CHAPTER 4 – FORCED COOLING ASSISTED LASER BENDING

The experimental observations recorded from varying laser power, scanning speed, and beam diameter, for natural and forced cooling conditions are described in this chapter. Furthermore, the effects of cooling conditions on bend angle, temperature, micro-hardness, and tensile strength are discussed. Microstructure analysis using a scanning electron microscope (SEM) is also described to analyze material structure-property correlations and phase transitions. This section also discusses the edge effect for both natural and forced cooling conditions as measured by a coordinate measuring machine.

4.1. Bend Angle

The variation in the bending angles under natural and forced cooling conditions during laser bending of mild steel are presented in this section. Overall, the steady increase in bending angle with forced cooling and optimal process parameters is observed. The influence of cooling conditions i.e natural and forced on bend angle at different process parameters is shown in Figs. 4.1 to 4.8.

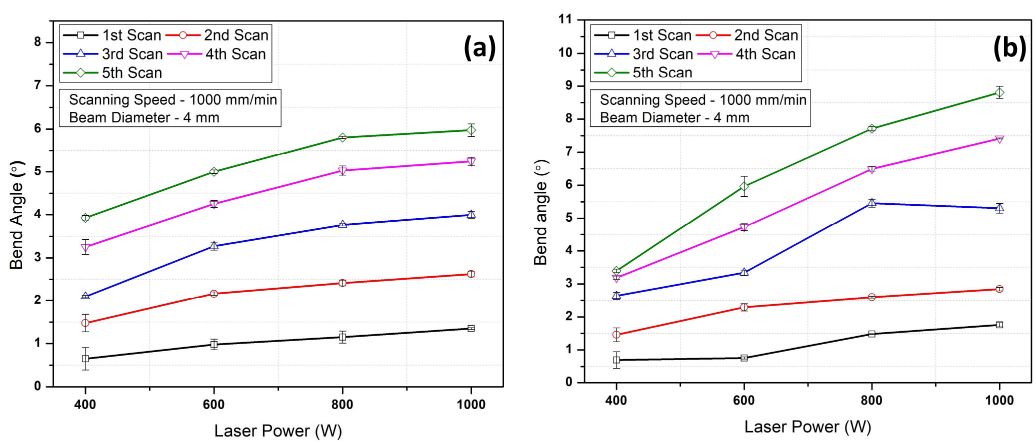

Fig. 4.1. Change in bend angle with laser power at scanning speed 1000 mm/min (a) natural cooling condition (b) forced cooling condition.

The influence of laser power and number of scans on bend angle under natural and forced cooling conditions at a constant scan speed of 1000 mm/min is shown in Figs. 4.1 (a and b). The observations reveal that by combining higher laser power and multiple passes, the material experiences greater cumulative heating, which enhances its deformability and results in a higher bending angle [118].

The bend angles obtained under forced cooling conditions are higher compared to natural cooling conditions, as shown in Fig. 4.1 (b). It is due the sustained temperature gradient achieved through forced cooling. Yadav et al. [58] observed that longer cooling time and forced cooling can help to maintain temperature gradient, which contributes to larger bend angle.

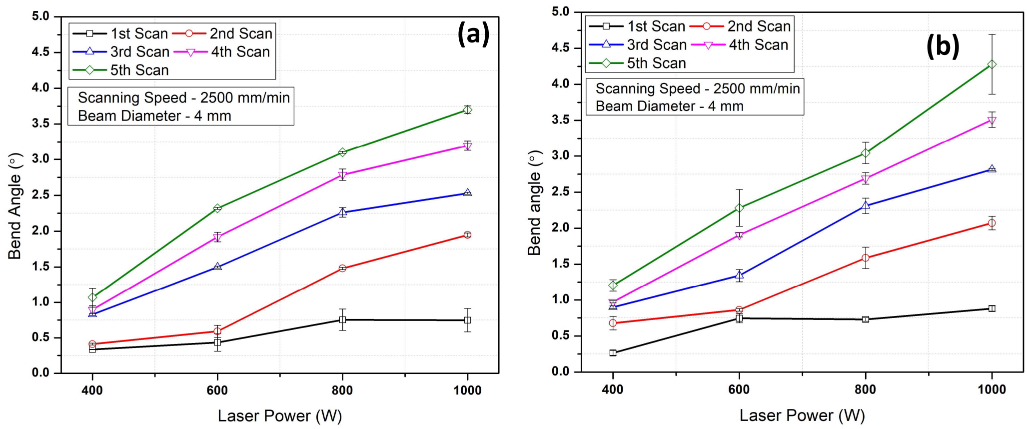

Fig. 4.2. Change in bend angle with laser power at scanning speed 2500 mm/min (a) natural cooling condition (b) forced cooling condition.

A visual representation of the decreasing trend in bend angle with increasing scan speed up to 2500 mm/min is observed in Figs. 4.2 (a) and (b).Yadav et al. [209] reported that the difference between top and bottom surface deformation reduces with high scanning speed. It is observed that process parameters influence considerably the outcome of the laser bending process. Figs. 4.1- 4.2 show that the higher scan speeds in combination with different laser powers result in smaller bending angles as compared to lower scan speeds. It is because when the scan speed is increased, the laser beam spends less time interacting with the material. As a consequence of the shorter heat transfer duration, the material has less time to absorb the heat energy from the laser beam. Observations reveal an increase in bending angle at high laser power and with forced cooling but the effect of higher scan speed is dominating. This is due to shorter cooling time leading to lower heat dissipation and lower scan speed does not contribute to a significant temperature drop at the sample surface. Lambiase et al. [139] also concluded that with the higher laser power and lower scan speed, the interaction time increases, which leads to a higher bend angle.

The highest recorded bending angle is 8.81°°, which is achieved with the combination of a laser power (1000 W) and a scan speed (1000 mm/min) along with forced cooling. It is because the forced cooling condition at the bottom surface enhances the temperature gradient. Cheng and Lawrence Yao [203] also reported high deformation of material due to the steeper temperature gradient in forced cooling condition. The lowest bend angle 1.20° is achieved with a specific combination of laser power 400 W, scanning speed of 2500 mm/min, and natural cooling. This is because the higher scan speed with natural cooling decreases laser-worksheet interaction time, which reduces the temperature gradient, resulting in low bend angle. It has been observed that the bend angle is drastically enhanced after each scan. This is because the worksheet is preheated after every scan. In contrast to this, cooling is required in multi-scan laser bending to achieve steep temperature gradient [26]. Due to this, the forced cooling conditions lead to a larger bending angle as depicted in Fig. 4.2 (b).

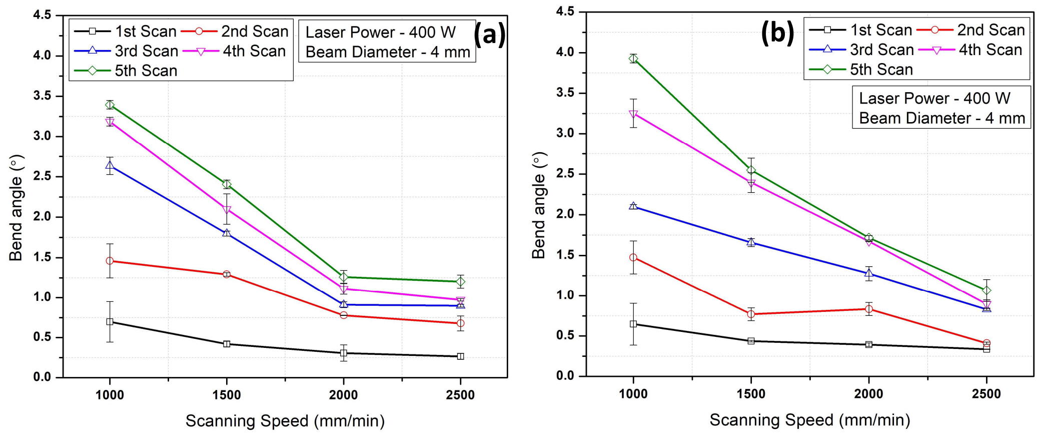

Fig. 4.3. Change in bend angle with scan speed at laser power of 400 W (a) natural cooling condition (b) forced cooling condition.

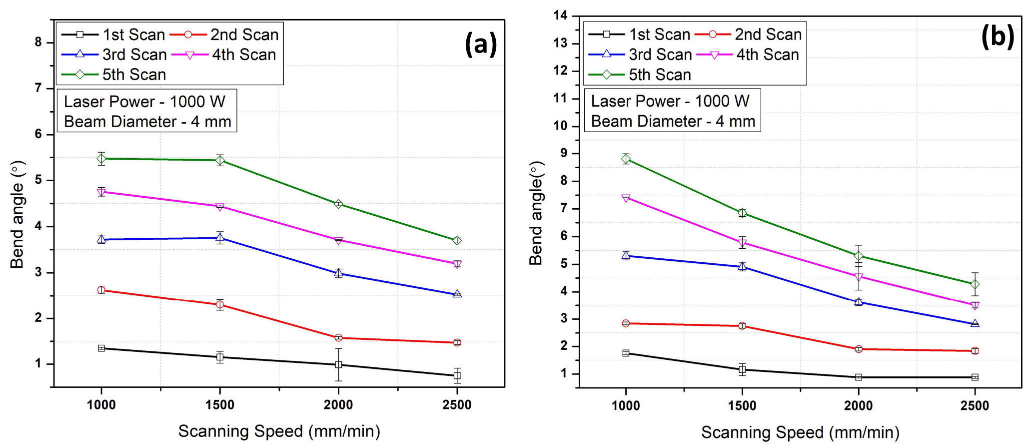

Fig. 4.4. Change in bend angle with scan speed at laser power of 1000 W (a) natural cooling condition (b) forced cooling condition.

