CHAPTER 2-LITERATURE REVIEW

An extensive literature has been reviewed from earlier research papers. It has been observed that laser forming is a big attraction for researchers in the field of manufacturing. In this chapter literature review in aspects of various conditions of laser forming is presented. It has been revealed in the literature that various techniques can be used to enhance the bend angle of metal sheet. Various researchers have tried to improve laser bending process characteristics. Following are some studies in laser forming process.

2.1. Materials used for Laser Bending Process

Shen and Yao [85] investigated the influence of mechanical properties on low carbon steel during laser bending process. They observed that the bending process of low carbon steel has resulted in an enhancement of the ultimate tensile strength and yield strength. Furthermore, it has been observed that fatigue life decreases with increase in scanning speed. Safari and Farzin [86] used continuous wave CO2 laser for the bending of mild steel tailor-machined blanks. They reported that for tailor-machined blanks, thick and thin sections have almost the same bending radius. Hoseinpour Gollo et al. [87] studied the influence of laser bending on St12 and 304 alloy steel sheets by using pulsed Nd: YAG lasers. They reported that the material parameters play a significant role in enhancing the bending angle in the laser bending process for both materials. Knupfer and Moore [88] examined the effect of parameters of laser bending on the metallurgical and mechanical properties of aluminium alloy and low carbon steel. They observed that the highest tensile strength for AA2024-T3 and highest yield strength for AISI1010. They found that in the case of AISI1010 steel, the cumulative line energy during laser bending did not exceed 600 Joule/mm for achieving the desired strain and for AA2024-T3 aluminum alloy, the cumulative line energy did not exceed 480 Joule/mm to achieve the ultimate tensile strength. They suggested that the high value of hardness in low carbon steel may be due to the formation of bainite after laser bending process.

Guglielmotti et al. [89] used diode laser to bend the aluminium foam sandwich panels. They observed high formability of aluminium foam sandwich panels by diode laser bending process. Masoudi Nejad et al. [90] performed numerical and experimental investigations to explore the effect of process parameters on laser bending of an aluminium-copper two-layer sheet. They suggested that due to more ductility and lower manufacturing cost laminated sheets are used for the laser bending. Quadrini et al. [91] demonstrated the laser bending of open-cell aluminium foam, which is difficult to bend by mechanical conventional methods. Chan and Liang [92] investigated the effect of deformation of aluminium-based metal matrix composites during laser bending process. They reported that a larger bend angle achieved with transverse scanning along rolling direction. As the aluminium based composite foam are gained popularity in industry and can be successfully bend with laser bending process [93]. Labeas [94] developed a numerical simulation three dimensional model for the laser bending of r 6013-T4 and 2024-T351 aluminium components and observed that with the increase of thickness of sheet bend angle is decreased.

Kant and Joshi [95] investigated the curvilinear laser bending of magnesium M1A alloy sheets and described that a higher scanning path curvature resulted in a larger bend angle. They suggested that laser bending of high thermal conductivity materials can be processed with higher scanning speed and lower stand-off distance.

Yadav et al. [58] focused on investigating the effect of line energy on duplex stainless steel during laser bending. They observed improvements in mechanical properties and grain structure after laser bending of duplex stainless steel. Chakraborty et al. [96] investigated the coupling mechanism involved in laser forming of stainless steel. By using Finite Element Analysis (FEA) a scanning strategy they suggested for the forming of deep pillow-shaped surfaces. Chen and Xu [97] focused on the continuous wave laser forming technique of thin stainless-steel (SS) sheets. Their research aimed to investigate the process parameters and conditions that lead to high bending angles and optimize the laser forming process for thin SS sheets. According to their findings, the researchers observed that under optimized conditions, the continuous wave laser forming technique resulted in high bending angles in thin stainless-steel sheets. Yilbas et al. [98] specifically investigated the laser bending of 304 stainless steel sheets. The researchers reported that the laser-scanned surface of the stainless steel sheets was free from cracks and cavities. Nath et al. [99] analysed the thermal effect on D36 shipbuilding steel sheet during laser forming. The effect of temperature distribution, thermal flux distribution, and thermal gradient distribution on the D36 surface was investigated using a finite element model (FEM). They observed the bend angle increases with the increase in thermal gradient within the workpiece material.

Guan et al. [100] investigated how different material properties of plain steel sheets influence the laser forming process. They observed that the plain steel sheets were more susceptible to deformation and could achieve higher bend angles during the laser forming process. They reported that materials with higher thermal expansion coefficients are more likely to exhibit larger bend angles during laser forming. Marya and Edwards [101] explored the laser bending process for two titanium alloys, namely the near-alpha Ti-6Al-2Sn-4Zr-2Mo alloy and the metastable beta Ti-15V-3Cr-3Al-3Sn alloy. It was observed that the combination of the lower yield temperature and higher thermal expansion coefficient in the Ti-6Al-2Sn-4Zr-2Mo alloy results in higher initial bending during the laser bending process. Bartkowiak et al. [102] used an Nd:YAG laser for the laser forming of titanium alloy Ti-6Al-4V and examined the influence of laser bending on the material properties. They reported that laser forming of titanium alloy can be successfully processed without the need for coating by using a pulsed Nd:YAG laser source.

Chen et al. [103] investigated the curve irradiated laser bending process for titanium alloy sheets and reported that the bend angle decreases with an increase in path curvature. Shidid et al. [104] investigated the influence of input parameters on Grade-2 titanium sheets during laser forming. They observed the large increment in bend angle after first scan of laser due to the surface coating. Otsu et al. [105] examined the thermal effect on bend angle of titanium during laser forming. They reported that the bending angle of titanium increased with an increase in grain size and furthermore, they found that the bending angle decreased after annealing. Fan et al. [106] investigated the influence of phase transformations on the laser bending process of Ti-6Al-4V alloy. They reported that phase transformations occur in the Heat Affected Zone (HAZ) during laser bending of Ti-6Al-4V alloy. These phase transformations in the HAZ can have significant effects on the material's microstructure, mechanical properties, and resulting bend angle.

Yau et al. [107] explored the laser bending of A42 nickel alloy and provided insights into the relationship between the bending angle and reported that the bending angle of A42 nickel alloy during laser bending is significantly affected by process parameters. Che Jamil et al. [108] investigated the laser bending of thin-walled nickel micro-tubes and observed that the high thermal conductivity of the material also contributed to an increase in the bend angle.

Wang et al. [109] conducted a study on the laser bending process for brittle materials, specifically using silicon sheets. They proposed an alternative mechanism (pulsed laser bending) specific to the laser bending of silicon sheets instead of TGM and BM mechanisms. They suggests that multiple passes of laser scanning had a cumulative effect on the deformation and bending of the silicon material. Exner and Löschner [110] investigated the effect of process parameters on silicon during laser forming. They reported that the bend angle can be controlled by varying the process parameters during laser bending of silicon, it suggests that the choice and adjustment of specific input parameters can influence the deformation behavior and resulting bend angle of the material.

Wu et al. [111] conducted a study on the laser bending of brittle materials using CO_2 continuous wave (CW) laser and Nd:YAG pulsed laser. They focused on investigating the effect of process parameters on the laser bending of silicon material. They found that bending silicon sheets was not possible using a CO_2 continuous wave (CW) laser. However, they were able to successfully achieve bending when using pulsed laser irradiation with an Nd:YAG laser. Choi and Baek [112] studied experimentally the deformation of plastic by YAG laser bending process. They observed that a higher bend angle was obtained in a thick sheet. In this sheet, the rigidity was increased due to the increased hardness of the irradiated zone after laser irradiation. Okamoto et al. [113] analyised by experimental and numerical analysis the deformation behavior of plastic in YAG laser bending. They described that the bend angle was achieved in plastic material due to the high viscoelasticity nature of material. Okamoto et al. [114] performed experimental study on laser bending of plastic with YAG laser. They suggested that plastic can be deformed successfully by laser irradiation under thermal stresses. A higher bend angle was achieved under certain energy density and increased during rapid cooling process after laser irradiation.

2.2. Process Parameters in Laser Bending

The laser bending technique is influenced by a various conditions and number of process parameters [115]. Numerous studies have been conducted to investigate the influence of various conditions and input parameters on laser bending processes. These parameters can be broadly classified into the following categories:

1. **Laser Parameters:** Laser input parameters play a crucial role in laser bending processes, and optimizing these parameters is essential to achieve the highest possible bend angle. The leading laser input parameters are laser power, laser scanning speed, beam diameter, wavelength, beam shape, frequency, duty cycle and number of laser scans.

2. **Geometrical Parameters:** The geometry of the sheet being bent in laser bending processes is a crucial factor that significantly affects the bending outcome. The most significant sheet geometry parameters are length, thickness and width.
3. **Material Properties:** The material properties of the workpiece are crucial factors that greatly influence the laser bending process. The material properties, which have significant effect on bending, are mechanical properties, thermal properties and material absorptivity.
4. **External Constraint Parameters:** External conditions and arrangements in laser bending process also enhanced the bend angle of work piece. Forced cooling conditions, clamping, temperature, corrosive environment and external mechanical load are important external factors that can influence the laser bending process and enhance the bend angle of the workpiece.

The effect of these parameters and conditions on laser bending process is described in the following:

2.2.1. Laser Power

Maji et al. [33] conducted an experimental study on the bending behavior of steel sheets during laser bending. They reported that the bending angle increased with an increase in laser power due to high input. Hsieh and Lin [116] conducted a study on the deformation behavior during pulsed laser forming of 304 stainless steel sheets at different laser powers. They observed that the bend angle increased with the increase in laser power and laser radiation time. Roohia et al. [117] studied the effect of temperature gradient magnitude on the bend angle and reported that the bend angle increases with high temperature gradient at maximum laser power.

Kotobi et al. [118] investigated the influence of process parameters on bending angle and maximum tensile residual stresses using finite element modelling and neural networks method. It has been observed from the results that bend angle is directly proportional to laser power. The peak temperature increased linearly with laser power which results more heat input from laser beam [119]. Roohi et al. [120] studied the influence of laser forming process conditions on Al6061- T6 strips and reported that that increase in laser power increases temperature gradient across sheet thickness leads to increase in bending angle. Mulay et al. [121] suggested an analytical method for the increment in bend angle of AISI 304 steel sheets by using multiple laser scans. It was observed that the bend angle increased with increase in laser power and higher variation in the bend angle per scan. This could be due to the variation in strain energy stored with higher laser power though the variation in the bend. Fetene et al. [52] carried out FEM simulation and experimental study for multi pass laser bending of AH 36 steels strips and reported that bend angle increases with increase of laser power.

Yau et al. [107] investigated the laser bending behaviour of a thin steel alloy strip and observed that bend angle increases with increase of laser power and above a critical value, an increase in laser power does not result in any further increase in bending angle. Gisario et al. [122] explored the titanium for laser bending and investigated the influence of the process parameters such as laser power, number of scans on bending angles. They observed that high laser power and number of scans lead to larger bending angles. Viorel et al. [123] studied the influence of input parameters of high power diode laser bending process on AISI 304 stainless steel sheet. The laser power was selected for the experimentation from 100 to 300 W. They reported that the effect of lower value of laser power on bend angle is negligible and as increased the value of laser power, higher bend angle obtained. Nejad et al. [124] numerically and experimentally investigate the influence of parameters on laser thermal bending of aluminium-copper two-layer sheet. They described that higher laser power levels result in higher temperatures and increased thermal expansion in the material, leading to larger deformations and bend angles.

