CHAPTER 5- ELECTROMAGNETIC FORCE ASSISTED LASER BENDING

In this chapter, experimental results of different levels of parameters i.e. laser power, scanning speed, beam diameter, applied current, and air gap with electromagnetic effect during laser bending of mild steel are discussed. The laser bending performance of mild steel is examined with respect to laser characteristics viz. bend angle, mico-hardness, microstructure, tensile strength and edge effect by altering the process parameters.

5.1. Bend Angle

The average values of bend angle at different conditions of laser bending with the application of electromagnetic force are reported in this section. It has been observed that bend angle gradually increases with the effect of electromagnetic force and optimum combinations of parameters. The variations in bend angle with electromagnetic assisted laser bending for mild steel under different conditions are shown in Figs. 5.1 to 5.5.

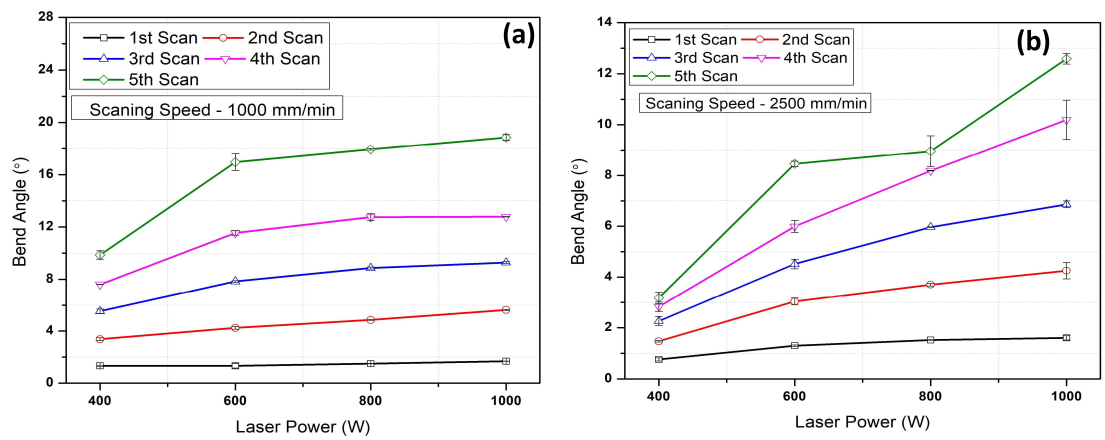

Fig. 5.1. Variation of bend angle with laser power at (a) scanning speed 1000 mm/min, beam diameter 4 mm, air gap 20 mm (b) scanning speed 2500 mm/min, beam diameter 4 mm, air gap 20 mm.

The influence of laser power, number of scans and scanning speed on bend angle of formed mild steel strip is shown in Figs. 5.1 (a & b). It is observed that the bend angle increases with the increase of laser power, number of passes and decreases with increase of scanning speed. The observation reveals that the bend angle increases with higher laser power and the number of passes, while it decreases with an increase in scanning speed. This phenomenon can be attributed to the thermal stresses generated during each pass. Plastic deformation occurs at both the upper and bottom surfaces, exhibiting a compressive nature. In addition, steel strip is attracted towards electromagnet and due to this an increase in bend angle is achieved. With the increase in number of passes and laser power the plastic deformation of upper surface of strip increases because the magnitude of compressive stresses increases at upper surface. In each laser scan, peak temperature at both top and bottom surfaces of strip increases than the previous laser scan. The work piece is preheated in the previous laser pass, which results the increases in bend angle after every laser scan [8].

It is clearly revealed that the value of bend angle gradually increased with laser power and decreased with the increase in scanning speed. The highest bend angle18.85° is obtained at laser power of 1000 W and scanning speed of 1000 mm/min and the lowest bend angle 3.17° is obtained at laser power of 400 W and scanning speed of 2500 mm/min, as shown in Fig. 5.1 (a) and (b). It is observed that the maximum bending of material is achieved due to the combined effect of electromagnetic force and laser power. Dutta et al. [27] supported the results that at lower scanning speed and higher laser power bend angle increases with the application of electromagnet force. Yadav et al. [58] reported that the slow scanning speed is responsible for the longer interaction time between the laser and the strip, which results in high-energy absorption and increases in bend angle. It can be seen from Fig. 5.1 (b) that the bend angle gradually increases with an increase in laser power at every level of scanning speed. It is mainly due to the more heat immersion, which leads to higher peak temperature and that results in the increase in bend angle [215].

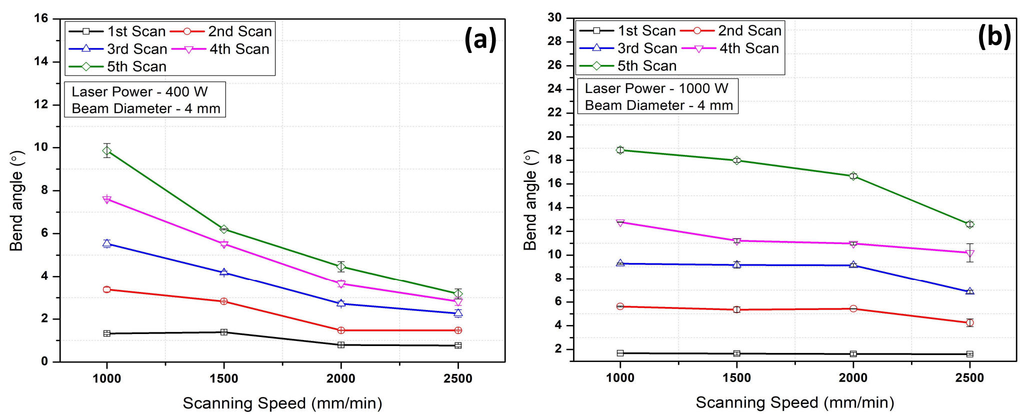

Fig. 5.2. Variation of bend angle with laser power at (a) scanning speed 1500 mm/min, beam diameter 4 mm, air gap 20 mm (b) scanning speed 2000 mm/min, beam diameter 4 mm, air gap 20 mm.

The trends in Figs. 5.2 (a) and (b) show that the increase in scanning speed results in lowering the bending angle. With the increase in scanning speed the time required to generate temperature gradient between upper and lower surface is not sufficient. Moreover, the material could not have sufficient time to soften at the line of scan. However, the effect of electromagnetic force and laser power is also considerable in this combination of parameters. The bend angle is increases by the combined effect of electromagnetic force of attraction and high laser power even at high scanning speed. Dutta et al. [27] reported in their study that compressive stresses are induced due to high laser power, which are also responsible for higher bend angle even at high scanning speed.