The change in bending angles with scan speed at laser power of 400 W under both natural and forced cooling conditions is shown in Figs. 4.3 (a) and (b). It has been observed that the bending angle is decreased when the scan speed is increased. This is because the low laser power and high scan speed attributed to the reduced temperature gradient between the upper and bottom surfaces of the material.

Based on the observations from Figs. 4.4 (a) and (b), it is evident that the bending angle decreases as the scan speed increases, irrespective of the cooling conditions (both natural and forced cooling). However, the higher bending angle is achieved at a laser power of 1000 W when compared to the laser power of 400 W. This is because the higher laser power is attributed to the high heat input, which is favorable for the deformation. In forced cooling conditions, higher bending angle is obtained as the rapid cooling assists in increasing the temperature gradient [58].

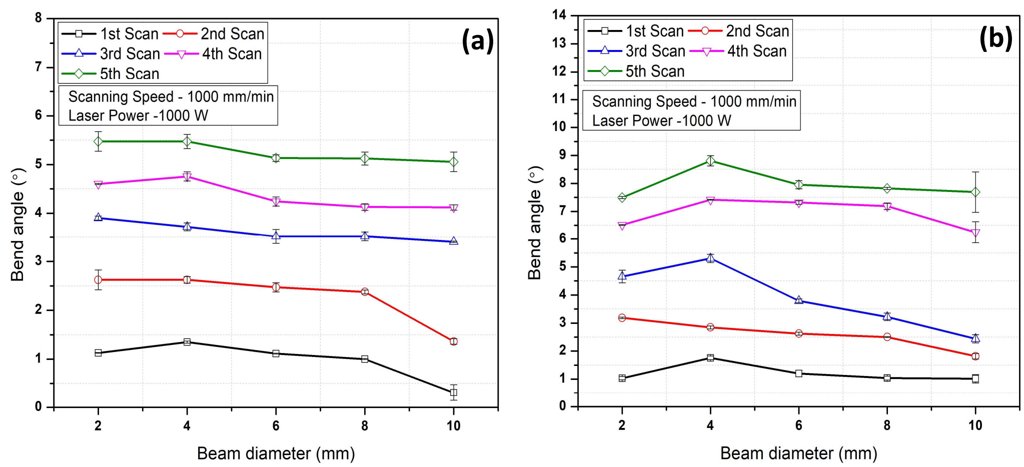

Fig. 4.5. Change in bend angle with beam diameter at scanning speed of 1000 mm/min (a) natural cooling condition (b) forced cooling condition.

The findings from Figs. 4.5 (a) and (b) highlight the influence of beam diameter at laser power of 1000 W and scanning speed of 1000 mm/min on the bending angle for both cooling conditions i.e. natural and forced cooling. The bending angle is found to be decreased by increasing the beam diameter for both cooling conditions. It is because the increase in beam diameter results in a lower concentration of heat in the laser bending process, which leads to lower bend angle. Kant et al. [243] observed in their study that increase in beam diameter the energy from the laser is spread over a larger area, which reduces the temperature gradient.

Fig. 4.5 (b) shows that the cooling effect has less influence at high beam diameter even at higher laser power. However, at these conditions the temperature gradient is more as compared to the natural cooling conditions.

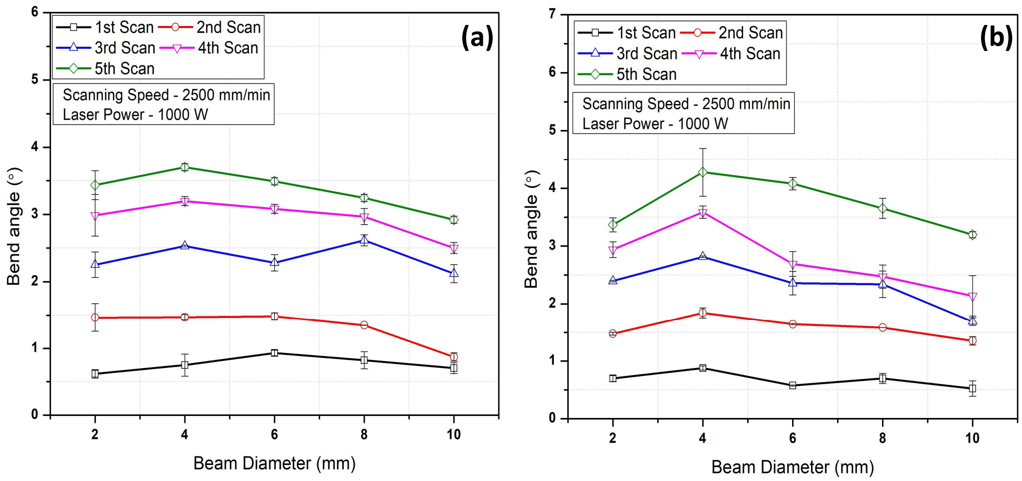

Fig. 4.6. Change in bend angle with beam diameter at scanning speed of 2500 mm/min (a) natural cooling condition (b) forced cooling condition.

The influence of higher scanning speed with variation of beam diameter laser power of 1000 W and scanning speed of 2500 mm/min for both cooling environments is shown in Figs. 4.6 (a) and (b). The bending angle is slightly higher in case of forced cooling compared to natural cooling as shown in Fig. 4.6 (b) shows. The bend angle achieved at the higher scan speed of 2500 mm/min is smaller as compared to the angle achieved at lower scan speed of 1000 mm/min, while the value of beam diameter is constant of 10 mm. The bending angle achieved at scan speed of 2500 mm/min and beam diameter of 10 mm is lower than scan speed of 1000 mm/min and beam diameter of 10 mm. It is due to the high heat input from higher laser power and low heat dissipation rate due to higher scan speed. Therefore, based on the comparison presented in Fig. 4.6 (a) and (b), the importance of forced cooling can be seen clearly and it can be observed that the forced cooling conditions promote more significant bending angles compared to natural cooling conditions because the rapid cooling maintains the high temperature gradient [209].

4.2. Temperature Analysis

The analysis of the temperature from the upper surface of mild steel sheets is reported in this section. Figs. 4.7- 4.10 show the effect of process variables for both natural cooling and forced condition on the upper surface temperature of work-sheet during laser bending process. For temperature measurement, the emissivity is estimated by mapping the temperature profiles of thermocouple with IR camera at different emissivity. Correlation of the temperature profile obtained from the thermocouple with the infrared camera can be found well, when the emissivity is set to 0.67 during multiple scans. Similar method to determine the emissivity of material is suggested by Goyal et al. [242] and Yadav et al. [58]. The highest temperature at the upper surface is analyzed for this study.

The maximum temperature (1652 °C) is observed at laser power 1000 W and scan speed 1000 mm/min in natural cooling condition as shown in Fig. 4.7 (a). The temperature is increased by increasing the laser power and number of scans. Fig. 4.7 (b) shows that during forced cooling condition, the highest temperature (1591°C) is recorded at laser power 1000 W. Figs. 4.7 (a) & (b) shows that the temperature is higher in natural cooling conditions compared to forced cooling conditions. This is due to less heat loss in the natural cooling than the forced cooling. On the contrary, natural cooling conditions are not enough to dissipate the high heat input, particularly when the scan speed is less, and may lead to oxidation or partial melting of work-sheets. Lambiase et al. [139] suggested that the natural cooling conditions with higher laser power and lower scan speed often lead to melting and material oxidation.

The forced cooling reduces material oxidation by acting as a shielding medium and decreases waiting time between consecutive scans, resulting in a higher bend angle [241]. Kant and Joshi [207] reported that when the cooling medium is water, it lessens the cooling time as well as reduces the melting and surface oxidation of the scanned surface. Fig. 4.8 (a) illustrates that even at high laser power, as the scanning speed is increased to 2500 mm/min, the surface temperature decreases. It is due to the high scan speed that does not provide adequate time to interact the sheet and laser beam. Yadav et al. [58] suggested that in order to generate sufficient temperature, low scan speed is a dominating factor, because it gives the laser beam and the worksheet more time to interact.

It is observed that the temperature is higher during the first scan at laser power of 800 W, which may be due to the material degradation that decreases the absorptivity of surface. It is revealed that in natural cooling the trend for the temperature remains same for all scans as the temperature increases after every scan due to preheating in previous scan. Fig. 4.8 (b) shows the lower temperatures observed in forced cooling conditions that can be attributed to the higher heat convection rate achieved through forced cooling. In forced cooling condition heat losses are more than natural cooling conditions due to the continuous cooling from the bottom surface.