Omidvar et al. [125] described the effect of process parameters on AA6061-T6 aluminum alloy sheets during the pulsed Nd:YAG laser bending process. They suggest increase in bend angle at higher laser power levels can be attributed to the higher thermal energy transferred from the laser to the workpiece, which leads to material deformation. Yang et al. [126] investigated the influence of process parameters on laser bending of 5A06 aluminum alloy sheet. The bend angle of 5A06 aluminum alloy sheet increased with the increase in laser power. This observation suggests that higher laser power levels resulted in greater deformation and bending of the aluminium alloy sheet.

Yadav et al. [127] experimentally investigated the bending behavior of stainless steel using fiber laser. The range of laser power considered in the study was from 250 to 750 W. The results of the study indicated that the bend angle increased with an increase in laser power. However, it was observed that after reaching a certain value, the bend angle remained constant even with further increases in laser power.

Akinlabi and Akinlabi [128] explored the effect of input parameters of laser bending process on titanium alloy sheet. They have selected three levels of laser power (600, 800, 1000 W) for the experimentation. They reported that at high power, smaller the radius of curvature formed. High laser power is inversely proportional to the curvatures as the laser power is increased, more energy is transferred to the material, leading to a higher thermal gradient and a more pronounced curvature. Sala et al. [129] investigated the effect of laser peen forming process parameters on bending of Ti-6Al-4V sheets. The researchers reported that the bend angle of the Ti-6Al-4V sheets increased with the increase in power density. Safari et al. [130] investigated the impact of process parameters on the laser forming of cylindrical surfaces. In their research, they focused on laser bending of stainless steel 304 and specifically examined the influence of different levels of laser power. The researchers selected three levels of laser power for their experimentation: 36 W, 72 W, and 108 W. They observed that as the laser power increased, the heat input also increased. This higher heat input subsequently led to a decrease in the radius of curvature of the stainless steel 304 samples.

Kalvettukaran et al. [131] focused on laser bending of rectangular cut-outs in AISI 304 plates. The researchers utilized finite element method simulations along with statistical techniques to investigate the impact of process parameters on the deformation of AISI 304 during the laser bending process. They observed that as the laser power increased, the temperature also increased. Furthermore, they reported that the bending angle of the rectangular cut-out increased with an increase in laser power and independent from cut out dimension in x-direction.

Waran et al. [132] investigated the bend angle and the effects of various parameters on stainless steel through laser bending. To conduct their analysis, they utilized Finite Element Simulation (FEM) along with Response Surface Methodology (RSM). The effects of laser power (125 to 375 W) during laser bending of stainless steel was examined. Their findings indicated that the bend angle exhibited a direct proportionality with the laser power. Hao and Li [133] presented an analytical model that describes the relationships between the bending angle and various processing parameters in laser bending. In their experimental observations, they found that the bend angle exhibited an direct relation with laser power. Wang et al. [134] focused on investigating the influence of radial scanning strategy on the bowl surface forming of a three-layer stainless steel composite plate. They observed that high bend angle achieved with symmetric scanning strategy and the bending angle increased with the increase of laser power.

Cheng and Lin [135] utilized neural networks to investigate the influence of forming parameters on laser bending of 304 stainless steel sheets. They found that the bend angle in laser bending of 304 stainless steel sheets was a function of line energy. Magee et al. [136] provided more detailed insights into the effects of process parameters on the laser bending of aluminium and titanium alloys. They found that by increasing the line energy a corresponding increase in the bend angle of the aluminum and titanium alloys. This suggests that a higher energy input promotes greater deformation and bending during the laser bending process.

2.2.2. Scan Speed

Kotobi and Honarpisheh [137] conducted a study exploring the use of steel-titanium bimetal sheets for laser forming. They observed that the bend angle increased as the scanning velocity decreased during laser forming of steel-titanium bimetal sheets. Souza et al. [138] reported in their study that the bend angle of steel sheets linearly increased with the low value scan velocity. Lambiase et al. [139] investigated the relationship between scanning speed and bend angle. They found that a higher value of the bending angle was achieved when the scanning speed was decreased. Safari [140] used finite element method to explore the influence of process parameters during laser bending of a plate. They observed that higher scanning speed reduces the interaction time between the laser beam and the plate, which affects the heat flux induced into the material, resulting in a decrease in the bending angle.

Li and Yao [141] studied the laser bending process using different combinations of parameters. In their research, they explored the effects of various parameters on the resulting bend angle. They observed that doubling the scanning speed resulted in a 30% decrease in the bend angle. Shichun and Jinsong [142] investigated the influence of process parameters on the deformation of sheets in laser bending process. They reported that scanning speed had a significant effect on both the bend angle and mechanical properties in the laser bending process. They observed that observed that the deformation in the irradiated zone increased when using low scanning speeds during the laser bending process.

Arnet and Vollertsen [143] explored the laser bending of St14 for the convex shapes. The found that at lower feed rate more energy is observed during laser bending of material, which leads to more deformation. Siqueira et al. [144] conducted an experimental study on laser forming of high-strength aluminum alloy using a Yb-fiber laser. They investigated the effects of varying scanning speed on the bending behavior and mechanical properties of the alloy. The study examined the range of scanning speed from 3 mm/s to 30 mm/s. They found the bending angles as a function of the speed and increased with decrease in scan speed.

Zhang et al. [145] studied the bending deformation of tube by applying four different scanning schemes. They investigated the influence of scanning velocity on bend angle and suggested that scanning velocity plays an important role to generate temperature gradient. They observed that the bending radius initially decreased and then increased with an increase in scanning velocity during the laser forming. Chan and Liang [146] investigated the effects of scanning speed on the deformation behavior of the hardened high carbon steel. They reported that the high bending angle observed with an increase in scanning velocity during the laser bending process of a hardened high carbon steel.

Ramos et al. [147] conducted a study investigating the effect of process parameters on AA 2024-T3 sheets during the laser bending process. They employed scanning electron microscopy and Vickers micro-hardness tests to analyze the microstructure and strength of the bent specimens. They observed that the process parameters have significant effect to enhance the bend angle and achieve superior mechanical and microstructural properties after laser bending of specimen. They reported that the bend angle increased at lower scanning velocity and fine grain refinement was obtained in irradiated zone.

Majumdar et al. [148] utilized continuous wave CO_2 laser with a power of 2 kW for the bending of AISI 304 stainless steel. The researchers aimed to investigate the effect of laser process parameters, specifically scan speed on the bending angle of the stainless steel. They examined the microstructure and phase transformation behavior of AISI 304 stainless steel during laser bending using a scanning electron microscope. They found that high bending angles and grain refinement in the irradiated zone were observed when using minimum scanning speed during the laser bending. Kant and Joshi [149] developed a numerical model to investigate the bending mechanism of magnesium M1A alloy sheets during multi-pass laser bending. They reported that edge effect increased with the increase in scanning speed. Behera et al. [150] used Taguchi method for the experimentation of laser bending of Al worksheet. They reported that an increase in scan speed was responsible for a decrease in the bending angle.

2.2.3. Beam Diameter

The beam diameter is a critical parameter in laser bending, and optimizing it is essential to achieving the desired bending results in materials processing. Many studies and research efforts have focused on investigating the effect of beam diameter on the bending characteristics in laser bending processes. Kotobi et al. [118] investigated the bending behavior of samples and its relationship with beam diameter during the laser bending process. They reported that the maximum bending angle achieved at the minimum value of the beam diameter. Maji et al. [43] performed experimental investigations on pulsed laser bending of stainless steel sheet to study the effects of process parameters. They suggested that bend angle decreased with the increase of spot diameter due to the laser beam energy is applied to the wider surface, thereby the intensity of the temperature gradient reduces. Raza et al. [151] investigated the effect of multi-scan laser bending process parameters on 304L stainless steel. They found that an increase in spot size resulted in a decrease in the final bending angle. This effect was attributed to a reduction in melt depth and transverse plastic strain, an increase in the width of the plastically deformed region, and the higher energy density in the heated zone associated with larger spot sizes.

Fetene et al. [52] carried out FEM simulation and experimental study for multi pass laser bending of AH 36 steels strips and reported that bend angle increases with decrease beam diameter.

Maleki et al. [152] investigated the laser forming of steel with the aim of creating a V-shaped bend. They examined the variation of process parameters and their impact on the bending behavior. They reported that the beam diameter is the most influential parameter in achieving higher bend angles during laser forming. The increase in beam diameter reduce the concentration of heat results in lower bend angle. Reza Ghoreishi and Mahmoodi [153] Reza Ghoreishi and Mahmoodi [159] proposed a statistical model to predict the bending angle in laser forming of bi-metal sheets. According to their findings, the bending angle decreased with an increase in the beam diameter.

The beam shape is a crucial factor in laser bending processes, as it directly affects how thermal energy is distributed and the material absorbs that energy. Various studies have delved into the influence of beam shape on the bend angle in laser bending processes.

Chejamil et al. [154] examined how the beam geometry affects the bending behavior and other aspects of the laser bending process. They conducted experiments using both triangular and rectangular beam geometries. The findings of their study indicated that the choice of beam geometry had a significant impact on the bend angle and edge effect during laser bending.

Fauzi et al. [155] examined the effects of traditional beam profile on edge effect in laser forming technique of stainless steel (AISI- 304) work-piece. In this research, six different beam geometries (Diamond transverse, Triangle, conventional circular beam, House, Diamond and Rectangle) were used to reduce the edge effect as shown in Fig. 2.1. They found that the diamond transverse beam produced the highest bend angle and the rectangle beam produced the lowest bending angle. Triangular beam offered less bend angle deviation when compared to diamond transverse beam. This was because of triangular beam geometry produces wider plastic distribution. Temperature gradient is vital to decrease the edge effect with the variation in beam geometry. This study shows that geometry of beam has great effect on edge effect and bend angle during the process.

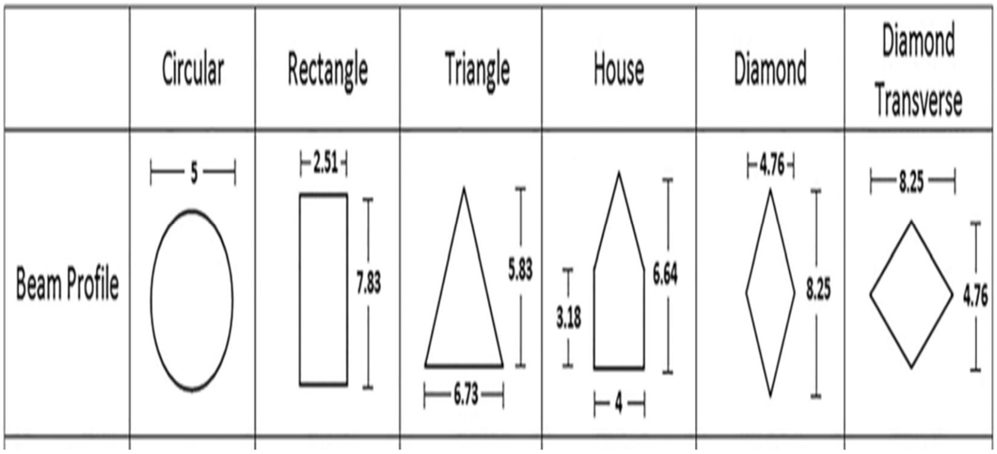

Fig. 2.1. Beam profiles [155] (With Permission (Appendix 2.1) Copyright © 2019, Springer Nature).