Due to the elevated temperature, the thermal stress is notably higher at the upper surface, consequently leading to an increase in plastic deformation [250]. The results obtained from Figs. 5.2 (a) and (b) show that the values of bend angle increase with every laser scan even at high scanning speed. Similar trends in results are reported by Roohi et al. [120]. Thus, the plastic deformation of mild steel strip occurs due to the electromagnet force, higher laser power and low scanning speed. The trends in Figs. 5.2 (a) and (b) show that the increase in scanning speed results in lowering the bending angle. With the increase in scanning speed the time required to generate temperature gradient between upper and lower surface is not sufficient. Moreover, the material could not have sufficient time to soften at the line of scan.

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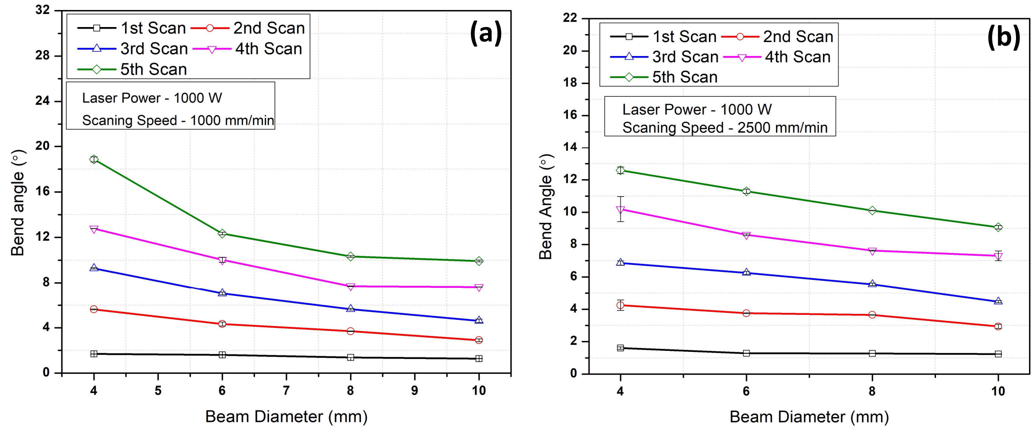


Fig. 5.3. Variation of bend angle with beam diameter at (a) scanning speed 1000 mm/min, air gap 20 mm (b) scanning speed 2500 mm/min, air gap 20 mm.

The influence of laser geometry in terms of beam diameter on bend angle is shown in Figs. 5.3 (a) and (b). The highest bend angle value of 18.85° is obtained at the laser power 1000 W, scanning speed 1000 mm/min and beam diameter 4 mm. The bend angle decreases with the increase in beam diameter shown in Fig. 5.3 (a). This is mainly due to the heat flux density and heat absorption. Because, with the increase in beam diameter the flux density and heat absorption rate is decreases, resulting in low peak temperature and temperature gradient [251]. The bend angle increases from 1st pass to 5th pass. It may be due to the preheating of mild steel strip due to previous scans. When scanning speed is increased with beam diameter as shown in Fig. 5.3 (b) bend angle has a reverse relation with both parameters. The higher value of bend angle remains higher with higher laser power at beam diameter of 4 mm even at speed of 2500 mm/min but it is lower than that the value of bend angle achieved at 1000 mm/min scanning speed. The lowest value of bend angle 9.92° is observed at 10 mm beam diameter. The reason for decreasing in bend angle with increase in beam diameter is that by increasing the beam diameter, the laser beam energy is applied to the wider surface, thereby the intensity of the temperature gradient reduces [118].

The results show that beam diameter and laser power have great influence on bend angle. The significant value of bend angle can be achieved by controlling the diameter of beam. Further, the beam diameter can be controlled by adjusting the distance between the focusing lens and the metal strips [184]. Shi et al. [31] also reported that the bending angle increases with the increase in laser power and decreases with the increase in laser spot diameter and scanning speed.

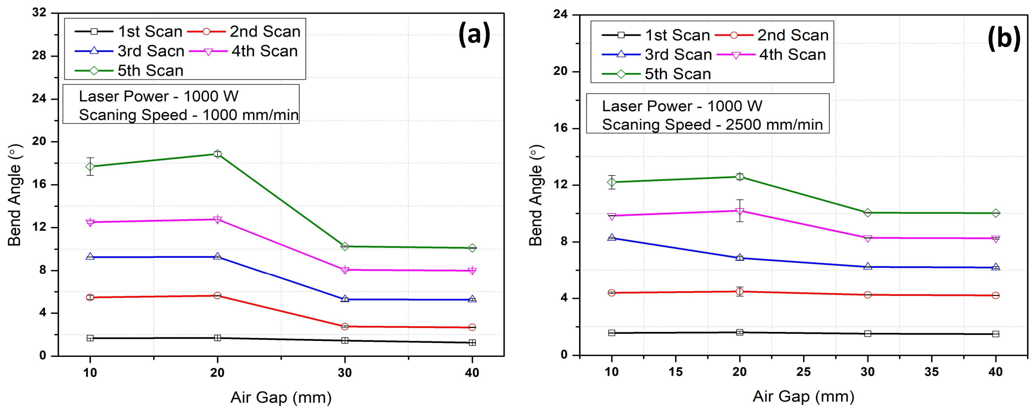


Fig. 5.4. Variation of bend angle with air gap at (a) scanning speed 1000 mm/min, beam diameter 4 mm (b) scanning speed 2500 mm/min, beam diameter 4 mm.

The position of specimen in the influence of electromagnetic field also plays vibrant role in variation of bend angles under different conditions. Fig. 5.4 (a) shows that the highest value of bend angle of 18.85° is obtained at air gap of 20 mm and the centre of electromagnet. This is mainly due to decreasing electromagnetic force as the distance between the magnet and mild steel strip increases. Consequently, electromagnetic attraction force increases as the distance decreases between the mild steel strip and electromagnet. Therefore, the value of bend angle (18.85°) is highest at 20 mm distance between the substrate strip and electromagnet.