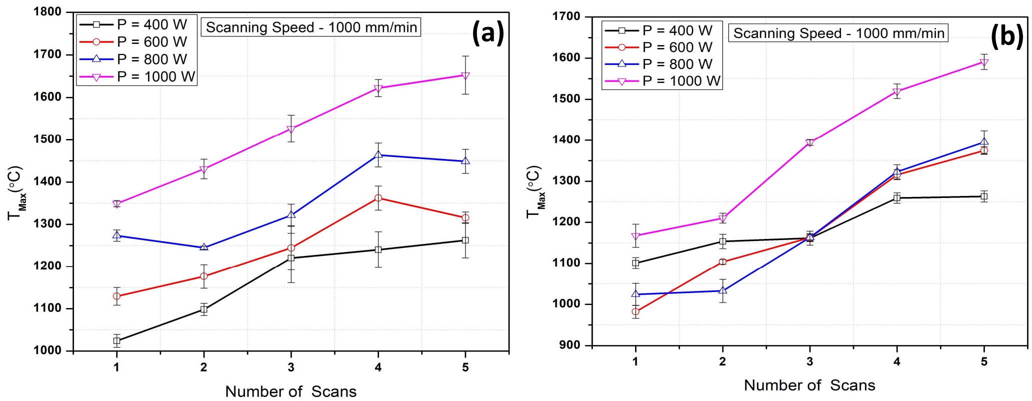

Fig. 4.7. Temperature distribution with laser power at scanning speed of 1000 mm/min (a) natural cooling condition (b) forced cooling condition.

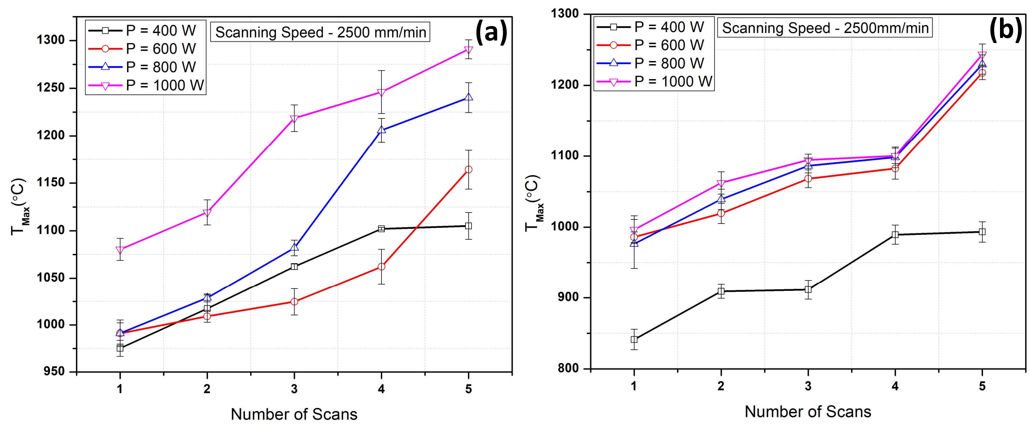

Fig. 4.8. Temperature distribution with laser power at scanning speed of 2500 mm/min (a) natural cooling condition (b) forced cooling condition.

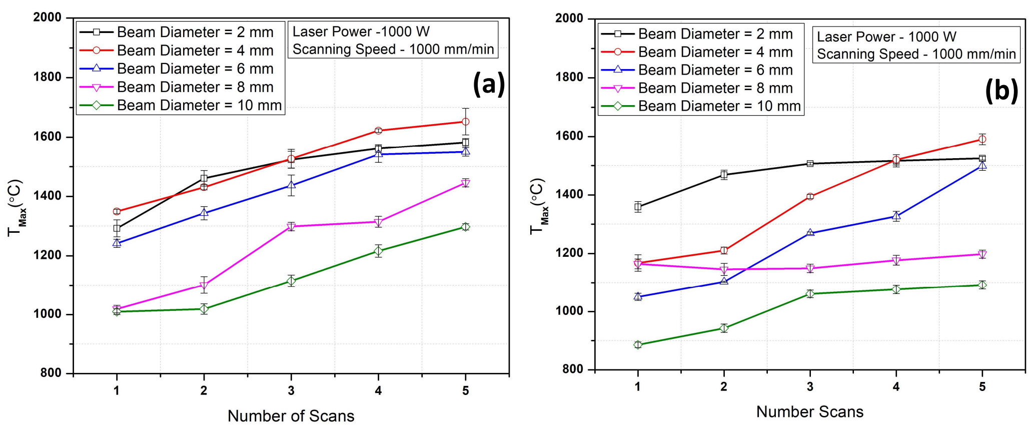

Fig. 4.9. Temperature distribution with beam diameter at scanning speed of 1000 mm/min (a) natural cooling condition (b) forced cooling condition.

It can be observed that the difference in temperature is marginal at 2 mm and 4 mm beam diameter. The peak temperature is obtained at 4 mm and 2 mm beam diameter. It is due to the lower beam diameter; heat concentration is more in smaller area.

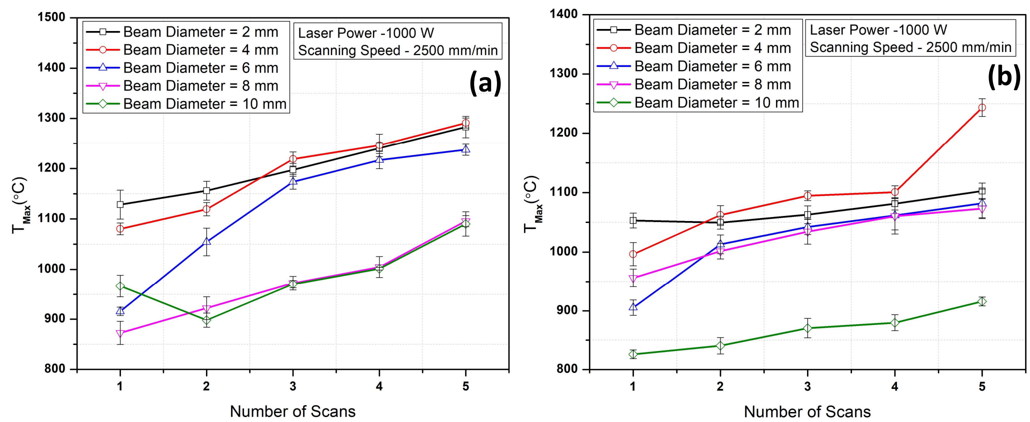

Fig. 4.10. Temperature distribution with beam diameter at scanning speed of 2500 mm/min (a) natural cooling condition (b) forced cooling condition.

The lowest temperature is recorded at 10 mm beam diameter with minor difference of temperature value obtained at 8 mm beam diameter. Masoudi Nejad et al. [90] reported that the heat affected area increases with beam diameter which reduces the heat concentration. Fig 4.9 (b) shows that the peak temperature is obtained at beam diameter of 4 mm. It has been found that in forced cooling conditions peak temperature is less than natural cooling condition. That may be due to high heat dissipation at the bottom surface in forced cooling conditions can lead to a decreased temperature. It is observed that the variation in temperature is less in all scans. It can be seen from Fig. 4.10 (a) and (b) that by increasing the scanning speed, the surface temperature is decreased.

4.3. Edge Effect

Edge effect in laser bending is a complex phenomenon that involves the interplay of various material and input parameters. The impact of cooling conditions and process variables on edge effect toward the scan line is shown in Figs. 4.11-4.12. Edge Effect can be calculated as the ratio of maximum variation of bend angle along the scan line to average bend angle.

As the laser power increases for both natural and forced cooling environments, it can be observed from Fig. 4.11 that the edge effect becomes more pronounced. Similar findings were reported by Yadav et al. [209]. Edge effect reduces at higher laser power in forced cooling condition as compared to natural cooling condition. This may be the result of the uniform temperature distribution occurs in forced cooling condition.

The influence of laser power on the edge at a 2500 mm/min scanning speed under forced and natural cooling conditions is shown in Fig. 4.11.

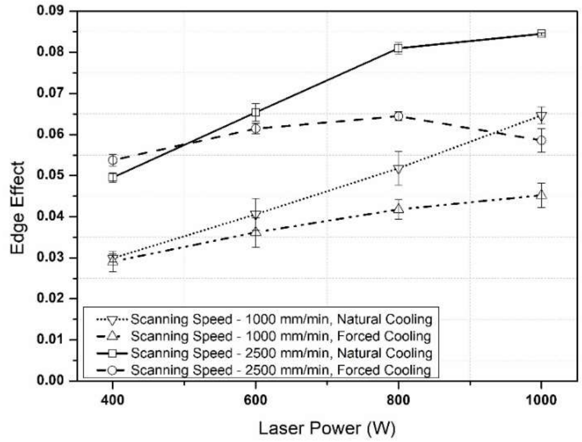

Fig. 4.11. Edge effect variation with laser power along the scan line under natural and forced cooling conditions.

It has been noted that as both scan speed and laser power increase, the edge effect becomes more obvious. This might be as a result of the uneven temperature distribution brought on by a high laser and high scanning speeds, which ultimately cause variances in material deformation. Similar finding has been reported by [14]. Furthermore, forced cooling helps in distributing the heat generated by the laser more evenly thus reducing temperature variations across the material. This leads to more uniform temperature distribution, which in turn minimizes the edge effect [203].

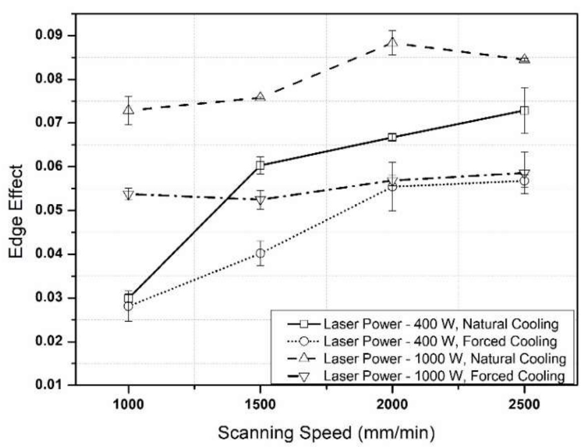

Fig. 4.12. Edge effect variation with scan speed along the scan line under natural and forced cooling.

