CHAPTER 1- INTRODUCTION

Forming is an emerging technique which is widely used to shape industrial components [1]. Efforts has been continuously made by the researchers to enhance the forming process [2]. The forming of sheets by conventional methods with dimensional accuracy is very difficult and power consuming [3]. Also, the conventional forming methods, such as mechanical bending or stamping, can often lead to two common challenges: the edge effect and the spring back effect [4]. For most industries, the main focus is to fulfil the customer expectations by providing high quality products at the lowest cost and within the shortest time. The invention of lasers light amplification by stimulated emission of radiation (laser) in the 20th century has a profound impact on the manufacturing industry, enhancing precision, speed, flexibility, and quality across various manufacturing processes [5].

The first working ruby laser was built by American physicist and engineer Theodore H. Maiman in 1960 [5]. Laser beam sources are widely used in many manufacturing industries due to their dimensional accuracy and economic advantages [6-8]. Modern industries demand advanced, high processing efficiency, and precise processes to form industrial parts with higher production rates. Laser forming is such type of forming process widely utilized to form industrial parts [9]. it is a free-forming process in which a small volume of material is melted by using a laser beam and then moved in a controlled manner to shape or form a part [10]. Laser forming has been introduced three decades ago and it gained popularity ever since due to high dimensional accuracy [11]. Laser Forming is an developing manufacturing process to produce desired shape by plastic strain induced by non-uniform thermal stresses [12]. The control of plastic strain difference between the top and bottom surfaces is a fundamental principle in forming processes, allowing for the desired shaping and deformation of materials [13, 14]. Laser forming does offer advantages in terms of fastidiousness and potential cost savings, its availability and applicability increased across industries [15].

The industry, including various sectors such as aerospace, automotive, and manufacturing, is constantly focused on finding ways to reduce high labor costs and processing costs associated with manufacturing operations [16]. Laser forming offers several advantages in terms of eliminating the cost of specialized dies and reducing setup time [17]. The combination of non-consumable tools, flexibility in process parameters, reduced material waste, rapid prototyping capabilities, and improved efficiency contributes to the cost-effectiveness of laser forming [18, 19]. In laser forming, a defocused laser beam is used as the tool to shape and deform hard materials, and the forming process occurs due to induced thermal stresses rather than external forces [20]. The cooling effect is added to improve the properties of material. For rapid prototyping and manufacturing, it becomes an inexpensive and flexible manufacturing process [21, 22].

Laser forming process has been used for both ferrous and non-ferrous metals [23]. Non-ferrous metals are used in aerospace and automobile industries due to desirable properties like light weight, resistance to corrosion and machinability. Generally, Aluminum, Titanium, Copper, lead, Zinc, Tin and nickel are widely used in numerous industries [24-26]. In aerospace industries, compressor blades and structures are formed by laser-based forming of aluminum and titanium alloy's [27]. The material of the bent sheet plays a crucial role in the outcome of the forming process. The thermal and mechanical properties of the material significantly influence the forming behavior and the final result. Ferrous metals are characterized by their tensile strength, durability, magnetic properties, and their composition typically includes iron as the main component, along with varying amounts of carbon, nickel, chromium, and other elements [28]. The factors including low cost, high strength, wide range of properties, and a ease of fabrication have indeed made ferrous metals a preferred choice for various applications, including construction, automotive, machinery, appliances, packaging, and many more [29]. The laser forming technique has gained wide acceptance in these industries for the forming of all materials. In addition, laser forming method has minimum influence on the material properties of the formed parts as compared to other conventional processes [30, 31].

However, the higher setup costs and dimensional accuracy hinders its use in complex shapes such as automobile and aerospace parts. Some recent processes have emerged as a better alternative to such problems. Laser bending is one of such processes, which was introduced three decades ago and accepted in industrial sectors because of good dimensional accuracy [32]. It is an emerging technique that utilizes non-uniform thermal stresses to induce plastic strain and shape desired components [33]. Laser bending provide improved control over the process and potentially mitigate the spring back and edge effect as compared to some traditional methods [34-36].