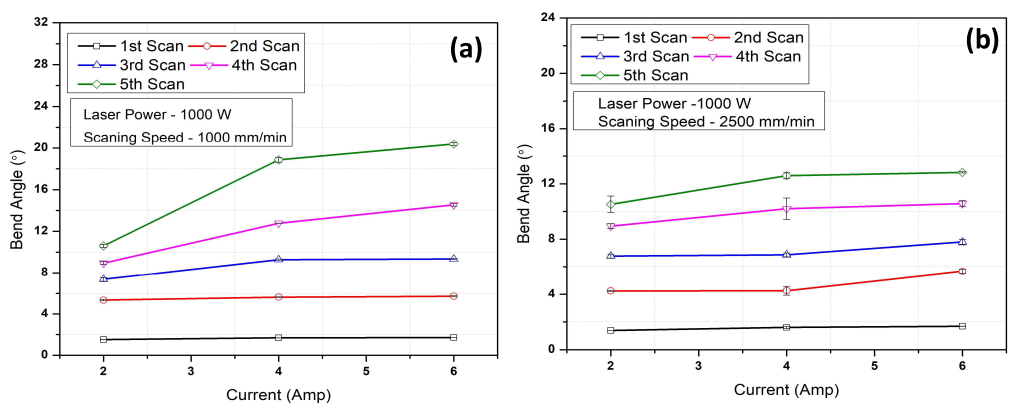


Fig. 5.5. Variation of bend angle with applied current at (a) scanning speed 1000 mm/min, beam diameter 4 mm, air gap 20 mm (b) scanning speed 2500 mm/min, beam diameter 4 mm, air gap 20 mm.

Laser power and air gap has a great impact on bend angle as shown in Fig. 5.4 (b). It is observed that when laser power is increased to 20 mm air gap, the bend angle also increases on scanning speed 2500 mm/min. Consequently, the highest value of bend angle 12.58° at the scanning speed of 2500 mm/min is also obtained on laser power 1000 W as shown in Fig 5.4 (b). The bending angle increases by increasing the laser power. This may be due to the higher residual stress are induced in the strip, resulting in high bend angle at higher laser power [252].

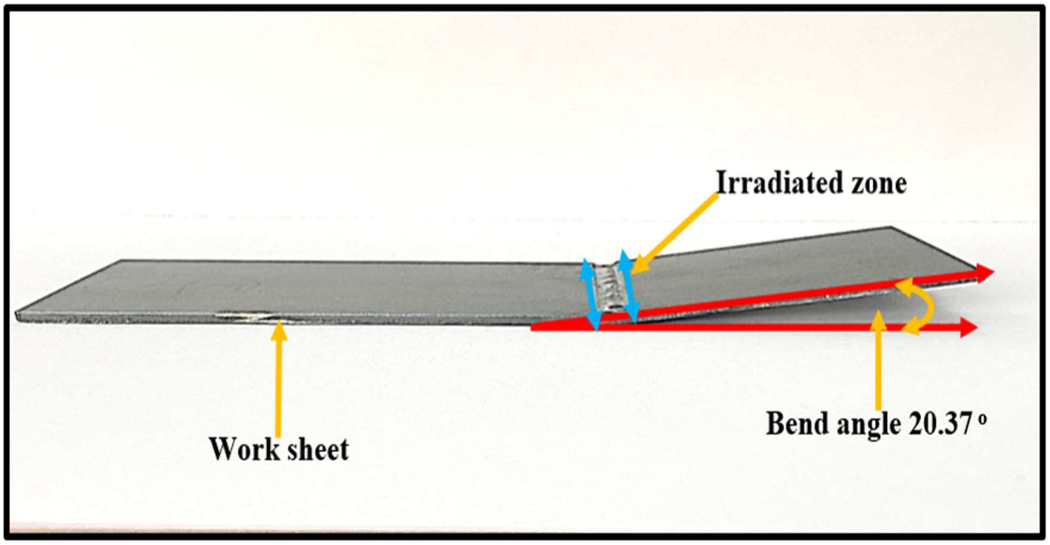


Fig. 5.6. Pictorial representation of bending of mild steel sheet with maximum bend angle (20.37°).

The electromagnetic field is generated with DC current supply has great impact on the electromagnetic attraction of strip, which resulting higher values of bend angle. Figs. 5.5 (a) and (b) illustrate the influence of direct current on bend angle with the proportion of electromagnetic field generation. As it is observed that when the direct current is increased, the magnetic force also increases because this bend angle is gradually increased after every pass. The highest value of bend angle 20.37° is obtained at 6 amp current with laser power of 1000 W and scanning speed of 1000 mm/min as shown in Fig. 5.5 (a). The Pictorial representation of bending of mild steel sheet with maximum bend angle (20.37^0) is shown in fig. 5.7. Choi and Baek [112] reported in their research that when the value of applied current increases, the magnetic force increases, resulting in higher bend angle. However, in Fig. 5.5 (b), it can be seen the bend angle is obtained at higher scanning speed with the impact of applied current is less.

5.2. Edge Effect

The influence of electromagnetic force and process parameters on edge effect along the laser scan line is shown in Figs. 5.7-5.11. Edge Effect can be calculated by the ratio of maximum variation of bend angle along the scan line to average bend angle.

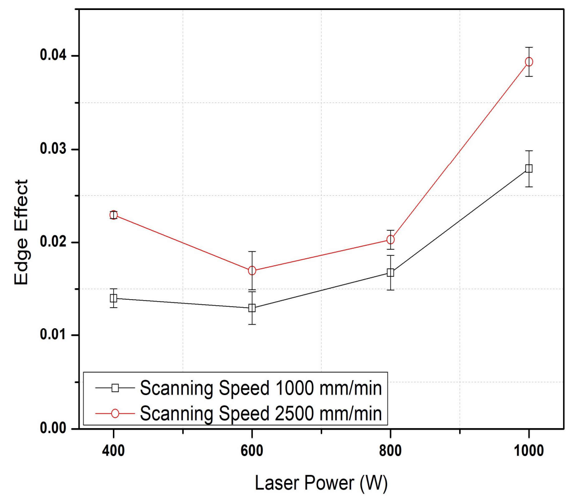


Fig. 5.7. Edge effect versus laser power.

It is observed from Fig. 5.7 that the edge effect is increased with the increase in laser power. It may be due to the reason that the temperature variation is more at high laser power. At high laser power the amount of energy delivered by the laser, is increased, the intensity or impact of the "edge effect" also increases. The thermal expansion of heated zone increases with the increase of the heat input energy [225]. However, the effect of magnetic force significantly affected the edge effect. It is observed that the worksheet is attracted towards the electromagnetic field, which results in the uniformity in bend angle along the scan line.