The effect of scanning speed on the edge effect while using a laser power of 400 W and 1000 W is shown in Fig. 4.12. It is revealed that when scan speed increases, the edge effect continuously intensifies. The increased laser scan speed causes the laser to engage with each spot on the material for a shorter amount of time, which may result in insufficient heat absorption and more localized heating, may increases the edge effect. In contrast, at lower scanning speed the heat distribution is more uniform. Similar trends has been reported by [184] and [8].

The influence of scanning speed on the edge effect under both forced and natural cooling circumstances is depicted in Fig. 4.12 while a constant laser power of 400 W and 1000 W is maintained. It was found that the edge effect becomes more pronounced with the enhancement in scanning speed under natural cooling conditions. It may be due to the fact that as scanning speed increases, less time is required for the material to cool between successive laser scans, leads to incomplete dissipation of heat. It results more pronounced thermal gradients and uneven temperature distribution towards the scanning. Consequently, the edge effect becomes more prominent due to the non-uniform cooling process. Similar trends has been reported by [27]. The minimum edge effect is achieved at lower scanning speed (1000 mm/min) under natural and forced cooling conditions. Forced cooling helps maintain a uniform temperature distribution towards the scan line during the laser bending, leading to a reduction in the edge effect. Although forced water cooling may not directly raise the temperature gradient in the width direction, it plays significant role for preserving temperature uniformity and limiting the heat-affected zone [201].

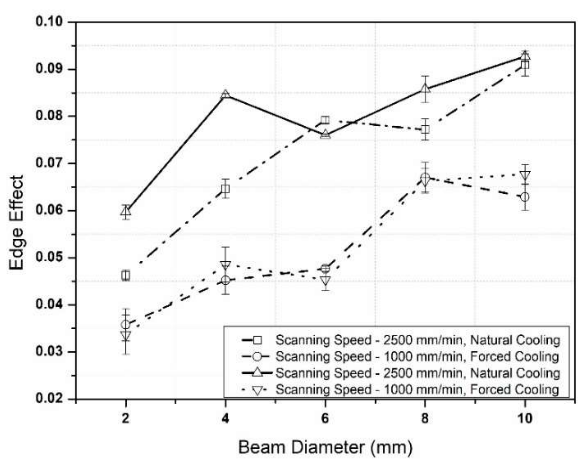

Fig. 4.13. Edge effect variation with beam diameter along the scan line under natural and forced cooling.

The effect of beam diameter on the edge effect is illustrated in Figure 4.13 under both forced and natural cooling conditions. It notices that as the beam diameter increases, the edge effect becomes more apparent. However, it is also observed from results that when beam diameter increases, the bend angle decreases. As beam diameter increases, the variation in the relative bending angle increases. A smaller beam diameter focuses more energy into a smaller area, results higher energy density. The concentrated energy can lead to more efficient and controlled heating, which in turn influences the bending behaviour. Hu et al. [233] reported that beam diameter is a significant parameter for relative variation in bending angle and reduction in the edge effect is observed for smaller beam diameter. Further, small beam diameter allows more controlled and gradual temperature transition from the treated area to the untreated region. Forced cooling effectively reduces temperatures after each scan, potentially leading to altered material behaviour and improved bend angles with minimum edge effect [206].

Similar effects for beam diameter on edge effect are observed with increase of scanning speed under forced and natural cooling condition as shown in Fig. 4.13. The marginal difference in minimum edge effect may be attributed to greater laser power and a smaller beam diameter as shown in Figs. 4.13. A higher laser power coupled with a smaller beam diameter concentrates the energy in a specific area, results more controlled and uniform temperature distribution. This helps mitigate temperature gradients and reduce the edge effect.

4.4. Microstructure Analysis

Microstructural analysis with Scanning Electron Microscopy (SEM) has been analyzed to reveal the effect of cooling conditions with the variation of process parameters (laser power, scanning speed and beam diameter) for the change in microstructure properties of materials during laser bending.

The SEM micrographs for the highest bend angle at laser power of 1000 W, scanning speed of 1000 mm/min and beam diameter 4 mm under natural and forced cooling condition are shown in Figs. 4.14 (a-b).

Fig. 4.14 (a) shows the top surface of laser irradiated mild steel strip after five passes under natural cooling condition and Fig. 4.14 (b) shows the top surface of irradiated mild steel strip under forced cooling condition.

It can be seen that grains are refined at upper surface after laser irradiation in both conditions but the rapid cooling may lead to formation of pearlite and more grain refinement. The phase transformation of ferrite to pearlite at these conditions is due to more strain hardening at the upper surface. The average grain size in natural and forced cooling conditions is observed 5.3 μm and 4.1 μm respectively.

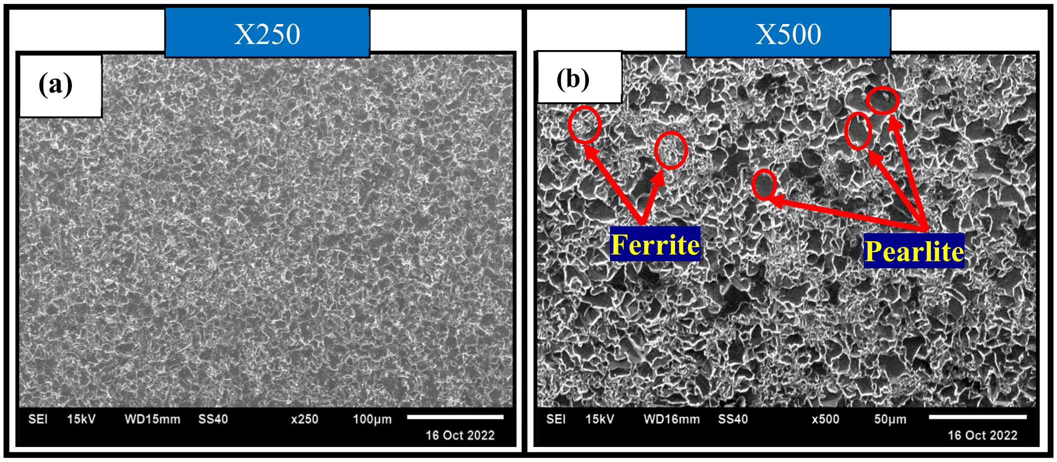

Fig. 4.14 (a) Structure analysis at laser power 1000 W, scan speed 1000 mm/min, and beam diameter 4 mm under natural cooling condition (i) upper surface at 250X zoom (ii) upper surface at 500X zoom.

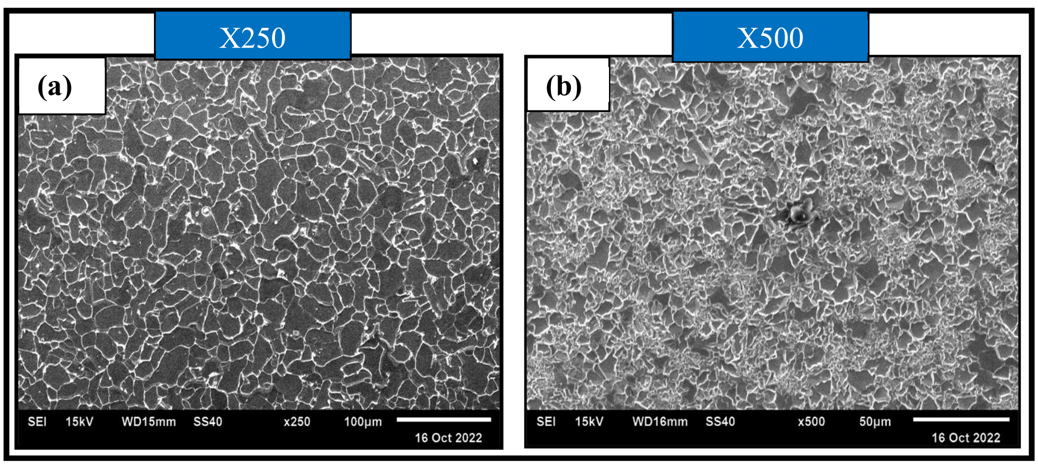

Fig. 4.14 (b) Structure analysis at laser power 1000 W, scan speed 1000 mm/min, and beam diameter 4 mm under forced cooling condition (i) upper surface at 250X zoom (ii) upper surface at 500X zoom.

It can be also observed at higher laser power the plastic deformation of material is more and faster cooling may be lead to the fine grain refinement in shown in Fig. 4.14 (b). Akinlabi and Akinlabi [128] reported that faster cooling rates resulting from higher laser power can lead to a more refined microstructure with smaller grain sizes. The phase transformation from ferrite to pearlite is shown in Fig 4.14 (a) as visible white part on the micrographs is ferrite and the dark part is the pearlite. Similar trends in results are also discussed by [58] and [36]. Fetene et al. [244] observed grain refinement and reduction in grain size with an increasing number of laser passes.