Ablat and Qattawi [161] suggested that by optimizing the laser beam shape, it is possible to control the temperature gradients, heating rates, and cooling rates more effectively. This, in turn, can lead to increased plastic deformation and higher bend angles in the work piece. Safdar et al. [156] investigated the effect of various laser beam geometries on laser tube bending. They employed finite element modelling techniques to simulate the bending process and analyse the outcomes. The findings of their study indicated that a higher bending angle could be achieved by using a circular beam geometry.

2.2.4. Duty Cycle and Pulse Duration

The duty cycle is a measurement that represents the ratio of the pulse-on time to the total time. The pulse duration refers to the length of time during which a single laser pulse emits energy. The effect of duty cycle and pulse duration on the bending behavior is significant in achieving the desired bend angle during laser bending process.

Chen and Xu [157] used continuous wave and pulse lasers for bending process and reported that continuous laser offered a higher bend angle and pulse laser provided high precision. Maji [158] used pulse laser for micro-forming of thin sheets. The study involved exposing laser beams to two different shape worksheets, rectangular and circular, and observing the deformation that occurred under various process conditions, including laser power, pulse duration, and beam diameter. They reported that in single pulse forming, deformation increased with laser power and pulse on time and decreased with beam diameter. However, for multiple pulses, smaller pulse times resulted in higher deformation due to the generation of high temperature gradients.

2.2.5. Number of Laser Scans

Thomsen et al. [159] investigated experimentally the influence of number of scans on bend angle during laser bending process. They observed that by increasing the number of scans and using a small incremental length for each pass had a positive effect on the total bend angle. By performing multiple scans with small incremental lengths, able to achieve a larger overall bend angle compared to a single pass.

Lawrence et al. [63] studied the laser bending of mild steel by using high power diode laser. They observed that the bend angle increases with the increase in number of scans. The results are indicated in Fig. 2.2.

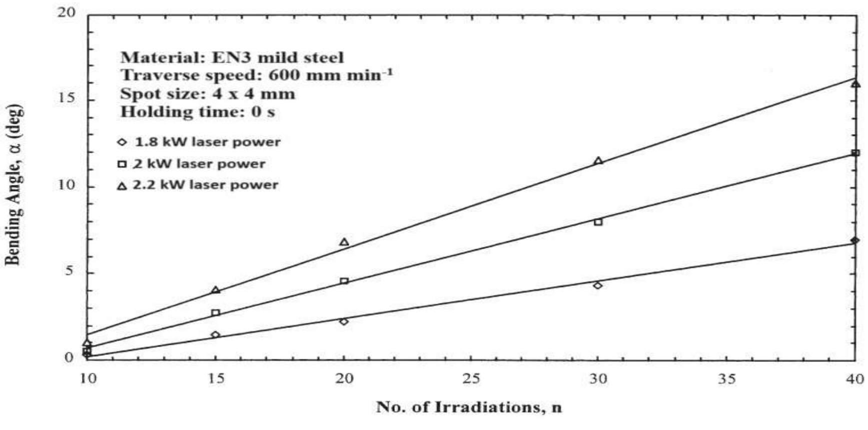

Fig. 2.2. Variation of bend angle with laser power and number of scans [63] (With Permission (Appendix 2.2) Copyright © 2001, Elsevier).

Das and Biswas [160] investigated the effect of operating parameters and the number of scans on the bending of mild steel plates using a CO_2 laser. They found that multiple passes had a pronounced effect on the angular deformation of the mild steel plates. Specifically, they observed that the angular deformation increased with an increase in the number of passes.

Casalino and Ludovico [161] proposed the use of a feed-forward neural network for the laser bending process. Their study investigated the relationship between the number of scans and the resulting bend achieved during the process. They found that increasing the number of scans led to a higher bend in the material being processed. Edwardson et al. [162] provides insights into the relationship between bulk material temperature, bend angle per pass, hardness, and strain hardening during multi-pass laser forming of mild steel, Ti6Al4V, and AA5251 sheet materials. They found that that the bend angle per pass increased as the bulk material temperature increased. Additionally, the researchers observed that as the number of scans increased, the hardness and strain hardening of the material also increased.

Wu et al. [163] employed both simulation and experimental methods to investigate the plastic deformation characteristics of silicon sheets during the laser bending process. The results obtained from their research indicated that thicker silicon sheets exhibited a slower rate of plastic deformation during laser bending compared to thinner sheets. The high bending angle is achieved with the increase in laser scans and the increment is smaller after every pass. It has been observed that surface coatings of graphite burnt off by repeated irradiations result in decrease of absorptivity.

Griffiths et al. [164] discussed the behavior of graphite coating under repeated irradiation and its impact on energy absorption and bend angle in the context of laser processing. According to their findings, the graphite coating on the material burnt off as a result of repeated irradiations. They observed that initially, as the number of scans increased, the bend angle of the material also increased. Navarrete and Celentano [165] provide insights into the behavior of graphite-coated AISI 304 stainless steel sheets during multi-pass laser forming processes and shed light on the relationship between the number of passes and the resulting bending angles. They found that the as the number of irradiations or laser passes increased, the larger bending angles were obtained with lower rates after each pass.

Paunoiu et al. [166] focused on the laser forming of AISI 304 stainless steel sheets using a high power diode laser. The process parameters selected for the experimentation were laser power levels from 100 to 300 W, scan speed 4 and 8 mm/s, and the number of scans 2, 4 or 6. The cumulative effect of multiple scans also contributed to an increased bending angle. Nath et al. [167] reported that utilizing multiple passes in a bending process leads to a significantly higher bend angle compared to a single pass. According to their findings, the bend angle achieved through multiple passes was approximately 430% higher compared to a single pass.

Cheng et al. [22] described the effect of process parameters and bending mechanism on the bend angle of sheets with varying thickness The bend angle during laser bending processes increases with an increasing number of laser passes. Mazdak et al. [168] evaluate the impact of effective parameters on the laser bending process of a two-layer sheet composed of steel and aluminium. They reported that the bending angle increased by 103% and 63% when the number of laser scans was 15 and 25, respectively. Based on the simulation results, it has been observed that the bending angle increases with the number of laser passes.

Lambiase et al. [169] compared single and multi-pass laser forming of thin AISI 304 stainless steel sheets using a high power diode laser. They concluded that multiple laser scans resulted in a larger bending angle in the thin AISI 304 stainless steel sheets. Chan et al. [170] focused on investigating the deformation behavior of a chromium sheet during the laser bending process. The researchers examined the influence of the number of laser irradiations on bend angle. The bend angle increased with an increase in the number of irradiations during the laser bending process of a chromium sheet. Ponticelli et al. [171] introduced a fuzzy model to describe the laser-assisted bending process. In their research, they investigated the influence of various laser process parameters on the bending process. They suggested that the number of passes required in the laser-assisted bending process could be reduced by utilizing the highest laser power setting.

Yang et al. [172] investigated the impact of various parameters on the saturated convex bending curvature of a aluminum 7075 panel using laser shock forming. The researchers focused on three specific factors: overlapping ratio, number of repeated shocks, and laser power intensity. They suggest that laser shock forming is influenced by multiple parameters, including the overlapping ratio, the number of repeated shocks. According to their findings, when the aluminum panel was subjected to five shocks from laser beams at a high laser power intensity, the cumulative effect of the shockwaves led to increased plastic deformation and bending of the panel. Gudur and

Simhambhatla [173] described a hybrid approach involving fiber laser during part fabrication, where multiple laser passes are used to achieve a desired angle or shape. They observed that there is an increase in the change in bend angle for every subsequent 200 laser passes. This change in bend angle is attributed to two factors: thermal softening of the material and heat accumulation.

2.2.6. Absorptivity

Kant et al. [174] focused on the experimental investigation of laser bending for magnesium alloy M1A sheet. In order to enhance the absorptivity of the sheet coated with a graphite spray. The experiments conducted by using a 2.5 kW continuous wave CO_2 laser machine. In the reported experiments, the researchers found that the process parameters, including laser power, scanning velocity, and beam diameter, had a significant effect on the absorptivity.

Gautam et al. [175] conducted a study to explore the impact of various surface coatings on the laser forming process of mild steel sheets. The objective was to enhance the absorptivity of the mild steel sheet, and two distinct coatings were chosen: commercial lime and cement. The researchers performed experiments using different combinations of laser power and laser scan speed for each coating. The obtained results were compared uncoated bent specimen. It has been observed that the bending of mild steel with cement coating increased than the lime coating and uncoated specimen due to the coating increases the absorptivity of material.

Dutta et al. [176] studied the experimental investigation of the effect of coating with black enamel paint on laser bending of mild steel. By achieving a higher bend angle, the researchers demonstrated the potential of the enamel paint coating to optimize the laser forming process. The coating burnt off after every pass due to heating of laser beam. They suggested that coating after each scan can produce larger bend angle.

Barletta et al. [177] conducted a study in which they compared the laser bending of thin aluminum metal sheets with and without a coating of Al_2O_3 (alumina). The researchers also investigated the influence of process parameters on the bending behavior of the coated sheets. They found that high bend angle achieved with high laser power and low scan speed for Al_2O_3 coated aluminium thin sheets. Because of the compact and dense nature of the alumina coating likely contributes to its improved energy absorption properties, making it an effective coating for laser bending applications. Chen et al. [178] employed a pulsed Nd: YLF (Neodymium-doped

Yttrium Lithium Fluoride) laser for the laser bending of stainless steel specimens. They observed that the absorptivity of the material increased as the wavelength of the laser beam decreased.

Fan et al. [179] conducted an experimental and numerical study on the phase transformations of AISI 1010 steel during laser bending. They explored the effect of surface coating on the absorptivity of the steel and suggested that applying a graphite coating to the surface exposed to the laser could increase its absorptivity. Abedi and Hoseinpour Gollo [180] investigated the effects of coating on AISI 304 stainless steel sheet with a Cr_2O_3 oxide layer during the laser-forming (LF) process. The researchers applied Cr_2O_3 layers with different thicknesses to the samples and examined the resulting impact on absorptivity and bending angle during laser forming. Their findings revealed that as the coating thickness of the Cr_2O_3 layer increased, there was a significant increment in both absorptivity and bending angle. They suggest that applying a Cr_2O_3 oxide layer with a thickness of up to 6 μm resulted in enhanced absorptivity. Abazari et al. [181] and Tavakoli et al. [182] covered the metal with graphite coating to enhance the absorptivity of material. They reported that the bend angle can be increased with the coating of the surface under laser irradiation due to the high absorption of energy. Singh [183] studied CO_2 laser bending process and described from their experimental results that in the context of CO_2 laser bending, hydrated lime coating was found to be superior to graphite coating. Yadav et al. [184] explored that bend angle can be improved by increasing the absorptivity by different coatings.

