contact and zero mechanical load applied problem, i.e., the die and punch constraints are removed, thus reducing the non-linearity of the problem. ABAQUS- Implicit (standard) is seen to solve the bending problem more efficiently than Explicit. So, the bending simulation has been done using the Explicit procedure and thereafter the completed model was exported to ABAQUS- Implicit (Standard).

In the present study, bending process is addressed as a non-linear problem. The material nonlinearity, boundary nonlinearity and geometric nonlinearity are the three types of nonlinearities considered in the simulation. Boundary nonlinearity is observed due to the change in boundary conditions that occurs during the bending process.

3.8 Analysis of laser forming (Simulation with ABAQUS)

Abaqus workflow for laser bending your 2-ply clad sample (SS430 0.6 mm + AA1050 1.4 mm; total 2.0 mm thick; sample $150 \times 22 \times 2$ mm). The material properties (with sources), model geometry/assembly, element/mesh guidance, how to apply a moving Gaussian laser heat source in Abaqus (DFLUX approach), analysis steps (coupled thermo-mechanical), boundary conditions, output to monitor, and tips for accuracy & convergence. Assume the laser parameters you used elsewhere in this project: continuous laser, beam diameter 0.8 mm (so beam radius $w = 0.4$ mm), power $P = 1000$ W, scan speed $v = 40$ mm/s, and 20 scans.

Simulation plan for laser forming (laser bending) of your 2.00 mm clad strip of SS430 (0.6 mm) + AA1050 (1.4 mm), sample size $150 \times 22 \times 2$ mm³. The modelling strategy, thermal heat-source model (Gaussian moving source), ABAQUS implementation tips

(elements, steps, and subroutines to use), meshing, boundary conditions, time stepping, and outputs to extract the bend angle.

The power of the laser source used in the laser bending procedure follows a Gaussian distribution, derivable from a Gaussian function, as outlined in Eq. (7).

$$Q = \frac{2\alpha P}{\pi R^2} e^{\frac{-2r^2}{R^2}} \quad (7)$$

Let Q represent the intensity of the incident heat flux, and r denote the distance from the center of the laser source. α , P , and R represent the material's absorption coefficient, laser power, and laser spot radius, respectively [45]. Using $P = 900$ W, $R = 0.0004$ m, and an example $\alpha = 0.35$ (SS), the peak surface flux $Q = 1.39 \times 10^9$ W/m². Apply this moving flux along the scan path (y-coordinate increasing with time). For a scan speed $v = 30$ mm/s and stroke length $L = 22$ mm, the scan time $t = \frac{L}{v} = 22 \times \frac{30}{30} = 22$ s for 30 numbers of laser scan passes. Laser bending process simulation using ABAQUS based on the mechanical and thermal distributions by developing a finite element model with these properties, as shown in Tables 3.9 and 3.10.

Table 3.9 Tensile properties of SS430 (0.6 mm) and AA1050 (1.4 mm) [4]

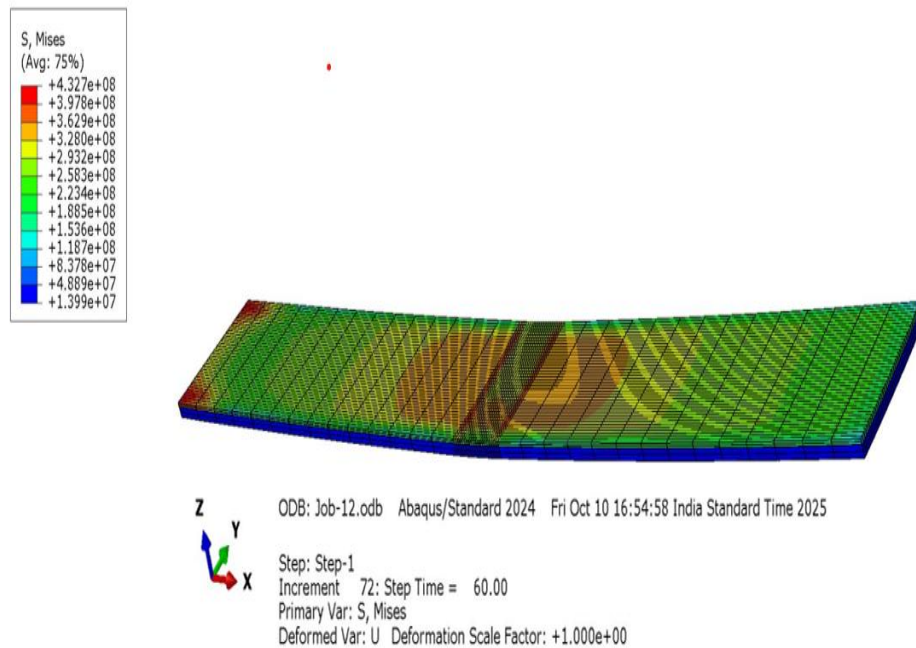
S. No.	Property	Unit	SS430 (base)	AA1050 (base)
1	Young's modulus (E)	MPa	2×10^5	0.7×10^5
2	Poisson's ratio (ν)	—	0.30	0.33
3	Yield strength (0.2% offset)	MPa	290	30
4	Ultimate tensile strength (UTS)	MPa	470	75

Table 3.10 Temperature-dependent properties [4]

S.No.	Temperature-dependent property	Unit	SS430	AA1050
1	Density (ρ)	kg/m ³	7750	2710
2	Thermal conductivity (k)	W/(m·K)	26	222
3	Specific heat (C)	J/(kg·K)	460	900
4	Coefficient of thermal expansion (α)	/K	10.4×10^{-6}	24×10^{-6}

Implement the DFLUX user subroutine (ABAQUS), which allows assigning a heat flux to an element integration point as a function of current coordinates and time (moving source). Alternatively, ABAQUS with predefined fields or time-dependent concentrated loads can be used; however, DFLUX is the standard for modelling moving Gaussian heat. Fig. 3.10 (a), and (b) shows the variation in stresses, and temperature moved up at the free end due to bending in ABAQUS.

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3.10 (a)

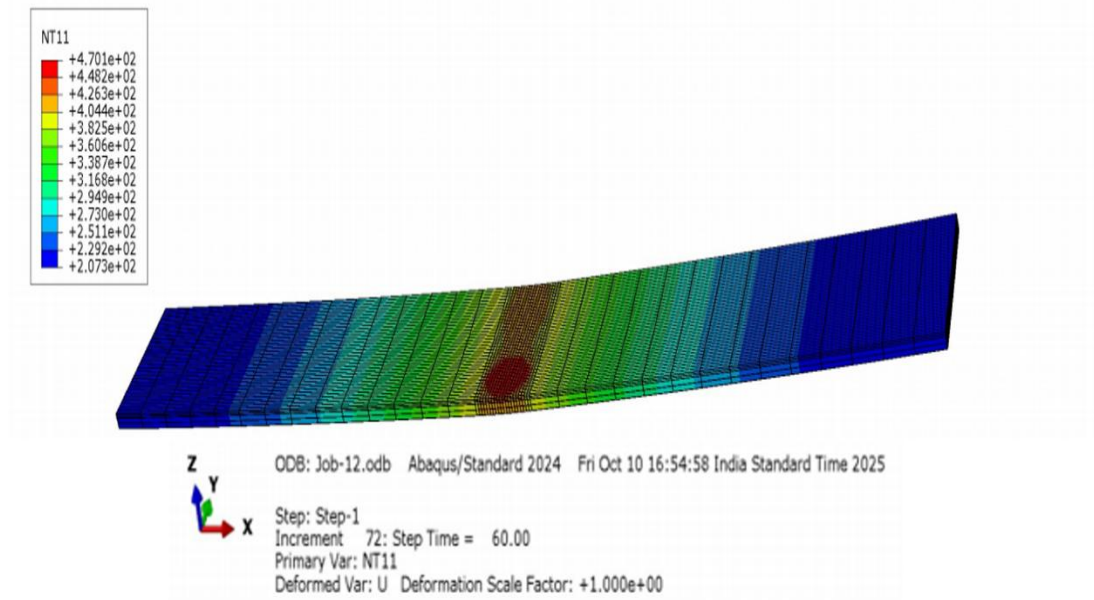


Fig. 3.11 (a)Variation in temperature due to bending **(b)**Variation in stresses due to bending

The thermal conductivity of the AA1050 layer is $222 \text{ W/m}\cdot\text{K}$, whereas that of SS430 is approximately $26 \text{ W/m}\cdot\text{K}$. Laser bending necessitates constant irradiation to precisely bend sheets at the specified angle. Clad sheets require mechanical and microstructural characteristics post-laser irradiation. This arrangement allows the thermally conductive layer to absorb and dissipate more heat, establishing a gradual temperature gradient over its thickness, which is crucial for the temperature gradient mechanism employed in laser forming. The thicker AA1050 prevents interface melting and separation, increasing heat stability and clad integrity.

3.9 Experimental setup for laser bending

The experiments utilized a diode laser machine that generates a continuous wave laser (Laserline model: LDF 4000-30), equipped with an ABB robotic arm (IRB 4600-60),

as illustrated in Fig. 3.12. The laser head was affixed to a robotic arm with six degrees of freedom and a work envelope of 10 m². The standoff distance of 100 mm and beam diameter of 0.8 mm remained constant during the experiments. The experimental setup for the laser bending operation is illustrated in Figure 3.11.

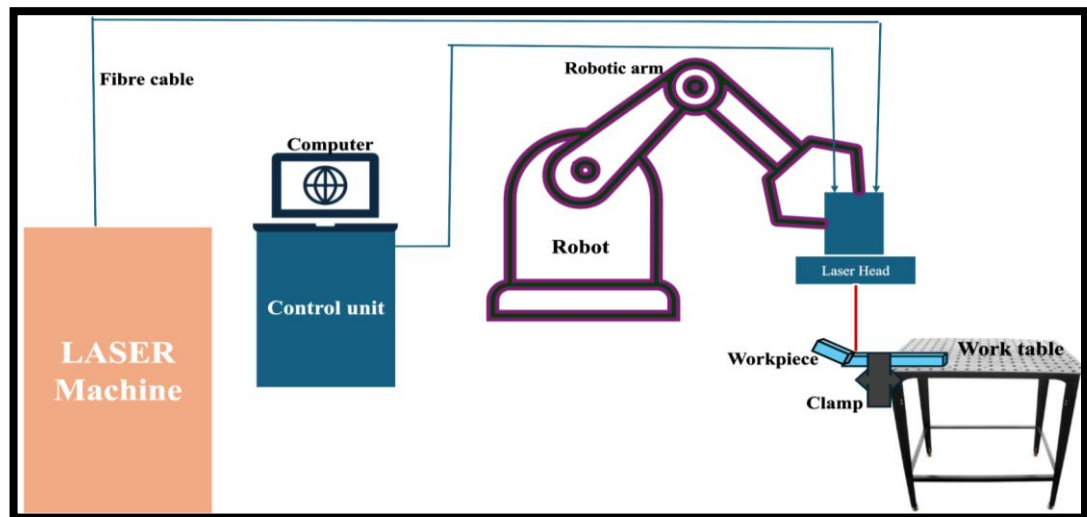


Fig. 3.12 Schematic diagram of Experimental setup for laser bending

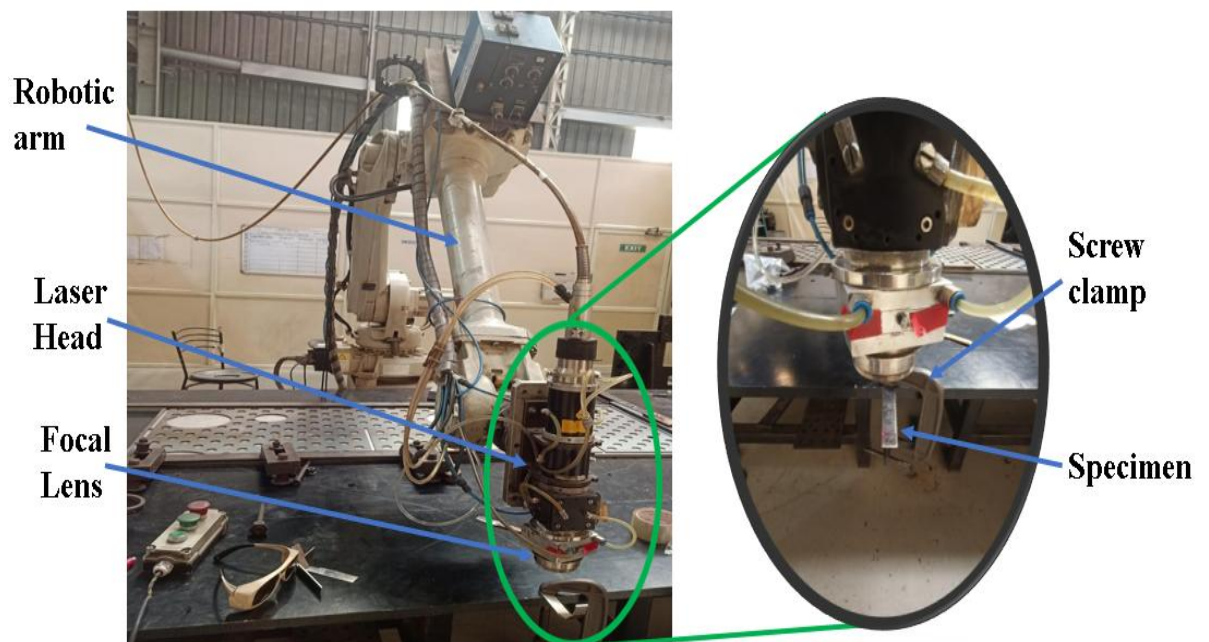


Fig. 3.13 Experimental setup for laser bending operation

When the clad specimen was put on a worktable, the laser beam was irradiated on the upper surface of the SS430 layer. This was done in such a way that one end of the specimen was free while the other end was clamped. Several alternative combinations of characteristics were used in the pilot tests conducted to determine the optimal bend angle. Figure 3.12 depicts the experimental setup that was used for the laser bending operation.