1.1. Laser Bending Process

The basic principal of laser bending is ‘Flame bending’ which is introduced by ship building industries [37]. In flame bending, control and focus of flame is challenging, which can be overwhelmed with laser bending process [38].

In laser bending, the material sheet is typically clamped from one side while the other end remains free. When the laser beam irradiates a specific zone on the material surface, rapid localized heating occurs. The irradiated zone experiences thermal expansion due to the absorbed energy from the laser beam. However, the surrounding cold material resists this expansion, leading to induced compressive stresses in the irradiated area. At the same time, the surrounding area of the workpiece, which is not directly heated by the laser, remains relatively cooler and does not experience the same level of thermal expansion [17]. As a result, tensile stresses are induced in the surrounding area. The combination of induced compressive stresses in the heated zone and tensile stresses in the surrounding area leads to a bending moment in the material. This bending moment causes the workpiece to deform and bend [39].

In laser bending of sheet metals, the development of residual stress in the heated region is an important factor in controlling the bending angle [40]. The final shape of the work sheet is described by the scanning path of laser irradiation [41]. By precisely controlling the laser beam parameters, such as laser power, and scanning speed, the thermal gradient and resulting stress distribution can be managed to achieve the desired bending angle and shape. A line diagram of the laser bending process is shown in Fig. 1.1. One of the main advantages of laser bending is the absence of a physical tool interacting with the material [42, 43].

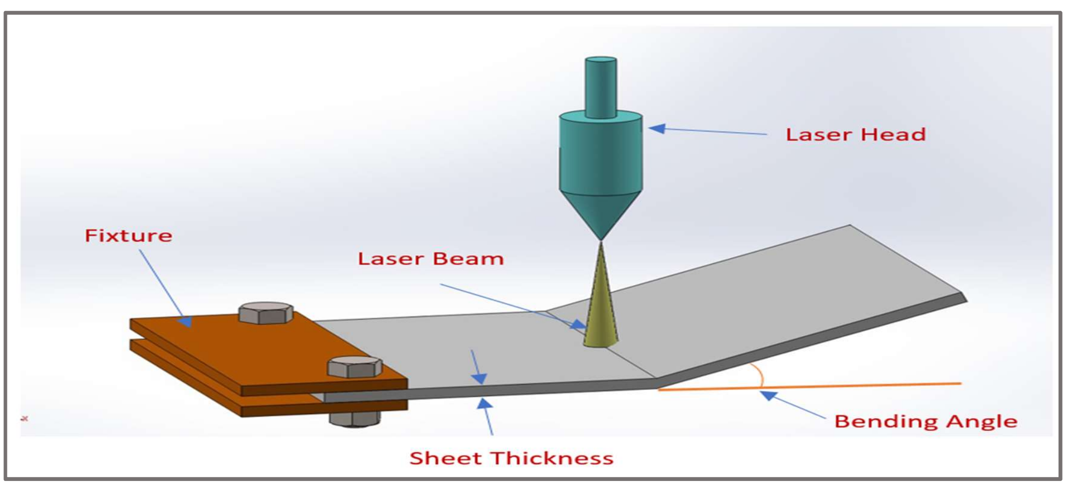

Fig. 1.1. Line diagram of laser bending process.

Three mechanisms responsible for laser bending are 1. Temperature gradient mechanism (TGM), 2. Buckling mechanism (BM) and 3. Shortening or upsetting mechanism (UM) as shown in Fig. 1.2. Bending is only possible with TGM and BM while UM assists in thickening and shortening of the work piece [44-46].

1.1.1. Temperature Gradient Mechanism (TGM)

Temperature gradient mechanism (TGM) is most common mechanism used in laser bending process [47]. It is developed due to high temperature difference with the thickness of sheet. Small bend angles can be produced in thick plates by TGM [48, 49]. A large temperature gradient is produced in this mechanism. TGM is initiated with small beam diameter as compared to thickness and high feed rate [50]. High feed rates should be used for higher thermal conductivity materials [51, 52]. In this mechanism, high temperature at the upper surface and lower temperature at bottom of the metal causes the workpiece to bend [53, 54]. TGM occurs in two stages heating and cooling of the work sheet. During heating, the thermal expansion occurs in the heated zone which results the bending of the work sheet opposite side to laser source known as counter bending. The thermal expansion is resisted by temperature difference of upper and bottom surface of work sheet which results compressive stresses in the heated zone [55]. The bending of material occurs, when induced thermal stresses reach the temperature dependent flow stress. The plastic deformation is compressive at upper surface and in small amount at bottom surface due to low temperature [56]. During cooling the material contracts towards laser source. The shortening at the upper surface is due compressive plastic deformation which results the bending of work piece [38]. TGM is one of the most leading mechanisms in laser forming in which more than 3° bend angle can be achieved in a single pass [57, 58].

