Light amplification by stimulated emission of radiation (LASER) is a coherent and monochromatic beam of electromagnetic radiation capable of generating intense heat on solid matter, which enables several types of novel and economical processing of materials, i.e., cutting, drilling, welding, forming, surface treatment etc. The applications of laser in these areas are advantageous compared to their conventional counterparts. The idea of using lasers for bending or forming of sheet material was introduced by Kitamura in Japan (Kitamura 1983). Since then, significant interests had been created toward the use, development and improvement of laser metal forming technology among the researchers, scientists and engineers for its practical and economical applications in industries like aerospace, automotive, ship building, electronic industries etc. This thesis deals with the theoretical and experimental investigations on analysis and synthesis of laser forming process for making sheet metal parts. Laser forming is a thermal forming technique, which is a non-conventional sheet metal forming process. In this chapter, laser metal forming process has been introduced first, followed by an extensive survey of literature on the studies of continuous and pulsed laser bending, and 2D and 3D laser forming. The previous studies carried out by various researchers on the experimental investigations, analytical, numerical and empirical modeling of the laser forming processes have been discussed. This is followed by the aims and objectives for the work presented in this thesis. The contributions made in the present thesis and organization of the thesis have been discussed at the end of the chapter.

1.1 Introduction to the Laser Forming Process

This section describes the laser forming process, its applications in various areas and the process parameters involved. Next, the different mechanisms of laser forming process have been discussed followed by their advantages and limitations. The necessity for the modeling and analysis of the process has been felt at the end of the section.

Process description

Laser forming is a non-traditional forming process used for flexible fabrication of sheet metal components of different shapes by the controlled defocused laser beam-induced thermal stresses without applying any external mechanical force. It has promising applications in rapid prototyping and shape correction in aerospace, ship building, automobile industries and microelectronics. During laser forming, localized heating of the surface using a controlled beam without surface melting causes the differential expansion of the material in a confined region due to non-uniform temperature distributions. Due to the continuity of heated region with the surrounding material, the free expansion of hot region is resisted, resulting in permanent deformation of the part when the thermal stress becomes more than the temperature dependent flow stress of the material. The overall deformation in the sheet material is determined by the complete thermal cycle (heating and cooling) associated with laser processing. It is a complex thermo-elasto-plastic process, which depends on complex interactions of a large number of process variables. The simplest of laser forming processes is a simple straight line bending operation, as shown schematically in Fig. 1.1 (Asibu, E.K., 2009).

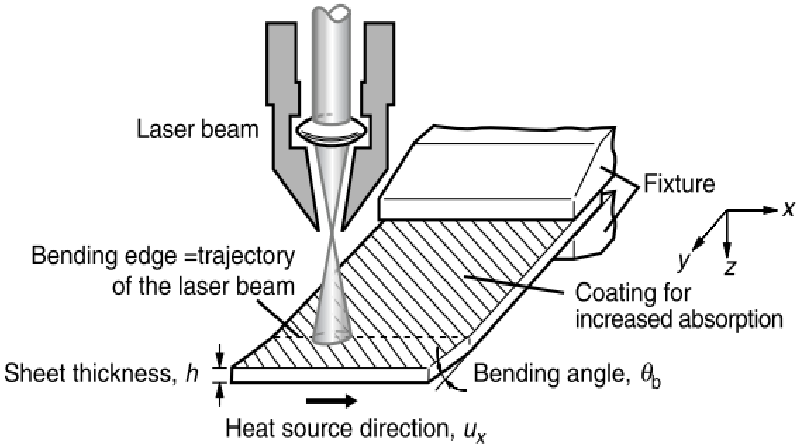


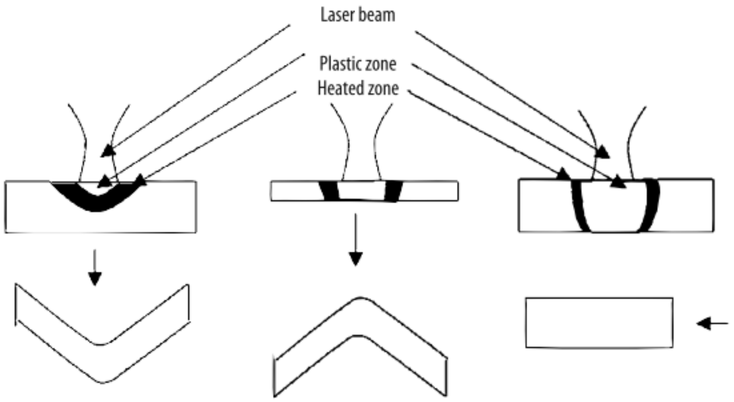
Fig. 1.1: Schematic view of the laser bending process (Asibu, E.K., 2009).

In the laser forming arrangement shown in Fig. 1.1, one side of the sheet material is clamped in a fixture and the beam is scanned or irradiated linearly parallel to the free side of the sheet. Such a simplified arrangement is useful for typical V-shape bends in the sheet. However, more complex, and nonlinear scanning patterns can be used for producing complex shaped 3D parts. The final shape of the bend is determined by the actual laser processing strategy employed. This includes the consideration of three types of process parameters, i.e., parameters related to the laser source, work-piece geometry and material properties. Laser energy parameters are laser power, scan speed, spot diameter, number of laser scans, wavelength etc. The parameters related to the work-piece geometry are sheet dimensions, such as its length, width and thickness. The performance of the process also depends on the temperature dependent thermo-physical properties of the work-piece material. The related thermal properties are coefficient of thermal expansion, thermal conductivity, specific heat etc. and mechanical properties are density, Young’s modulus, poisson’s ratio, yield stress etc. Apart from these properties, the process also depends on the absorptivity of the sheet surface, method of holding the work-piece, scanning sequence in multi-scan laser forming process, cooling conditions, and others. The deformation mechanisms vary depending on the processing conditions or the combinations of the process variables as discussed below.