3.10 Selection of a laser beam source and characteristics

The selection of a laser beam source and its properties is an important stage in laser-based manufacturing processes because it affects energy absorption, heat distribution, and process efficiency. The diode, operating mode, beam quality, wavelength, and power output must all be carefully selected based on the material qualities and application. For forming procedures such as laser bending, a continuous wave laser with consistent power and good beam quality is typically preferred to ensure uniform heating and regulated temperature gradients without material removal. Furthermore, characteristics such as spot size, intensity distribution, and beam stability play an important role in achieving reproducible deformation and reducing flaws. As a result, an optimum mix of laser source and beam properties is required for accurate control, dependability, and performance. In the present work a diode laser Laserline LDF 4000-30 was selected.



Fig. 3.14 A laser diode

3.10.1 Diode laser

A diode laser, like the high-power laser system depicted in Fig.3.13, is a solid-state laser source that produces laser radiation directly from semiconductor diode arrays. These lasers are frequently utilized in industrial material processing because of their high electrical-to-optical efficiency, small size, and outstanding operating stability. Diode laser systems combine and connect numerous laser diodes via optical fibers to produce a high-power, continuous wave beam with generally uniform energy distribution. Diode lasers, unlike classic CO₂ or Nd:YAG lasers, require less maintenance and have higher wall-plug efficiency, making them cost-effective for long-term applications.

Diode lasers are very useful in sheet metal applications such as laser bending because they provide stable and regulated heat input, which is required to provide uniform thermal gradients without producing excessive melting or surface damage. Their continuous wave operation allows for smooth and steady heating of the material, which promotes plastic deformation via thermal expansion and contraction mechanisms.

Furthermore, diode lasers often operate at wavelengths with high absorptivity for many metallic materials, which improves energy economy and process performance. The robust construction, integrated safety features, and precise power control of industrial diode laser systems, as shown in the image, make them ideal for forming, surface treatment, cladding, and welding applications requiring reliability, repeatability, and thermal control.

3.10.2 Continuous wave with Gaussian profile

The selection of an appropriate laser beam type is an important aspect in determining temperature distribution, bending precision, and process stability when laser bending sheet metal. Continuous wave (CW) lasers are extensively used in laser bending applications because they provide a continuous beam with a constant power output, resulting in a consistent and controlled heat input to the sheet [57]. This continual thermal loading creates uniform through-thickness temperature gradients, which are required for predictable bending mechanisms like the temperature gradient mechanism (TGM). Unlike pulsed lasers, which use cyclic heating and cooling to induce localized melting or surface imperfections, continuous wave lasers interact with the material largely by thermal diffusion, gradually heating the sheet until plastic deformation occurs without material removal. The 100% duty cycle and stable beam parameters of CW lasers enable precise control over bending angle and repeatability, while their superior beam quality enhances process consistency. Therefore, for laser bending of sheets where smooth deformation, dimensional accuracy, and microstructural integrity are required, continuous wave lasers are generally the most suitable choice.

A Gaussian beam profile, as shown in Fig. 3.15 is the most common and naturally occurring laser intensity distribution in laser-based manufacturing processes, with a

maximum power density at the beam center and a progressive drop toward the periphery based on a Gaussian function. This smooth, axisymmetric energy distribution causes intense localized heating at the point of laser incidence, resulting in steep and well-defined temperature gradients within the material [58].

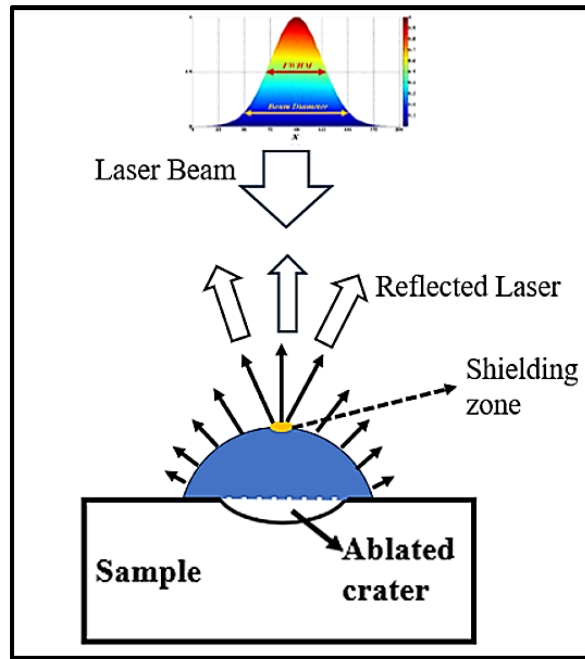


Fig. 3.15 Profile of a Gaussian beam

Laser bending of sheet metals is especially helpful because it promotes controlled plastic deformation through mechanisms such as the temperature gradient mechanism, in which the top surface experiences stronger thermal expansion than the lower surface, resulting in bending with material removal or melting. The nature of decline of intensity from center to edge allows smooth heat diffusion, lowering the risk of thermal shock, excessive residual strains, and surface cracking [59].

Furthermore, the Gaussian beam profile provides superior beam stability and focusability, allowing for precise control of the heat-affected zone and bending angle. Because the peak intensity is focused in the center, careful consideration of laser

power, scanning speed, and spot size is required to avoid localized melting or ablation, particularly for thin sheets or low-melting-point materials. Despite this constraint, Gaussian beams' predictable thermal behavior and repeatable interaction features make them ideal for applications that demand high dimensional accuracy and surface integrity. As a result, Gaussian beam profiles are widely used in laser bending, welding, and surface modification procedures that need precisely controlled energy input and homogenous deformation.

Most laser applications require the laser beam to be focused, modified, or shaped using lenses and other optical elements. In general, we can approximate laser-beam propagation by assuming that the laser beam has an ideal Gaussian intensity profile, which corresponds to the theoretical TEM₀₀ mode. Understanding the fundamental features of Gaussian beams is crucial for choosing the right optics for a laser application. These laser modes define the spatial and temporal distribution of electromagnetic energy within a laser beam, and they play an important role in determining how the laser interacts with materials during its processing. The fundamental transverse electromagnetic mode (TEM₀₀) is ideal for manufacturing applications due to its high beam quality, focus-ability, and near-Gaussian intensity distribution. This mode allows for accurate energy delivery, resulting in homogenous heating, well-defined temperature gradients, and better control over activities like laser bending, welding, and cutting. Higher-order transverse modes (TEM₀₁, TEM₁₀, etc.) show non-uniform intensity patterns with many peaks, leading to uneven heating and lower process stability as shown in Fig.. Temporal modes determine whether the laser works in continuous or pulsed mode, which influences the heat cycle imposed [60].

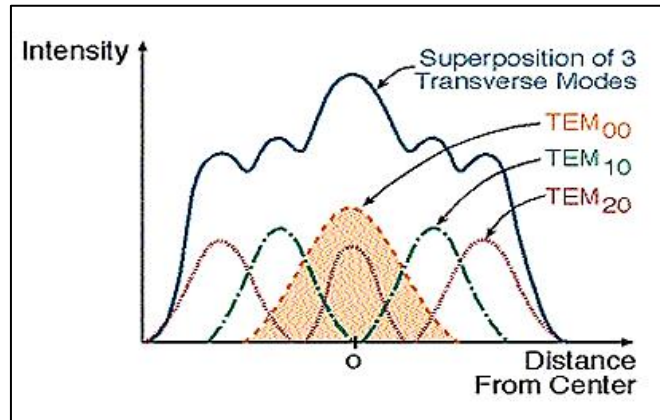


Fig. 3.16 Number of mode patterns

Transverse modes are spatial patterns that characterize the distribution of light contained within an optical resonator. The resonator's eigenmodes are transverse modes. The integral equation relating the fields at the cavity's two opposing mirrors can be obtained using the Fresnel-Kirchoff version of Huygen's principle. Resonator modes are collections of transverse patterns with the characteristic that the precise pattern returns to the same spot after one round trip through the resonator. The transverse modes of the resonator are represented by these self-replicating sets of intensity patterns. Generally, these modes are close to plane waves multiplied by the eigenmode's transverse amplitude and phase characteristics. The mathematical solution to the resonator's equation determines these modes, which are called (TEM) nm for transverse electric and magnetic. Every transverse plane inside the resonator will typically have a distinct field pattern for transverse mode patterns. The number of intensity nodes of the resonator mode pattern along the x and y axes is indicated by the n and m subscripts in the (TEM) nm mode designator, respectively [60]. In other words, the x and y axes in rectangular coordinates are orthogonal to the

z, or resonator propagation, axis as well as to each other. Fig. 3.15 shows a number of mode patterns.

A Gaussian laser beam is a type of laser that has a Gaussian intensity profile. The intensity distribution is bell-shaped, with maximum intensity at the center and decreasing towards the edges (see Fig. 3.16).

A laser beam can be described by a general equation as given below [61]:

$$E(x,y,z,t) = u(x,y,z) e^{j(kz - \omega t)} \quad (8)$$

Where $u(x,y,z)$ is a Gaussian transverse profile that varies slowly along the propagation direction (the z axis), and remain Gaussian as it propagates:

$$u(x,y,z) = \frac{1}{q(z)} e^{\frac{-jk(x^2+y^2)}{2} \frac{1}{q(z)}} \quad (9)$$

The parameter q is called complex beam parameter. It is defined in term of two quantities w, beam waist and R, radius of curvature of spherical wavefronts.

$$\frac{1}{q(z)} = \frac{1}{R(z)} - j \frac{\lambda}{\pi w^2(z)} \quad (10)$$

The magnitude of electric field of laser electromagnetic wave is therefore given by

$$|E(x,y,z,t)| = |u(x,y,z)| = \left| \frac{1}{q(z)} \right| e^{\frac{-(x^2+y^2)}{w^2}} \quad (11)$$

With the corresponding intensity profile which is square of amplitude of electric field and depicted in Fig. 3.16

Intensity = Amplitude²

$$I(x,y,z) = \left| \frac{1}{q(z)} \right|^2 e^{\frac{-2(x^2+y^2)}{w^2}} \quad (12)$$

The spot is Gaussian and its size is determined by the width of the beam 'w'.

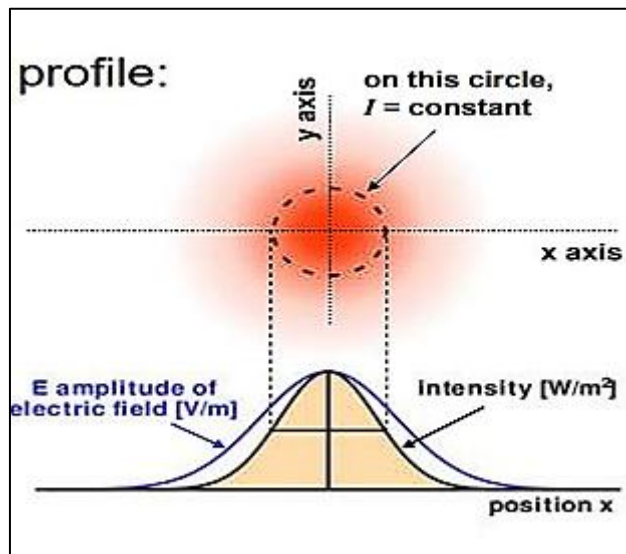


Fig. 3.16 Bell-shaped Gaussian intensity profile of Laser beam

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Mechanical properties

The mechanical properties of the SS430/AA1050 clad sheet and its constituent layers, as summarized in Table 4.1 and illustrated in Fig. 4.1, clearly demonstrate the influence of material composition and interlayer interaction on the overall deformation behaviour. The SS430 layer exhibits the highest strength among the three materials, with a yield strength of 327 MPa and an ultimate tensile strength of 464 MPa, accompanied by a relatively high elongation of 32.62 %. The higher strain hardening exponent ($n = 0.24$) of SS430 indicates a strong work-hardening capability, which is beneficial for resisting localized necking during plastic deformation.