2.2.7. Workpiece Geometry

The geometry of the workpiece, including its length and thickness, can have an impact on the bend angle achieved during the laser bending process. The thickness of the sheet is directly involved in generating the temperature gradient between the top and bottom surfaces of the sheet during laser bending. Zahrani and Marasi [185] focused on investigating the impact of various process parameters on the bending angle achieved during the laser bending process. The process parameters considered in the study were laser power, beam diameter, scan speed, and sheet thickness. The beam diameter and number of passes are the primary factors affecting the bending angle in laser bending, while the sheet thickness has an inverse relationship with the bending angle. Cheng et al. [186] examined the influence of sheet size, specifically the variation of sheet width and sheet length, on the deformation of low-carbon steel sheets in the laser bending process. According to the findings of this study, an increase in sheet width during laser bending of low-carbon steel sheets leads to a decrease in the bend angle due to the increased heat sink effect. It has been found that an increase in sheet width during the laser bending process leads to a decrease in the peak temperature at the top surface of the workpiece. Cheng et al. [187] provides insights into the deformation characteristics of thin plates with varying thickness during the laser bending process. It has been observed that the bending strain for constant laser power and scanning speed decreases first then remains nearly constant when the thickness increases. According to their findings, the decrease in bending strain with increasing sheet thickness can be attributed to the larger heat sink effect, which leads to a decrease in peak temperature during the laser bending process. They described that at lower scanning speeds during the laser bending process, energy is more uniformly distributed across the thickness of the material.

Chakraborty et al. [188] aimed to improve the bend angle of formed stainless steel by using laser. They employed a combination of experiments and finite element (FE) simulations to investigate and optimize the laser forming process. According to their findings, laser forming performed by scanning a laser beam on both the concave and convex sides of mechanically bent specimens. In their observations, they noted that the bending angle was higher when the laser scan applied on the convex side compared to the concave side. It has been observed that during laser scanning on the convex side of the mechanically bent specimens, an increase in the bend angle was observed. However, in contrast to this, when laser scanning was performed on the concave side, an opposite trend was observed. Ganesh Kumar et al. [189] focused on investigating the laser bending behavior of SS-304 steel with varying thicknesses and power densities. According to their findings, they reported that the bend angle exhibited specific trends in relation to the sheet thickness and power density. They observed an inverse relationship between the sheet thickness and the resulting bend angle. Additionally, they found that the bend angle increased with the power density. Ngiejunbwen et al. [190] examined the influence of sample thickness on the deformation of aluminum 2024 using an Nd:YAG laser. The researchers found an inverse relationship between sheet thickness and the amount of deformation observed. They noted that the forming depth, which refers to the extent of deformation or bending achieved during the laser bending process, decreased with an increase in sheet thickness.

2.2.8. Workpiece Clamping

The proper clamping of workpieces is a critical aspect of laser bending processes. Researchers continue to explore and refine clamping techniques to enhance the efficiency and accuracy of laser bending for various applications. Birnbaum et al. [191] investigated the influence of clamping on the laser forming process. They carried out experiments in two conditions: (i) the sheet was clamped in a cantilevered manner (ii) the sheet was simply put on a platform. Both the clamped and free specimens were scanned at distances of 40 mm, 25 mm, and 10 mm from the left edge. For both (clamped and unclamped) cases, the greatest bend angle was achieved when scanning was carried out at 25 mm distance from the left edge and the lowest bend angle was achieved when the scanning was carried out at a distance of 10 mm from the left edge. Except for 10 mm distance case, the bend angles for the clamped sheet were greater than those for the unclamped sheet. Edwardson et al. [192] investigated the effect of clamping conditions, specifically two clamp conditions: cantilever and V-block. They reported that bend angle remained equal for both clamp conditions (cantilever and V-block) for the first 15 scans and then showed a marginally higher bending for the V-block condition. They observed that the rate of increase in bend angle per scan was higher in the V-block condition compared to the cantilever condition. They reported that difference in the rate of bend angle increase between the cantilever and V-block conditions being attributed to changes in beam area. Hu et al. [193] examined the performance of two types of clamping conditions: the conventional method, in which the sheet is clamped at one edge, and the laser scan method, in which clamps are used at the start and end points. They observed that the "edge effect" was minimized when clamps were placed at the start and end points of the laser scan.

2.2.9. Mechanical Properties

The mechanical properties that influence the performance of the laser bending process include yield strength, coefficient of thermal expansion, Poisson's ratio, and modulus of elasticity. Yanjin et al. [194] observed that certain material properties such as Young's modulus, thermal expansion coefficient, and specific heat have a direct influence on the temperature during the laser bending process. Guan et al. [100] used finite element method (FEM) simulations to investigate the relationship between the bending angle and various material property parameters, including Young's modulus, yield strength, thermal expansion coefficient, specific heat, and thermal conductivity. The simulation results indicated that a larger bending angle can be achieved with a material having lower Young's modulus and yield strength. The bending angle was found to be directly proportional to the thermal expansion coefficient. It has been observed that the bending angle was observed to decrease with an increase in heat conductivity. They purposed that higher bending angle can be achieved for the material with lower specific heat and density. The obtained results demonstrated in the Fig 2.3.

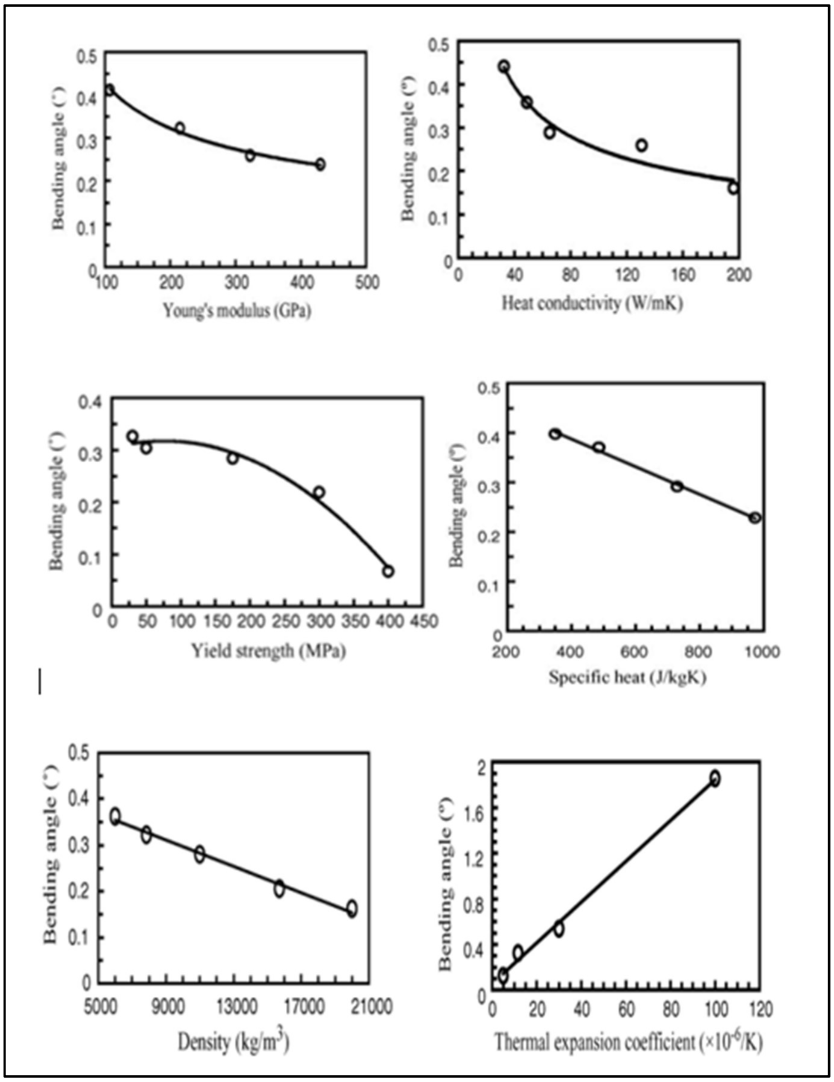

Fig. 2.3. Influence of Young’s modulus, heat conductivity, yield strength, specific heat, density, thermal expansion, on bending angle [100] (With Permission (Appendix 2.3) Copyright © 2005, Elsevier).

Kyrsanidi et al. [9] focuses on the numerical and experimental investigation of the laser forming process of metallic plates. They examined the temperature dependency of the mechanical properties of the material during laser forming. The researchers observed that the mechanical properties of the material have a significant influence on the bending behavior of the sheet during the laser bending process. Vásquez-Ojeda and Ramos-Grez [37] focused on CO_2 laser bending of stainless steel AISI 302 plates. In their study, they observed that the bend angle increased with an increase in the thermal expansion coefficient of the material. Maji et al. [195] provided insights into the optimization of multi-scan laser forming for AISI 304 stainless steel sheets. By understanding the effects of process parameters and developing an empirical model for predicting the bend angle, the researchers aimed to facilitate the production of developable surfaces using laser forming techniques. The observation of refined microstructures indicates that the laser forming process influenced the material's structural properties.

2.2.10. Thermal Properties

The thermal properties do have a significant influence on the temperature distribution within a material sheet. Li and Lawrence Yao [196] focused on investigating the impact of thermal properties on the temperature near the starting point in order to gain a deeper understanding of the mechanisms involved in forming processes. They observed that when the thermal conductivity of the material decreases, both the peak temperature and the temperature gradient of the material increase.

Hu et al. [53] examined the impact of process parameters and thermal properties of stainless steel on the laser bending process. According to their findings, the authors observed that when working with stainless steel, which is known to have lower heat conductivity compared to other materials, certain combinations of process parameters led to larger buckling deformations. They described that the materials having lower thermal conductivity or poor heat dissipation properties, a large temperature gradient can occur. Bejan and Kraus [197] reported that the temperature gradient directly proportional to the thermal conductivity of material. Halmešová et al. [198] investigated the impact of different laser powers during the deposition process on various thermal properties of a structure composed of 316 L stainless steel and Inconel 718. The thermal properties examined included thermal expansion, specific heat, thermal diffusivity, and thermal conductivity. The researchers observed that as the laser power increased, the thermal properties of the material decreased. Torabnia and RezaeePazhand [199] focused on investigating the effect of material properties on the bending angle and temperature distribution during the laser forming process. They suggested that material properties have a significant impact on the bending angle.