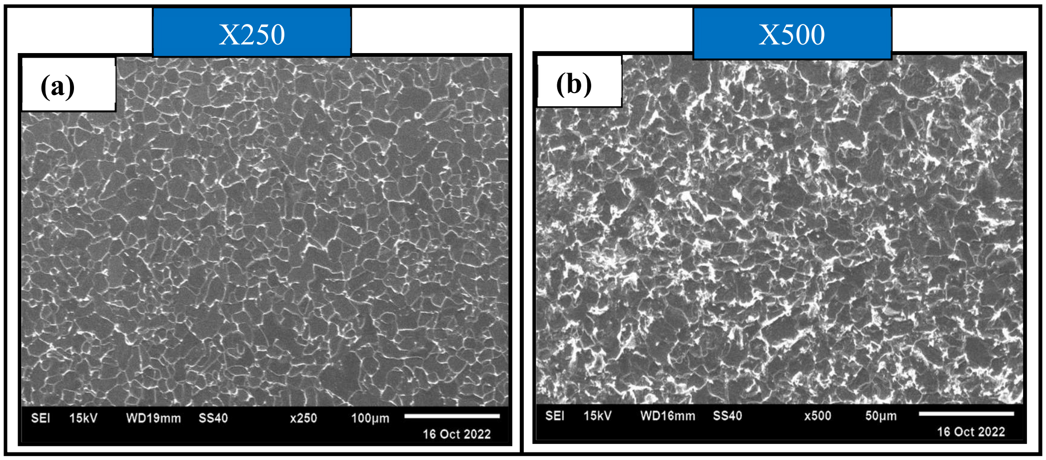

Fig. 4.15 (a) Structure analysis at laser power 600 W, scan speed 2500 mm/min under natural cooling condition (i) upper surface at 250X zoom (ii) upper surface at 500X zoom.

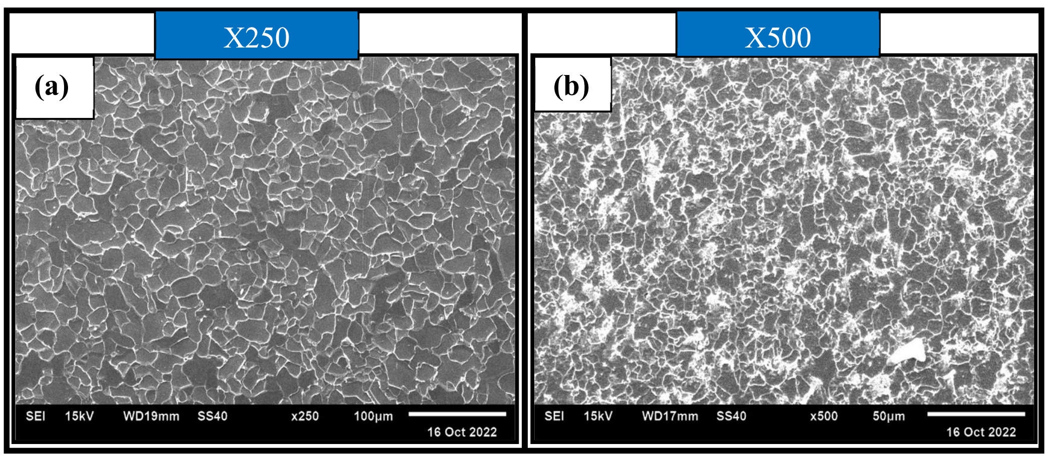

Fig. 4.15 (b) Structure analysis at laser power 600 W, scan speed 2500 mm/min under forced cooling condition (i) upper surface at 250X zoom (ii) upper surface at 500X zoom.

The figures of 4.15 (a) and (b) illustrate the effects of a low laser power of 600 W, as well as the higher scanning speed of 2500 mm/min, on the microstructure for both natural and forced cooling conditions. It has been observed that the lower laser power (600 W) and higher scanning speed (2500 mm/min) resulted in uneven grain structure at the irradiated zone. The lower laser power of 600 W might not provide enough energy to achieve the desired temperature for grain refinement. Insufficient heat input can result in slower heating and cooling rates, allowing for grain growth and coarsening. The average grain size at lower laser power (600 W) and higher scanning speed (2500 mm/min) under natural and forced cooling conditions is observed 8.2 µm and 7.1 µm respectively. Higher scanning speeds, such as 2500 mm/min, can result in shorter exposure times to the laser beam at each point. This limited exposure time may not allow sufficient time for nucleation and grain growth inhibition processes, leading to uneven structure. It is also observed that in natural cooling condition the structure is coarser as compared to forced cooling condition. Natural cooling may not provide sufficient cooling rates compared to forced cooling methods, which can lead to larger grain sizes. Another reason of fine grain structure in forced cooling is the rapid cooling can create a higher cooling rate and a larger temperature gradient, which helps to overcome the energy barrier for nucleation which increases the nucleation rate of new grains reported by [203].

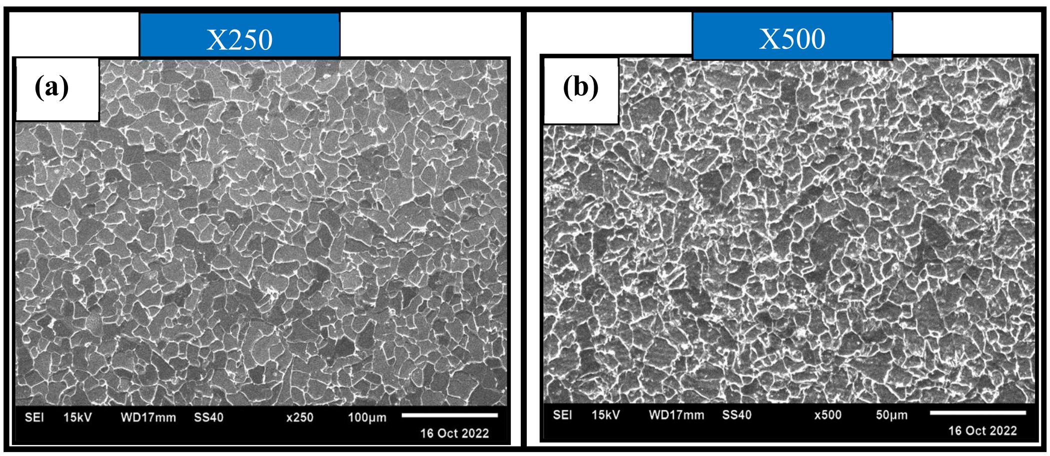

Fig. 4.16 (a) Structure analysis at laser power 1000 W, scan speed 1000 mm/min, and beam diameter 10 mm under natural cooling condition (i) upper surface at 250X zoom (ii) upper surface at 500X zoom.

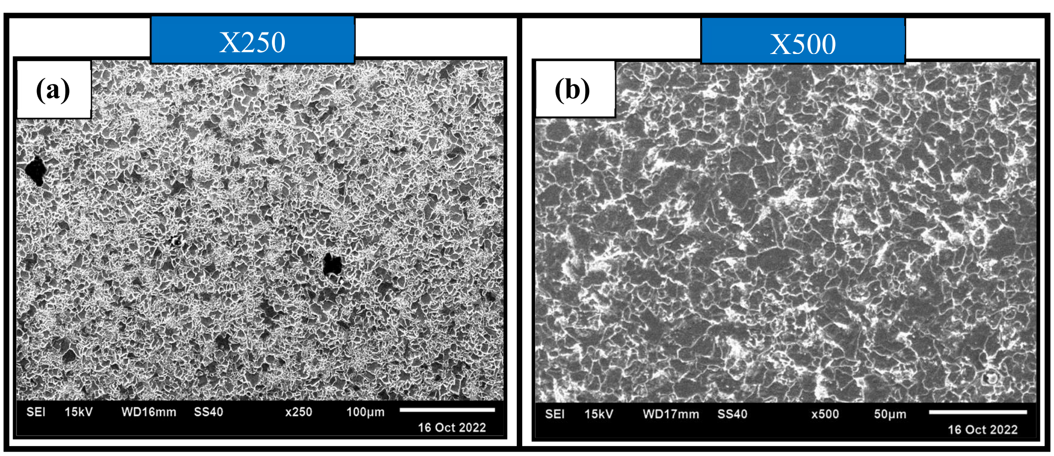

Fig. 4.16 (b) Structure analysis at laser power 1000 W, scan speed 1000 mm/min, and beam diameter 10 mm under forced cooling condition (i) upper surface at 250X zoom (ii) upper surface at 500X zoom.

The micrographs form the top surface of laser irradiated mild steel workpiece at laser power 1000 W and scanning speed 1000 mm/min and beam diameter 10 mm under natural and forced cooling condition is shown in Figs. 4.16 (a-b). It is observed that increasing the beam diameter during laser irradiation, under both cooling conditions, results in an uneven structure compared to the structure obtained with a lower beam diameter. When the beam diameter is increased, the laser energy is distributed over a larger area on the material's surface. This can lead to variations in the heat distribution and thermal gradients across the irradiated region. The uneven heat distribution can result in uneven melting, solidification, and subsequent microstructural features. In case of natural cooling condition, slower cooling rates allow for more grain growth and coarsening, leading to the formation of larger grains in the microstructure [245]. The average grain size at beam diameter of 10 mm under natural and forced cooling conditions is observed 12.7 μm and 10.2 μm respectively.

4.5. Micro-Hardness

The variation in micro hardness of mild steel along the laser scan line is shown in Figs. 4.17 - 4.20. The average of seven indents is reported for the final value of Vickers micro-hardness.