When the laser power is set at a low level, the heat input energy into the material is also low. However, the presence of an electromagnetic field has a strong influence, and this combination has the effect of minimizing the "edge effect". Similar findings are reported by Dutta et al. [27].

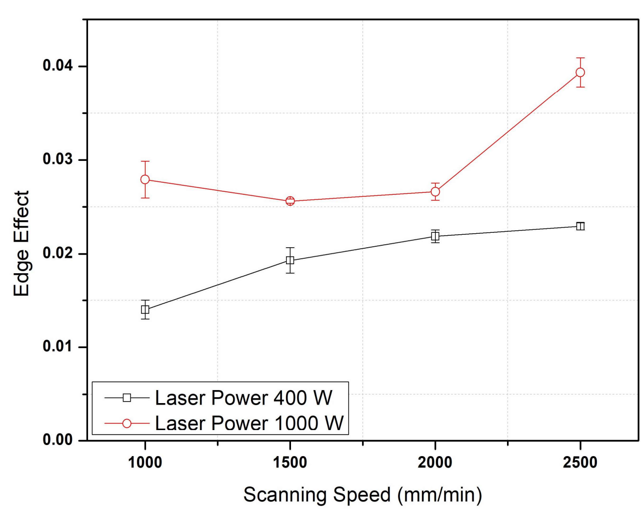


Fig. 5.8. Edge effect versus scanning speed.

A higher scanning speed results in a greater influence of the edge effect on the material being processed as shown in Fig. 5.8. As the scanning speed of the laser beam is increased, the edge effect becomes more pronounced. This may be due to, at higher scanning speeds, the amount of time the laser beam spends interacting with any specific point on the workpiece is reduced. When there's less time for the laser to interact with the material at the edges, it can lead to uneven heating, cooling, or material response, resulting in a more pronounced edge effect. On contrast to this, the low scanning speed provide sufficient time to laser beam and worksheet, which may provide uniform temperature distribution along the scan line. The low scanning speed combined with the presence of the electromagnet, results in a stable and controlled positioning of the worksheet during the laser processing operation. The strong magnetic attraction, generated by the electromagnet, plays a crucial role in achieving a uniform bend angle along the scan line during laser processing.

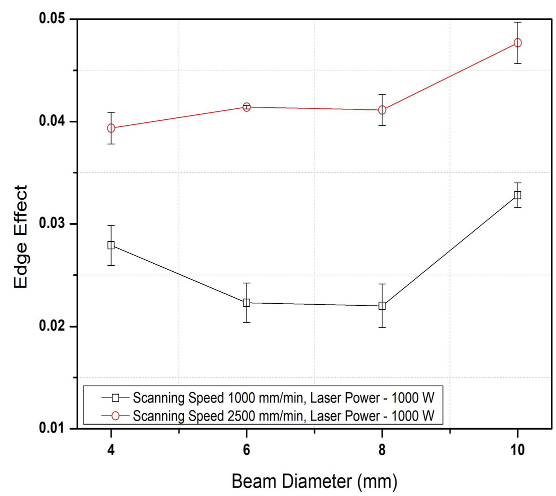


Fig. 5.9. Edge effect versus beam diameter.

The influence of beam diameter on edge effect is shown in Fig. 5.9. It is observed that the with the increase in beam diameter edge effect is vary considerably. The higher edge effect is observed when using a higher beam diameter during a laser processing operation. It may be due to the increase in the beam diameter, the laser delivers heat energy over a larger surface area of the material being processed. The broader distribution of heat energy can lead to uneven temperature distribution within the material. The edge effect is likely more pronounced because the uneven temperature distribution can lead to greater variations in material properties near the edges of the processed area. Hu et al. [233] also reported that edge effect reduces with smaller diameter due to the high concertation of heat at small area of worksheet. The electromagnetic force contributes to minimize the variation of bend angle along the scan line.

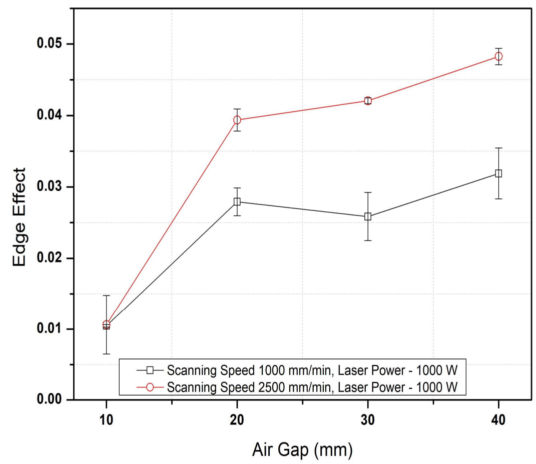


Fig. 5.10. Edge effect versus air gap.

The distance between the work sheet and electromagnet during experimentation is referred as air gap. The air gap is adjusted by the movement of electromagnet through grooves in fixture. Fig. 5.10 illustrates that the maximum edge effect is observed at a higher air gap. It may be due to the magnetic effect decreases as the electromagnet moves away from the worksheet. As the air gap increases (the distance between the worksheet and the electromagnet), the intensity of the magnetic field decreases. When the distance between the worksheet and the electromagnet is reduced (a lower air gap), this results in stronger magnetic attraction between them, which improves the edge effect.

The edge effect reduces with the increase of current supplied to electromagnet as shown in Fig. 5.11. It is observed that with the increase of current, it results in a stronger magnetic field being generated by the electromagnet.

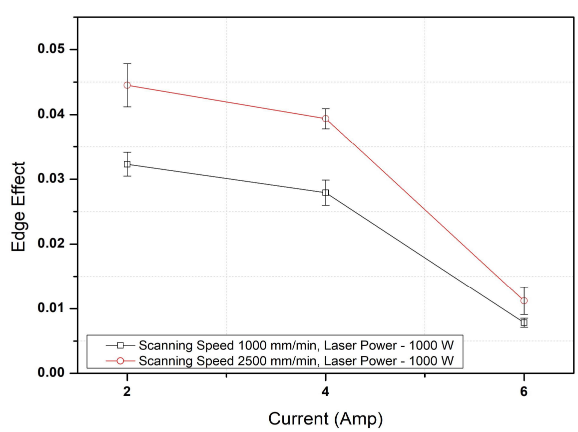


Fig. 5.11. Edge effect versus current.