The BM and the UM need a uniform temperature gradient along workpiece thickness in comparison to TGM [38]. Both the TGM and BM techniques enable the production of out-of-plane bending or folding in sheet metal [59].

1.1.2. Buckling Mechanism (BM)

Buckling Mechanism is used for thin sheets where the temperature differences do not exist in top and bottom part of metal sheets [60]. When high conductivity materials are irradiated with large beam diameter as compared to sheet thickness with slow speed of beam than buckling mechanism ensued [61, 62]. Uniform thermal expansion in BM is due to the negligible temperature gradient. Compressive stresses in heated regions are induced due to the restriction of thermal expansion by surrounded cooler material. Due to this, buckle is formed in heated zone [38]. When the sheet thickness is small and the coefficient of thermal expansion and temperature dependent flow stress are high, the tendency of buckle is to be extended with laser irradiation. The bending of the workpiece starts when the plastic deformation occurs in buckle due to thermal stresses exceeding the temperature dependent flow stresses. This mechanism is used to bend thin sheets and bending direction is towards or away from laser beam depends upon internal stresses, and external forces [56]. The large bend angle can be generated in a single laser scan than the TGM [63].

1.1.3. Upsetting Mechanism (UM)

The upsetting mechanism (UM) is also known as shortening mechanism as work piece becomes short in length along the direction in the laser irradiated region [64]. UM is similar to buckling mechanism, however the beam diameter is much lesser than sheet thickness in case of UM [65]. Which makes the work piece rigid enough to restrict the buckling. The temperature gradient in this mechanism is negligible [38]. This mechanism occurs when laser scanning of thick sheet is processed at slow laser scan speed and small beam diameter [66]. As the temperature difference is not existed between the upper and bottom surface the thermal expansion is same for both surfaces. Which is resisted by surrounding cooler material. As a result, compressive stresses are generated in heated zone. The plastic deformation occurs when induced thermal stresses reaches the temperature dependent flow stress. The plastic deformation is compressive and almost same at the upper and bottom surfaces [38]. The sheet is compressed along the thickness, results shortening and thickening of work sheet [56].

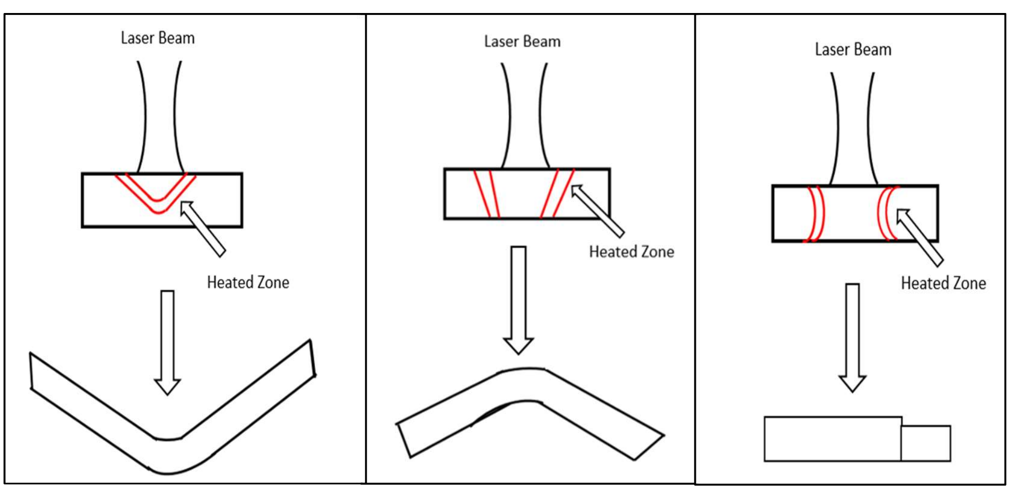

Fig. 1.2. Laser bending mechanism (a) temperature gradient mechanism (TGM) (b) buckling mechanism (BM) (c) upsetting mechanism (UM).