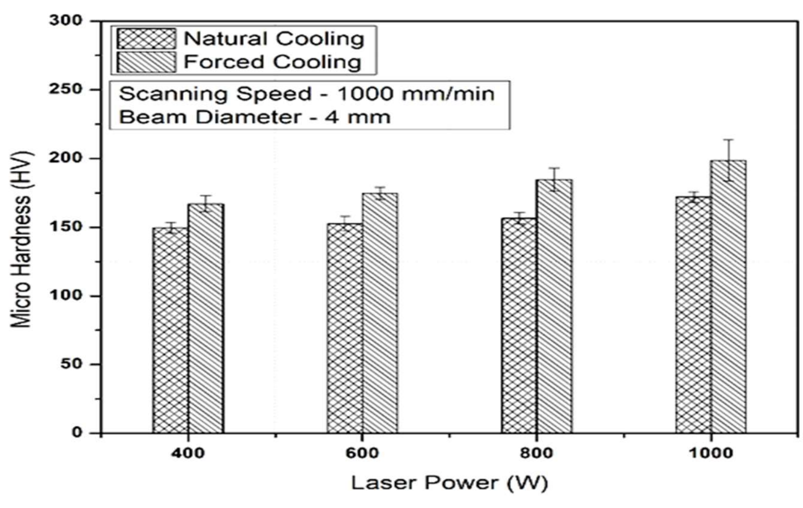

Fig. 4.17. Change in micro-hardness with change of laser power at constant scanning speed of 1000 mm/min and beam diameter 4 mm.

The variation of micro-hardness along the laser scanning line of laser irradiated worksheet for different laser powers is shown in Fig. 4.17. As a result of laser scanning with natural cooling for mild steel, the average micro-hardness values were 149.5, 152.5, 156.4 and 172 HV for laser power of 400, 600, 800 and 1000 respectively and average micro-hardness values for forced cooling were 167, 174.7, 184.6, and 198.5 HV respectively as shown in Fig. 4.17. It has been observed that the maximum reading of micro hardness (198.5 HV) is recorded with forced cooling conditions at 1000 W of laser power and 1000 mm/min of scan speed. Furthermore, it has been found that increased values of micro hardness in the irradiated zone are due to high laser power in both cooling environments. This is because of the high heat input due to high laser power causing phase transformation (ferrite to pearlite) and subsequent high hardness in the irradiated zone as shown in Fig. 4.14 (a). Dutta et al. [246] and Fetene et al. [8] concluded that the high laser power is accountable for the phase transformation during laser bending process, which results increase in micro-hardness.

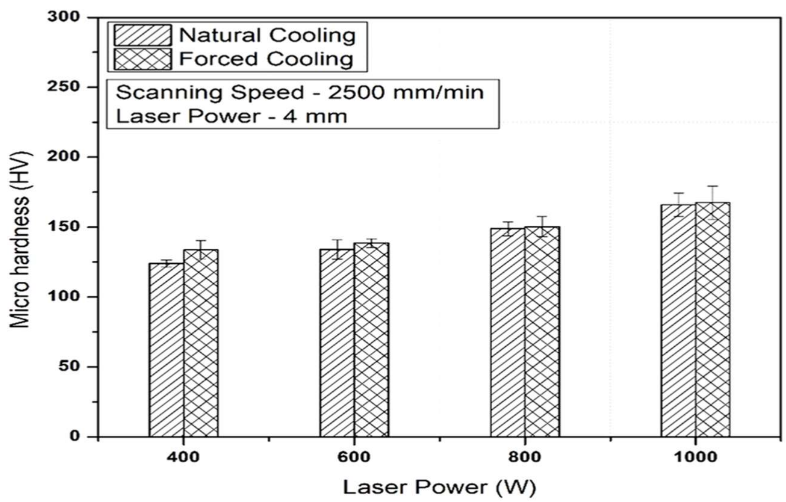

Fig. 4.18. Change in micro-hardness with change of laser power at constant scanning speed of 2500 mm/min and beam diameter 4 mm.

The micro hardness decreases with the increase in scan speed of 2500 mm/min for both the cooling conditions as shown in Fig. 4.18. This is due to the fact that the low scan speed (1000 mm/min) provides the adequate time for the work-sheet and beam to interact, which is not the case when the scan speed is high i.e. 2500 mm/min. The high temperatures obtained during low scan speed leads to higher hardness. Many authors [184], [247] and [52] reported similar findings in their study. It is observed that the micro-hardness is higher in forced cooling condition for both combination of higher and lower scan speeds. It is because the quenching of material in forced cooling condition restricting the specimen melting and rapid cooling may lead to phase transformation [58]. Another reason is phase transformation and fine structure is obtained is obtained in forced cooling condition. Bartkowiak et al. [102] reported that the surface hardness is increased by applying cooling in laser bending process.

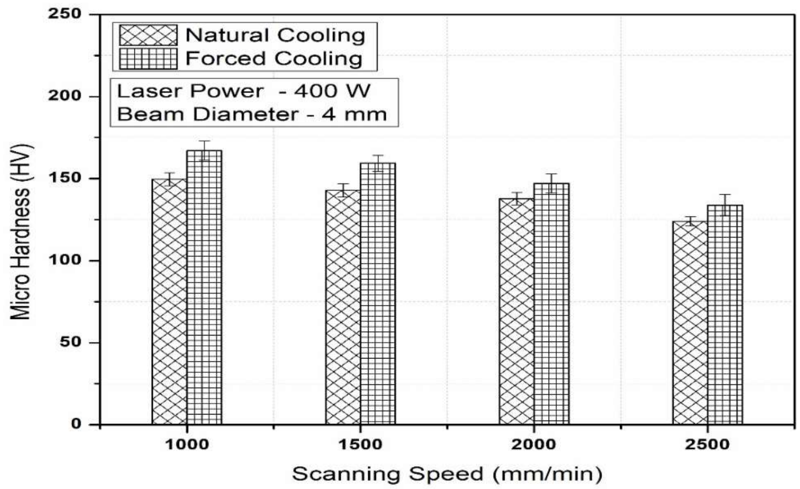

Fig. 4.19. Change in micro-hardness with change of scanning speed at constant laser power of 400 W and beam diameter 4 mm.

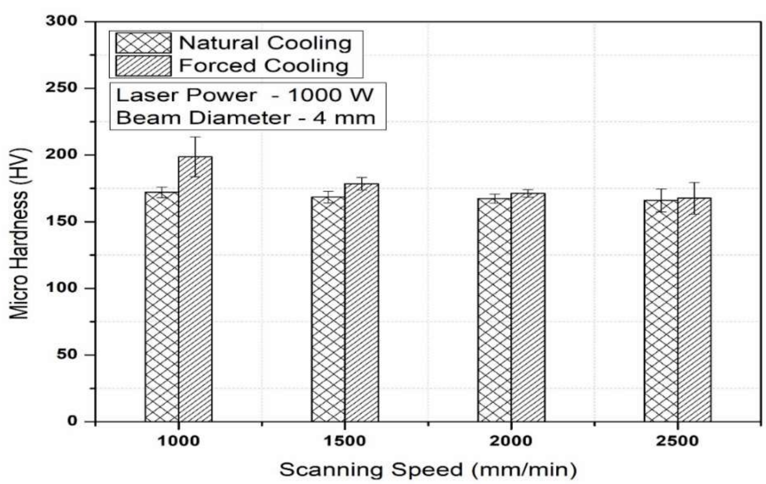

Fig. 4.20. Change in micro-hardness with change of canning speed at constant laser power of 1000 W and beam diameter 4 mm.

The effect of scanning speeds with lower and higher value of laser power under 400 W and 1000 W respectively for both cooling environments natural and forced on the micro-hardness is shown in Figs. 4.19 and 4.20. It has been observed from Fig. 4.19 that the micro-hardness decreased with the increase of scanning speed in both conditions. This may be due to the decrease in interaction time between the laser beam and material produces lesser heat in the irradiated zone, which results in coarse grain structure at higher scanning speed as shown in Fig. 4.15 (a). The uneven structure may be responsible for the lower value of micro-hardness at higher scanning speed. Fig. 4.20 shows that with the increase of laser power at even with increasing of scan speed micro-hardness also increased than the values of micro-hardness obtained at laser of 400 W. Cheng and Lawrence Yao [203] also reported that high laser power provides high heat in irradiated zone results fine structure lead high micro-hardness. Maji et al. [195] reported that both strain hardening and the formation of a refined grained microstructure can occur simultaneously and contribute to the overall increase in micro-hardness in the laser-irradiated zone.

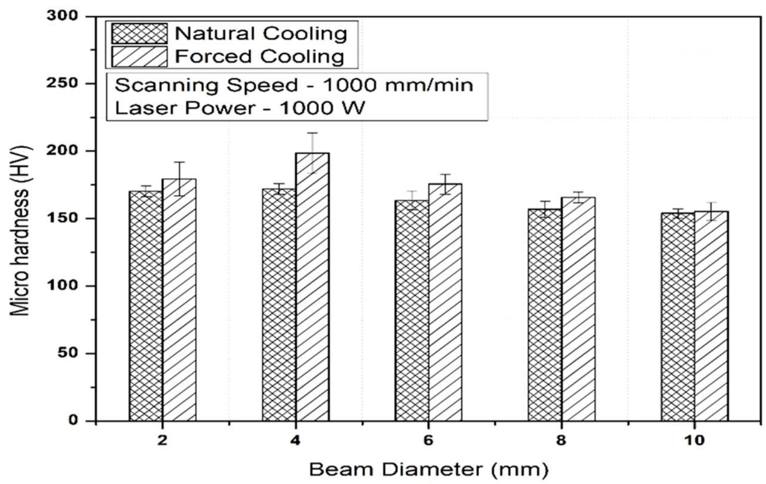

Fig. 4.21. Change in micro-hardness with change of beam diameter at constant laser power of 1000 W and scanning speed of 1000 mm/min.