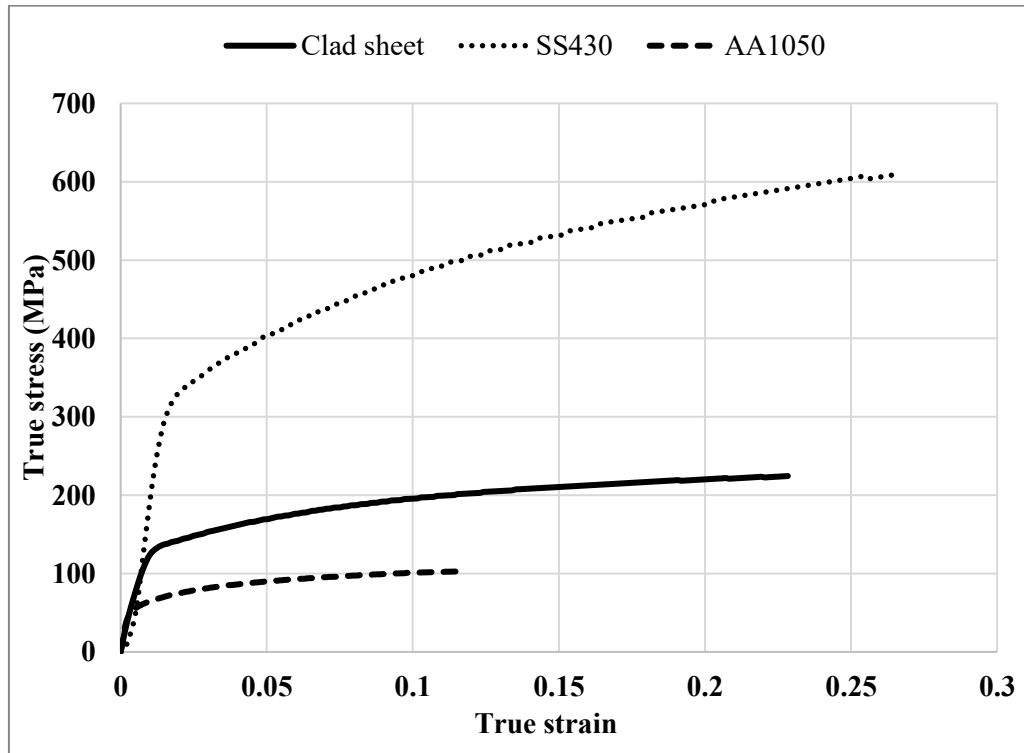


Fig. 4.1 True stress vs. true strain plots of clad sheet and constituent layers

In contrast, the AA1050 layer shows significantly lower yield and tensile strengths of 47 MPa and 63 MPa, respectively, along with a lower elongation of 13.05 %. The comparatively smaller strain hardening exponent ($n = 0.13$) reflects its limited work-hardening ability, which is characteristic of commercially pure aluminium and results in early onset of plastic instability under tensile loading.

The mechanical response of the clad sheet lies between those of its individual layers, with a yield strength of 133 MPa and an ultimate tensile strength of 186 MPa. The elongation of the clad sheet (30.22 %) is notably closer to that of SS430 than AA1050, indicating that the stainless steel layer predominantly governs the ductility of the composite structure. The strain hardening exponent of the clad sheet ($n = 0.20$) further confirms this intermediate behaviour, suggesting a balanced contribution from both the high-strength SS430 and the low-strength, high-compliance AA1050 layers. This synergistic mechanical response demonstrates that cladding effectively combines the strength and work-hardening capacity of SS430 with the deformability and load accommodation of AA1050, resulting in a composite material that exhibits enhanced ductility with moderate strength. Such a combination is particularly advantageous for forming processes, including laser forming, where controlled plastic deformation without premature failure is essential.

Table 4.1 Mechanical properties of clad sheet and constituent layers

Material	Yield strength (MPa)	Tensile strength (MPa)	% elongation	Strain hardening exponent, n
SS430	327 ± 4.54	464 ± 5.44	32.62 ± 1.18	0.24
Clad sheet	133 ± 3.26	186 ± 3.26	30.22 ± 1.28	0.20
AA1050	47 ± 1.69	63 ± 2.05	13.05 ± 0.35	0.13

4.2 Combinations of process parameters

The range for the laser power (Factor-A) is chosen as 700 to 1100 W, the number of scan counts (Factor-B) as 50 to 70, and the scan speed (Factor-C) between 20 and 40 mm/s. These ranges ensured plastic deformation without delamination or melting at the interface. It was through the application of Response Surface Methodology that the final settings were statistically refined. For the purpose of developing the experimental design, a central composite design matrix was utilized. This design was derived from the three process parameters and the optimal combinations of those factors, which resulted in twenty experimental runs. Initially, a series of pilot experiments was conducted to determine the minimum and maximum limits of the parameters in a random manner. On behalf of the pilot experiments, the detailed combinations of process parameters are given in Table 4.2.

Table 4.2 Controlled Factors ranges

Factor	Name	Units	Minimum	Maximum
A	Laser power	W	700	1100
B	No of scan		50	70
C	Scan speed	mm/min	20	40

4.3 Design of experiments

Twenty separate experiments were carried out, and the bend angle was produced as a consequence of each specific combination of control parameters was evaluated. The results of these studies are provided in Table 4.3.

Table 4.3. Bend angle as an output for various runs

Run	A: Laser power (W)	B: Scan counts	C: Scan speed (mm/s)	Bend angle (degree)
------------	-------------------------------	-----------------------	---------------------------------	--------------------------------

1	900	60	30	39.84
2	900	60	30	39.84
3	700	50	40	30.80
4	1100	70	20	33.02
5	1100	60	30	36.74
6	900	60	30	39.84
7	900	60	30	39.85
8	900	60	40	38.59
9	700	70	20	34.70
10	1100	50	40	34.12
11	700	70	40	33.10
12	900	60	20	38.18
13	900	60	30	39.84
14	700	60	30	35.92
15	900	50	30	36.97
16	1100	50	20	31.72
17	900	70	30	38.77
18	1100	70	40	34.42
19	900	60	30	39.84
20	1100	70	40	34.41

The laser beam radiated on SS430 side. All 20 samples bend at various runs as shown in Fig.4.2.



Fig. 4.2 Bend samples

4.4 Analysis of variance

To assess the suitability of the experiment and the adequacy of the developed model, three process parameters were examined using analysis of variance (ANOVA), with a 5% significance level. The efficacy or ineffectiveness of the elements examined in this study, as well as the degree to which each process component is effective, are also displayed in this table. It is evident that every parameter chosen for this model that has a p-value below 0.05 is one of the process's effective parameters. It was apparent that all the parameters selected in the preceding step were regarded as effective parameters in the ANOVA table, as parameter screening was used before the optimisation stage to identify and select the effective parameters for the optimisation stage. The F-value shows the effectiveness of each process parameter. In general, a parameter's effectiveness was reflected by a higher F-value. The parameters that have the most significant impact on the bending angle are the number of scans, laser power, and scan velocity, as indicated by the F-value in the table. Table 4 also displays the ANOVA of the optimised model. The model's F-value of 1.431E+06 indicates its significance. It is observed that laser power has a significant effect on the bend angles,

while the number of scans has the strongest effect among the three parameters, and scan speed has a relatively smaller but still significant effect on bending angles. The ANOVA results for the response surface quadratic model are shown in Table 4.4.

Table 4.4 ANOVA response for the developed model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	197.57	9	21.95	3.593E+05	< 0.0001	significant
A-Laser Power	1.61	1	1.61	26321.59	< 0.0001	
B-No of scan	8.10	1	8.10	1.326E+05	< 0.0001	
C-Scan speed	0.4000	1	0.4000	6547.62	< 0.0001	
AB	2.00	1	2.00	32738.10	< 0.0001	
AC	4.50	1	4.50	73660.71	< 0.0001	
BC	0.5000	1	0.5000	8184.52	< 0.0001	
A ²	33.24	1	33.24	5.442E+05	< 0.0001	
B ²	10.80	1	10.80	1.768E+05	< 0.0001	
C ²	5.96	1	5.96	97513.43	< 0.0001	
Residual	0.0006	10	0.0001			
Lack of Fit	0.0005	5	0.0001	3.58	0.0939	not significant
Pure Error	0.0001	5	0.0000			
Cor Total	197.57	19				

model used a second-order regression and desirability function to maximise bend angle while preserving interfacial integrity and avoiding thermal distortion. It is observed that the

scattering of the test points around the diagonal linear plot indicates that the experimental results are reliable. The regression model predicted the bend angle and evolved a regression equation containing three parameters for the prediction, which is expressed in Eq. (4). The equation is composed of parameters for which the corresponding p-values are less than 0.05. The coded equation can predict effects for given factor levels. Comparing factor coefficients in the coded equation helps determine the influence of each factor.

Bend angle (θ°)

$$= 39.84 + 0.4010A + 0.9000B + 0.2000C - 0.5000AB + 0.7500AC \\ - 0.2500BC - 3.48A^2 - 1.98B^2 - 1.47C^2 \quad \dots\dots \text{Eq. (4)}$$

In two-factor interaction analysis, the combined effect of laser power and scan count is significant, while the combination of scan speed and laser power alters the bend angle more significantly. The combination of scan passes and scan speed has a less significant impact among the three interactions. Among the curvature effects (nonlinear behaviour) of A^2 (Laser power squared), B^2 (number of scans squared), and C^2 (Scan speed squared), A^2 has shown a significant impact on the angle, followed by B^2 and C^2 , respectively. The p-values confirm that the model is appropriate and that no unexplained trend remains in the experimental results.

As the laser power escalates from 700 W to 900 W, the bend angle correspondingly rises from 36° to 39° . As power increases from 900 W to 1100 W, the bend angle diminishes. The reduction in bend angle may be associated with the softening impact on the steel and aluminum layers. In a location, an increase in laser power correlates with an increase in thermal energy, which subsequently elevates the temperature gradient throughout the

thickness, so augmenting the bend angle. The bend angle increases from 37° to 39.84° as the scan count rises to 63.

4.5 Effect of input parameters on response variables

However, after this point, it begins to decrease due to the material softening. The selected and optimized values of 917 W (laser power), 33 mm/s (scan speed), and 63 scans (Prediction point after analysis of results, these values used for confirmation test for the optimized result) were derived from a Central Composite Design (CCD)–based RSM analysis. These values lie within the experimentally validated safe operating range. The influence of various laser parameters on the bend angle is shown in Supplementary figure 4.3 (a)-(c).

According to the pass number increases in steps of 10, i.e., 50, 60, and 70. The increased number of scan counts results in more repetitive irradiation over the sample surface, which helps increase the bend angle. In supplementary Fig. 4.3 (c), it is depicted that the maximum bend angle value is obtained at an optimum scan velocity of 30 mm/s. The bend angle initially increases from 38° to 39° when the scan velocity increases from 20mm/s to 30 mm/s, and then decreases to 38° during the further increase in the scan velocity up to 40mm/s. Additionally, as shown in Supplementary Figure 5, the maximum bend angle is achieved during the experimental run (number 19) listed in Table 4.3. With the same experiment conditions, an increase in the scan velocity from 30 to 40 mm/s reduced the bend angle from 39° to 38.5° . This drop occurred because, as the scan speed increases, the quantity of heat energy concentrated on the sample surface along a predetermined scan path decreases. It is worth noting that because SS430 sheets have a higher heat transfer coefficient than the AA1050 layer, the bend angle reduces as the scan speed drops. Therefore, if the scan speed is low, the temperature of the upper surface of the sheet rises but quickly transfers the heat in the thickness direction.