The increase in the intensity of the magnetic field due to the higher current reduces the intensity or prominence of the edge effect during the process. The combined effect of laser power and high magnetic force minimizes the edge effect. In a way, electromagnet acted as a fixture that restrained the movement of strip. Thus, uniform bend angle was obtained along the width direction [27].

5.3. Microstructure Analysis

Microstructural analysis has been analyzed to reveal the effect of process parameters of electromagnetic assisted laser bending on the mechanical properties. The SEM micrographs for the highest bend angle **(**20.37°**)** at laser power of 1000 W, scanning speed of 1000 mm/min, beam diameter 4 mm and applied current 6 amp are shown in Figs. 5.12 (a-d).

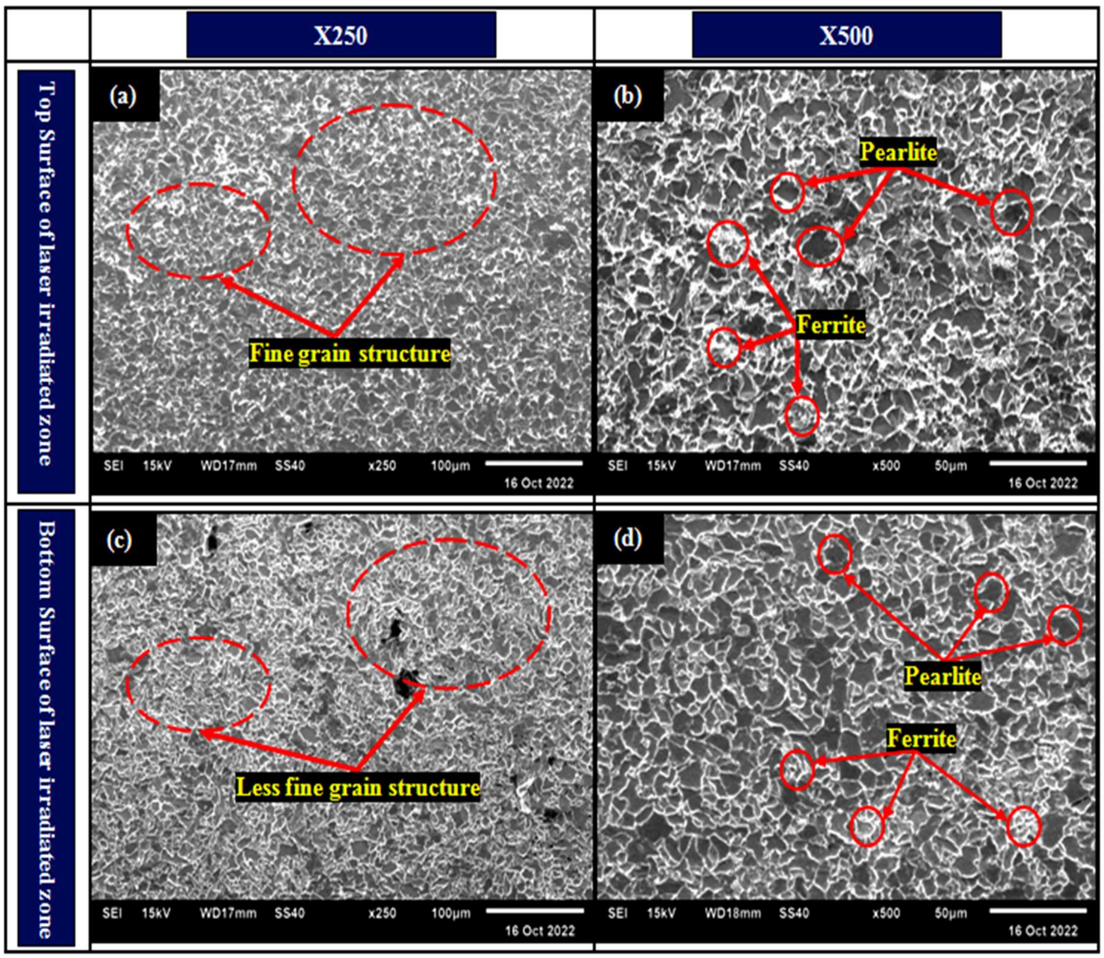


Fig. 5.12. Microstructures at laser power 1000 W, scanning speed 1000 mm/min, (a) upper surface at 250X zoom (b) upper surface at 500X zoom (c) bottom surface at 250X zoom (d) bottom surface at 500X zoom.

Figs. 5.12 (a) and (b) show top surface of laser irradiated mild steel strip after five passes. It can be seen that the grains are refined at upper surface after laser irradiation. Because the strain hardening is more at the upper surface due to the higher temperature. The phase transformation from ferrite to pearlite is may be the hardening of material after recrystallization. The average grain size at laser power 1000 W, scanning speed 1000 mm/min is observed 4.1 µm.

Fetene et al. [52] reported that after each pass the grains are finer than previous scan which may be the reason for workpiece hardening. As shown in Figs. 5.12 (a) and (b) grains are finer at the upper surface than bottom surface; it may be due to the temperature difference. It can also be observed at higher laser power more plastic deformation and cooling rate is observed than the lower laser power, resulting in fine grain structure.