2.2.11. Forced Cooling

The main challenge for the researchers is to develop the process precise and proficient. In recent years, researchers have concentrated on finding solutions to difficulties caused by excessive material melting and oxidation during multi-pass laser bending techniques. Guo et al. [200] focused on examining the impact of process parameters on pulsed laser bending of aluminum 6061 alloy sheets. They found that water cooling produced a lower bend angle than natural cooling during pulsed laser bending of the aluminum 6061 alloy sheet. However, after 55 scans, the bend angle increment with water cooling conditions exceeded that of natural cooling. Shen and Yao [201] numerically investigated the influence of force water cooling systems on the temperature distribution and bending angle of the plate. They developed a numerical thermo-mechanical analysis model with moving boundary conditions to simulate the movement of a laser beam and a moving forced water cooling system. Cooling effects are explored using the suggested model at various laser powers and scanning velocities under varied cooling circumstances. The results show that forced water cooling can dramatically reduce temperature while having no negative effect on plate forming. The use of forced water cooling systems may improve the bending angle achieved in a single pass, especially if the cooling is applied to the top surface or both the top and bottom surfaces. Forced water cooling systems have no effect on the edge effect.

Thomsen et al. [202] determined the influence of cooling on the variation of bending angle, with particular attention to the heat-affected zone (HAZ) and edge effects. They observed that the lower bend angle obtained due to reduced heat effected zone (HAZ) from the high level of cooling. They reported that variations in the convection coefficient did not have a significant influence on the edge effects. Cheng and Lawrence Yao [203] investigated experimentally and numerically the effect of forced cooling on single-scan laser forming processes. The findings of their study would provide insights into optimizing the laser forming process, considering the effects of cooling and its interaction with laser power, scanning speed, nozzle offset, and cooling air pressure. The effect these parameters on the deformation mechanism, temperature and flow stress was investigated. They found that forced cooling during laser forming had significant effects on the deformation mechanism, temperature, flow stress, dimensional accuracy, and mechanical properties. Additionally, forced cooling reduced the waiting time between scans, indicating a potential improvement in process efficiency. Shen and Yao [204] examined the effect of scaled geometry on cooling time under various processing parameters, concentrating on the cooling criterion. Specifically, they investigated how the properties of stainless steel and aluminium alloy materials influenced the cooling time. Both numerical simulations and experimental methods were employed in this research. The results obtained from these two approaches indicated that the cooling time could be substantially reduced when employing the same temperature cooling criterion. This reduction was particularly pronounced for materials characterized by high thermal conductivity and large heat capacity.

Lambiase et al. [205] focused on investigating the impact of passive water cooling in laser forming of thin sheets made of AISI 304 stainless steel. The experiments were designed to explore the effects of different cooling media, laser scanning speed, laser power, and sheet thickness on the process. The results of their study indicated that the implementation of passive water cooling in laser forming led to a significant reduction in the cooling time between successive scans. This cooling method also proved effective in minimizing the oxidation of the irradiated surface. Moreover, they observed that the bend angle, which represents the deformation of the sheet, was only slightly affected by water cooling. One of the notable advantages highlighted in their findings was the increased process efficiency resulting from the reduced waiting time between scans.

Shen et al. [206] demonstrated that forced water cooling applied to both the upper and bottom surfaces of steel sheets during laser bending resulted in a significant reduction in temperature after each scan. This cooling method facilitated an increase in the bending angle and did not introduce any negative edge effects. Kant and Joshi [207] focused on the influence of forced cooling on the laser bending of magnesium alloy. They employed Finite Element Method (FEM) simulations to investigate how different process parameters, such as laser power, scan speed, and number of scans, affected the bending process. Additionally, they compared the output parameters between forced cooling and natural cooling conditions. The results of their study demonstrated a significant improvement in the performance of the multi-scan laser bending process when forced cooling was applied. The application of forced cooling led to enhanced bend angle, indicating an improved deformability of the magnesium alloy. This suggests that forced cooling facilitated more effective bending of the material compared to natural cooling conditions.

Paramasivan et al. [208] focused on the implementation of an moveable external cooling source to enhance the temperature gradient between the top and bottom surfaces during laser irradiation in the laser bending process as shown in Fig. 2.4. Their objective was to numerically investigate the effect of forced cooling on the bending angle of AISI 304 stainless steel sheets. The researchers reported that the external cooling source had a significant influence on both the bend angle and the temperature gradient across the plate thickness. The use of forced cooling resulted in a notable increase in the bending angle, approximately 20% higher compared to the conventional technique without external cooling. Furthermore, they observed that forced cooling had a substantial impact on reducing the Heat-Affected Zone (HAZ).

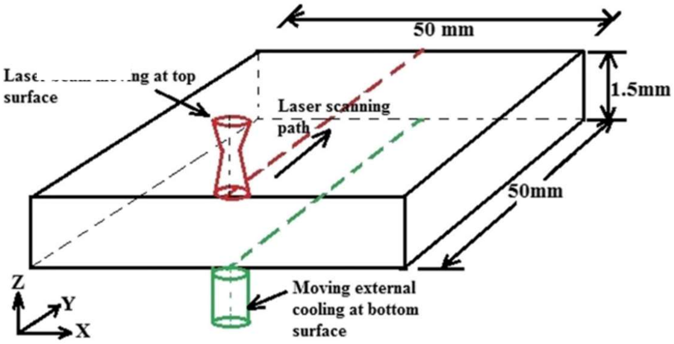

Fig. 2.4. Laser bending with moveable forced cooling arrangement [208] (With Permission (Appendix 2.4) Copyright © 2001, Elsevier).

Yadav et al. [209] aimed to develop a numerical model for analyzing the laser bending process and investigating the impact of forced cooling on the bend angle and edge effect. The researchers focused on studying the effect of forced cooling on the surface opposite to the laser scan. According to their findings, the application of forced cooling on the surface opposite to the laser scan resulted in a significant increase in the bend angle. However, they noted that the effectiveness of forced cooling was dependent on the line energy used. At high line energy, forced cooling exhibited positive results, leading to improved bend angles. However, adverse effects were observed at low line energy when forced cooling was applied. Furthermore, the researchers highlighted that the edge effect, which refers to the deformations or inconsistencies near the edges of the material, increased under the application of forced cooling at high line energy.

Yadav et al. [58] focused on examining the impact of three distinct cooling conditions on the process of multi-scan laser bending of stainless steel. The researchers observed that the temperature distribution remained similar across all three cooling conditions, despite variations in the number of scans. The study revealed that all three cooling conditions resulted in higher tensile strength and hardness values for the scanned specimens compared to the base material. Additionally, micrographs of the irradiated zone exhibited a fine grain structure under all three cooling conditions. Furthermore, the researchers noted a significant increase in the bend angle of the steel strips subjected to the laser bending process under the forced cooling condition. Additionally, they observed an improvement in the mechanical properties of the bent steel strips. The forced colling arangment used in their study is presented in Fig. 2.5.

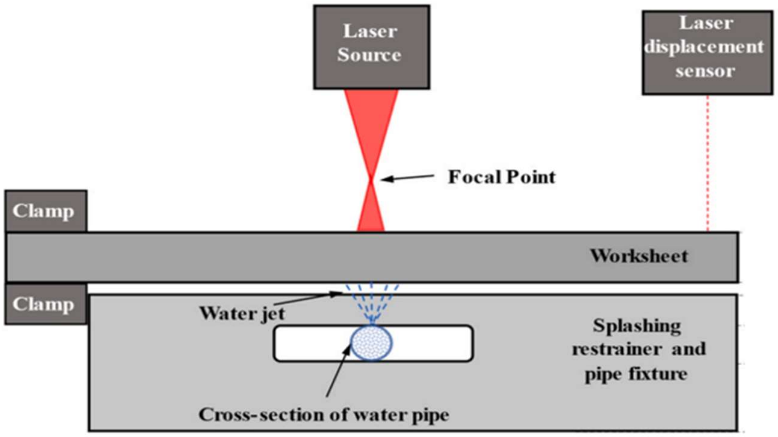

Fig. 2.5. Forced cooling arrangement [58] (With Permission (Appendix 2.5) Copyright © 2022, Elsevier).

Khandandel et al. [210] focused on the development of a novel cooling strategy for laser tube bending using circumferential scanning. The researchers conducted experimental investigations to assess the impact of this cooling method on the bending angle achieved during the process. The study reported that the bending angle obtained after each scan increased by more than 1.5 times when utilizing the novel cooling strategy, while requiring minimal energy and less time compared to non-cooling conditions. This indicates that the new cooling technique significantly enhanced the efficiency of laser tube bending utilizing the circumferential scanning method. Additionally, the research highlighted that the new cooling technique had a notable effect on reducing the heat-affected zone (HAZ) during the bending process. By implementing the novel cooling strategy, the extent of the HAZ was significantly reduced. Khandandel et al. [211] focused on investigating the impact of forced cooling on laser tube forming of AISI 304L, both numerically and experimentally. The researchers aimed to assess the effectiveness of forced cooling on the bending process and its potential implications for residual stress and corrosion. The study reported that local cooling, applied at a specific distance from the laser beam, demonstrated high efficiency in tube bending.

2.2.12. External Load

Another method to enhance the bend angle and accuracy is to apply assisting-load, which is utilized to support the deformation. Many researchers used different methods to enhance the bend angle and mechanical properties of laser bending process. Gisario et al. [212] focused on investigating the external-force assisted high power diode laser bending process of grade 2 titanium and AA 7075 T6 aluminum sheets. The researchers aimed to achieve high bend angles and control springback effect by utilizing the contact pressure generated by a hydraulically driven tool. They evaluated the bend angle for both titanium and aluminum sheets using the load applied by the hydraulically driven tool. Furthermore, they assessed the process accuracy achieved through the external-force laser assisted bending of these materials. The researchers observed high bend angles and controlled springback by employing the contact pressure of a hydraulically driven tool. Nowak et al. [213] conducted a study on the effect of external pre-loads on the bend angle of steel plates during laser bending as shown in Fig. 2.6. They demonstrated the feasibility of mechanically assisted laser bending with high efficiency and reported that large bending deformations of plates were achieved under mechanical load.

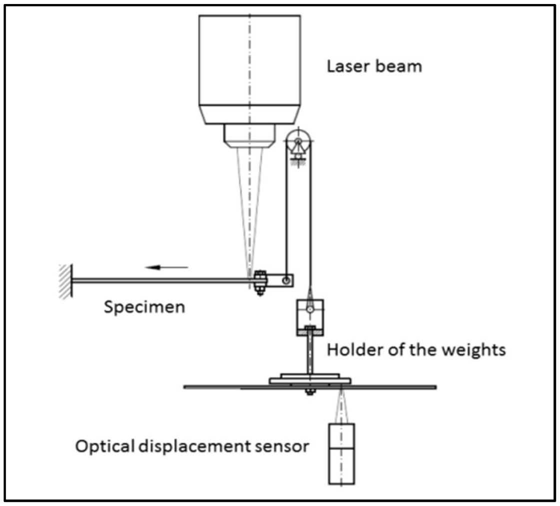

Fig. 2.6. Laser bending under mechanical load [213] (With Permission (Appendix 2.6) Copyright © 2018, AIP Publishing).