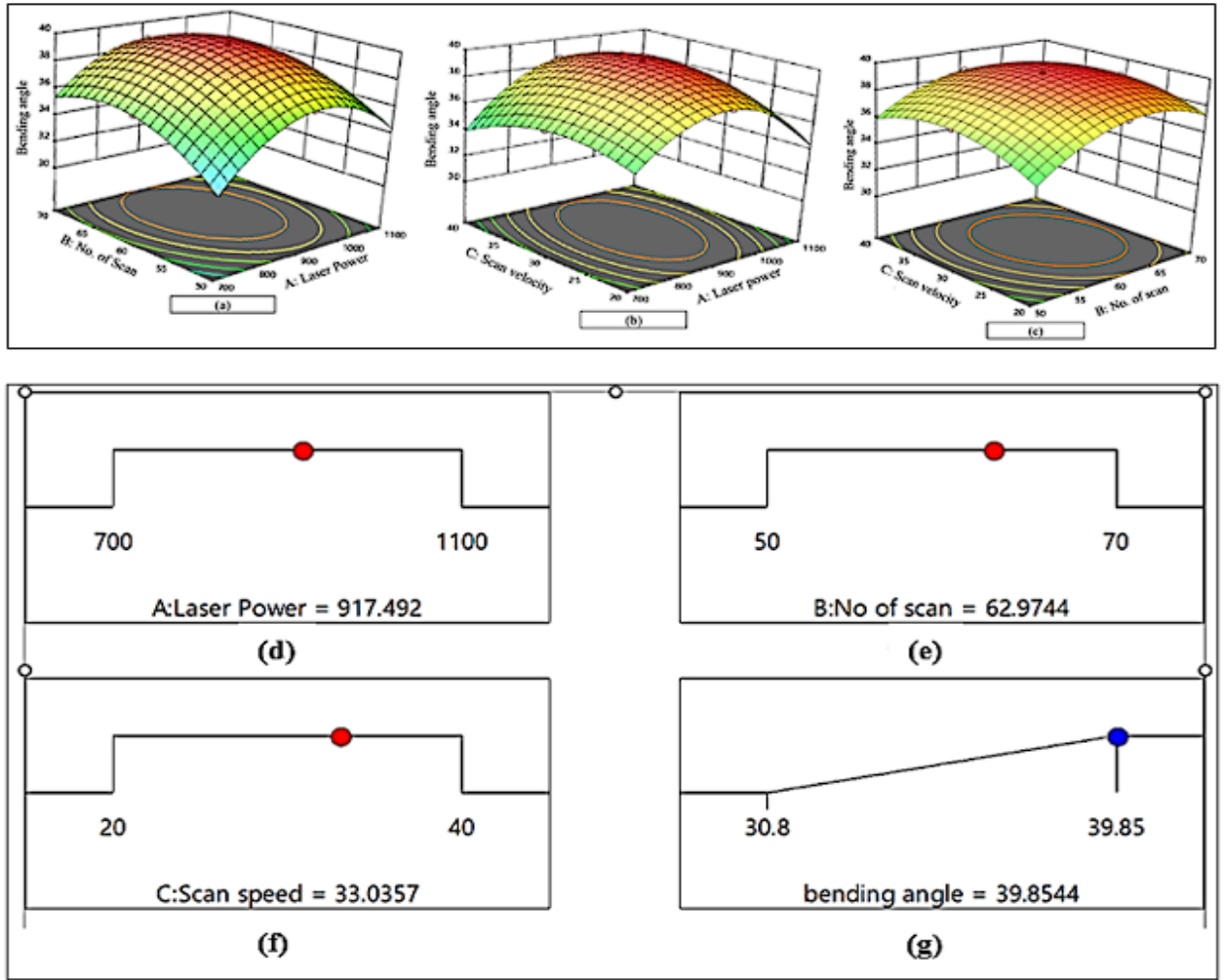


Fig. 4.3. Three-dimensional surface diagrams with combinations of input parameters (a) scan counts and power vs. bend angle (b) scan velocity and power on bend angle (c) scan velocity and scan counts vs. bend angle; and optimum parameters (d) power, (e) no. of scans, (f) scan velocity and (g) bend angle

Fig. 4.3 (a), (b), and (c) show three-dimensional surface diagrams, based on Eq. (4), which can be used to observe the response to different combinations of input parameters affecting the bend angle. Fig. 4.3 (a) depicts the value of each parameter, i.e., the number of scans and power to achieve an optimum value for the bend angle. The focus of the optimization process parameters is to obtain a higher value for the bend angle. It is observed that as the laser power

and scan speed increase, the bend angle also increases. However, increasing the laser power, along with the scan counts, results in a decrease in the bend angle. The highest value of the bend angle predicted by the model is 39.84° , at a combination of laser power of 900 W, 60 scans, and a scanning speed of 30 mm/s. An initial increase in laser power and scan speed enhances the bend angles by creating sufficient thermal gradients for plastic deformation; however, beyond critical thresholds, further increases in these parameters reduce the bend angle due to competing thermal-mechanical effects. At moderate settings (900 W, 30 mm/s), SS430 reaches ideal plastic deformation temperatures, while AA1050 effectively conducts excess heat away. However, at higher parameters, such as 1100 W and 40 mm/s, the system exceeds material limits. As a result, SS430 begins to soften as it approaches its recrystallization temperature, reducing its deformation capacity. Meanwhile, AA1050's heat dissipation capability becomes overreached, which may potentially lead to localized heating and interfacial damage. The model's minimum prediction error and excellent residual clustering demonstrate its promise for process optimisation in heterogeneous clad sheet laser formation, as well as the response surface-based approach's ability to anticipate complex thermo-mechanical behaviour.

4.6 Optimization and model validation

It is evident that the optimization goal is maintained within the defined experimental ranges for all three factors. Based on the regression model, the predicted point for each factor represents the optimal combination, which is found to be very close to run no. 19 in Table 4.3. The maximum bend angle obtained from the optimization is 39° , based on the predicted process parameters. An error of 2.14% was obtained between the predicted value and the highest value obtained from the experiments for the bend angle. This close agreement

indicates that laser power, scan speed, and scan count were well-controlled, and the material reaction was similar across the experiments. An experimental test is conducted, and the predicted optimal value is compared with its actual value, as given in Table 4.5.

Table 4.5 Validation of predicted results

Factor	Name	Optimum goal	Low level	High level	Prediction point
A	Laser power	In range	700	1100	
B	No. of passes	In range	50	70	62.974
C	Scan speed	In range	20	40	33.036
Response Y	Bend angle	Maximize	30.80	39.84	39.854
Predicted response	Desirability	95% PI low	95% PI high	Observed response	Relative error
39.854	1	39.8451	39.8637	39	2.14%

Based on the regression model, the predicted point for each factor represents the optimal combination, which is found to be very close to run no. 19 in Table 4.3. The maximum bend angle obtained from the optimization is 39°, based on the predicted process parameters. An error of 2.14% was obtained between the predicted value and the highest value obtained from the experiments for the bend angle. This close agreement shows that laser power, scan speed, and scan count were well-controlled, and material reaction was similar across trials. Physical experiment does not modify the regression model's optimal bend angle parameters. The predicted vs. actual regression plot shows residual clustering around the diagonal, confirming the durability and goodness-of-fit of the optimization strategy. Model predictions align with

experimental outcomes throughout the design space, without bias or heteroscedasticity, due to diagonal alignment. The absence of significant outliers or residual curvature suggests that the RSM's second-order polynomial model effectively captures nonlinear interactions among process parameters.

4.7 Microstructure and evolution of texture

The microstructure of a 2-ply clad sheet's individual layers, determined by the Electron Backscatter Diffraction (EBSD) technique before laser forming, is displayed in a colour-coded scale in Fig. 4.4 for SS430 with AA1050 with a transition zone. It is observed that, away from the transition zone, the grains of AA1050 are relatively coarse, with an average grain size of 33.68 μm , but the grains are finer with an average grain size of 5 μm closer to the transition layer, and the grains are oriented along the length of the transition layer. It is also observed that the grains of SS430 are equiaxed, with an average grain size of approximately 12.72 μm , and this grain size remains consistent even closer to the transition layer. Further scanning electron microscopy is done to visualize the interaction of both layers, and the image is juxtaposed vertically with IPF maps for better understanding. The dotted structure pertains to the diffusion of Fe atoms, mainly observed to occur at the transition layer, where the grains of aluminium, being softer than steel, appear to be distorted due to high pressure during the clad bonding operation in rolling. This distortion of grains in the transition layer is not uniform along the length of the sample and depends upon the pressure distribution during roll bonding.

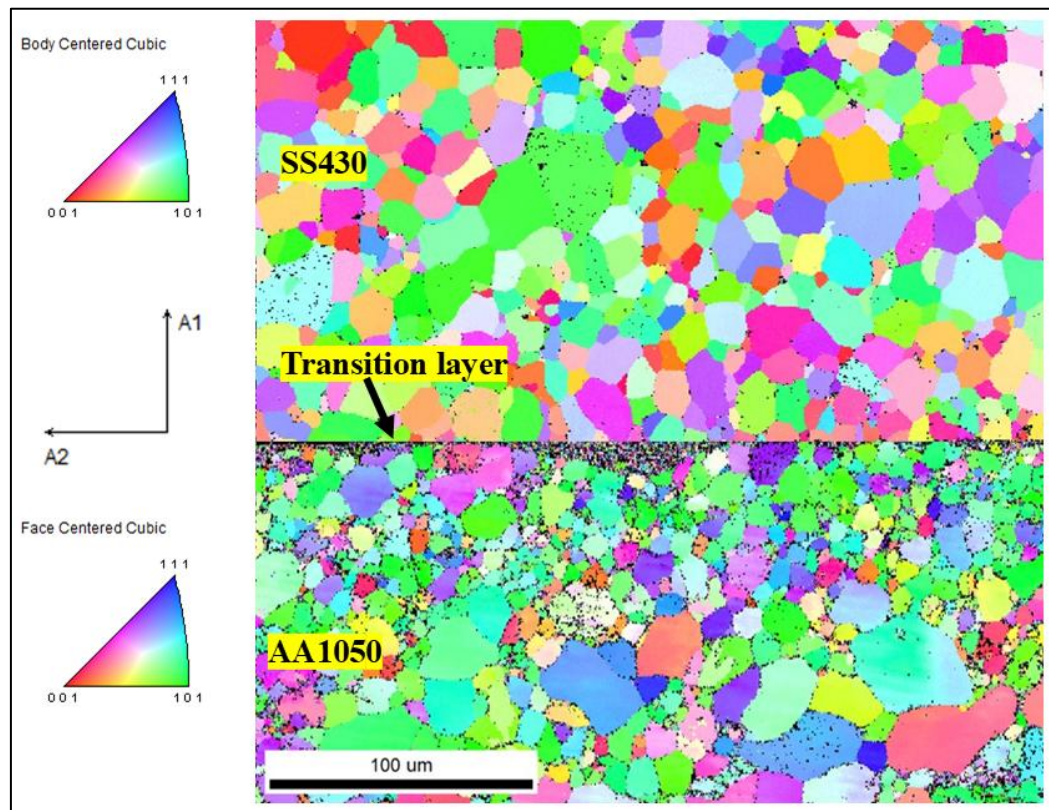


Fig. 4.4 A colour-coded IPF showing microstructure of SS430 and AA1050 with transition layer

4.8 Microstructure of irradiated surface

The micrograph of the laser-irradiated cross-section of a 2-ply sample, captured by a scanning electron microscope (SEM). This image vividly displays the microstructural characteristics of the sample, including phase boundaries, which distinguish the different layers of AA1050 and SS430. Fig 4.5 shows the two views of the laser bent specimens, and the bend axis the SEM analysis is focussed in Fig. 4.6 (a)

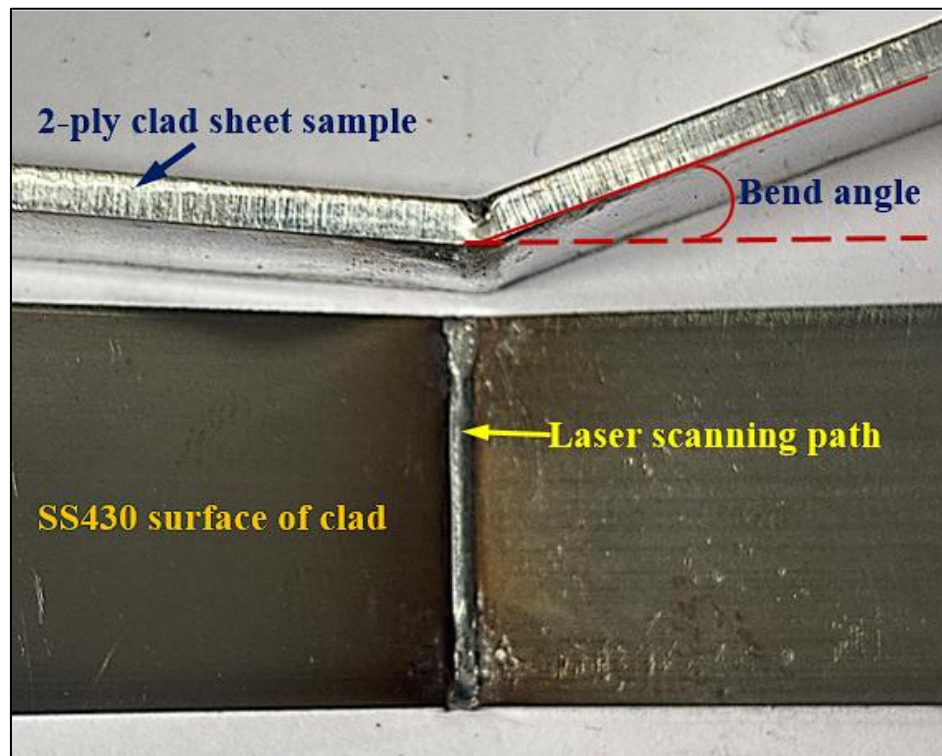


Fig. 4.5 Two views of a bent specimen using laser irradiation

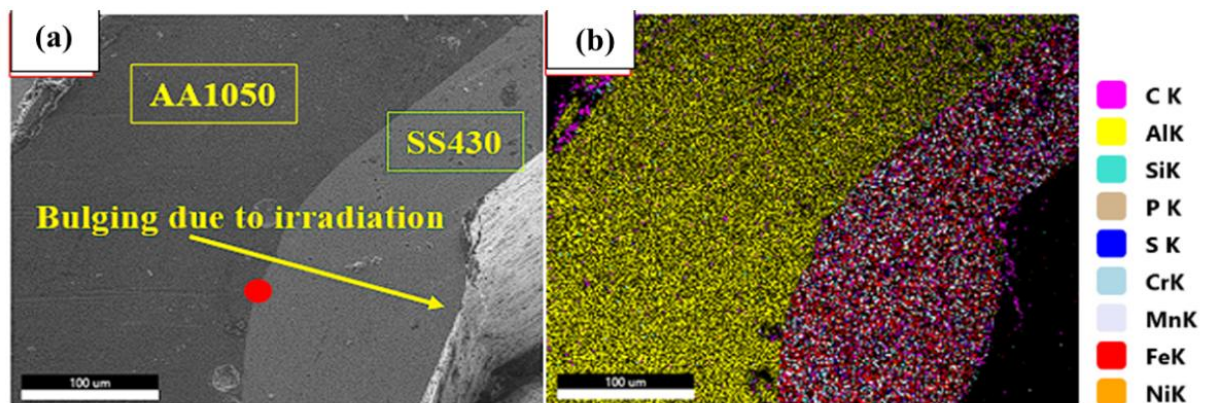


Fig. 4.6 (a) Microstructural characteristics after laser processing showing boundaries of different layers of AA1050 and SS430 and (b) elemental mapping using EDAX