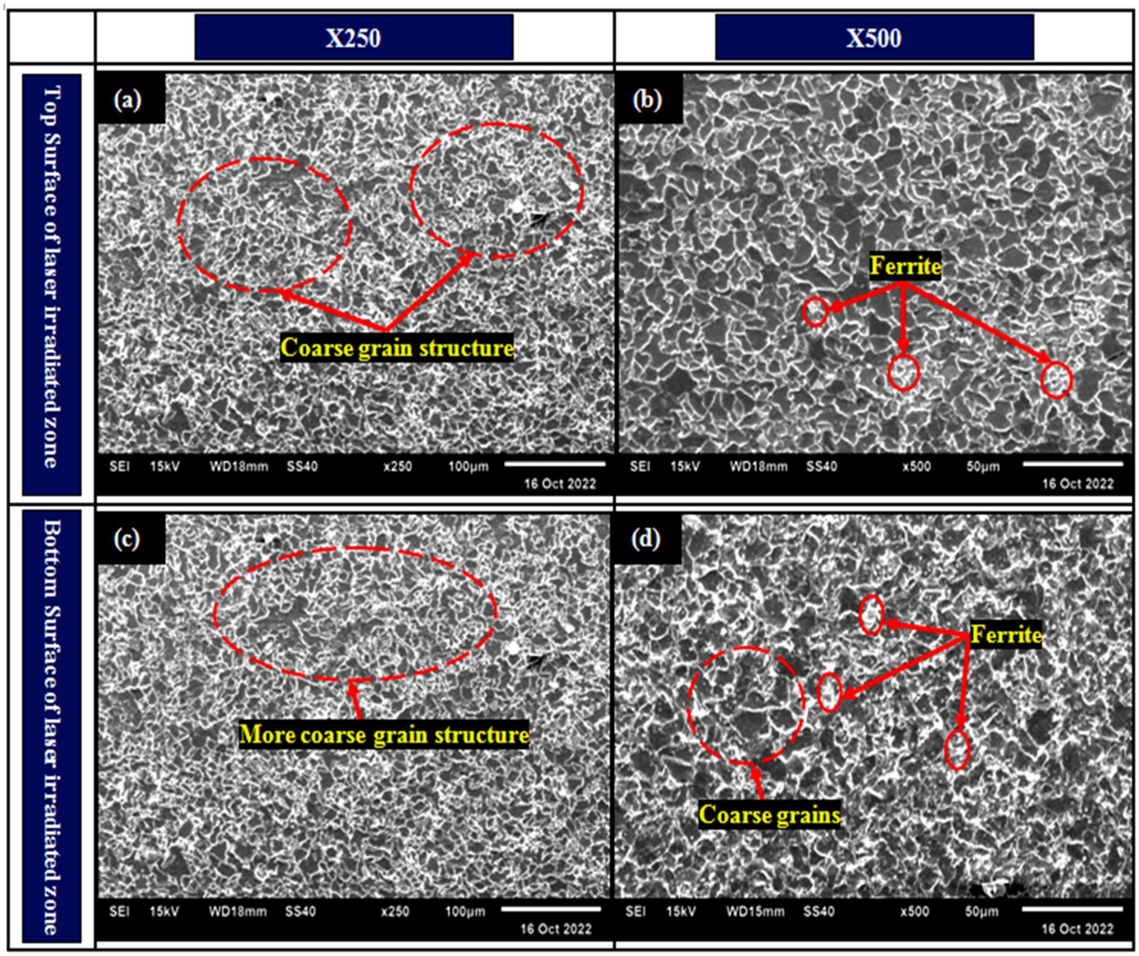


Fig. 5.13. Microstructures at laser power 400 W, scanning speed 2500 mm/min, (a) upper surface at 250X zoom (b) upper surface at 500X zoom (c) bottom surface at 250X zoom (d) bottom surface at 500X zoom.

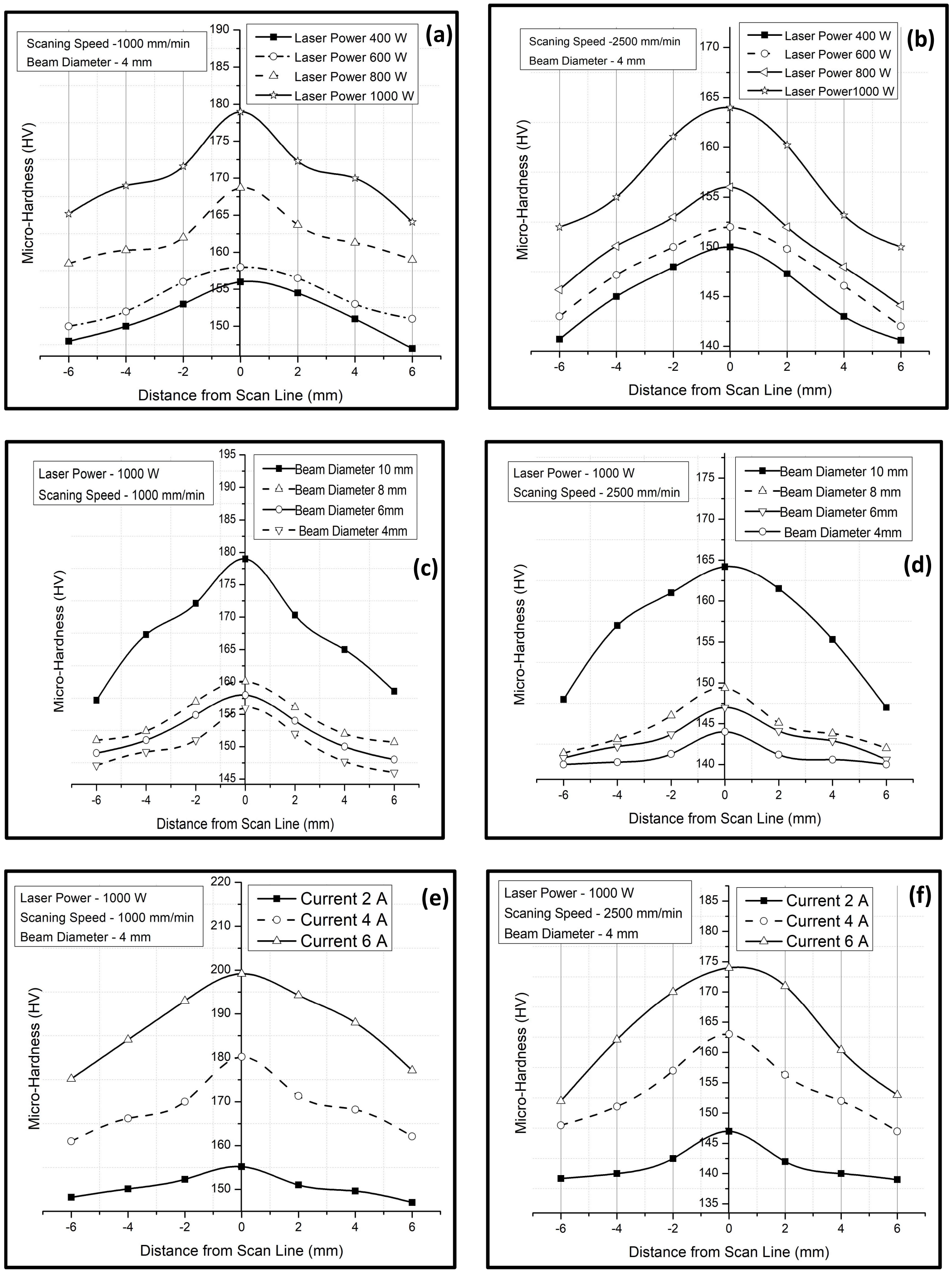
The visible white part on the micrographs is ferrite and the dark part is the pearlite, as shown in Figs. 5.12 (a-d). Similar trends in results are also discussed by Cheng and Lawrence Yao [203] and Souza et al. [138]. Fetene et al. [8] reported that the grain refinement in the irradiated zone of laser bending is due to increase in the number of laser pass.