Mechanisms of laser forming process

There are various mechanisms of laser forming process depending on the processing conditions or specific combinations of the process variables, i.e., component geometries and laser processing conditions. In laser forming, though the deformation takes place through the heating and cooling cycles, Frackiewicz (1993) stated that about 25 variations of thermal forming mechanisms had been investigated in the Center for Laser Technologies of Metals (CLTM) of the Polish Academy of Sciences (PASc.) and Kielce Technical University, Poland. The mechanisms of laser forming process can be classified based on the existence of thermal gradient. The thermal forming mechanisms with the existence of temperature gradient are the Temperature Gradient Mechanism (TGM), Residual Stress Point Mechanism (RSPM) and Martensite Expansion Mechanism (MEM); and those without temperature gradient are the Buckling Mechanism (BM), Upsetting Mechanism (UM) and Residual Stress Relaxation Mechanism (RSRM). However, the three main mechanisms of laser forming process mostly reported in literature are TGM, BM and UM. Now, among these three mechanisms, the TGM is the most common one and widely used mechanism because of its ease of control. The details of different mechanisms and their comparisons are discussed below.

The temperature gradient mechanism (TGM) is the most widely reported laser-forming mechanism, also called the bending mechanism because an out of plane bend is produced, as shown in Fig. 1.2 (a). Due to the rapid heating of the surface by the defocused laser beam and slow heat conduction into the sheet, a steep temperature gradient along the thickness sets in and thus, results in a differential thermal expansion. To create a high temperature gradient, laser beam must traverse the workpiece at such a speed that the thermal diffusion depth is small compared to the workpiece thickness. The thermal diffusion depth is approximately given by $d_{th} = \sqrt{\kappa\tau} = \sqrt{\kappa d/v}$, where κ, τ, d and v are thermal diffusivity, interaction time, laser spot diameter and laser scan speed, respectively (Steen and Mazumder, 2010). For establishing TGM, $d_{th} < s, or \sqrt{\kappa d/v} < s, or\, \kappa d/s^2 v < 1$, where s is sheet thickness and $\kappa d/s^2 v$ is Fourier's number. Therefore, the TGM become dominant, if the Fourier number is very small, less than one. In TGM, as the material is heated, the thermal expansion of the top surface becomes greater than that of the bottom surface, initially. This results in a bending opposite to the laser beam, which is called counter-bending. Due to this bending moment, a small amount of plastic tensile strain occurs at the heated top surface. With further heating, the bending moment opposes the counter-bending away from the laser beam, and the yield stress of the material is reduced with the temperature rise. Once the thermal stress reaches the temperature-dependent flow stress of the material, any additional thermal expansion is converted into a plastic compressive strain, because of the fact that the free expansion is restricted by the surrounding material. During cooling, the material contracts again in the upper layer, and as it has been compressed, there is a local shortening of the upper layer, and a bending angle develops that finally bends the specimen towards the laser beam. Generally, the TGM may be used for bending thick sheets along straight lines towards the laser beam. The irradiation of the surface may be repeated in order to increase the bending angle. The amount of bending per pass is approximately 1–3° (Steen and Mazumder, 2010). It remains constant for the first few passes for a given material, laser power and beam size. Thereafter, the bending angle per pass starts to fall owing to work hardening and thickening of the material at the bent edge.



(a) (b) (c)

Fig. 1.2: Mechanisms of laser forming process (a) TGM, (b) BM and (c) UM (Steen and Mazumder, 2010).

The BM is activated by laser parameters that do not yield a temperature gradient in the thickness direction. It works at low laser scan speed with large irradiated area in relatively thin sheets, where the thermal diffusion length is higher than the sheet thickness and the moment of inertia is low due to lesser sheet thickness. If there is small temperature gradient through the depth, then the expansion resulting from the uniform heating will cause a bulge to appear (Figure 1.2 (b)). As the centre of the bulge is hotter than the edges, it can bend plastically but the edges tend to bend elastically. Due to heating, thermal compressive stresses develop in the sheet, that results in a large amount of thermo-elastic strain, which, in turn, causes a local thermo-elasto-plastic buckling of the material. The direction of the bending angle is not defined by the process itself, as it is for the TGM. The direction of movement of the bulge or the bending direction can be either positive or negative and this depends on the process parameters, initial bend, a residual stress or an applied stress (i.e., by a forced air stream acting on the bottom of the sheet), internal stresses, and external or gravitational forces. The rate of bending is in the range of 1–15° per pass. This is considerably greater than that for the TGM, because considerably more energy is put into the sheet by using the low scan speed and large beam diameter. The BM may be used for bending thin sheets along straight lines towards or away from the laser beam. Like the TGM, the bending angle can be increased by repeating the process.

In UM, nearly uniform temperature and hence, nearly equal plastic deformation occurs along the thickness of the sheet, but the stiffer geometry or higher sheet thickness offers more moment of inertia, buckling is prevented and uniform compression (in plane strain) is resulted with a slight bending towards laser beam. The upsetting mechanism (UM) is shown in Fig. 1.2 (c). For the UM, the process parameters are similar to the BM, but the dimension of the heated area is smaller compared to the sheet thickness. Due to nearly homogeneous heating of the sheet and the restrictions in thermal expansion from the surrounding material, the sheet is compressed with an almost constant strain along the thickness, causing a shortening of the sheet and an increase in thickness. This mechanism can be used to bend a pipe with various kinds of cross-sections and to form complex shape along with TGM. Therefore, some of these mechanisms can accompany each other, or switch from one mechanism to another depending on the selection of process parameters and other conditions.

.

Advantages and limitations

Laser forming has many advantages over conventional forming techniques, such as, it offers great flexibility, good accuracy and precision without any spring-back action. Unlike mechanical forming, it requires no hard tooling, also is economically suitable for rapid manufacturing. The process has the programmability and possibility of automation, which can be used to integrate with other laser processes, such as cutting or welding processes. Many difficult-to-form hard and brittle materials, such as titanium alloy, nickel alloy, ceramics, etc., can be processed with a little distortion or degradation by laser forming. The process produces asymmetric bent because of scanning pattern used and also generates non-uniform deformation along the heating direction due to variation of heat sink and mechanical restraint. Like many other manufacturing processes, it has also got some limitations, such as the process is somewhat slow, tensile yield stress increases and ductility of the processed material decreases during the process, and fracture toughness and fatigue life of the formed components get deteriorated for some materials.