The grains are in the range of coarse to fine, depending upon the thermal gradient in the thickness direction of the steel layer. The grain refinement at the surface is attributed to rapid heating and cooling cycles, which cause recrystallization and dynamic recovery. Thermal

cycling leads to the nucleation of new grains at high-angle grain boundaries, thereby reducing the overall grain size. However, the grains beneath the refined grains remain coarse, as evident in the microstructure.

The bulging of the SS430 layer observed in cross-sectional SEM imaging during laser irradiation is a strong indicator of asymmetric thermal gradients and directional heat flux across the SS430–AA1050 interface. This deformation suggests that the SS430 layer, with its lower thermal conductivity, retains more heat near the irradiated surface, resulting in localized thermal expansion and upward displacement. In contrast, the highly conductive AA1050 substrate rapidly dissipates heat, maintaining a cooler temperature and reinforcing the through-thickness thermal asymmetry. This directional heat flow from the irradiated SS430 surface into the AA1050 generates compressive stresses at the interface and tensile stresses within the SS430 layer, contributing to its bulging and stress accumulation. The image also shows a bulge in the thickness of the SS430 layer, which is also an irradiated surface. Fig. 4.6 (b) also shows an elemental map with a colour code captured by energy-dispersive X-ray spectroscopy (EDAX), which depicts the spatial distribution of multiple elements within the same location in both layers of the sample. It employs a colour labelling to distinguish between elemental concentrations. In this map, the yellow region in the corner of the image is rich in aluminium, as it corresponds to the prominent Al peak in the EDAX spectrum. Meanwhile, the right reddish region is rich in elements including iron (Fe), chromium (Cr), manganese (Mn), and nickel (Ni).

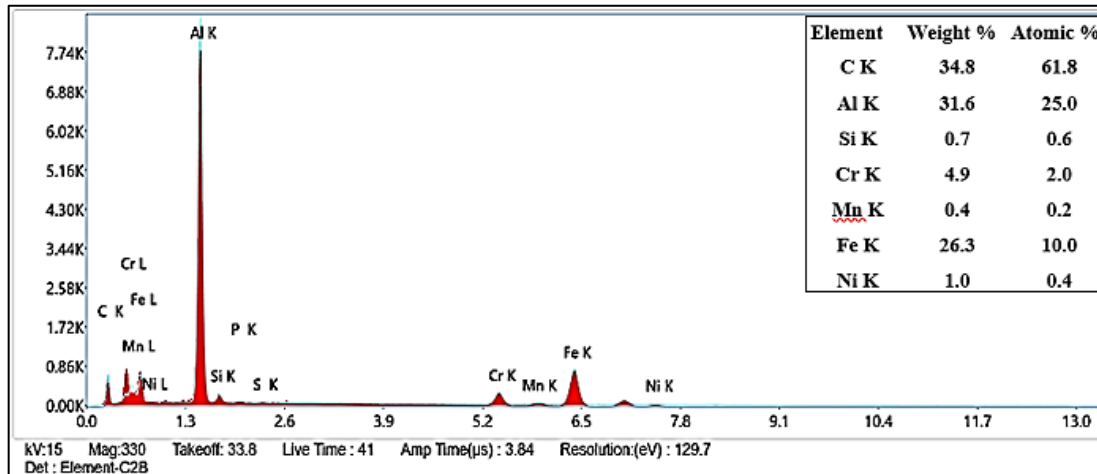


Fig. 4.7 EDAX spectrum plots captured at the transition zone of both the layers of AA1050 and SS430

The EDAX spectrum plots, captured at the transition zone of both layers, shown in Fig 4.7, depict the intensity (counts) of X-ray emissions as a function of energy (keV). The EDAX study reveals that aluminium (Al) is the primary element in the investigated region, as indicated by the strong Al K peak in the spectrum. In addition to aluminium, several additional elements have been discovered. The $K\alpha$ and $K\beta$ peaks indicate the presence of light elements, such as carbon (C) and silicon (Si). The spectrum also reveals the presence of several transition metals, including iron (Fe), chromium (Cr), manganese (Mn), and nickel (Ni), which are detected via both their L and K lines.

A very narrow heat-affected zone is observed to form towards the depth of the sheet, followed by a banded structure at the outer part of the bend. The high surface temperature of a thin layer of SS430 substantially refines the microstructure of the laser-irradiated zone of bending. In the irradiated zone, the average grain size is found to be $3\mu\text{m}$. Fig. 4.8(a) shows the presence of some coarser grains, which may be attributed to the number of scans along a predetermined path.

Grain boundary maps provide a detailed visualization of the distribution of Low-Angle Grain Boundaries (LAGBs) and High-Angle Grain Boundaries (HAGBs) within the microstructure. Electron Backscatter Diffraction (EBSD) analysis reveals that 95.3% of the grain boundaries are LAGBs (misorientation $< 15^\circ$), indicating that deformation is primarily accommodated through grain refinement. In contrast, 4.7% of the boundaries are HAGBs (misorientation $> 15^\circ$), which serve as barriers to dislocation movement and contribute to strain localization. The predominance of LAGBs suggests that deformation is occurring mainly through dislocation activity rather than significant grain boundary sliding or recrystallization. The presence of black regions along grain boundaries after laser bending indicates martensitic transformation, where plastic deformation is absent due to the phase change. Steel 430, with its moderate carbon content ($\sim 0.15\%$), formed martensite under rapid heating and quenching conditions. While chromium stabilizes ferrite, exposure to high temperatures can induce austenite formation, which subsequently transforms into martensite upon cooling. Additionally, multiple laser passes may result in martensite tempering, which can potentially affect hardness.

The predominance of LAGBs suggests that deformation is occurring mainly through dislocation activity rather than significant grain boundary sliding or recrystallization. The presence of black regions along grain boundaries after laser bending indicates martensitic transformation, where plastic deformation is absent due to the phase change. Steel 430, with its moderate carbon content ($\sim 0.15\%$), formed martensite under rapid heating and quenching conditions. While chromium stabilizes ferrite, exposure to high temperatures can induce austenite formation, which subsequently transforms into martensite upon cooling. Additionally, multiple laser passes may result in martensite tempering, which can potentially affect hardness.

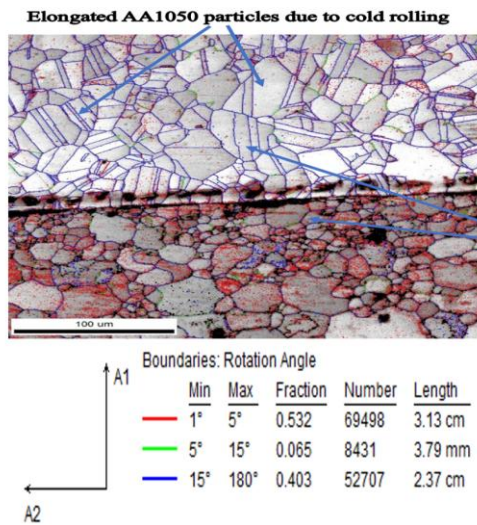


Fig. 4.8 (a) Before deformation

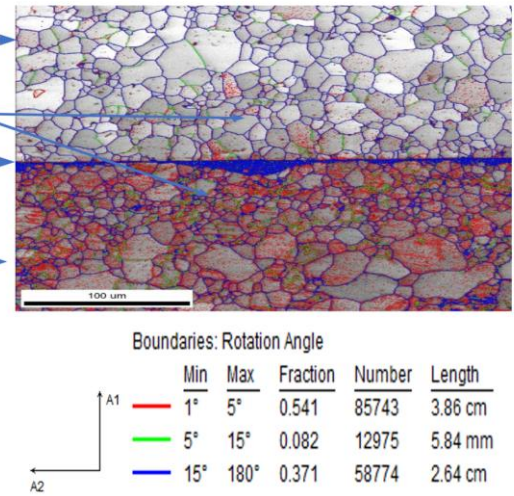


Fig. 4.8 (b) After deformation

Laser bending transforms a dislocation-rich structure (LAGBs) into a more recrystallized and relaxed structure (HAGBs), especially in the aluminum layer, due to cyclic thermal–mechanical effects. The evolution of LAGB to HAGB enhances bend angle uniformity and reduces residual stresses, improving the overall forming behaviour of SS430–AA1050 clad sheet as shown in Fig. 4.8 (a) and (b).

The EBSD result of the kernel average misorientation (KAM) map is shown in Fig. 4.9 (b). KAM maps provide insights into the local strain distribution within the material by analysing geometrically necessary dislocations (GNDs). These dislocations accommodate strain gradients and play a crucial role in work hardening. Green regions indicate areas with a higher magnitude of dislocation density. These regions have undergone significant plastic deformation, exhibiting a higher degree of lattice distortion. The blue regions correspond to areas with minimal dislocation density, meaning that these grains have experienced lower plastic strain. The transition from blue to green highlights the variation in local misorientation, which directly corresponds to the heterogeneous distribution of plastic strain in the material. The presence of green regions indicates intense plastic strain, which suggests

that slip systems are highly active. The blue regions indicate that certain grains have a lower degree of strain accumulation, possibly due to crystallographic orientation or phase interactions. During deformation, grains undergo gradual lattice rotation, which affects the misorientation distribution. The evolution of LAGBs and HAGBs is linked to this rotational behaviour [55]. The grain boundary map image of irradiated surface of SS430 and kernel average misorientation map illustrated in Fig. 4.9.(a) and 4.9 (b).