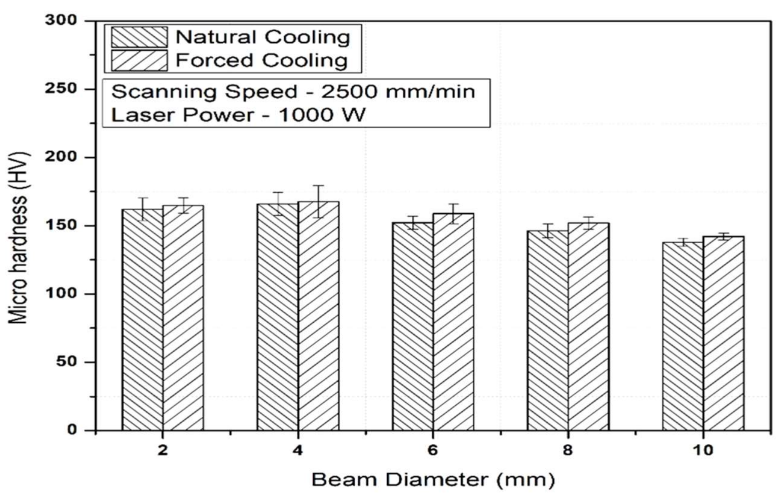

Fig. 4.22. Change in micro-hardness with change of beam diameter at constant laser power of 1000 W and scanning speed of 2500 mm/min.

The influence of scan speeds (1000 and 2500 mm/min) with beam diameter for both conditions on micro-hardness is represented in Figs. 4.21 - 4.22. The high value of micro hardness 165.8 HV is recorded for 4 mm beam diameter with forced cooling condition and is represented in Fig. 4.21. The lowest reading of micro hardness 137.8 HV is recorded at beam diameter of 10 mm with natural cooling condition is represented in Fig. 4.22. As shown in the figures, the micro hardness decreases with the increase in beam diameter for both cooling conditions. This may be because the increase in beam diameter reduces the heat concentration at irradiated zone results in coarse grain structure, causing lower micro hardness [245]. Masoudi Nejad et al. [90] reported similar trends. In forced cooling conditions high laser power and low scan speed provide high micro-hardness due to high heat input that leads to a fine structure in the irradiated zone [245]. The SEM micrograph presented in Fig. 4.16 (b) shows the grain refinement of mild steel strip at irradiated zone under forced cooling condition, which may be the cause of higher micro-hardness.

4.6. Tensile Testing

Micro-tensile tests are used to examine the impact of laser scanning on mechanical characteristics. The specimens used for the micro tensile testing before and after the test are shown in Figure 4.23.

Fig. 4.23. Before and after testing tensile test specimens.

The stress-strain curves for laser-bent samples at higher scanning speed (2500 mm/min) and higher laser power (1000 W) under forced and natural cooling conditions are depicted in Fig. 4.24. The ultimate tensile strength of processed specimen under different working environments i.e. natural and forced cooling conditions is presented in Figs 4.25- 4.30. The average value of three trails is reported as final result.

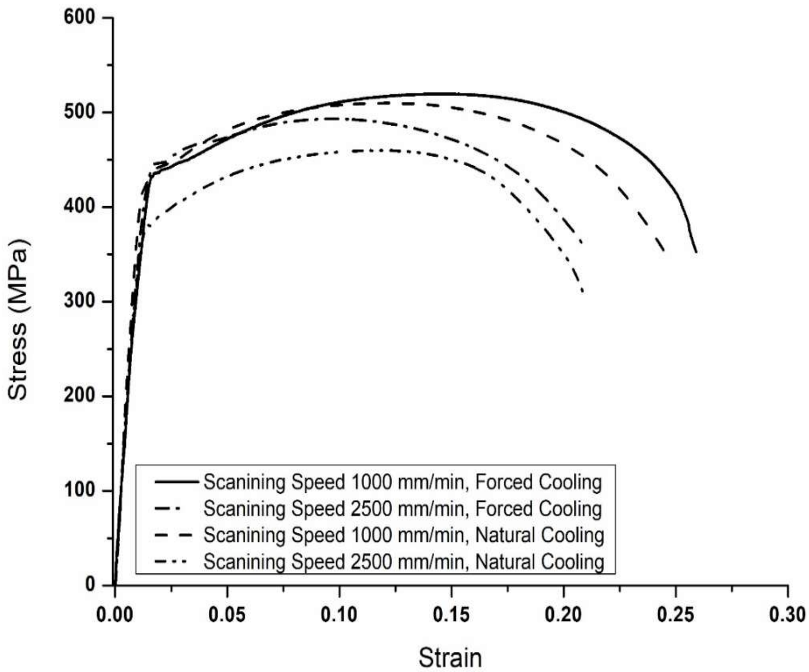

Fig. 4.24. Stress-Strain curves obtained from the tensile test of specimens, at laser power of 1000 W under natural cooling condition.

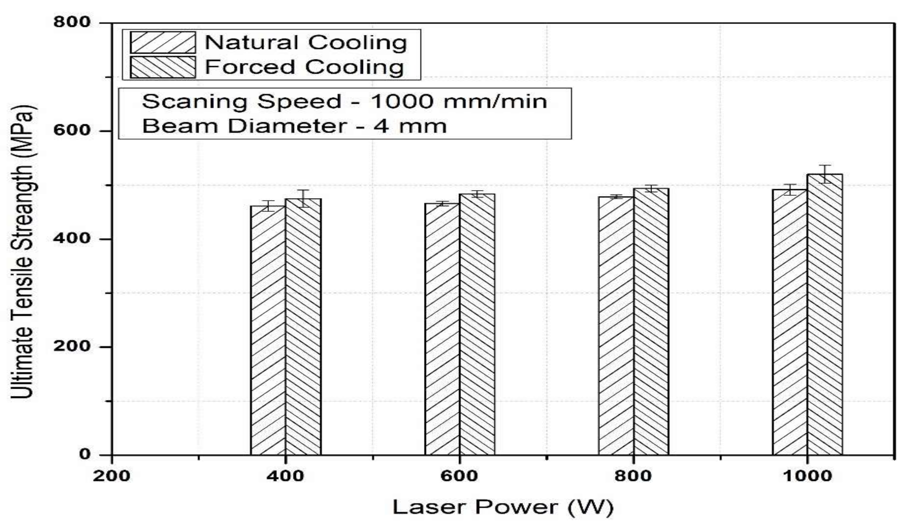

Fig. 4.25. Variation of tensile strength with laser power at scanning speed 1000 mm/min and beam diameter 4 mm.

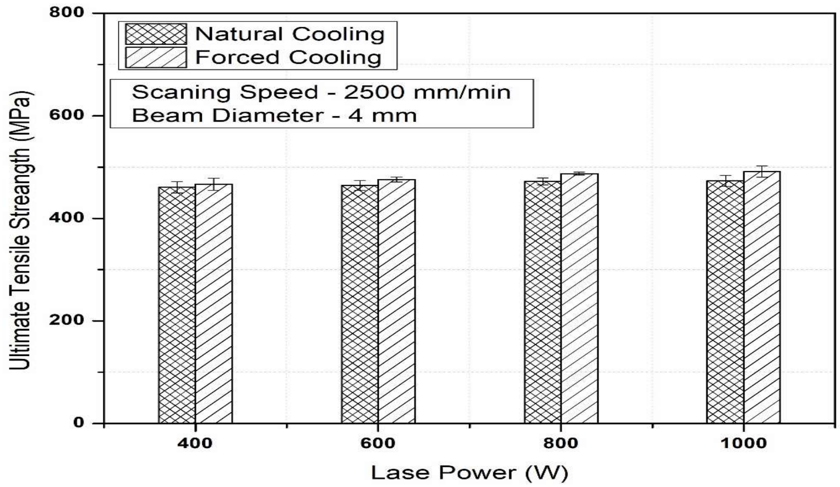

Fig. 4.26. Variation of tensile strength with laser power at scanning speed 2500 mm/min and beam diameter 4 mm.

Highest tensile strength 471 MPa is observed with laser power 1000 W, scan speed 1000 mm/min and beam diameter 4 mm under forced cooling condition as shown in Fig. 4.25. This is because of the high heat input at high laser power and rapid cooling followed by the forced cooling which results in fine grains in the irradiated zone. The similar findings also reported by [58]. Another reason of higher ultimate tensile strength may be the decrease in ductility of bent mild steel sheet due to the quenching effect during forced cooling conditions [248]. Fig. 4.26 shows the trend as the laser power increased the micro-hardness is also increased even with the decrease of scanning speed. This may be due the refine grain structure is obtained as the laser power increases as shown in SEM results. Singh [183] reported that the hardness of laser formed sheet increased with laser power because of higher peak temperature.

The influence of scanning speed with lower power (400 W) and higher laser power (1000 W) on tensile strength is presented in Figs. 4.27 and 4.28 for both cooling conditions i.e. natural and forced cooling conditions. It has been observed that when the scanning speed is increased the ultimate tensile strength decreases. It may be because of the lower heating at higher scan speed causing less deformation resulting in lower strain hardening [120].

On the contrary, at higher laser power even at high scan speed for both cooling conditions i.e., forced and natural, the ultimate tensile strength increases. It can be linked with the reduction of ductility with high laser power, leading to higher ultimate tensile strength [85]. Another reason is high laser power causes high heating and forced cooling led to multiple heat treatment [58].