Modeling and analysis of laser forming process

It has already been mentioned that laser forming is a complex thermo-elasto-plastic process and depends on the interaction of a large number of process parameters related to laser irradiation, thermo-physical properties of workpiece material, sheet geometry, and others (Steen and Majumder, 2010). For practical application of LF process, automation of the process is required to make it feasible and economical to be adopted by industries. The LF process in its present stage is far from automation and it has limited applications in small series production, rapid prototyping, shape correction and precision adjustments in sheet metal industries. Generally, the heating pattern, or location of the heat lines, is determined by skilled artisans employing heuristic rules and experience. For making a desired shape, the experienced or skilled workers locate the heat lines using their knowledge or feel for the deformation that will result, and relies on visual comparison to a template with corrective processing through an iterative process. Therefore, the process has not become so popular and is not applied to large scale industry because of the lack of automation or due to the difficulty of determining the process parameters and scanning patterns to produce any desired shape within a reasonable time. Automation of the process requires integrations of different software and hardware components, development of predictive models for both forward and inverse analyses, control scheme and formulation of robust path planning algorithms. Moreover, modeling and optimization of the laser forming process is essential for better understanding and application of the process for achieving the optimum performance. Therefore, modeling and analysis of the laser forming process in both forward and inverse directions is inevitable to make it a practical process in industries.

1.2 Literature review

The research work on laser metal forming carried out by various researchers in the past can be classified broadly into different categories like laser bending of different materials with both continuous and pulsed modes of laser irradiations, 2D and 3D laser forming of different shapes, etc. Various types of studies on laser forming process currently available in the literature, such as experimental work on the effects of process parameters and process optimization, process modeling, change in material properties due to laser forming, 2D and 3D laser forming etc. have been reviewed here. At the end, some gaps have been identified in the existing literature and objectives have been formulated for the present study.

1.2.1 Continuous Wave (CW) Laser Bending

Continuous Wave (CW) laser bending process had been investigated on different materials to study the effects of various process parameters on the responses through experiments, and different process models were developed based on analytical, numerical and empirical approaches for a better understanding of the process. The investigations carried out by different researchers, both experimental work and process modeling are discussed below.

Experimental Investigations

Experimental investigations had been carried out on CW laser bending process for both single and multiple scans on different materials at micro- and macro-scales using various types of lasers. The effects of laser forming on material properties of the laser formed components had also been investigated by various researchers. The research work carried out by different investigators to study the effects of different process parameters on deformations are discussed below.

Yao et al. (1998) investigated the laser bending of lead frame materials (A42 nickel alloy steel) with a low power Nd:YAG laser. They observed that the final bending angle increased with the laser power and number of laser scans, and decreased with the scan speed and holding time between two successive scans in multi-scan process.

Shichun and Jinsong (2001) studied the effects of different process parameters related to the laser source, material and work-piece geometry on bending angle in laser bending of sheet metals. The laser energy parameters included laser power, scan speed, beam spot diameter and number of scans. The experimental results revealed that the bending angle increased with the laser power and number of scans, and decreased with the scan speed and beam spot diameter. The bending angle increased with the increase of thermal-effect index, which is defined as the ratio of coefficient of thermal expansion to the product of density and specific heat, as given by $R = \frac{\alpha_{th}}{\rho c_p}$. Among the sheet geometric parameters, only the sheet thickness was found to have significant influence on the bending angle and it decreased with the increase in sheet thickness.

Experimental investigations on the effect of scan velocity with constant line energy (p/v) in laser forming of low carbon steel (AISI 1010) had been conducted by Li and Yao (2001). It was seen that the bending angle increased with the increase of scan speed at constant line energy but the rate of increment reduced due to a large strain rate at the high scan speed.

Marya and Edwards (2001) investigated the laser forming of two titanium alloys and developed an empirical model for bending angle and section thickening. The effect of the multiple laser irradiations on the bending angle and section thickening were also studied for the two alloys, a near-alpha alloy and another metastable beta alloy. Bending angle was found to depend on the yield temperature and thermal expansion coefficient of sheet materials, and the bending rate was observed to decrease with the number of scans due to section thickening and also buckling, if present.

Experimental investigations on the geometric effect of deformed sheet on bending angle in multi-pass laser forming process was carried out by Edwardson et al. (2006). It was concluded that the bending rate decreased with the number of pass due to increase in incident area of laser spot and consequently, reduction of energy fluence because of component deformation.

Birnbaum et al. (2007) conducted both numerical and experimental investigations to study the effect of holding the work-piece, and laser scan position with respect to the clamped edge on its final deformation in laser forming process for both single and multiple laser scans. It was shown that as the operating distance (that is, the distance of laser scan line from the clamped edge) decreased, the bending angle also decreased. Average bending angle in case of clamped sample was found to be more than that of the unclamped case.

Edwardson et al. (2010) also presented a review of the influencing factors on multi-pass laser forming of sheet metal made of different materials, i.e., mild steel, Ti6Al4V and AA5251 under temperature gradient mechanism using experimental data and numerical simulations.

Shi et al. (2011) investigated the effect of work-piece geometry on bending angle and forming accuracy in laser bending of DC01 steel material. The average bending angle was found to reduce with the increase in plate length and increased with plate width due to the variation of temperature distributions and mechanical restraint from the surrounding cold material. Bending angle was found to decrease rapidly with the increase in plate thickness.

The effects of laser forming on the changes in material properties are important for application and performance of the laser formed components. Several researchers had investigated the changes in properties of different materials in laser forming, which is briefly reviewed below.

The effects of laser forming on the material properties of mild steel were investigated by Thomson and Pridham (2001). It was reported that laser formed parts could perform almost like conventionally formed parts and yield strength of the material increased locally in the formed sections.

Merklein et al. (2001) investigated the changes in microstructure and mechanical properties of aluminum and aluminum alloys after laser forming. The grain structure and microstructure of formed parts were investigated both quantitatively and qualitatively using optical and electron microscopy. Different values of microhardness and microstructutre were found at different zones of the laser formed samples.