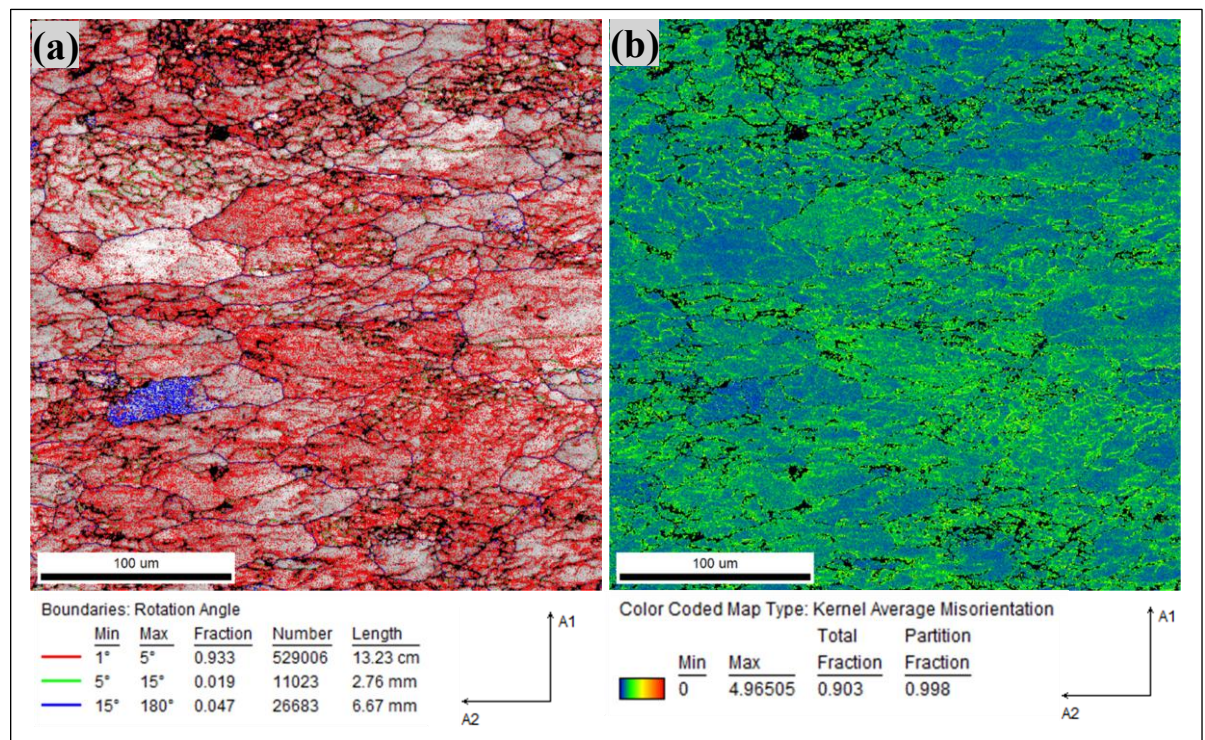


Fig. 4.9 (a) Grain boundary map image of irradiated surface of SS430 and
(b) kernel average misorientation map

4.9 Texture evolution of AA1050 before and after laser irradiation

The pole figures of the {001} and {111} planes exhibit a peak intensity of 4.680 in multiples of random orientation (MRD), indicating a robust texture, followed by a peak intensity in the {110} planes, as shown in Fig. 4.10(a). It is noticed that the sheet material possesses a good

texture. The poles are taken with respect to a lattice plane of a certain family of planes and plotted along an appropriate reference axis, i.e., the longitudinal and transverse directions (LD and TD), as shown in the figure. A1 is the longitudinal direction (LD) and A2 is the transverse direction (TD). The close-packed structure is observed in the family of planes in FCC is $\{111\}$.

Fig. 4.10 (b) shows that the peaks are distributed randomly, indicating a strong texture observed in the samples taken from the tested specimen after laser bending. The highest peak intensity (5.506 MRD) is seen in the $\{001\}$ plane, and the $\{111\}$ and $\{110\}$ planes show random peaks with an intensity of 4.413 MRD. It can be concluded that the peaks, distributed randomly, increase in the planes of $\{001\}$, $\{111\}$, and $\{110\}$ with laser bending, resulting in a stronger texture than that of specimens tested without laser bending. In this case, the grains oriented in $\{001\}$ planes are observed with a texture of sharp peaks concentrated in some areas when compared with the pole figures in the planes of $\{111\}$ and $\{110\}$, where the peaks are distributed at random. The pole inversion observed in the EBSD pole figures indicates significant texture evolution during laser bending. The reduction or shift in pole intensity is linked to grain reorientation and recrystallisation phenomena, which directly influence the anisotropic mechanical behavior during deformation. Although comprehensive mechanical characterization was not conducted beyond microhardness, the hardness data effectively capture the local strengthening or softening behaviour induced by thermal cycling. Conventional tensile or fatigue testing was not feasible due to the non-uniform, localized deformation zones created by laser forming and the scale of affected regions relative to standard test specimen dimensions.

The pole figure for the planes $\{001\}$, $\{110\}$, and $\{111\}$ of the sample taken before and after laser bending of AA1050 from the sheet as shown in Fig. 4.10 (a-b).

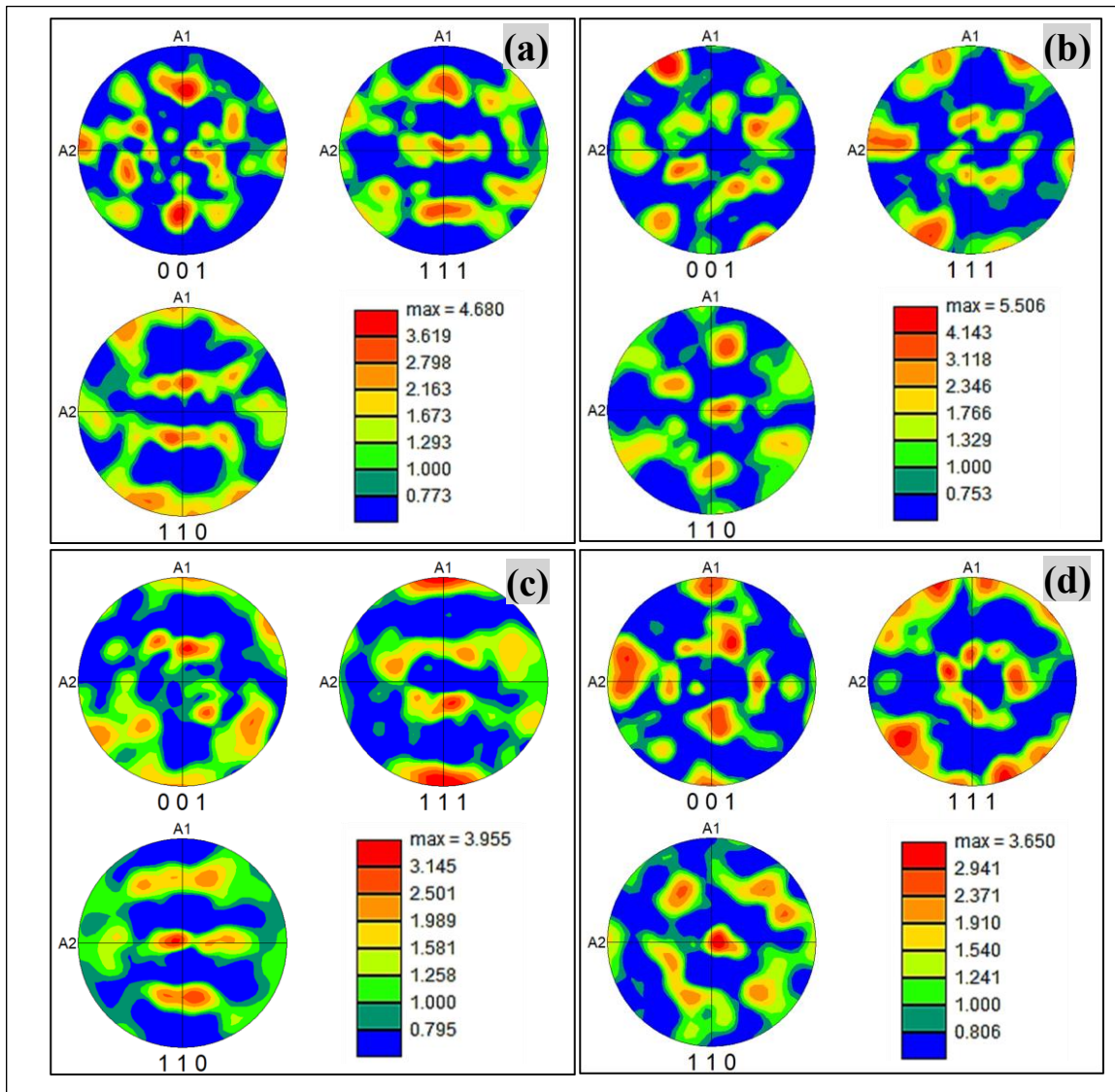


Fig. 4.10. Harmonic texture before and after laser processing of (a), (b) AA1050 and (c), (d) of SS430, respectively

4.10 Texture evolution of SS430 before and after laser irradiation

The harmonic texture plots for the planes $\{001\}$, $\{111\}$, and $\{110\}$ are shown in Fig. 4.10 (c) before laser irradiation. In SS430, being a ferritic in structure, the closed-packed structure is generally found in the family of planes $\{110\}$. The poles are taken with respect to a lattice plane of a certain family of planes and plotted along an appropriate reference axis, i.e., the longitudinal direction (A1) and the transverse direction (A2), as shown in the figure. In the case of $\{001\}$ facial plane of lattice, a random distribution of peaks is observed with an intensity of 3.1 in terms of multiples of random distribution (MRD), indicating a dull texture. In the plane of $\{111\}$, the peaks are found to be located in the poles of A1 with an intensity of 3.945 MRD, suggesting a good texture, whereas in the crystallographic planes of $\{110\}$ the closed-packed plane, the peaks are observed to be uniformly distributed about the normal direction but the intensity in terms MRD is lower than other two planes.

The harmonic texture plots of SS430 for three different crystallographic planes after laser irradiation are shown in Fig. 4.10 (d). The intensity of peaks in terms of MRD is observed to be distributed at random in plane $\{001\}$, whereas the peaks are distributed uniformly in plane $\{111\}$. In the case of plane $\{110\}$, the highest peak is observed at the centre in the normal direction, with an intensity of 3.65 MRD. However, the rest of the peaks are shallow, with an intensity of approximately 2.0 MRD, indicating a poor texture. Based on the MRD values and their distribution pattern, it may be concluded that the heat of irradiation has refined the crystals to the extent of a dull texture. This could also be attributed to metallurgical transformations in the ferrite's structure. The degradation of texture on the irradiated surface (SS430) is due to direct laser exposure, which induces rapid heating and cooling, resulting in surface recrystallisation and grain coarsening. This disrupts the crystallographic texture. In contrast, the layer below the irradiated one experiences moderate, uniform heating, allowing for recovery and subgrain formation without melting, thus enhancing crystallographic

alignment and improving texture quality. EBSD analysis confirmed stronger texture indices in the subsurface region of the AA1050 layer just below the irradiated surface.

4.11 Residual stress and microhardness

The distribution of residual stress (tensile and compressive) in both layers of SS430 and AA1050 in the transverse section, which aligns with the bending axis, is shown in Fig. 4.11 (a)-(d). The 3-dimensional Debye-Scherrer rings (D-S rings) formed on the innermost layer of SS430, the mid-bend zone, and the outermost thickness of AA1050 are shown in Fig. 4.11 (b), (c), and (d), respectively, along with the residual peaks. The characteristics of D-S rings provide vital information on the resulting microstructure. Multiple diffractions from constituent phases can be recorded simultaneously in a single exposure [56]. Fig. 4.11 (b) shows a D-S ring for the steel layer extracted from the irradiated surface using Cr-K α radiation under normal incidence. The full width at half maximum, averaged throughout the entire circumference of the rings, is provided and shows that the ring is non-uniform in its irradiated layer of steel. The D-S ring for the transition layer is depicted in Fig. 4.11 (c) and shows an inner multiple peaks of lower intensity due to the presence of both Fe and Al atoms in the zone. A Continuous and uniform D-S ring is obtained in the coarse-grained AA1050 layer and is shown in Fig. 4.11 (a). It is observed that the residual stress in the innermost layer is compressive, with a magnitude of 253 ± 35 MPa, whereas the stress in the mid-layer of AA1050 is also compressive, with a magnitude of 29 ± 5 MPa. It is interesting to observe that the residual stress at the outermost thickness of AA1050 is tensile in nature, with a magnitude of 56 ± 7 MPa. Although a collimator diameter of 50 μm limits the distribution of residual stress from point to point, the best possible distribution captured through thickness. The variation in residual stress may be ascribed to the differing thermal coefficients of the layers and the phase transition, particularly in SS430, due to its irradiation surface. The

temperature gradient in the irradiation zone encompasses the volume of SS430 and part of the AA1050 layers, but decreases abruptly when heat approaches the bottom surface of the AA1050. Aluminium, exhibiting nearly double the thermal coefficient of expansion compared to steel, expands correspondingly in response to the heat gradient. In the immediate cooling cycle, the SS430 layer endeavors to contract; nevertheless, the aluminum layer, having expanded twice, impedes the full contraction of this layer, leading to a compressive residual stress in the steel layer. The lowest layer expands; nevertheless, during the cooling process, this layer cannot contract freely due to the rigidity of the steel layer, resulting in the establishment of tensile residual stress in the AA1050 layer. The residual stress is evaluated on the surfaces of SS430 and AA1050 in the width direction by directing the X-ray beam onto the laser path crossed in the sample. The nature of residual stress is compressive in SS430 and tensile in AA1050, consistent with the trends seen in Fig. 4.12 and Fig. 4.13 in the transverse direction. The development of tensile residual stress in AA1050 and compressive residual stress in SS430 after laser processing is mostly influenced by their disparate thermal contraction and conductivity characteristics. Upon rapid and significant cooling from excessive temperatures caused by laser irradiation, both materials experience thermal contraction; however, AA1050 possesses a coefficient of thermal expansion that is 2.5 times greater than that of SS430. This disparity results in AA1050 contracting more than SS430. The metallurgical bonding at the interface of SS430 restricts the contraction of AA1050, creating a mechanical constraint that induces tensile residual stress in the AA1050 layer. In contrast, SS430 undergoes compressive stress as it counteracts the contraction force given by AA1050 [58]. Figure 4.11 (e) illustrates the microhardness distribution inside the bent zone of the SS430 layer and the AA1050 layer. The microhardness in the laser-irradiated

region of the SS430 layer varies from 200 to 272 HV0.5, whereas the hardness at a distance of 1mm from the core section ranges from 153 to 159 HV, distant from the irradiated area.