Fetene et al. [214] developed an ANN model for laser-assisted bending using a FEM model. They conducted experimental tests on a cantilevered sheet with a mechanical load, varying several process parameters as shown in Fig.2.7. The researchers concluded that bending can be improved by employing a mechanical load during the laser-assisted bending process.

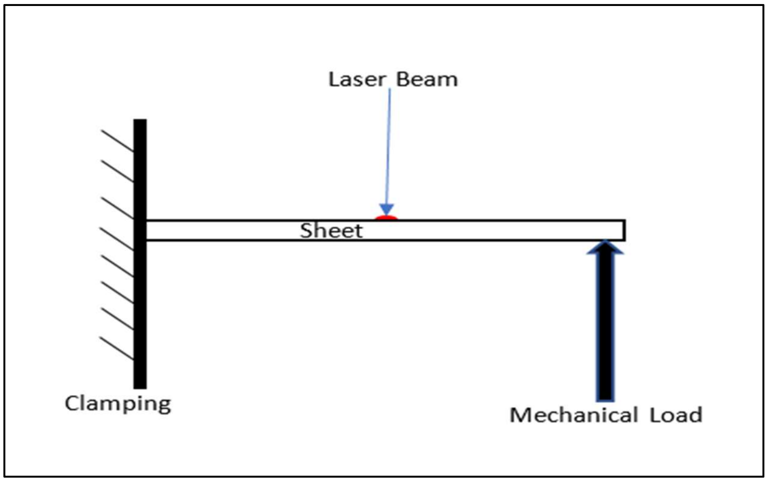

Fig. 2.7. Laser bending with external mechanical load [214] (With Permission (Appendix 2.7) Copyright © 2016, Springer Nature).

Kant and Joshi [215] proposed a method by using a mechanical load that moves in a path parallel and synchronous to that of the laser beam. Using the finite element approach, they created a three-dimensional sequential thermo-mechanical non-linear elasto-plastic numerical model of laser-assisted bending. The effects of transient load examined for stress-strain distribution and bend angle distribution. The simulation findings demonstrated that mechanical loading increased the compressive stresses at the top surface and the tensile stresses at the bottom surface. This made it achievable to produce bend angles with greater magnitudes without using more energy than necessary, as was necessary for multi-pass laser bending operations. They reported that the bend angle increased with increase in mechanical force. The edge effect was higher for mechanical loads of greater magnitude.

Kant et al. [216] proposed a new technique of laser-assisted bending with a moving load. The researchers aimed to analyze the influence of pre-displacement on the bend angle, edge effect, and springback in the bending process. They compared the laser-assisted bending technique with the conventional laser bending process without an external mechanical load. In their experimentation, they assessed the impact of pre-displacement on the bend angle, edge effect, and springback. They observed that these parameters significantly affected by the application of an external load. Specifically, they found that by utilizing the moving pre-displacement load technique, they were able to achieve a high bend angle without experiencing springback and edge effects. Gisario et al. [217] explored that stainless steel sheets can be bent with the use of lasers to produce sharp angles. First, bending trials carried out by using a combination of laser irradiation and an additional bending device based on the kinematics of deformable quadrilaterals. In order to determine the most effective processing settings, the laser's operational parameters namely, scanning speed, power, and number of passes were changed. They show how the unique airplane shapes exhibited in Fig. 2.8 could be achieved by combining thermos-mechanical bending and hybrid BM with TGM and laser bending. According to their findings, large bending angles of 70 to 140° can be obtained with the assistance of lasers as well as external forces.

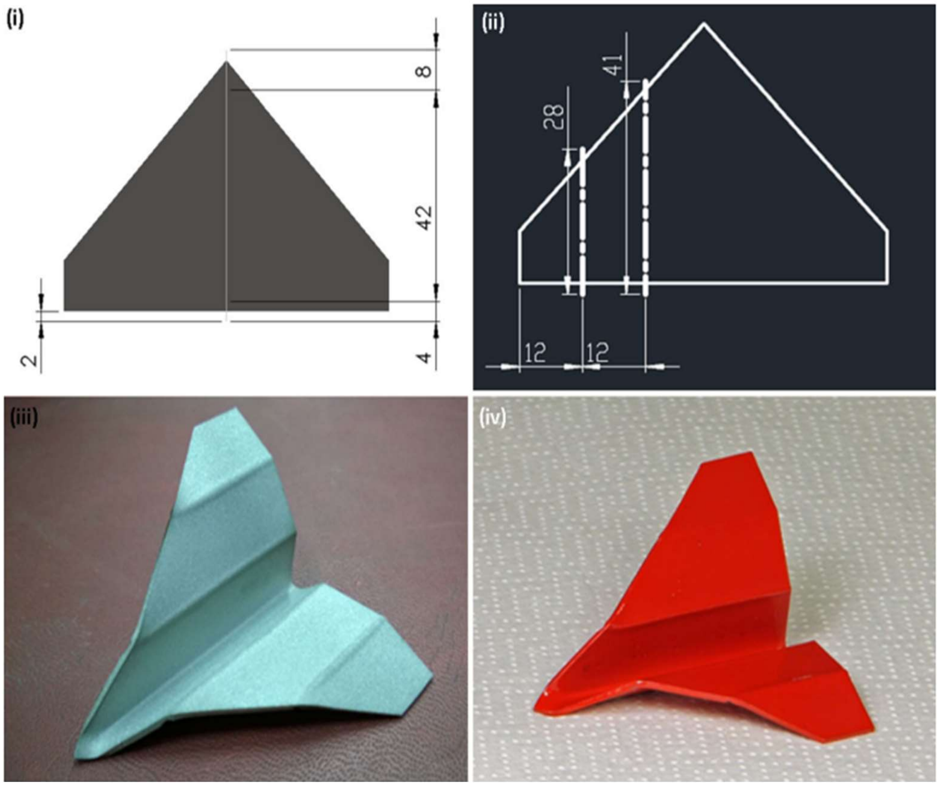

Fig. 2.8. Bending of an aircraft from steel blanks: (a) design of bending strategy (b) lateral bending; (c) raw aircraft after bending; (d) final aircraft [217] (With Permission (Appendix 2.8) Copyright © 2015, Springer Nature).

Guo et al. [218] developed a mathematical model of laser bending angle for buckling mechanism under preload. The proposed approach is based on a thermal buckling angle model without preload by assessing stress and strain in the heating zone and taking preload variables into account. The proposed model depends on the original thermal buckling prediction model, meets the requirements of the Fourier number, process parameters, and preload values. The free end of the plate was applied with preload as shown in Fig. 2.9. In comparison to the experimental data, the average bending angle error is less than 3.7% for different preloads and 5.1% for different laser powers. Overall, the findings demonstrated that the suggested model is capable of properly predicting the bending angle.

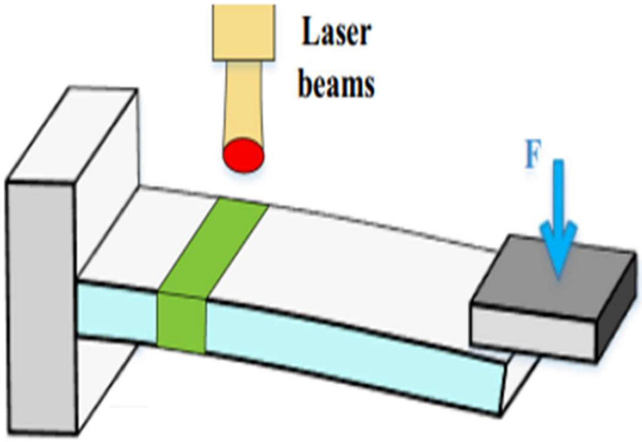

Fig. 2.9. Laser bending under preload [218] (With Permission (Appendix 2.9) Copyright © 2020, Springer Nature).

Wang et al. [219] examined the laser bending of titanium alloy sheet by using finite element simulation and experiments were also carried out to confirm the model and the results. The trials were carried out in the order that the specimen was first loaded longitudinally with the preload clamp to generate the arch shape. The laser was then used to scan across the surface of the specimen along the arch height. The results revealed that the thermal effect of the laser varies greatly depending on the preload. Larger preload is more beneficial in terms of increasing plastic deformation and bending precision. Guo et al. [220] demonstrated the use of laser scanning and laser-assisted four-point bending to create high-stiffened aluminum alloy structures. The process parameters were selected bending moment 149.5–195.5 N·m; laser power 800–1200 W; scanning distance 60–100 mm; scanning speed 1–9 mm/s. According to the time order indicated in Fig. 2.10, the typical laser-assisted four-point bending process is separated into mechanical-bending, laser scanning, cooling, and unloading stages. They reported that mechanical load and scanning speed have a highly significant influence on the amount of deformation, while laser power and scanning distance have no significant influence on the amount of deformation.

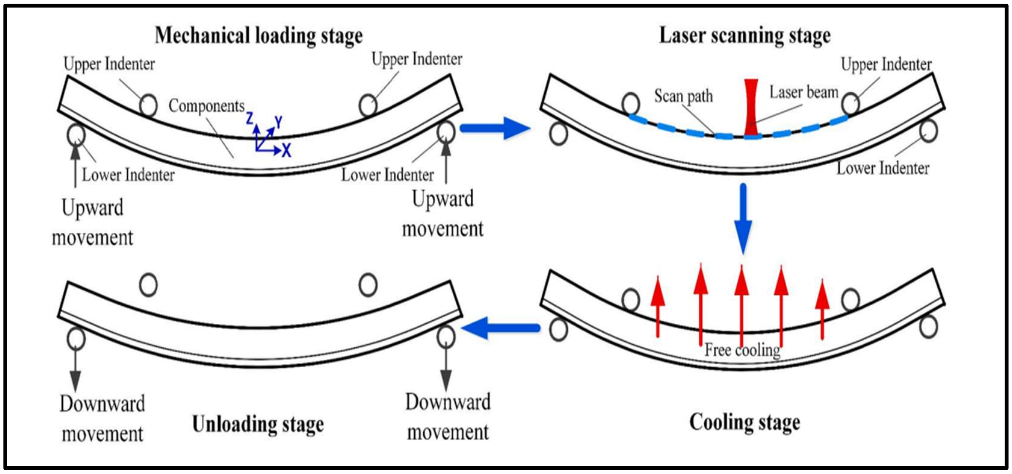

Fig. 2.10. Laser bending mechanism under load [220] (With Permission (Appendix 2.10) Copyright © 2016, Elsevier).

Roohi et al. [221] studied the external force assisted laser forming process to achieve higher bend angles. They observed an increase in equivalent plastic strain with an increasing number of laser scan passes. The researchers found that applying an external force in addition to laser irradiation enhanced the final forming of the sheet, but noted that the main drawback of force-assisted laser bending techniques was the need for physical contact during bending as shown in Fig. 2.11.