Chan and Liang (2002) investigated the deformation behavior and microstructure of hardened high carbon steel in laser bending. A CO_2 laser was used to bend the samples for different laser powers, scan speed and number of scans. A relatively linear relationship between bending angle and number of scans was obtained. A threshold heat input was found to be needed for bending to occur. The bending angle was also seen to increase linearly with increase in line energy. The microstructure and microhardness profile of the sheets deformed at both low- and high-energy inputs were examined. For a certain value of energy density, melting was observed at the scanned surface and the microstructure was significantly different across the thickness of bent region.

Majumdar et al. (2004) investigated the effect of various process parameters on laser bending of AISI 304 stainless steel sheet using a high power (2 kW) continuous wave CO_2 laser. Microstructural changes and phase analysis were also carried out to study the effects of laser irradiation and thermal stress on the microstructure and phase transformation behavior of the sheet. The Vickers' micro-hardness of bent zone was found to increase compared to the as-received sample.

Phase transformations during laser forming of AISI 1010 steel were experimentally and numerically investigated by Fan et al. (2007) using finite element analysis with a phase transformation kinetic model. The flow stresses of material were obtained from the constitutive relationship of the phases. The effects of work hardening, recrystallization and phase transformation were considered to model the laser forming process. Results predicted by the developed model were also validated by conducting a number of controlled experiments.

Mechanical properties of low carbon steel after laser forming were investigated by Shen and Yao (2009) under different laser processing parameters. Tension tests were conducted and it was shown that the yield strength and tensile strength were improved while the percentage elongation was reduced. Fatigue life under different laser processing conditions was studied using low-cycle fatigue tests based on the distribution of residual stresses as well as residual strains after laser forming. Compressive residual strain was found to be the most important reason for improving the fatigue life of low carbon steel after laser forming.

Walczak et al. (2010) studied the microstructural changes and corrosion behavior of laser formed AISI 302 stainless steel sheet. Graphite coated samples were formed by a 60 W CO_2 laser in raster scanning manner and the repeated increase in temperature caused sensitization of the material. Numerical simulation was carried out to determine the temperature distribution and it was found that the non-irradiated side was affected more by the sensitization than the irradiated side.

More recently, Knupfer et al. (2012) investigated the residual strains of laser formed low carbon steel (AISI 1010) and aluminium alloy (AA2024-T3) components for single and multi-scans under both temperature gradient and upsetting mechanisms using neutron diffraction technique. In TGM, gradient of the through-thickness transverse residual strain distributions at the laser irradiated zone was found to increase with the number of passes and line energy up to its saturation value (where the efficiency of bending is the maximum). The gradient decreased with the line energy above its saturation value.

Investigations on laser forming process were carried out by various researchers on the parametric study and materials properties of the formed components. However, process modeling is required for the prediction of outputs for a set of inputs. It is also important for better understanding of the process. Process modeling of laser forming process carried out by various researchers is discussed below.

Process Modeling

Modeling of CW laser bending process was carried out by various researchers (Magee et al., 1998; Shen and Vollertsen, 2009) using different approaches, i.e., analytical, numerical and empirical (statistical regression and soft computing-based methods) etc., as discussed below.

Analytical Modeling

Analytical models, developed based on the theory of heat transfer, elasto-plastic mechanics, and simplified assumptions, relate the outputs to the inputs of the process and explain the dependence of the outputs. Among different mechanisms of the laser forming process, TGM is the most widely reported laser forming mechanism in laser forming of sheets. Most of the analytical models were developed to predict the deformation or the out-of-plane bending in laser forming under TGM condition. Some models were also developed to predict the deformation in laser forming process under BM and UM, as discussed below.

Vollertsen (1994) first proposed an analytical model for calculating the bending angle, in which bending angle is linearly proportional to the laser power and inversely proportional to the scan speed and square of sheet thickness. The model was developed based on the assumption of elastic-bending theory without considering the counter-bending effect. The model did not explain the dependence of bending angle on laser beam diameter and it overestimates the bending angle compared to the experimental results. Temperature calculation in thermal processing of material with a moving heat source like laser forming can be done by analytical method as used by Papazoglou (1981) in case of welding.

Yau et al. (1997) developed a two-layer model, which adopted plastic bending theory and also considered counter-bending during the heating and cooling cycles. The formula derived contained two parts, the first part was similar to Vollertsen's model and the second part involves the influence of material properties, sheet thickness and beam diameter on the bending angle. However, the model depicts a weak dependency of bending angle on the beam diameter. The model yielded a very high bending angle in comparison with the experimental results.

Kyrsanidi et al. (2000) established an analytical model for the prediction of distortion caused by laser forming of metallic sheets. The developed model was parametric, which considered plate dimensions, laser irradiation parameters and temperature dependent material properties. A very good correlation was found between the results obtained from the proposed model and experiment.

An analytical model was developed by Cheng and Lin (2000b) for the temperature field in laser forming of sheet metal. The effects of laser forming parameters on the temperature distributions were also studied using the developed model. A finite plate with a Gaussian beam moving at a constant velocity and temperature dependent thermal conductivity of material were considered to establish the model. Cheng and Lin (2001) further extended their work and developed a model for estimating the bending angle. In modeling the bending angle, deformations during both heating and cooling were taken into account. The proposed model was verified with experimental results and was found to be satisfactory.

A more complete approach was made by Shen et al. (2005). They presented an analytical model based on the assumption that the plastic deformation takes place during heating and during the cooling, the plate undergoes elastic deformation only. The developed model did not state about the increase in bending angle due to counter-bending effect.

An analytical model of bending angle was developed by Cheng et al. (2005) considering the size effect or sheet dimensions. The model was developed based on the solution to a moving strip heat source over a finite sized sheet. The pre-bending effect among consecutive segments on the scanning path was also taken into account to calculate the deformation. The results predicted by the model were compared with that of the other analytical model and numerical simulation, and found to be in good agreement.

McBride et al. (2005) developed a simplified analytical model to predict bending angle in terms of laser power, scan speed and spot diameter, and also for estimating the local changes in curvature considering the area energy, interaction time and sheet thickness for iterative laser forming of sheet metal under TGM. The model was also able to determine the threshold and saturated energy, which could be used to identify the optimum process parameters in laser bending operations.