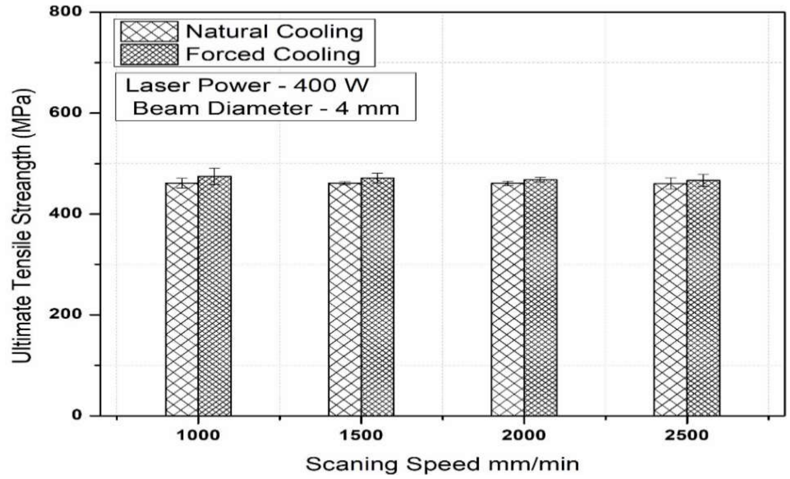

Fig. 4.27. Variation of tensile strength with scanning speed at laser power 400 W and beam diameter 4 mm.

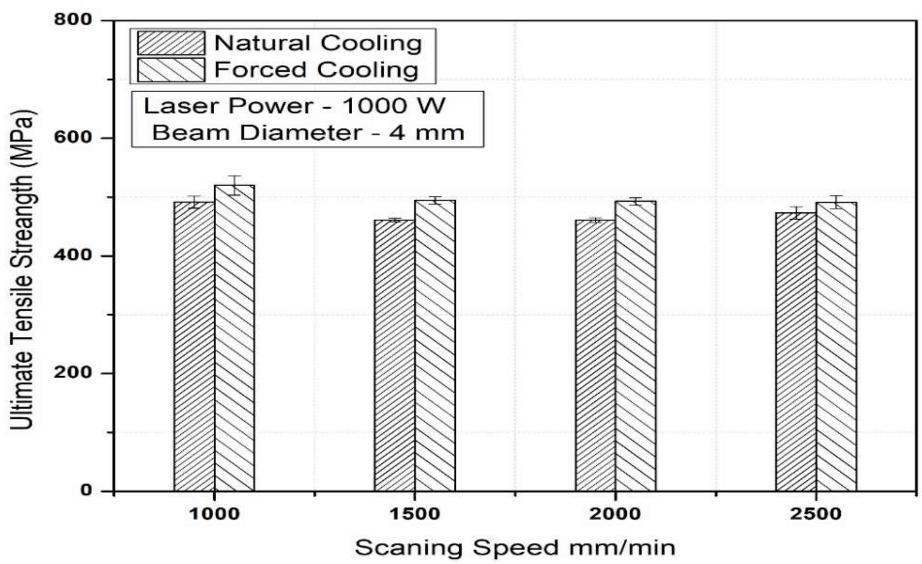

Fig. 4.28. Variation of tensile strength with scanning speed at laser power 1000 W and beam diameter 4 mm.

On the contrary, at higher laser power even at high scan speed for both cooling conditions i.e., forced and natural, the ultimate tensile strength increases. It can be linked with the reduction of ductility with high laser power, leading to higher ultimate tensile strength [85]. Another reason is high laser power causes high heating and forced cooling led to as multiple heat treatment [58].

The effect of beam diameter on the ultimate tensile strength for both cooling conditions i.e. natural & forced is shown in Figs. 4.29 and 4.30 shows. It has been observed that the ultimate tensile strength decreases with an increase in beam diameter.

Yang et al. [249] reported that larger laser spot size typically leads to a more diffuse heat distribution during the laser processing results lower tensile strength.

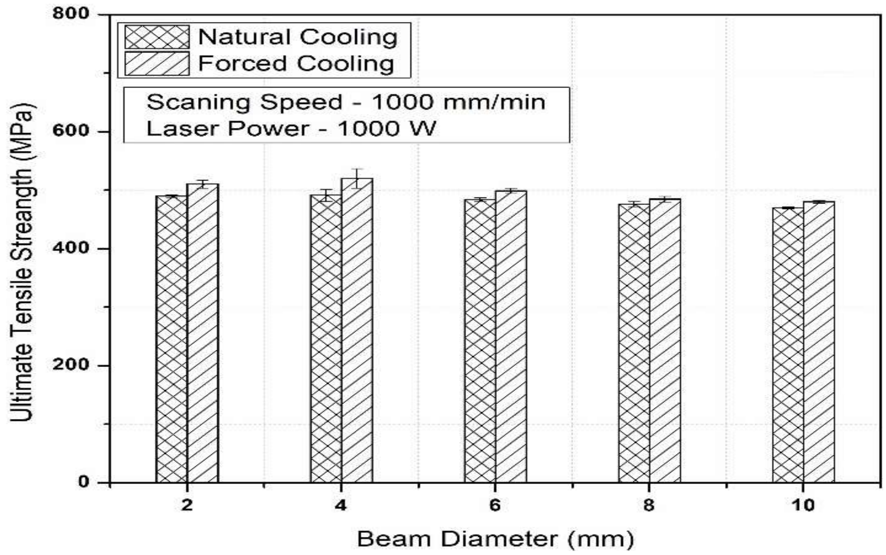

Fig. 4.29. Variation of tensile strength with beam diameter at laser power 1000 W and scanning speed of 1000 mm/min.

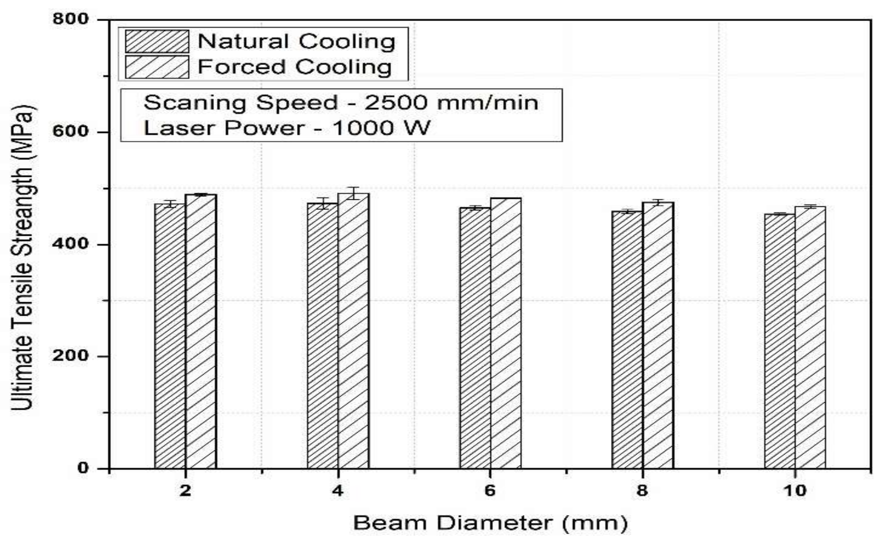

Fig. 4.30. Variation of tensile strength with beam diameter at laser power 1000 W and scanning speed of 2500 mm/min.

The lowest ultimate tensile strength 431 MPa is obtained for lowest laser power of 400 W, scanning speed of 2500 mm/min and beam diameter of 10 mm during natural cooling condition as shown in Fig. 4.30. It may be due lower heating and insufficient interaction time between material and laser beam during the bending process leads to reduced deformation, which subsequently results in lower levels of strain hardening [58].

4.7. Summary

This chapter investigated the possibilities of forced cooling assisted laser bending with multiple laser irradiations. The experiments are carried out in both natural and forced cooling environments for a different set of process conditions. The effect of various parameters, such as scan speed, laser power, beam diameter, and number of scans on bend angle, temperature distribution and edge effect are investigated in both natural and forced cooling environments. The mechanical and metallurgical properties of bent specimens are also examined.

- ❖ The results revealed that forced cooling increased the bend angle. The effect of process parameters also showed different trends when forced cooling was used versus natural cooling.
- ❖ The bend angle per scan increased with an increase in the number of scans, laser power and decrease in scanning speed and beam diameter.
- ❖ The maximum temperature at the upper surface of worksheet increases with the increase in laser power and number of scans under both natural and forced cooling condition.
- ❖ The uniform temperature distribution is observed in the forced cooling situation, which results in a reduction in the edge effect at all parameters.
- ❖ Microstructural research reveals that the forced cooling has a substantial impact on the formation of the fine grain structure. The high laser power and multiple scans are attributed to ferrite to pearlite phase transition.
- ❖ The samples with forced cooling, high laser power, low scanning speed, and smaller beam diameter exhibited higher mechanical properties such as hardness and tensile strength.
- ❖ The tensile strength increased with forced cooling, high laser power, low scanning speed, and smaller beam diameter, whereas ductility decreased.

The chapter concludes that forced cooling increased bend angle while maintaining material characteristics at high laser power, low scan speed, and small beam diameter. In a forced cooling condition, the minimum waiting time between successive scans and the number of scans is required to achieve a desired bend angle, resulting in less material degradation due to overheating. It emphasizes the capability of this approach for expanding industrial applications in a variety of industries, including aerospace, marine and automobile, where high deformation with high precision is a requirement.