CHAPTER 6 -CONCLUSIONS AND FUTURE SCOPE

Several studies report that the applications of laser bending in manufacturing industries are limited due to low bend angles and long production times during multiscan laser bending. Even though researchers made efforts to increase efficiency by applying external assisted force, optimization of process parameters, using repeated irradiations, forced cooling conditions, etc., but the bend angle improved up to certain limit. Additionally, limited research has been done on the edge effect that occurs due to the conditions of laser bending process. Moreover, the effects of post-bending on microstructure and mechanical properties have not been extensively studied. The objective of this study to enhance the bend angle per scan during laser bending of mild steel by applying forced cooling and electromagnetic force assistance on free end. The current study explores the effects of process variables (laser power, beam diameter, scan speed) on the bend angle under both forced and natural cooling conditions. Additionally, the study thoroughly investigates the mechanical characteristics (hardness and tensile strength) and metallurgical properties (microstructure using SEM) of the bent specimen for both natural and forced cooling environments. Furthermore, the effect of the air gap between the worksheet and the electromagnet and the applied current on the characteristics of the laser is explored. The Enhancement of accuracy and efficiency of laser based bending process further enhanced with controlled electromagnet, which seemed to be potential field of research both in term of accuracy and efficiency of result. The different technical findings and overall conclusions are as follows:

6.1. Forced Cooling Assisted Multi-Scan Laser Bending

An experimental study on multi-scan laser bending of mild steel is performed for both natural and forced cooling conditions. The objective of the proposed study is to determine how different cooling regimes, such as forced and natural, affect mild steel during the laser bending. The impact of laser variables such as beam diameter, scanning speed and laser power on bending angle, edge effect, micro-hardness and tensile strength is examined. The microstructure analysis is also examined by scanning electron microscope (SEM). The resulting conclusions are as follows:

- It is concluded from the findings that, in the presence of forced cooling, increase in laser power is accompanied by a decrease in scan speed and a small beam diameter resulting in an increase in bend angle. This may be due to the higher laser power, lower scan speed, and a smaller beam diameter can contribute to the development of a steep temperature gradient in a material, especially when combined with forced cooling conditions.

- The edge effect can be reduced with the low beam diameter and scan speed under forced cooling condition. The precise control over laser parameters can help mitigate irregularities caused by edge effect. When the laser power is increased during laser processing, it can result in a higher variation in the bending angle along the scan line. This is because more energy is being delivered to the material, leading to an increase in the edge effect. The observation suggests that achieving a uniform temperature distribution helps reduce the edge effect.
- Higher laser power and slower scanning speed result in higher temperature on the top surface during the laser scanning process for both natural cooling and forced cooling conditions.
- In the natural cooling condition, the maximum surface temperature is higher as compared to the forced cooling for all process conditions. This may be due to the heat loss in the natural cooling is less than the forced cooling. In addition, the rapid cooling at the bottom surface in forced cooling contribute to decrease temperature of lower surface than upper surface of sheet.
- SEM micrographs of the bent specimen showed that phase transition and fine grain structure are observed at 1000 W laser power, 1000 mm/min scan speed, and 4 mm beam diameter. However, under forced cooling conditions, additional grain refinement is accomplished at laser power of 1000 W, scanning speed of 1000 mm/min, and beam diameter of 4 mm. This is mainly attributed due to high temperature gradient.
- The ultimate tensile strength of bent samples is increased under forced cooling conditions with an increase of laser power and reduction in scanning speed. This might be attributed to a decrease in ductility imposed by a higher laser power and lower scan speed under forced cooling conditions.
- The higher micro-hardness is achieved at higher laser power, lower value of scan speed and beam diameter under forced cooling condition. It may be due to a more grain refinement and phase transformation at these parameters.
- Overall, the results demonstrated that forced cooling significantly improved the bend angle during multi-scan laser bending. The microstructural composition,

mechanical characteristics, and edge effect of the bent specimens were also improved by the forced cooling condition. It also decreased the total manufacturing time by shortening the time between subsequent scans. The findings demonstrated the potential of forced cooling to increase the overall efficiency of the laser bending process in industries.

6.2. Electromagnetic Force Assisted Laser Bending

The proposed study is focused on the development and enhancement of forming characteristics during electromagnetic-force-assisted laser forming. The arrangement of electromagnetic-force-assisted laser forming is successfully investigated for the different combinations of laser power, beam diameter and scan speed. The influence of input parameters on electromagnetic-force-assisted laser bending of mild steel is analyzed with respect to bend angle, edge effect, micro-hardness, tensile strength and microstructure. The following significant conclusions are obtained:

- From the obtained results, it has been observed that the input process parameters have significant effect on the bend angle. The highest bend angle is obtained on laser power of 1000 W and scanning speed of 1000 mm/min and the lowest bend angle is obtained on laser of 400 W and scanning speed of 2500 mm/min. Because the higher laser power and slower scanning speed are responsible for high peak temperature, which results in increases of bend angle.
- In addition, it has also been revealed that the value of bend angle is increased after every five laser scans for all experimental conditions. This is mainly due to the high heat produced by increasing the number of laser scans.
- Applied current plays an important role in bend angle. For a specific gap, bend angle increased with the increase in applied current. It may be due to the magnetic attraction increases with the increase in current.
- At high power, low scan speed and higher magnetic field, the worksheet strongly attracted towards the electromagnet, which results uniform bend angle along the scan line. This also reduced the edge effect. Thus, the edge effect is very less in electromagnetically assisted laser bending.
- Scanning electron microscope (SEM) images demonstrate the grain refinement embryonic microstructural changes are obtained during electromagnetic-force-assisted laser bending at higher laser power (1000 W) and lower scanning speed (1000 mm/min).

- The highest value of micro-hardness is obtained on laser power of 1000 W and scanning speed of 1000 mm/min and the lowest value of micro-hardness is obtained on laser of 400 W and scanning speed of 2500 mm/min. Results of high hardness are mainly attributed due to the fine grain structure of irradiated zone.
- In conclusion, this research contributes the enhancement in bend angle by the application electromagnetic field. The dimensional accuracy of bent specimen in the form of edge effect can be reduced by electromagnetic assisted laser bending. These findings have the potential to revolutionize manufacturing industries where precision and dimensional accuracy of products are critical. Like other laser bending processes, electromagnetic force-assisted laser bending also leads to improvements in the mechanical and metallurgical properties of the materials. The study highlights its potential to positively impact the manufacturing industry by enhancing product quality and precision.

6.3. Scope for Future Work

Although many research findings are available on laser based bending in the literature, several issues need further investigations. Some of these are as follows:

- There are some publications in the literature on use of different coating in laser bending process. However, this aspect may further be investigated to enhance the process.
- Exploration laser bending under forced cooling for non-linear irradiation paths and complex geometries.
- Study of underwater laser bending under different conditions.
- Effect of forced cooling during laser bending with different thickness of material.
- The FEM model for laser assisted bending by using permanent magnet and electromagnet.
- There is a need for more experimental exploration of laser bending of non-ferrous metals using electromagnetic force.
- More experimental research on the metallurgical characteristics of various materials is required.

6.4 Limitations of Present Research work

1. The expenses associated with experimental setup for present study is significantly greater as compared to conventional methods.

2. The complexity of the experimental setup in the current research presents a limitation compared to the straightforward nature of traditional laser bending methods.
3. It is slow a process as compared to traditional bending methods.