An analytical model was presented by Shen et al. (2006a) to determine bending angle during laser forming of sheet metal. Plastic deformation was considered during heating and cooling with a history-dependent incremental stress-strain relationship. In the model, the laser parameters, temperature dependent material properties and sheet thickness were taken into account. Bending angles predicted with the model were found to be good not only for TGM and BM but also for coexisted TGM and BM.

Shi et al. (2007) developed an analytical model of temperature field in laser forming process based on the similarity in temperature distributions. Dimensionless parameters were used in the model and it was shown that the temperature distributions were similar for the plates of different thicknesses. The temperature field calculated from the model was in good agreement with the results of simulations.

The above models were developed based on several simplified assumptions and applicable to single straight scans only. However, these models become cumbersome and difficult to incorporate the variations of absorptivity and temperature dependent thermal and mechanical properties with time. Moreover, these models are not applicable to irradiations on curved sheets and multi-scan laser forming process.

Numerical Modeling

Numerical models developed based on finite element method (FEM), finite difference method (FDM) etc. are beneficial in determining the temperature and deformation fields produced by laser scanning and give better insight into the process through transient temperature and stress-strain distributions. Several numerical models were developed by various researchers (Hsiao, 1997; Zhang, 2005; Jung, 2006); some important ones are briefly reviewed here.

Numerical simulations were first carried out by Vollertsen et al. (1993) to obtain temperature and bending angle distributions in laser forming process using the finite difference method (FDM) and the finite element method (FEM). The effect of change of mesh size during discretization was found to be more on temperature field compared to deformation field. FEM model provided better results than FDM model because of the assumptions and simplifications made for the later due to limitations in calculating the effect of sheet thickness correctly.

Hsiao et al. (1997) presented a finite element model for Inconel 625 specimens. Transient angular distortions were obtained from the FE-simulation. The possibility of modeling a laser tube bending and a dome shape forming was proposed. The need to develop a technology to form a plate into a pre-determined shape using both heating patterns and heating conditions was also suggested.

A three-dimensional transient FEM analysis was carried out by Ji and Wu (1998) to obtain the temperature field in laser forming of sheet metal. Good correlation was found between the solutions obtained by FEM and FDM. It was reported that peak temperature of the upper and lower surface increases with the increase in laser power but decreases with the increase of sheet thickness and scan speed.

Kyrsanidi et al. (1999) performed FE analysis on laser bending of sheet metal using a CO_2 laser. The temperature dependent thermal and mechanical properties of the material were taken into account. The developed method was able to calculate the transient temperature, stress-strain and final deformed shape. The predicted results were in good correlation with the experiments.

Li and Yao (2000) used the finite element analysis to investigate strain rate effects on deformation in laser forming at constant peak surface temperature of the plate. They (2001) had also extended the numerical study to laser tube bending, investigating wall thickness variation, cross-section ovalization and bending radius.

A non-linear 3D finite element simulation of laser bending of sheet metal had been carried out by Hu et al. (2001) to determine the temperature, stress-strain distributions and bending angle. The FE analysis had been carried out on different materials by varying the different process parameters. The FE calculated bending angle was seen to increase with the increase of laser power and number of laser scans and decrease with the increase of scan speed. The simulation results were found to be in good agreement with the experimental results.

The variation of bending angle along the scan line called edge effects in laser forming was investigated by Bao and Yao (2001) using both numerical simulations and experiments. Temperature dependent material properties and strain rate dependency of flow stress were taken into account in studying the transient deformation and mechanism of edge effects. The FE results were validated through the experiments.

The deformation field during the laser bending of sheet metal was studied by Wu and Ji (2002) using the 3D thermo-elasto-plastic finite element method. The form and change of displacement field obtained from FEM simulation was identical with the experimental results, and the calculated bending angle was in good agreement with the experimental data.

Cheng and Yao (2002) proposed a microstructure integrated finite element model in order to increase model accuracy in predicting bend angle and mechanical properties in laser forming operations, which involved an adequate constitutive model to better describe the hot flow behavior.

FE modeling of laser forming process had been carried out by Zhang and Michaleris (2004) using both Lagrangian and Eulerian approaches. Sheet length was found to have significant effect on the bending angle in their analysis. Eulerian approach was seen to be faster than the Lagrangian approach but it overestimated the bending angle.

Zhang et al. (2004) had carried out the FE analysis of laser forming process considering the effect of discretization in predicting the deformation. The minimum discretization needed for the convergence and accurate results were determined. The simulation results were found to be satisfactory compared to the experimental results.

Zhang et al. (2005) presented a model to predict fatigue life of sheet metal after laser forming. Microstructure integrated finite element modeling were incorporated in the developed model and experiments were conducted on low carbon steel to validate the model. The predictions from the model were found to be consistent with the experimental results.

Griffiths et al. (2010) conducted FE analysis of laser forming process at macro- and micro-scale. In macro-scale, the laser forming process was studied under TGM of laser forming considering the effects of surface coating, variation of absorptivity and geometry with multiple laser scans. Laser micro forming had also been investigated in case of short laser pulses. FE analysis was seen to be an effective tool for developing a better understanding about deformation and mechanism of laser forming process for its application at both macro- and micro-scale.

Hu et al. (2012) presented an efficient simulation method for laser forming of large sheet using multilayer shell element. The proposed method was found to be effective in FE simulating the laser forming of large plates with less computational time. The results were also found to be satisfactory compared to the experimental values. Thermal stress due to laser bending of AISI304 material was investigated by Yilbas et al. (2012) using FE analysis. The results were also validated by experiments.

Zhou et al. (2013) investigated laser thermal forming of thin sheets using FE analysis and experiments. Two types of deformations were identified in the forming process, i.e., in-plane and out-of-plane deformations. The effects of geometry and material properties were also studied using both experiments and simulations.

FE simulation of laser forming of D36 ship building steel was carried out by Dixit et al. (2013) to study the effect of scan speed on bending angle and it was found to reduce with the increase of scan speed.

Numerical models developed based on finite element method takes long computational time for multiple laser scan forming process, which is required for making 3D shape for practical applications of the laser forming process in industry. Finite element analysis of laser forming process is nonlinear, transient in nature and requires fine mesh sizes and small time step size for good convergence, which increases the required computation time and memory space.