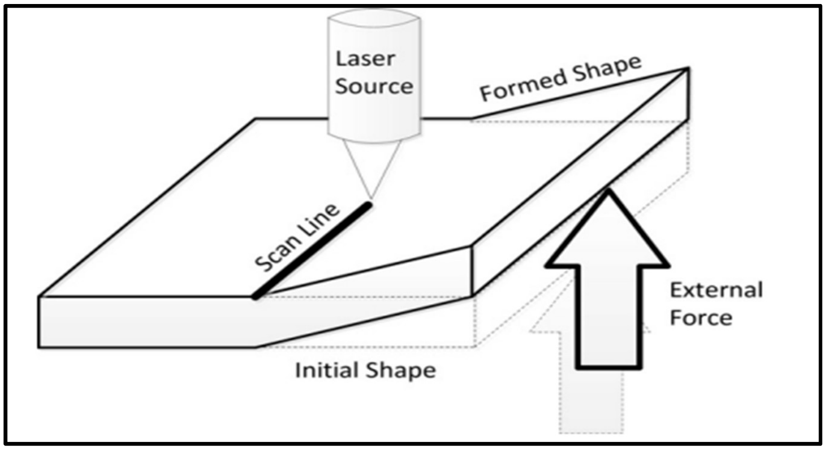

Fig. 2.11. Laser bending process under external force condition [221] (With Permission (Appendix 2.11) Copyright © 2012, Elsevier).

All of the investigations demonstrate that the mechanical loads applied to the free end of the sheet can enhance the bending angle, but physical contact between the sheet and the mechanical load may have an effect on the properties of the bent specimen. Fetene et al. [8] provided a solution to the physical contact problem in force-assisted laser bending by utilizing permanent magnets on the free end of the workpiece as shown in Fig. 2.12. They observed that the bend angle increased with the effect of magnetic attraction. However, they encountered challenges related to fixing and removing the workpiece due to the strong permanent attraction between the magnet and the workpiece. Additionally, the magnetic force introduced variation in the bend angle, which could reduce the overall accuracy of the bending process.

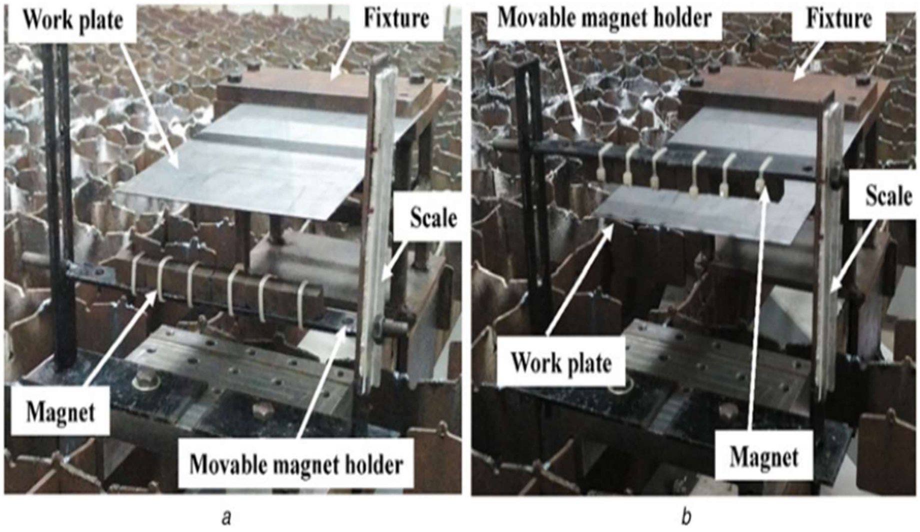

Fig. 2.12. Laser bending under magnetic field [8] (With Permission (Appendix 2.12) Copyright © 2017, Wiley).

However, recently some studies seems to be found as potential solution for such problems. Dutta et al. [27] developed a setup of electromagnetic-force-assisted laser bending process and found significant results in terms laser characteristics. Some researchers also described techniques to enhance the bend angle during laser bending process. Khandandel et al. [222] proposed a new idea for designing a path strategy for 2D and 3D forming of tubes using the laser technology. This design makes it possible for all designers to easily extract the path strategy of a desired tube shape to be precisely formed by laser tube forming process and increased the process accuracy. Hennige et al. [223] proposed various strategies to enhance the bend angle in the bending process. One of the strategies suggested was the implementation of closed-loop control of the process. The suggestion of employing closed-loop control indicates that the researchers recognized its potential to improve the bending process and achieve better bend angles.

2.3. Edge Effect in Laser Bending Process

The edge effect is the undesirable deformation or curved bending edge along the scanning line due to asymmetrical forming process [224]. Another reason is the higher temperature differences in the entrance and exit points [225]. Jha et al. [226] reported that the edge effect could be minimized to some extent by increasing the number of laser scanning passes. Zhang et al. [227] focused on analysing the edge effect on bending angles in the laser bending process of DP980 high-strength steel. They employed a finite element model to investigate this phenomenon. The researchers observed that the edge effect of laser bending becomes more prominent as the laser scanning velocity increases. This suggests that higher scanning velocities lead to increased edge effects, which can negatively affect the bending angles achieved during the process. To mitigate the edge effect, they proposed a varying velocity scanning strategy. According to their findings, the varying velocity scanning strategy was successful in significantly reducing the edge effect and increasing the bend angle of the laser bending process. Shen et al. [228] focused on investigating the edge effects in laser bending using a varying scan speed. The researchers developed a numerical model to simulate and analyze this phenomenon. The results of their study demonstrated that by implementing a varying scan speed, it is possible to significantly reduce the edge effect in laser bending.

Ghadiri Zahrani and Marasi [229] aimed to experimentally investigate the impact of various process parameters on the edge effect in laser bending. The parameters they considered included beam diameter, laser power, scan speed, sheet thickness, number of scans, and scan path position. The researchers observed that some process parameters had a significant effect on the laser bending process and the resulting edge effect. Specifically, the number of laser scans, sheet thickness, scan speed, and laser power were found to have a notable influence. They proposed that increasing the number of laser passes could lead to a significant reduction in the edge effect. They reported that as the beam diameter decreases, the effective results obtained in terms of edge effect. In addition, they observed that increasing the sheet thickness and scan speed had a decreasing effect on distortion.

Bao and Yao [230] involved a numerical investigation to understand the mechanism behind the edge effects observed in the laser bending process. The researchers observed that there was a significant temperature difference between the entrance and exit points of the laser bending process. Specifically, they found that the temperature at the exit point was considerably higher than that at the entrance point. They reported that the higher temperature at the exit point led to a concentration of laser heat in that region, which in turn resulted in non-uniform deformation. Shi et al. [231] aimed to explore the factors contributing to the variation in bending angles observed in the laser bending process. Both experimental and numerical investigations were carried out to shed light on this issue. The researchers identified two primary causes for the bending angle variation: non-uniform temperature distribution and non-uniform geometry. To mitigate the bending angle variation, the researchers employed various heating methods during the multi-scanning laser bending process. The experimental results indicated that the heating methods had a substantial impact on the bending angle variation along the heating line.

Shi et al. [225] improved the dimensional accuracy of bending of metal plate under the action of two unequal concentrated forces. As shown in Fig. 2.13. They applied two forces F_a and F_b on the free end of sheet, which results the reduce in edge effect.

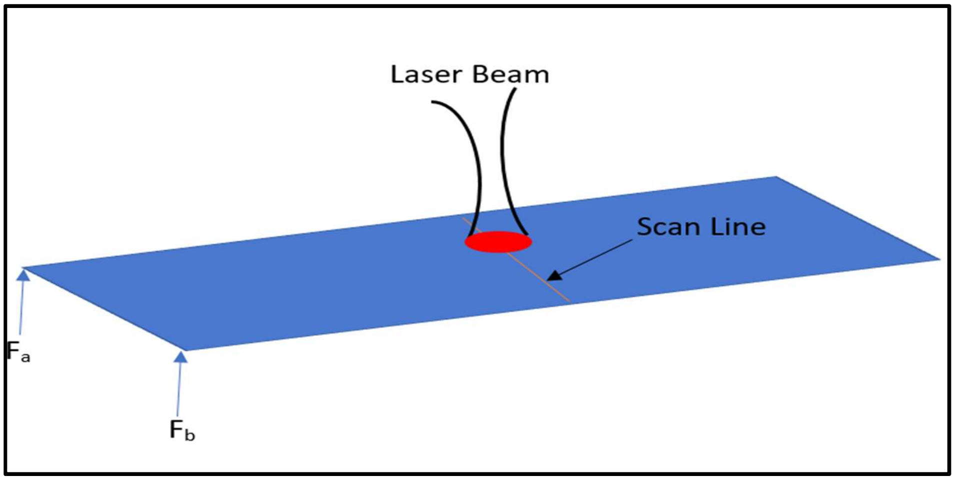

Fig. 2.13. A proposed scheme of reducing edge effect by applying two unequal forces at the free end [225] (With Permission (Appendix 2.13) Copyright © 2016, Elsevier).

Kant et al. [232] focused on investigating the edge effect in laser bending of magnesium alloy M1A sheets using a CO_2 laser machine. The researchers aimed to understand how various process parameters influenced the edge effect and the resulting bending characteristics. The experimental investigation involved analyzing the effects of three key process parameters: laser power, scanning velocity, and beam diameter. These parameters were varied to assess their impact on the edge effect during laser bending. The results of the study revealed that all three process parameters had a significant effect on the edge effect. Laser power and beam diameter primarily influenced the magnitude of the variation in bend angle along the irradiation path. However, they did not have a substantial impact on the overall bending profile. On the other hand, the scanning velocity affected both the variation in bend angle and the bending profile along the irradiation path. As the scanning velocity increased, the bend profile transitioned from a linear shape to a saucer shape.

Jha et al. [224] investigated the edge effect in laser bending of AISI 304 stainless steel. The researchers discovered that the edge effect is influenced by various process parameters. Additionally, they observed that laser bending can sometimes lead to the generation of multiple curvatures on a single laser scan path. This phenomenon, known as the multi-curvature effect, was found to be highly dependent on the laser scanning speed. To mitigate the extent of the multi-curvature effect, they suggested employing a higher number of passes during the laser bending process. By increasing the number of passes, it is possible to minimize the occurrence of the multi-curvature effect. Hu et al. [233] investigated experimentally the effects of the laser power, beam diameter, and scanning velocity on edge effects using Taguchi method. The results show that the most significant processing parameter on edge effects is beam diameter, and the combination of the laser power and scan velocity has the greatest interaction effect on edge effects. The experimental results for different process parameters are shown in Fig. 2.14.