The uneven grain structure is obtained at laser power 400 W and scanning speed 2500 mm/min due to low energy absorption as shown in Figs. 5.13 (a-d). Moreover, the bend angle obtained at same condition is lower than other conditions. The bending may be due to the peak temperature at the upper surface and recrystallization of grains in bottom surface is not successful as compared to upper surface, which results to more coarse grain structure, as shown in Fig. 5.13 (c) and (d). The high scanning speed does not provide sufficient time for interaction between the laser beam and worksheet, which may be responsible for low plastic deformation and coarse grain structure. The lower laser power of 400 W produces lower heat input during the laser bending process leading to uneven structure. The average grain size at laser power at laser power 400 W and scanning speed 2500 mm/min is observed 9.6 μm.

5.4. Micro-Hardness

The variation of micro-hardness of mild steel perpendicular to the scanning line at different laser powers, scanning speeds, beam diameters and applied currents is shown in Figs. 5.14 (a-g) presents. It can be noted that micro-hardness is increases with increase of laser power. Dutta et al. [246] and Fetene et al. [8] also reported that the heating of material is higher at high laser power, which results increases in hardness. It has also been observed that low scan speed (1000 mm/min) allows the sufficient time of interaction between the material and laser beam as compared to high scanning speed of 2500 mm/min. The effect of scan speeds (1000 & 2500 mm/min) with laser powers, beam diameters and applied currents on micro-hardness is shown in Figs. 5.14 (a-g). The common trend on both scanning speeds (1000, 2500 mm/min) is obtained that the micro-hardness gradually increased with laser power.

The highest value of micro-hardness (179 HV) is obtained at laser power of 1000 W and scanning speed of 1000 mm/min as shown in Fig 5.14 (a). This may be due to the higher heat produced with higher laser power, which is responsible for the finer structure, as shown in Fig. 5.12 (a). Moreover, another reason for the high hardness is that the ferrite structure transfers to pearlite at these parameters. The enhancement in micro-hardness represented the grain refinement is described Hall Petch formula by Wu et al. [253]. When scanning speed is increased to 2500 mm/min the value of micro-hardness 164 HV is obtained at laser power of 1000 W as shown in Fig. 5.14 (b).



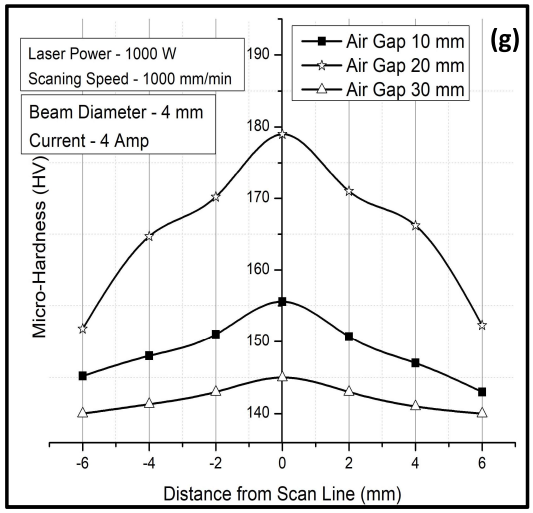


Fig. 5.14. Change in micro-hardness with change of (a-b) laser power (c-d) beam diameter (e-f) applied current and (g) air gap.

According to beam diameter, the micro-hardness decreases with increase of beam diameter, as shown in Fig. 5.14 (c-d). This may be due to the temperature gradient is decreases with the increase of beam diameter, which may be the cause of low temperature at the irradiated region resulting in low micro-hardness. Kant et al. [39] reported that heat flux density and temperature gradient decreases with increase in laser beam diameter. Similar research findings are also reported by Masoudi Nejad et al. [90]. The highest value of micro-hardness 199.2 HV is obtained at applied current of 6 amp on laser power of 1000 W and scanning speed 1000 mm/min as shown in Fig. 5.14 (e-f). The micro-hardness of laser-irradiated region depends on electromagnetic force of attraction. The increases in current value results in higher electromagnetic force of attraction, resulting in small plastic deformation along with laser scan line.

The variation in micro-hardness with the air gap of strip and electromagnet is shown in Fig. 5.14 (g). The higher value of micro-hardness (179 HV) is obtained at 20 mm air gap on laser power of 1000 W and scanning speed of 1000 mm/min. The optimum distance between the electromagnet and work material is 20 mm for laser power 1000 W and scanning velocity 1000 mm/min reported in this study. The higher distance decreases the electromagnetic forces of attraction as discussed for Figs. 5.4 (a) and (b). The value of micro-hardness decreases with the increase in distance from the scan line [27]. The highest value of micro hardness is obtained at the scan line due to the heat and refinement of grain structure in irradiated zone.

5.5. Tensile Strength

Micro-tensile test is performed to examine the impact of laser scanning on mechanical characteristics. The stress-strain curves for laser-bent samples at higher scanning speed (2500 mm/min) and greater laser power (1000 W) under forced and natural cooling conditions are depicted in Fig. 5.15. The tensile strength is measured along the scan line. It has been observed that the tensile strength decreases with the increase in scanning speed and beam diameter. In contest to that, higher value of tensile strength is observed at lower scanning speed and smaller beam diameter. It may be because of at a low lower scanning speed and smaller diameter the heating is more as compared to the high scanning speed and higher bend angle, which results in the larger heat affect zone.