Empirical Modeling

Empirical models built based on statistical regression analysis and soft computing methods are able to capture the nonlinear behavior of the complex manufacturing process like laser forming. Some of these studies are discussed below.

Cheng and Lin (2000a) used three supervised neural networks and regression analysis to predict bending angle formed by laser. The forming parameters, such as spot diameter, scan speed, laser power, and work-piece geometries including thickness were taken as input parameters and bending angle was considered as output to develop the model. The performances of the models were verified with experiments, and radial basis function neural network was found to be superior compared to other models in predicting bending angle.

A back-propagation neural network was utilized by Dragos et al. (2000) to predict bending angle in laser bending of sheet metal. The laser power, beam diameter, scanning speed, thickness of the material and number of scans were considered as the input parameters of the process and bending angle was the output. The bending angles determined by the neural network were found to be in good correlation with the experimental values. The proposed method was found to be helpful for carrying out online simulations and automatic control of the laser bending process.

Casalino and Ludovico (2002) used a back-propagation neural network to predict bending angle and select process parameters in laser bending under TGM and BM. The developed model was verified with experimental data and found to be satisfactory.

Chen et al. (2002) proposed an adaptive fuzzy neural network to predict bending angle in laser forming process. Energy density (defined as the ratio of laser power to the product of scan velocity and spot diameter), width, thickness of sheet, and scanning path curvature were taken as four inputs and bending angle was considered as the output of the network to develop the model. Good correlation was found between the results obtained from the model and experiments.

A fuzzy control system was developed by Kuo and Wu (2002) for controlling the laser bending process. The developed control system was found to be effective in controlling the laser bending process and it could increase the manufacturing efficiency. The proposed method was found to be feasible and effective for producing some shapes.

Pennuto and Choi (2005) studied laser bending of AM 355 semiaustenitic stainless steel sheet using evenly spaced multiple parallel laser irradiations. Laser power, scan speed, incident spot diameter, gap and dwell time between successive scans were considered as the inputs and bending angle was the output in their model. Statistical regression analysis was carried out to develop empirical model to establish the relationship between bending angle and process parameters for both the single and multiple parallel laser irradiations.

A model for bending angle in laser forming using adaptive network fuzzy inference system (ANFIS) was established by Shen et al. (2006b). The laser forming process parameters included in the model were laser power, beam diameter, scanning velocity and thickness of the plate. The performance of the ANFIS model was optimized by varying the type and number of membership functions. The prediction of the ANFIS model was found to be satisfactory by comparing with the experimental data.

Guarino et al. (2007) presented a neural network-based method for modeling the laser-assisted forming of thin aluminum alloy sheet. Good correlation was found between the trends of experimental and calculated values of the variables through the sensitivity analysis on the developed neural network model.

A back-propagation neural network model was developed by Wang et al. (2008) for modeling and optimization of the laser bending of aluminum alloy sheet. The developed model was able to predict the bending angle and process parameters within a reasonable accuracy.

Nguyen et al. (2009) developed an artificial neural network (ANN)-based model for the predictions of angular distortion and transverse shrinkage during the plate forming by induction heating. The developed model could predict the deformation satisfactorily and with less time compared to finite element analysis.

Du and Wang (2010) presented an improved back-propagation neural network model based on double chain quantum genetic algorithm for predicting the bending angle more accurately and optimization in laser bending of sheet metal.

Neural network-based model was also developed by Gisario et al. (2011) for the correction and adjustment of bending angle in mechanically bent samples using laser assisted bending. Good correlation was found between the experimental and model predicted results in both interpolative and extrapolative conditions.

It is understood from the above discussion that predicting the deformation due to multiple laser scans and determining laser heating parameters to achieve a desired bending angle are difficult using analytical models and numerical method. On the other hand, soft computing-based methods have been successfully used by several researchers for the analysis of laser bending process used in different applications. However, not much work had been reported on the analysis and design of process parameters in case of mult-scan laser bending process.

1.2.2 Pulsed Laser Bending

Sheet metal forming using laser heating in pulsed mode was also investigated by a number of researchers to study the effects of different process parameters on the deformation and properties of the laser formed samples. Experimental investigations and modeling of pulsed laser bending process conducted by various investigators are discussed below. FE analysis were also carried out by various researchers to determine the transient temperature field and deformation pattern in pulsed laser bending process considering various process parameters, such as laser parameters, laser beam shapes, single and multiple pulses.

Finite element analysis and experimental investigations were performed by Chen et al. (1999) on micro-scale bending of stainless steel with pulsed laser. A two-dimensional plane strain model was used to calculate the bending angle in pulsed laser bending, and the results were found to be in good agreement with the experiments. Sensitivity analysis was also performed using FE method to study the effects of different parameters. Surface reflectivity and coefficient of thermal expansion were found to have the most significant effects on the bending angle in pulsed laser bending process.

Numerical simulations of pulsed laser bending with a stationary pulsed CO_2 laser beam were carried out by Lee and Lin (2002) considering a single laser pulse and a line shaped beam. Transient temperature and deformation field, and residual stress distributions were calculated using the FE method. The numerically calculated bending angles were validated through experiments.

Zhang et al. (2002) presented an efficient method to reduce the computational time in calculating bending angle numerically in pulsed laser bending of thin stainless steel sheet considering only a few laser pulses.

Hsieh and Lin (2004) studied the transient deformation of thin AISI 304 stainless steel sheets heated by a single pulse of CO_2 laser beam numerically. The laser beam was assumed to be in Gaussian mode and the coupled thermo-elasto-plastic problem was treated as three-dimensional. The temperature field, deformation pattern, stress–strain states, and the residual stress distributions of the specimens were calculated numerically and the transient response of the bending angle was validated by experiments. A good agreement was obtained between the numerical simulations and the experiments under different operating conditions.

Experimental study and empirical modeling were carried out by Gollo et al. (2008) in laser bending of sheet metal with a pulsed Nd:YAG laser using Taguchi experimental design, L-9 array with four factors (Laser power, beam diameter, scan speed and pulse duration) each at three level. Regression analysis was performed to find out the relationship between factors and bending angle and a regression equation (first order polynomial) was obtained to predict bending angle. The effect of process parameters on bending angle was investigated and beam diameter was found to be the most significant factor. Bending angle was found to increase with the increase of laser power, beam diameter and pulse duration, and decrease with the scan speed.