1.2. Electromagnetic-Force-Assisted Laser Forming (EMFLF)

The use of controlled electromagnetic force in combination with laser heating for the laser bending process is an innovative and precise method. This technique offers several advantages, including the ability to apply force without physical contact and reach inaccessible areas. In Electromagnetic-Force-Assisted Laser Forming work piece is clamped from one side only and the magnet holder is placed over the top of the strip as shown in Fig. 1.3. The gap between the workpiece and magnet can be adjusted by the movement of the magnet holder. To activate the electromagnet and set the desired current level, the automatic power source is connected to the circuit. The ammeter is placed in series with the circuit to measure and monitor the current flowing through the electromagnet. By utilizing the attractive force generated by the electromagnet, laser bending processes can achieve enhanced bending angles compared to conventional bending methods. One of the main advantages of electromagnetic force is that the electromagnetic field does not have physical contact with the metal being formed. More precision in bending can be achieved by adjusting the power supply and gap between the electromagnet and work piece. In addition, the uniform distributed load in place of point-load is another benefit of electromagnetic-force.

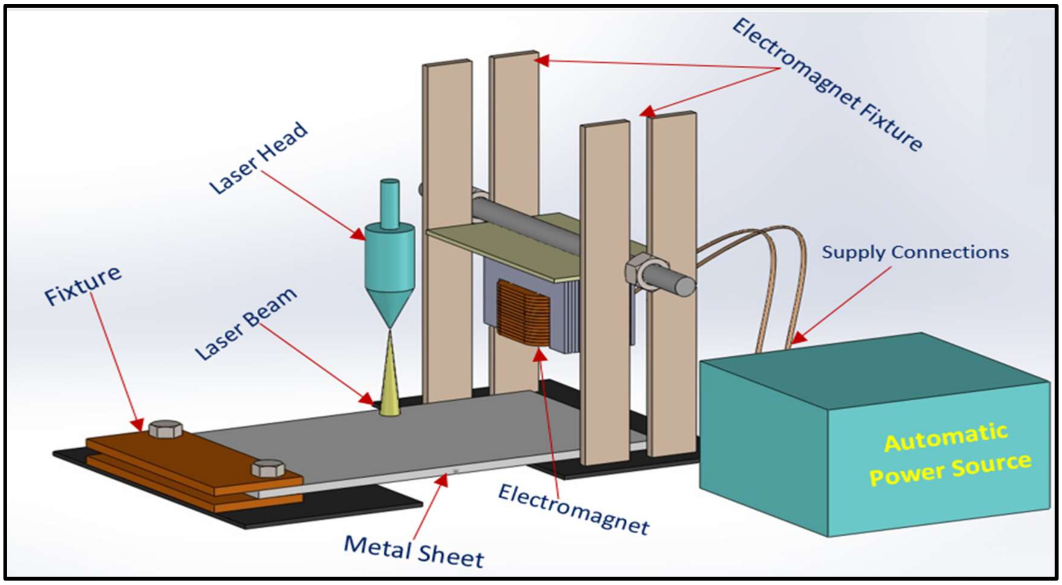

Fig. 1.3. Electromagnetic-force-assisted laser forming setup.

1.3 Applications of Laser Bending

❖ The application of laser technology in materials processing, including cutting, hardening, welding and forming, is indeed increasing rapidly [67].