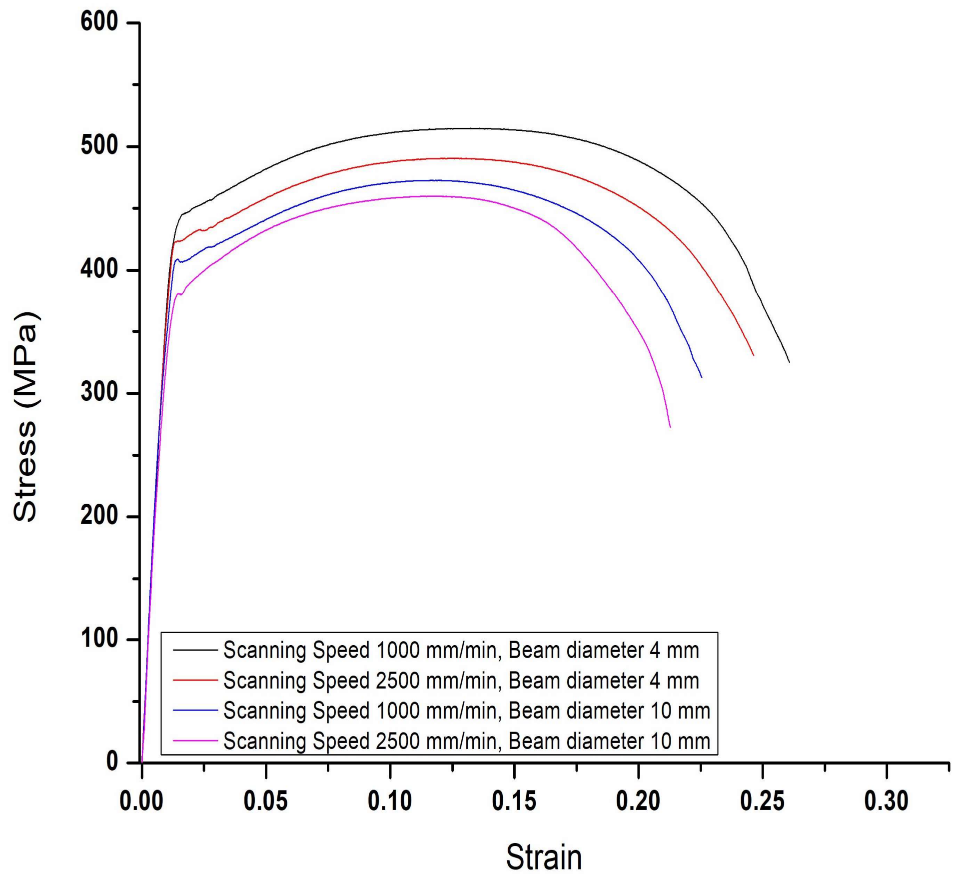


Fig. 5.15. Stress- Strain curve obtained from the tensile test of specimens.

The maximum tensile strength is observed at higher laser power as shown in Fig. 5.16. This may be due to the higher heating leading to more deformation, which results in high strain hardening. It is observed that the maximum tensile strength 546.85 MPa is observed at laser of 1000 W and scanning speed of 1000 mm/min. This may be due to the phase transformation occurs at high laser power of 1000 W and lower scanning speed of 2500 mm/min.

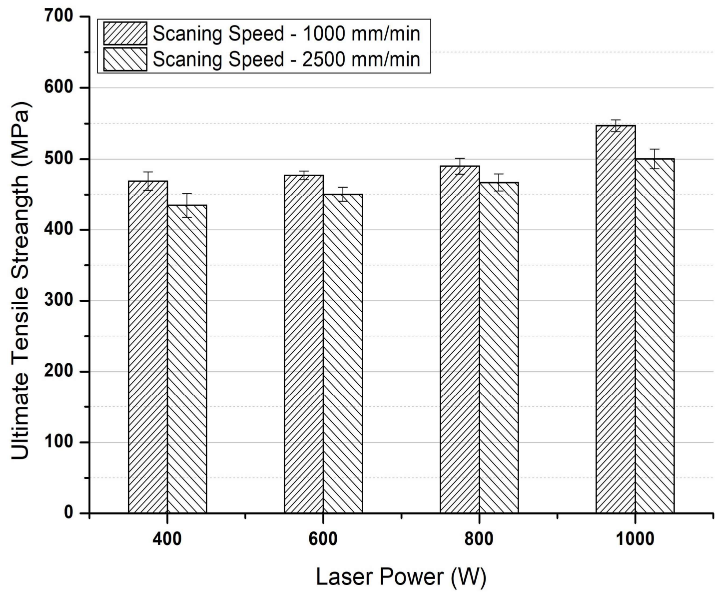


Fig. 5.16. Tensile strength variation with laser power.

The lowest tensile strength 434.32 MPa is obtained at laser power of 400 W and scanning speed of 2500 mm/min. This is because of low laser power and high scanning speed provide insufficient heat during the laser bending, which results coarse grain structure at irradiated zone. It is observed that when the scanning speed increases the highest tensile strength is obtained at high laser power. he increase in strength may be accompanied by reductions in ductility [85]. It is observed that the ultimate tensile strength increased with the increase in number of scans. Similar findings reported by [118]. The combined effect of high heat input from higher laser power and strong magnetic field attributes the fine grain structure, which may be responsible for the high strength. It is observed from Fig. 5.16 that the ultimate tensile strength is gradually increased with laser power.

5.6. Summary

This chapter proposes a forming procedure for obtaining large bend angles by laser irradiation with controlled electromagnetic force. The effect of various parameters, such as scan speed, laser power, beam diameter, and number of scans on bend angle, and edge effect is investigated. The mechanical and metallurgical properties of bent specimens are also examined.

- The application of electromagnetic force increases the bend angle significantly.

The bend angle increases with increasing laser power and decreases with increasing scan speed.

- The applied current has a significant impact on bend angle. For a certain gap, the bend angle increased with applied current. Further Increase in the gap results decrease in bend angle.
- The bend angle was the highest at high laser power, low scan speed, smaller beam diameter and higher magnetic force. The movement of the sheet is restricted because of the strong magnetic attraction during laser bending process. Due to this, the edge effect is reduced. Thus, the edge effect is very less in electromagnetically assisted laser bending.
- Micro-hardness increased with an increase in laser power and decreased with increased laser scan speed. The fine grain structure and phase transformation at high laser power leads to high micro-hardness. The coarse grain structure at higher scan speed is responsible for lower value of micro-hardness. It also exhibits an increase with applied current since higher current results in a stronger force of attraction, which could result in specific mechanical formation.
- The high value of ultimate tensile strength is obtained at higher laser power and lower scanning speed.

The ability to be adequately controlled in accordance with process requirements is the main advantage of electromagnetic force over other types of assisting forces. It may be precisely activated and deactivated during the beginning and end of laser irradiation, providing ease and accuracy. As a result, industrial implementation of this technology is more acceptable.