Gollo et al. further (2011) investigated the effects of process parameters, such as material, laser power, beam diameter, scan velocity, sheet thickness, number of passes and pulse duration on bending angle using numerical simulations and experiments. Moreover, Taguchi experimental design method was used to identify the significant process parameters and regression analysis was performed to obtain a closed-form equation for the prediction of bending angle in pulsed laser forming process. The spot diameter was found to have increasing effect on bending angle in pulsed laser bending (Gollo et al., 2008, ’11), which is opposite to the trend observed in case of continuous laser bending. The derived closed form equation was useful to determine process parameters, which could enhance the bending angle in laser bending process.

Qin et al. (2010) performed numerical simulations on plastic damage of an aluminum alloy due to a long pulsed laser irradiation. The temperature field and produced thermal stress were calculated using the FEM. Results obtained from the FE analysis were compared with the analytical solutions, and found to be in good agreement.

Yang et al. (2010) investigated the metallurgical changes of surface properties of stainless steel due to pulsed laser forming. The relationship between the surface properties of heat affected zone (HAZ) and the laser pulse parameters was also studied. The microstructure, micro-hardness and anticorrosion in HAZ generated by laser forming were examined.

Transient nonlinear 3D finite element simulation of pulsed laser forming process takes a long computational time because of finer mesh sizes at the laser irradiated zone and the small time steps required for the convergence and accuracy of prediction. Moreover, nonlinear regression analysis and soft computing-based methods could be a better option for modeling the complex process like pulsed laser bending process. A comparative study of continuous and pulsed laser bending processes for energy efficiency could be an interesting work to carry out.

1.2.3 2D and 3D Laser Forming

Investigations were carried out by various researchers (Shimizu, 1997; Edwardson, 2004; Reutzel, 2007) to make different 2D and 3D shapes by laser forming process using different approaches like experimental, computational, geometrical and heuristics, as discussed below. Hybrid method like combination of FEM and soft computing (Manevitz and Givoli (1999)) or FEM and geometrical method etc. was also applied by some researchers (Shimizu, 1997; Reutzel, 2007; Carlone et al., 2008).

Hennige (2000) presented some basic investigations on the differences in the forming behaviour of sheet metal parts using linear and curved irradiations. It indicated a strong influence of materials adjacent to the irradiated zone on the forming result, in case of curved irradiation paths. The reasons for this behavior were analyzed and discussed. Several irradiation strategies that could be derived from basic experiments were investigated for the case of mild steel spherical dome samples. In addition, first results of finite element calculations on laser forming along curved irradiation paths were also presented.

Edwardson et al. (2001) investigated 2D laser forming of mild steel sheet using a CO_2 laser source. The scan strategies tested were straight and radial lines and concentric circular patterns. The operative laser forming mechanism varied from the temperature gradient to the upsetting mechanism depending on beam parameters and traverse speed used. The final geometries of parts formed were verified using a coordinate measuring machine. It was possible to produce a controlled repeatable saddle shape using a concentric race-track strategy by employing the upsetting mechanism at the centre of the sheet.

Dearden and Edwardson (2003) presented a review of investigations carried out on 2D and 3D laser forming for both macro- and micro-scale applications. Limitations of practical 3D laser forming in macro-scale were identified through the studies of 2D and simple 3D laser forming.

Process synthesis of laser forming was extensively studied by Liu and Yao (2002,’04,’05) using different methods like response surface methodology, desirability function approach, principal curvature formulation, minimal strain optimization, large deformation elastic FE analysis etc. for forming some doubly curved surfaces, e.g., pillow and saddle shapes for both thin and relatively thicker sheets. Scanning paths were applied perpendicular to the principal curvature directions. Scanning paths and heating conditions were determined using the average of principal minimum strain direction and the ratio of in-plane to bending strains, respectively. The proposed methods were validated through experiments and FE simulations.

Cheng and Yao (2004a) also proposed a similar method of predicting scanning paths and heating conditions based on the strain field required to make any desired shape in laser forming of thin sheet. Cheng and Yao (2004b) presented a process synthesis methodology for laser forming of a class of shapes using genetic algorithm (GA). The effects of GA control parameters on the synthesis process were discussed. The effects of fitness function types on achieving multiple objectives were also investigated. The synthesis process was experimentally validated through several cases under diverse conditions including one that involved near thirty decision variables.

Experimental investigations were carried out by Yang et al. (2004) for forming 3D shapes from flat metal sheet by laser forming under temperature gradient mechanism (TGM) only. The effects of various process parameters on formed shapes were studied with different scanning strategies using both continuous and pulsed laser irradiations. Spherical domes were formed from both square and circular metal sheets by using cross spider scanning strategy and saddle shape was obtained using radial lines scanning strategy. The effects of different process parameters on the height of the formed shapes were also discussed for both the cases.

Thermo-mechanical FE analysis of laser forming process takes a huge computational time. To reduce computational time for predicting the deformed shapes and inverse analysis of 3D laser forming process, different methods were proposed by various researchers for determining the required deformations to form a 3D shape from a flat metal sheet using plane patches, planar development and differential geometry along with the large deformation FE analysis.

Kim and Na (2003) proposed two methods for determining scan paths and process parameters for making free curved shapes. The two methods, i.e., distance-based and angle-based approaches were studied using FE simulations and verified with experiments. The results obtained from the proposed methods were compared and found to be satisfactory.

In 2D free curve laser forming, a feedback control scheme for each single bending angle was suggested by Kim and Na (2005). A statistical method was incorporated and the effect of remaining errors was discussed. The methods of compensating the remaining errors were proposed and analyzed by computer simulations. Applicability of the proposed method was verified with experiments.

A predictive and adaptive approach was proposed by Edwardson et al. (2005) for forming continuous 3D surfaces. The proposed method was investigated for pillow shape and results were found to be satisfactory.

Differential geometry-based analysis was proposed by Reutzel et al. (2006) for the analysis of thermal forming process. The proposed analysis method was seen to be more computationally efficient than the FE method in predicting the deformation of plate for multiple line heating.