- The versatility, precision, and control offered by lasers make them indispensable in the production of critical components in electronics, aerospace, biomedical instrumentation, automobiles, and shipbuilding industries [38, 68, 69].
- By eliminating the need for expensive tooling and offering greater flexibility in the manufacturing process, laser bending enables faster and more cost-effective prototype evaluations in industry sectors include automotive, shipbuilding, chemical and sensor industries [70-72].
- Laser bending is widely used as an accurate and cost-effective process for various applications, including adjusting or aligning mating parts in welding constructions, shipbuilding industry, and straightening distorted parts such as car body parts [73-75].
- Sheet forming can indeed be a feasible alternative for cost-effective sheet metal forming in batch production sectors such as prototype, automotive, aerospace, and biomedical industries. [76, 77].
- Laser bending provides a viable solution for bending brittle materials [78, 79]

1.4. Advantages and Disadvantages of Laser Bending

Laser bending has several advantages that have been highlighted by researchers [80-83]. Here are some of the main advantages of laser bending:

- Laser bending has excellent control on laser beam.
- Laser bending is a non-contact of laser beam and material technique.
- Laser bending does not require any special tools and dies.
- Laser bending reduces the cost of small batch production by eliminating the need for special dies and their associated maintenance costs.
- The process is suitable for precise, accurate and small bend angles, particularly micro bending, which may not be possible with conventional bending method.
- It can be used for complex shapes used in aerospace and automobile industry.
- The bending can be obtained below the melting point of metal results reduce the defects.
- The laser can bend ferrous and non-ferrous allows even the metals which not able to bend with the conventional method.
- It is a high-energy efficiency process due to flexibility and control over the other

heat based bending processes like flame bending.

- ❖ A laser beam can be transported in complex areas through optical cables, where the conventional mechanical tools are not accessible.

Along with the advantages, there are some limitations observed in laser bending [38, 84]. These limitations include:

- ❖ Process effectiveness depends on absorptivity of material. Coating is required to increase the absorptivity.
- ❖ Sheet metals with high thickness are difficult to bend using laser bending methods.
- ❖ Laser bending process is a slow process as compared to conventional bending processes not suitable for mass production.
- ❖ Special care is required to avoid oxidation problems in sheet metal bending.
- ❖ Initial setup cost is high as compared to other press like die bending.
- ❖ It is very time-consuming process.

1.5. Scope of the Present Thesis

The objective of the thesis is to design and develop the electromagnetic assisted laser bending setup and study the performance of laser bending process under the influence of electromagnetic force and cooling conditions for the mild steel. The accuracy and efficiency of the laser processing are influenced by various factors, including laser process parameters such as laser power, scanning speed, and laser beam diameter, as well as electromagnetic setup parameters like air gap, current, and cooling conditions, encompassing both natural and forced cooling methods. The thesis explores efficient techniques to enhance the bend angle and minimum the edge effect. Evaluation of micro-hardness, tensile strength and microstructure analysis is also a part of the study.

1.6. Organization of the Thesis

The current research work has been presented in the six chapters: -

Chapter 1 introduces the laser bending processes and highlights the significance of electromagnetic force assisted laser bending process. It is an emerging technique for various industrial applications. The present research has focused on the development and optimization of electromagnetic force assisted laser bending process and the study of combined effect of forced cooling and laser bending input parameters on mild steel.

Chapter 2 presents the extensive literature review related to laser bending techniques. In this chapter the influence of various process parameters, cooling conditions and external load on laser bending characteristics are reviewed. Also, the effects of work-sheet geometry on laser characteristics are studied. Based on this review, research specific problems are identified, and objectives of the research are defined.

Chapter 3 demonstrates the experimental details and strategies that have been adopted for the experimentation. Moreover, the testing procedure for laser bending charactertics i.e., bend angle, edge effect, micro-hardness, tensile strength, scanned electron microscopy and testing sample preparation are discussed.

Chapter 4 summarizes the results and discussions of the study regarding laser bending of mild steel with different working environments. The laser bending performance has been examined with respect to bend angle, edge effect and various mechanical and metallurgical properties viz. micro-hardness, tensile strength and SEM microstructural analysis. The comparison of natural and forced cooling during laser bending for mild steel is also described.

Chapter 5 analyses and discusses the effect of electromagnetic force assisted laser bending on mild steel. The influence of laser parameters and electromagnetic conditions on mild steel during laser bending is also discussed.

Chapter 6 compiles the conclusions drawn from the present research work. Additionally, highlights the future scopes regarding laser bending.