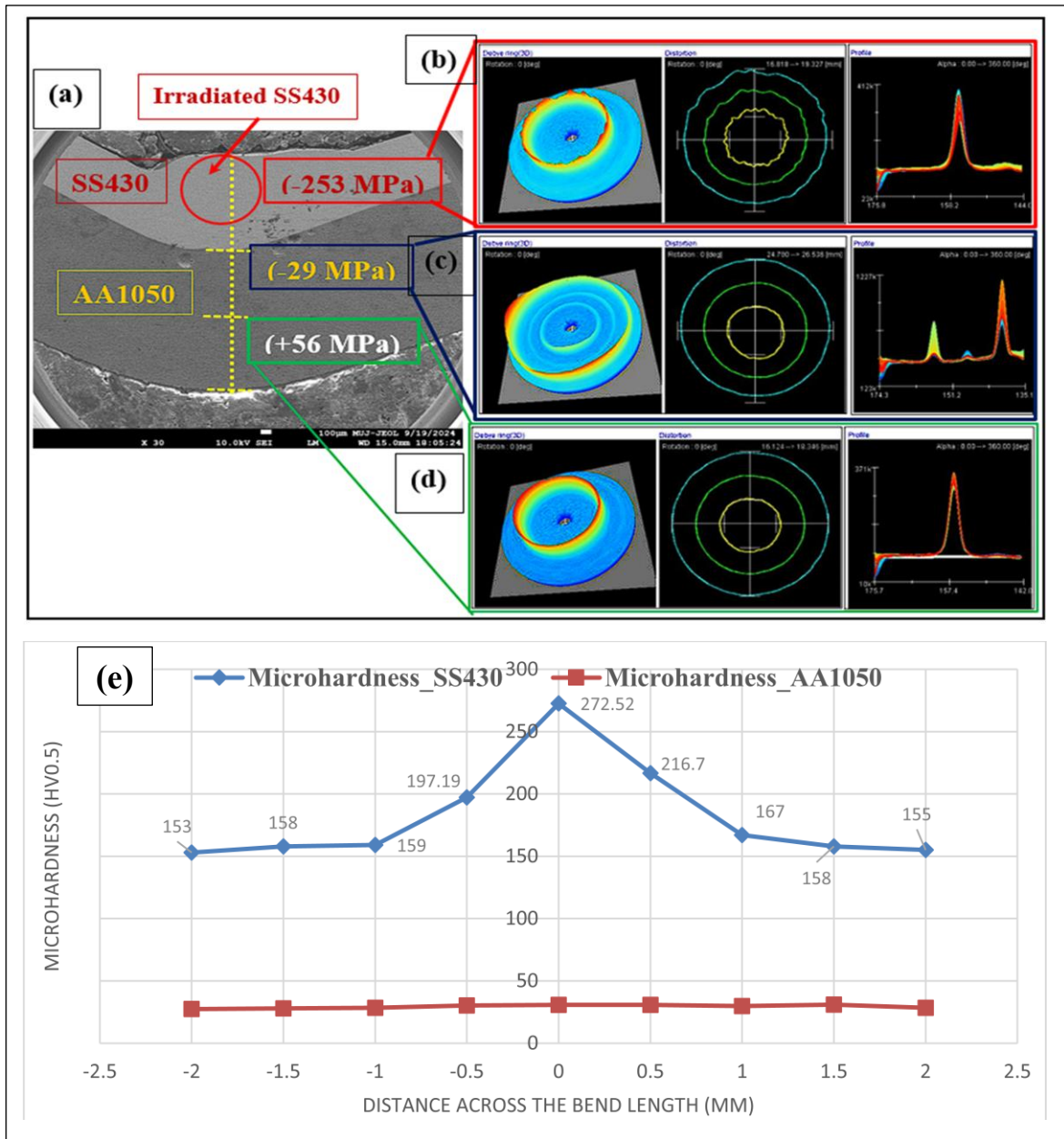


Fig. 4.11 (a) SEM image of cross-section of a laser processed sample (b) 3D Debye ring with residual peaks at SS430 (c) mid-section of AA1050 (d) bottommost portion of AA1050 and (e) Distribution of Vickers microhardness across the bent zone

A hardness of 272 HV0.5 results from grain refinement and phase change to martensite caused by fast heating and quenching by laser. The hardness of the AA1050 layer in the bent zone ranges from 27 to 30 HV0.5, demonstrating low distribution variation, owing to an insignificant phase shift resulting from the heat gradient.

The SEM picture depicts the cross-section of a laser-processed sample, featuring a 3D Debye ring with residual peaks at SS430, the mid-section of AA1050, the bottommost portion of AA1050, and the distribution of Vickers microhardness across the bent zone, as seen in Fig. 4.11(a-e).

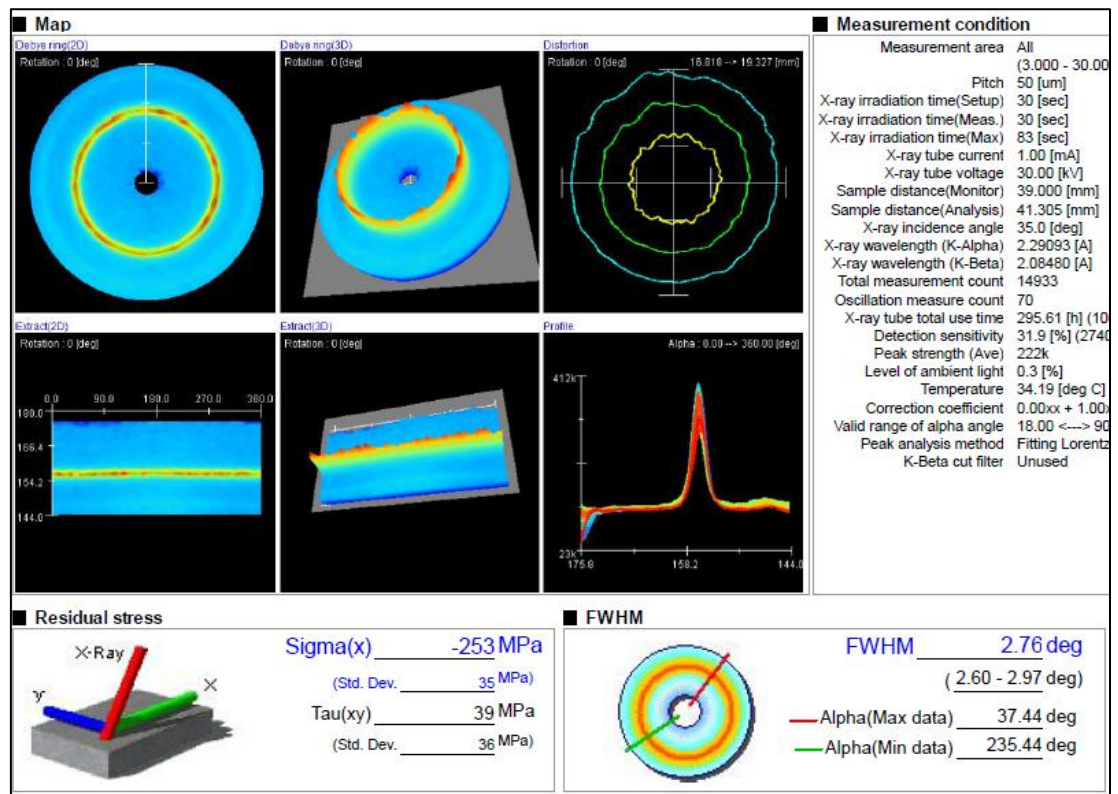


Fig. 4.12 Debye ring and measurement conditions for residual stress evaluation of SS430

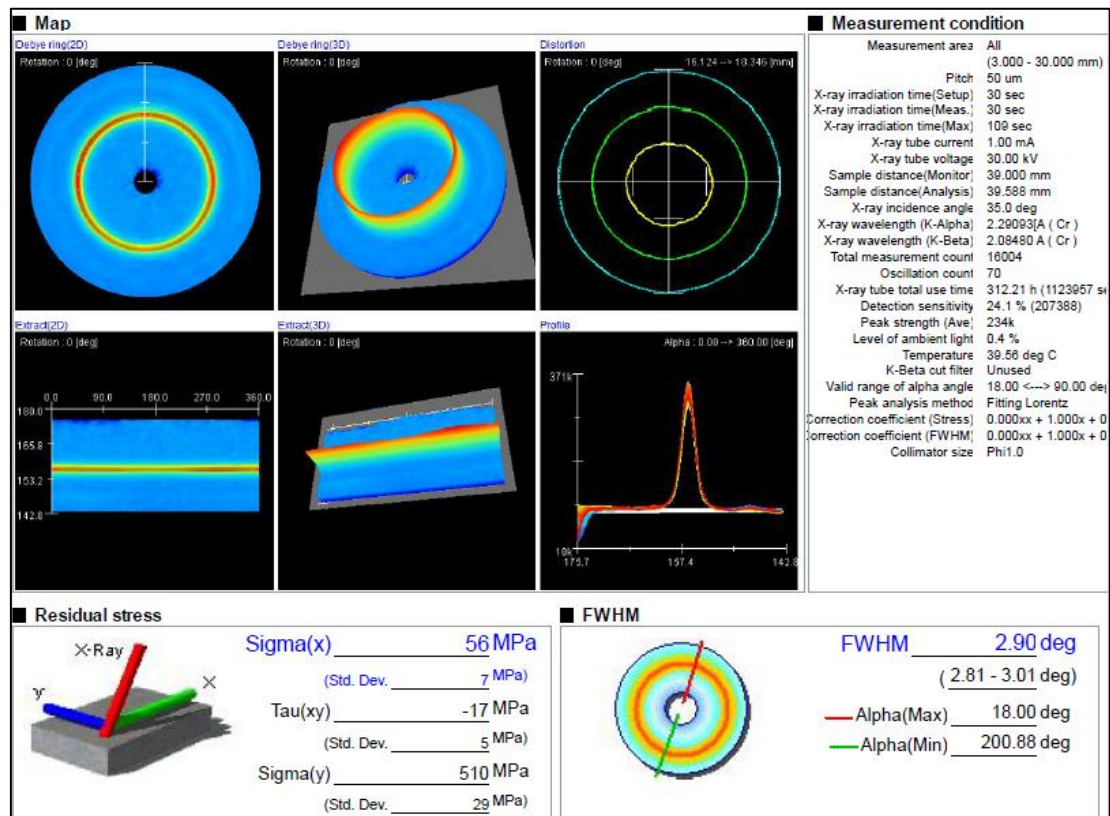


Fig. 4.13 Debye ring and measurement conditions for residual stress evaluation of AA1050

4.12 Summary

The work presents a comprehensive analysis of the experimental and numerical results obtained from the laser forming of a two-ply SS430/AA1050 clad sheet, with particular emphasis on bend angle prediction, process optimisation, and the associated microstructural and mechanical evolution. The mechanical properties of the clad sheet and its constituent layers show a clear gradation in strength and ductility. SS430 exhibits the highest yield strength, tensile strength, and strain hardening exponent, indicating superior strength and work-hardening capability. AA1050, in contrast, shows the lowest strength and strain hardening ability, along with limited elongation, reflecting its soft and highly compliant nature. The clad sheet displays intermediate yield and tensile strengths, with elongation and

strain hardening behaviour closer to SS430, demonstrating a balanced mechanical response. Overall, the cladding effectively combines the high strength and ductility of SS430 with the deformability of AA1050, producing a composite material with moderate strength, good ductility, and improved formability suitable for forming applications.

Since laser forming is governed by complex thermo-mechanical interactions, this chapter systematically evaluates the influence of laser power, scanning speed, and number of laser passes on the bending behaviour of the clad sheet using a statistically robust framework. A central composite design (CCD) integrated with response surface methodology (RSM) was employed to establish reliable correlations between the process parameters and the resulting bend angle. The experimental matrix comprised 20 carefully designed trials, ensuring adequate representation of linear, interaction, and quadratic effects, thereby enabling accurate modelling of the nonlinear nature of the laser bending process.

The analysis of variance (ANOVA) confirmed the statistical significance and adequacy of the developed RSM model for predicting the bend angle. The high F-value and low p-value demonstrated that the selected laser parameters exert a strong and meaningful influence on the response. Furthermore, the lack-of-fit was found to be statistically insignificant, indicating that the proposed model adequately describes the experimental observations. The predicted bend angles showed close agreement with the experimentally measured values, thereby validating the reliability of the developed regression model. This strong agreement between experimental and numerical results reinforces the suitability of RSM as an effective optimisation and prediction tool for laser forming of multi-layered clad sheet metals.