Carlone et al. (2008) developed a computational procedure for the inverse analysis of the laser forming process of three-dimensional metal sheet, characterized by double curvature. The procedure was based on the minimization of a vectorial fitness function, obtained by the comparison of the considered target surface with reference deformed surfaces, represented as sixteen point bicubic patches. An FEM-based computational approach was adopted to evaluate the reference deformed surfaces for the instruction of the processor.

Kim and Na (2009) proposed a new method for 3D laser forming of sheet metal. This method used geometrical information rather than a complicated stress–strain analysis. Using this new method, the total calculation time was reduced considerably while affording a strong potential for enhanced accuracy. Two different target shapes were formed by laser irradiation with the proposed procedure to validate the algorithm. The proposed methods were validated through experiments and numerical simulations, and were found to be effective and computationally faster.

FE analysis has been carried out by Yang et al. (2010) for forming a spherical dome shape from flat square-shaped sheet metal by laser forming under temperature gradient mechanism (TGM). An explicit dynamic analysis was performed to determine the temperature distributions and deformation. The FE results were validated through experiments.

Venkadeshwaran et al. (2010) investigated the laser forming of a circular plate for circular irradiation paths in discrete sections using finite element method. The quality of the formed surface in terms of a waviness parameter was studied with respect to the number of sections considered and laser passes. It was found that the discrete section symmetric laser heating with starting point shifted for each subsequent pass could reduce the waviness of the formed surface.

Seong et al. (2013) developed an inverse analysis method for 3D flame forming using geometrical method. Bending angles and shrinkages were determined by simple geometrical approach and converted to forming parameters through a database map representing the relationship between the geometrical and forming parameters. Experiments on plate forming were also performed to make a saddle shape for validation of the proposed algorithm. Results of the formed shape were found to be satisfactory when compared to the shape desired.

Both forward and inverse analyses of LF process had been carried out by various researchers to make different 2D and some 3D shapes using different methods, such as experimental, computational, and genetic algorithm-based approaches. However, the problem related to process synthesis of LF of 3D parts requires more attention. To apply the laser forming process to real-world problems, the issue of process synthesis, i.e., the inverse problem needs to be addressed, that is, to determine the process parameters (laser scanning paths and heating conditions) for a given desired shape. For general three dimensional shapes, determining laser scanning paths and heating conditions is not obvious, since their relationships to the deformation are extremely complex and difficult to obtain by analytical or numerical method. However, heuristics approaches or soft computing-based methods may be helpful to tackle such problems. Therefore, attempts of using soft computing-based methods for solving the complex inverse problem of laser forming process will be more appropriate compared to the other approaches.

1.3 Research Gaps and Motivation of the Study

In the past, some researchers had developed various models for analysis of both continuous and pulsed laser forming (LF) processes such as, analytical, empirical, numerical, soft computing-based etc. by considering various mechanisms and process parameters. Inverse analysis of LF process had also been carried out by many researchers using different methods, such as experimental, computational, and genetic algorithm-based approaches. However, there are still some research issues, which are to be solved. Thus, the problems related to process synthesis of LF of 2D and 3D parts are yet to be solved completely. Moreover, not much attention was paid to investigate the effects of different process parameters in pulsed laser forming process. No attempt was made to conduct the inverse analysis of pulsed laser bending process and compare its performance with that of CW laser forming. Moreover, not enough study was made on process synthesis of 3D laser forming process.

1.4 Aims and Objectives

Based on the literature review on laser forming of sheet metal, the following objectives have been set for the present study:

1. FE analysis of laser bending process for determining temperature distributions and deformations for both continuous and pulsed modes of laser irradiations and comparison of their performances along with experimental validation.

2. Experimental investigation and empirical modeling of multiscan CW laser bending process for studying the effects of different process parameters and producing a class of 2D shapes.

3. Modeling, optimization and inverse analysis of pulsed laser bending process using statistical regression analysis and soft computing-based methods.

4. Statistical regression analysis and neural network-based modeling for analysis and synthesis of 3D laser forming of a dome-shaped surface.

1.5 Contributions Made in this Thesis

- Finite element simulations of the laser bending process using both continuous wave and pulsed modes of laser irradiations under different processing conditions have been carried out and the results have been validated through experiments. The comparison of continuous wave and pulsed laser bending has been made through both the simulations and experiments.
- A systematic analysis on laser bending of sheet metal using continuous mode of laser irradiation has been conducted. The input-output relationships between the deformation and process parameters, developed in this study, had not been reported previously for the same process. The surface plots showing the correlations among process parameters and responses are presented in this thesis. The process synthesis method developed based on neural networks and neuro-fuzzy system for 2D laser forming process is novel, which could determine the scan paths and process parameters to obtain a class of 2D shapes.
- Pulsed laser forming process has been analyzed using statistical regression analysis and soft computing-based methods. The results presented on the effects of some process parameters in pulsed laser forming have not been reported earlier. Moreover, the process synthesis of pulsed laser bending was not previously reported in the literature.
- The effects of process parameters on 3D laser forming of dome-shaped surface were studied earlier by some other researchers through experiments and FE analysis. Moreover, process synthesis was not attempted in their studies. However, in the present thesis, this problem has been studied in detail through experiments, statistical regression analysis and neural networks-based modeling.

1.6 Outline of the Thesis

The present thesis consists of seven chapters. A brief introduction to the problem is given in Chapter 1. Chapter 2 explains the tools and techniques used for modeling and analysis of the laser forming process. The method of finite element analysis used in the present thesis and experimental details of laser metal forming process have been described in Chapter 3. Chapters 4 and 5 deal with statistical regression analysis and soft computing-based models on continuous wave (CW) and pulsed laser bending processes, respectively. Finally, Chapter 6 presents the analysis and synthesis of 3D laser forming of a dome-shaped surface using statistical regression analysis and soft computing-based methods. Concluding remarks are made and the scopes for future study are presented in the last, i.e., 7th chapter.

1.7 Summary

Laser metal forming process has been introduced at the beginning of this chapter. Gaps in the literature have been identified through an extensive and thorough review. The aims and objectives of the present thesis formulated based on the research gaps have been stated. The contributions made in this thesis have been described followed by an organization of the thesis.