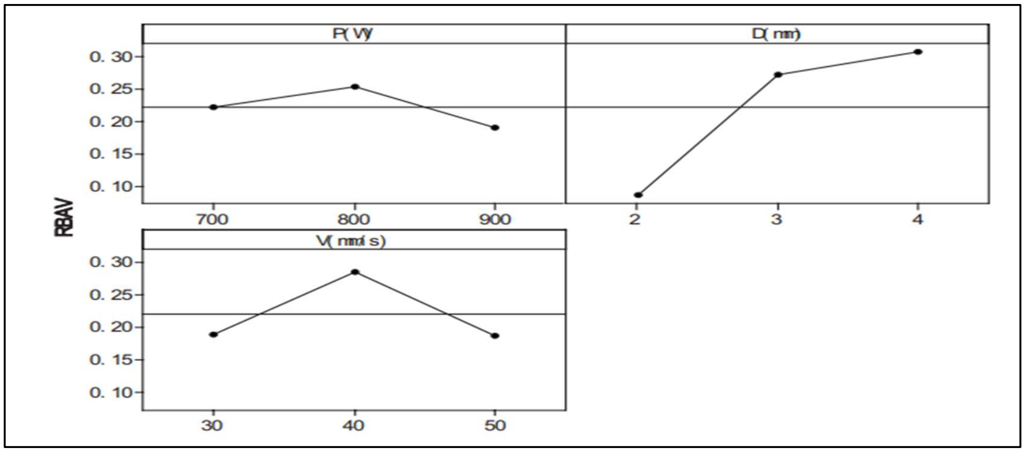

Fig. 2.14. Effects of laser power, beam diameter, and scan velocity on RBAV [233] (with permission (Appendix 2.14) Copyright © 2010, AIP Publishing).

2.4. Mechanical and Microstructural Properties

Studying the effects of laser bending on the mechanical and microstructural properties of materials provides valuable insights for manufacturing processes, material selection, and component design. It helps in developing robust manufacturing techniques and predicting the behavior of laser-formed components in various applications. By understanding, the interaction between the laser beam and the material during laser scanning, manufacturers can effectively harness this process for various applications such as shaping, forming, and bending of materials in a controlled and efficient manner. Laser scanning can induce strain hardening, dynamic recrystallization, and phase transformations, all of which can lead to significant alterations in the mechanical and microstructural properties of the heated region. By studying the mechanical and microstructural changes induced by laser scanning, researchers can optimize the process parameters, material selection, and subsequent heat treatments to achieve the desired properties for specific applications. Researchers studied to investigate the mechanical and microstructural changes that occur on a workpiece because of laser processing, by systematically varying the process parameters.

2.4.1. Microstructural Properties

There have been numerous studies published on the microstructure of workpieces during laser bending. Seyedkashi et al. [234] studied the laser bending of SUS304L/C11000 clad sheet and reported while laser irradiation may induce some localized microstructural changes in steel and copper layers, these changes are generally minimal compared to materials with lower thermal conductivity. High thermal conductivity of copper enhances the rapid distribution of heat and potentially prevent significant microstructural changes in the adjacent steel layer during laser processing. Ramos-Moore et al. [235] studied the microstructure characterization of laser beam bending of interstitial-free (IF) steel and AA6013 high-strength aluminium alloy. They described that during laser processing, when the surface temperature of the material surpasses a certain threshold, grain growth and melting occur due to the intense localized heating. The results showed various microstructure effects on materials, including grain boundary diffusion and changes in surface roughness. Liang [236] focused on examining the deformation and microstructure behavior of a high carbon steel during laser bending. The aim was to understand the changes that occur in the material because of laser processing. Furthermore, significant microstructural differences were observed across the thickness of the bent region. Near the top surface, a microstructure consisting of coarse martensite with retained austenite was observed. On the other hand, near the bottom surface, the microstructure consisted of martensite with retained carbide and bainite. Abdul Aleem [237] investigated laser bending of mild steel sheet. They observed melting and re-solidification takes place in adjacent region of heat-affected zone (HAZ). Fan et al. [179] demonstrates that laser bending can induce grain refinement in the HAZ of AISI 1010 steel, leading to changes in the material's microstructure and potentially improved mechanical properties.

2.4.2. Mechanical Properties

In recent years, numerous studies have been reported in the literature focusing on the investigation of mechanical properties after laser bending processes. By studying the mechanical properties affected by laser bending, researchers can optimize the process parameters, material selection, and subsequent heat treatments to achieve desired material behavior and ensure the performance and reliability of laser-formed components. The influence of compressive and tensile strains, residual stresses, and hardening during the laser bending process has been widely studied and reported by many authors. Merklein et al. [238] observed that the material experiences plastic deformation and the accumulation of dislocations, resulting in an increased hardness with the number of laser passes. Higher dislocation densities in certain regions lead to increased hardness. McGrath and Hughes [239] conducted a study where they investigated the fatigue life of laser-formed samples compared to stock plate samples. They observed a significant enhancement in the fatigue life of the laser-formed samples. The improvement in fatigue life was attributed to the laser-hardening mechanism. This mechanism involves subjecting the material to laser energy, which induces a phase transformation and rapid cooling. Yadav et al. [58] reported that the micro-hardness and tensile strength of stainless steel is increased after multiple laser scan bending of stainless steel.

2.5. Research Gaps

Based on the review of the published literature, several research gaps and possibilities for further investigation have been identified. Based on the literature review, the following research gaps have been identified:

- ❖ Many recent studies have endorsed to overcome problem of inaccuracy in sheet bending. Edge effect is one major issue in dimensional accuracy of laser bent specimen described by researchers.

- The previous studies show that the edge effect for sheet metals can be reduced with magnetic assisted laser bending. The main reason behind this is that metals are got attached with magnet. However, Dutta et al. [27] reported that permanent attraction between magnet and work piece generates problem in fixing and removing the work piece. Moreover, the variation occurred in bend angle due to the magnetic force, which may reduce the accuracy of the process. Electromagnetic-force assisted laser forming is one of the alternatives for sheet bending with high process accuracy. But the influence process parameters on edge effect during electromagnetic assisted laser bending has not been explored.
- Despite the many advantages of electromagnetic force assisted bending as reported by Dutta et al. [35], no further studies have been reported later.
- As reviewed from literature mild steel is commonly used to fabricate the structures in aerospace and automobile engineering [240]. No study has been reported to explore the possibilities of electromagnetic assisted forming of mild steel.
- The effect of process parameters i.e. laser power, scanning speed and beam diameter during electromagnetic force assisted bending are not thoroughly studied in terms of bend angle, micro-hardness, tensile strength and microstructural analysis.
- Many authors reported that to achieve higher bend angle, substantial waiting time between successive scans is required for cooling down the work sheet. The deformation of metal strip in the laser bending process is due to the thermal stresses and the overheating phenomenon may occurred in heating area.
- It is apparent from the literature that a forced cooling is a significant method to re-establish the temperature gradient after every scan in multi scan laser bending of metal sheets and avoid excessive surface oxidation and melting.
- The combined effect of forced cooling and laser process parameters on bend angle and mechanical properties of mild steel strip after multi scan laser bending process have not been thoroughly investigated.
- Heat accumulation around the HAZ can lead to several undesirable effects reported by [Shen et al. [241]]. Cooling is effectives to reduce heat effect and avoid metal oxidation. However, the optimization of process parameters with forced cooling for mild steel has not been investigated.

2.6. Research Objectives

The comprehensive review of the literature on the topic of laser bending has shed light on several facets of this manufacturing method. The review included laser bending mechanisms, process variables, scanning tactics, transformed materials, mechanical characteristics, and metallurgical modifications.

The impact of process variables like laser power, scanning speed, beam diameter, number of scans, and beam shape on laser bending was thoroughly investigated. Additionally, it was discovered that material characteristics, such as material properties, sheet dimensions, and coating, had a substantial impact on the bending performance. Furthermore, the importance of cooling environments as well as external force support is emphasized during the laser bending process. It was claimed that external force assistance and forced cooling might considerably increase the effectiveness and productivity of the operation. The process is very flexible when these process parameters are adjusted precisely. However, the dependability of each parameter on the others makes it difficult to optimize the process parameters for desired deformation. Thus, further investigation is required to optimize these process parameters.

The literature studies explored the continually increasing demand in the aerospace and automotive industries for laser-formed sheets with good dimensional accuracy and durable mechanical properties. The high strength materials like titanium, nickel alloys and steels are commonly used in manufacturing industries for the fabrication of small products like ribs and stringers. The innovation in laser forming process for the precise forming of these materials is required. These products require high accuracy in bending angle and inner radius. However, these materials are difficult to bend and straighten by conventional methods due to dimensional inaccuracy.

It has been observed from the literature that various researchers had been trying to attenuate the problems associated with conventional bending methods such as dimensional accuracy and lower bend angles [121, 223]. From literature it has been observed that bend angle and dimensional accuracy can be enhanced by applying cooling and external load during laser bending process. The main disadvantage of all techniques of mechanical force assisted laser bending is that bending is through physical contact. Fetene et al. [8] suggested a way to overcome this problem and used permanent magnets on the free end of workpiece. However, permanent attraction between magnet and work piece generates problem in fixing and removing the work piece. Moreover, the variation occurred in bend angle due to the magnetic force, which may reduce the accuracy of the process. However, recently some studies seems to be found as potential solution for such problems. Dutta et al. [27] developed a setup of electromagnetic-force-assisted laser bending process and found significant results in terms laser characteristics. Despite the many advantages of electromagnetic force assisted forming as reported by Dutta et al. [27], no further studies has been reported lately.

In addition, it has been observed from literature that the deformation of metal strip in the laser bending process is due to the thermal stresses and the overheating phenomenon may occurred in heating area. In the other hand, the small bending angle is obtained after each laser scan and waiting time is required between consecutive scans in order to re-establish the temperature gradient. Sufficient cooling is also required to avoid excessive surface oxidation and melting. In recent years, many scholars have carried out research on how to avoid excessive material oxidation and material melting in multi-pass laser bending process. Since, it is apparent from the literature that a forced cooling is a significant method to re-establish the temperature gradient after every scan in multi scan laser bending of metal sheets. However, it is crucial to thoroughly explore the combined effect of forced cooling and laser process parameters on bend angle and mechanical properties of mild steel strip after multi scan laser bending.

The literature review additionally glanced at how various metallurgical and mechanical properties change in materials during laser bending process. To ensure the intended performance and endurance of laser-bent components, it is important to comprehend variations in mechanical properties such as micro-hardness and tensile strength. The deformed materials' metallurgical studies also revealed the changes in structure and phase tranformation. It is significant to take into account that these mechanical and metallurgical changes will be obvious in external cooling and mechanical force assisted laser bending techniques. Therefore, more research into laser bending methods including external cooling and mechanical force is required in order to fully comprehend and assess various mechanical, and metallurgical properties. It is a crucial aspect of advancing this technology and making it more versatile and adaptable to diverse industrial needs.

Objectives: Based on the literature survey, the following objectives are decided:

1. To design and develop the experimental set up for electromagnetic-force assisted laser bending of sheets.

2. To study on the effect of process parameters (i.e., beam diameter, laser power and scanning speed) on the performance characteristics of the electromagnetic-force and forced convection cooling enhanced laser bending of mild steel sheets.
3. To characterize the bending mechanism, bend angle and edge effect during electromagnetic force assisted laser bending of mild steel sheets.
4. To analyze the mechanical and micro-structural properties of mild steel sheets bent through electromagnetic force assisted laser bending.
5. To analyze the bending mechanism, bend angle and edge effect during laser bending of mild steel sheets enhanced with forced convection cooling.
6. To analyze the mechanical and micro-structural properties of mild steel sheets bent through laser bending enhanced with forced convection cooling.