The individual and combined effects of laser power, scanning speed, and number of scans on the bend angle were analysed using three-dimensional response surface plots. The results

clearly indicate that laser power is the most dominant parameter influencing the bending response. An increase in laser power leads to a higher peak temperature and a steeper temperature gradient through the thickness, which promotes plastic deformation in the irradiated layer and consequently increases the bend angle. However, beyond a certain power level, excessive heat input may reduce the temperature gradient across the thickness due to heat diffusion, thereby limiting further increases in bending. Similarly, the number of laser scans exhibits a cumulative effect on bending, as repeated irradiation increases the total thermal energy absorbed by the material, resulting in progressive plastic strain accumulation and enhanced bending.

In contrast, scanning speed shows an inverse relationship with bend angle. Lower scan speeds increase the interaction time between the laser beam and the material, leading to higher heat input per unit length and larger temperature gradients, which favour bending through the temperature gradient mechanism. Higher scan speeds reduce the absorbed energy and limit the extent of plastic deformation, resulting in smaller bend angles. The interaction effects between laser power and scan speed, as well as between power and number of scans, further highlight the coupled nature of the laser forming process, particularly in clad materials where dissimilar thermal and mechanical properties coexist across the thickness.

Optimisation of the process parameters using the desirability function approach resulted in an optimal combination of approximately 900 W laser power, 60 laser scans, and a scanning speed of 30 mm/s, which produced a maximum bend angle of about 39°. A confirmation experiment conducted under these optimal conditions yielded a relative error of only 2.14% between the predicted and experimental values, demonstrating the robustness and predictive capability of the developed model. This result, also reported in the Abstract, underscores the

effectiveness of combining experimental design with numerical optimisation for achieving controlled and repeatable laser forming outcomes in multi-layered clad sheets.

Beyond macroscopic bending behaviour, this work also investigates the microstructural evolution and texture development induced by laser forming using electron backscatter diffraction (EBSD) analysis. The microstructural examination revealed that the laser-irradiated surface is most significantly affected by thermal cycling. In the SS430 layer exposed directly to the laser beam, pronounced grain refinement, increased misorientation, and a higher fraction of low-angle and high-angle grain boundaries were observed, indicating intense plastic deformation and thermal effects. In contrast, the underlying AA1050 layer, which is not directly irradiated, experiences indirect heating that promotes recovery and partial recrystallisation, resulting in an improvement in texture quality. This asymmetric microstructural response across the thickness highlights the inherent complexity of laser forming in dissimilar metal clad systems.

Texture analysis further revealed that laser irradiation leads to a degradation of crystallographic texture at the irradiated SS430 surface, whereas the AA1050 layer beneath exhibits a more favourable and stable texture after processing. These findings demonstrate that laser forming not only alters the macroscopic shape of the clad sheet but also induces layer-dependent microstructural and crystallographic changes, which are critical for understanding post-forming mechanical performance.

Residual stress analysis showed a distinct through-thickness stress distribution in the laser-formed samples. The innermost region of the SS430 layer was found to be under compressive residual stress, while the outermost region of the AA1050 layer exhibited tensile residual stress. This stress distribution is consistent with the temperature gradient mechanism, where

the rapid heating and subsequent cooling of the irradiated surface generate compressive stresses in the upper layer and tensile stresses in the lower layer. Such residual stress states play a crucial role in determining dimensional stability, fatigue behaviour, and service performance of laser-formed components.

Microhardness measurements across the bent zone further supported the observed microstructural trends. The laser-irradiated region of the SS430 layer showed a significant increase in hardness, ranging from approximately 200 HV to a maximum of 272 HV, attributed to grain refinement, thermal hardening, and strain accumulation caused by repeated laser scans. In contrast, the AA1050 layer exhibited minimal variation in hardness across the bent region, indicating that the thermal exposure was insufficient to cause substantial strengthening or softening in the aluminium layer. This distinct hardness response between the two layers once again emphasises the heterogeneous nature of deformation in clad sheets during laser forming.

Overall, the results presented in this chapter establish a clear and quantitative relationship between laser process parameters and bending behaviour while simultaneously linking macroscopic deformation with microstructural, textural, residual stress, and hardness evolution. The findings confirm that laser forming is a highly effective, controllable, and tool-less forming technique for multi-layered SS430/AA1050 clad sheets. The insights gained from this chapter provide a strong foundation for the conclusions drawn in the subsequent chapter and demonstrate the potential of laser forming for precision shaping of advanced laminated and clad sheet materials.

4.13 Industrial significance of the present work

The outcomes of this thesis have strong industrial relevance, particularly for sectors that demand high precision, flexibility, and efficiency in forming advanced sheet materials. The successful investigation of laser forming of multi-layered SS430–AA1050 clad sheet metal demonstrates the feasibility of a **tool-less, non-contact forming process**, which is highly attractive for modern manufacturing environments where rapid design changes, low-volume production, and tight dimensional tolerances are common.

From a **manufacturing and production standpoint**, the optimisation of laser parameters such as power, scan speed, and number of passes provides industries with a reliable process window to achieve controlled and repeatable bending without the need for expensive dies or presses. This significantly reduces tooling cost, setup time, and lead time, making laser forming an economically viable alternative for prototyping, customised components, and small-batch production. Industries such as aerospace, defence, and precision equipment manufacturing, where components often vary in geometry and are produced in limited quantities, can directly benefit from this approach.

The work also contributes to **process optimisation and quality control** by integrating design of experiments and response surface methodology with experimental validation. The development of a statistically validated predictive model for bend angle enables manufacturers to reduce trial-and-error experimentation and energy consumption, while ensuring consistent product quality. The low prediction error achieved under optimal conditions highlights the potential for implementing this methodology in automated and digitally controlled manufacturing systems aligned with Industry 4.0 principles.

From a **materials engineering perspective**, the study provides valuable insights into the thermo-mechanical behaviour of dissimilar metal clad sheets during laser forming.

Understanding the layer-wise microstructural evolution, texture changes, residual stress distribution, and hardness variation is critical for industrial adoption, as these factors directly influence component durability, fatigue life, and service performance. The observation of compressive residual stresses in the stainless steel layer and stable hardness in the aluminium layer suggests improved structural integrity and dimensional stability in formed components, which is essential for load-bearing and thermally cycled applications.

The findings are particularly significant for industries utilising aluminium–stainless steel clad sheets, such as automotive, rail transport, heat exchangers, cookware, and aerospace structures. These applications require a combination of lightweight design, corrosion resistance, thermal conductivity, and mechanical strength. The demonstrated capability to form such clad materials without delamination or surface defects expands their applicability to more complex geometries and advanced functional components.

Additionally, the enhanced hardness in the laser-irradiated SS430 layer indicates potential benefits in wear resistance and surface durability, which is advantageous for components exposed to friction, thermal loads, or harsh operating environments. This opens possibilities for laser forming not only as a shaping technique but also as a simultaneous surface modification process, thereby adding functional value without additional processing steps.

Overall, the present research supports the industrial transition toward flexible, energy-efficient, and digitally optimised forming technologies. By establishing a clear link between laser process parameters, deformation behaviour, and material integrity in multi-layered clad sheets, this work provides practical guidelines and scientific understanding that can facilitate the large-scale adoption of laser forming in advanced manufacturing industries.

CHAPTER 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 Conclusions

To optimize the parameters for a laser bending process of a 2-ply clad sheet, this study experimentally and statistically investigates the process parameters and microstructural evolution in the irradiated zone. The following conclusions are drawn:

1. Among the three parameters selected for optimizing laser bending operation, laser power and scan velocity have the greatest and least effect on the bend angle, respectively.
2. An optimised combination of 917 W laser power, with a number of scans and velocity of 63 and 33 mm/s, resulted in a maximum bend angle of 39° with a relative error of 2.14%.
3. In the samples without laser processing, it was observed that, away from the transition zone, the grains of AA1050 are coarser, but the grains are finer closer to the transition layer. It is also observed that the grains of SS430 are equiaxed, with an average grain size of approximately 12.72 μm , regardless of the presence of a transition layer.
4. In the case of AA1050 before irradiation, the pole figures of {001} and {111} planes show a higher intensity of peaks (4.680 MRD), indicating a strong texture that is followed by the intensity of the peaks in {110} planes. After laser irradiation, the peaks are distributed randomly, indicating a strong texture with a peak intensity of 5.506 MRD.

5. Without laser irradiation on SS430, in the plane of $\{111\}$, the peaks are found to be located in the poles of A1 with an intensity of 3.945 MRD suggesting a good texture whereas in the crystallographic planes of $\{110\}$ the closed packed plane, the peaks are observed to be uniformly distributed about the normal direction but the intensity in terms MRD is lower than other two planes. After irradiation, the intensity of the peak decreases, indicating a poor texture, which could be due to phase transformations in the ferrite structure to martensite.
6. It is observed that the residual stress in the innermost layer is compressive, with a magnitude of 253 ± 35 MPa, and the stress in the mid layer of AA1050 is also compressive, with a magnitude of 29 ± 5 MPa. It is interesting to observe that the residual stress at the outermost thickness of AA1050 is tensile in nature, with a magnitude of 56 ± 7 MPa.
7. The microhardness in the laser-irradiated zone of the SS430 layer ranges from 200 HV to a maximum of 272 HV, whereas the hardness in the AA1050 layer across the bent zone does not vary significantly.

5.2 Scope for Future work

(a) The configuration can be optimised to improve a variety of process characteristics, such as the utilisation of a variety of lasers and the utilisation of a variety of materials that are not constructed of metal. Furthermore, to achieve improved mechanical properties, it is possible to investigate technological developments, such as laser shaping. Simulation can be carried out to validate experimental findings, as stated in the second point.

(b) Furthermore, simulation can be utilized to do thermal stress analysis, distortion analysis, microstructural analysis, and phase analysis, among other types of analyses. In light of the fact that businesses require the formation of complex materials with high precision and minimal distortion, laser forming offers significant room for development.

(c) Future research is expected to focus on expanding its applicability to encompass complex alloys, composites, and multilayer laminated sheets, which are utilized in the aerospace, biomedical, and micro-electronics industries. This is projected to be the primary focus of future research.

(d) The introduction of enhancements in beam control, such as artificial intelligence-assisted route planning and real-time heat feedback, will result in increased precision and repeatability. This will be accomplished through the implementation of these innovations.

(e) The utilization of ultra-fast lasers, fibre lasers, and hybrid laser forming (laser with mechanical loading) would make it feasible to acquire high-strength lightweight materials that have a minimal amount of residual stress.

(f) By employing numerical simulation, digital twins, and predictive models founded on machine learning, it will be feasible to optimise parameters and reduce the amount of trial and error considered. In general, laser shaping is well-positioned to develop into a significant industrial technology that is not only automated but also adaptable and environmentally beneficial.

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List of Publications based on the Research Work

The following are the publications in journals and conferences based on the present work.

International Journals: -

1. Praveen Kumar Singh and Vijay Gautam (2025) "Experimental and Numerical Investigations for Laser Bending of a Three-Ply Clad Sheet Metal". Transaction of Indian Institute of Metals (Springer) 78:157 [https://DOI.org/10.1007/s12666-025-03631-w](https://doi.org/10.1007/s12666-025-03631-w).
2. Praveen Kumar Singh and Vijay Gautam (2025) "Investigations on laser bending of a 2-ply clad sheet and its microstructural evolution". Journal of Process Mechanical Engineering (Sage). DOI: 10.1177/09544089251368601

International Conferences: -

1. Praveen Kumar Singh and Vijay Gautam, "An advanced sheet metal forming process through laser technique", International symposium on fusion of science and technology (ISFT-2024), held at [J.C. Bose University of Science and Technology, YMCA Faridabad, Haryana](#), during Jan 04-08, 2024.
2. Praveen Kumar Singh and Vijay Gautam "Review- Laser forming technique, an advanced sheet metal forming process." International conference of research and innovation (ICARI-2024), held at Delhi state centre, Institution of Engineers, India, on Jan 28, 2024

3. Praveen Kumar Singh and Vijay Gautam "Laser bending of two ply sheets" International conference on Recent Advances in Mechanical Engineering for Sustainable Development (ISME-2024) held at Delhi Technological University, Delhi -110042 during July 11-13, 2024.

CURRICULUM VITAE

Mr Praveen Kumar Singh did B.Tech in Mechanical Engineering from U.P. Technical University, Lucknow, Uttar Pradesh (presently AKTU, Lucknow) in 2011 and M.Tech in Production Engineering from GB Pant Engineering College, Ghurdauri, Pauri Garhwal, Uttarakhand (Uttarakhand Technical University, Dehradun) in 2014, respectively. He is pursuing Ph.D in Mechanical Engineering from Delhi Technological University, India since January 2023 under the guidance of Prof. Vijay Gautam. He has published two SCI/SCIE-indexed papers and three international conference papers. He has three years of teaching experience at leading institutions, including the College of Technology, GBPUAT Pantnagar, Uttarakhand, and AIT Rampur, Uttar Pradesh. His research interests include mechanics, welding, reinforcement-based composites, optimization techniques. and forming of laminated composites.