CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Extensive research work is being done in laser cutting for improving the quality of cut. The quality of cut depends upon many control factors or parameters such as laser beam parameters (laser power, pulse width, pulse frequency, modes of operation, pulse energy, wavelength, and focal position); material parameters (type, optical and thermal properties, and thickness); assist gas parameters (type and pressure) and processing parameters (cutting speed). The laser cutting is a very complex and nonlinear process due to involvement of many process parameters. Many researchers have investigated the effect of these process parameters on different quality characteristics such as material removal rate (MRR), kerf quality characteristics (kerf width, kerf deviation and kerf taper), surface quality (cut edge surface roughness, surface morphology), metallurgical quality characteristics (recast layer, heat affected zone, oxide layer and dross inclusions) and mechanical properties (hardness, strength).

![Diagram of various cut quality attributes](image)

**Figure 2.1:** Schematic illustration of various cut quality attributes of interest. $K_{\text{ent}}$: kerf width at entry side; $K_{\text{ext}}$: kerf width at exit side; $R_a$: surface roughness; $t'$: thickness of sheet; 1: oxidized layer; 2: recast layer; 3: heat affected zone (HAZ)

The quality characteristics of research interest are shown in Figure 2.1. Laser beam cutting is most commonly used for the cutting of different categories of materials because
It is superior to any cutting method due to material versatility, no tool wear or change of tool, high material utilization, production flexibility, precise cuts with narrow kerf, faster cutting process, better accuracy and cut edge quality [Dubey and Yadava (2008b)].

A lot of experimental and theoretical investigations have been performed on the laser cutting of different categories of materials such as ceramics, composites, advanced engineering materials (superalloys), difficult-to-laser-cut materials. Most of the experimental investigations are based on one parameter at a time (OPAT) investigation. But this approach is costly, time consuming, and requires performance of a large number of experiments. Here only one parameter is varied at a time. Some researchers have also used design of experiments (DOE) based methods such as Taguchi methodology (TM), response surface methodology (RSM) and factorial design (FD).

In theoretical investigations, most of researchers have tried to develop theoretical models for different quality characteristics and also studied the effect of different process parameters. All investigations on laser cutting process have been divided mainly into four parts, i.e. experimental investigations in laser cutting, theoretical investigations in laser cutting; modeling and optimizations in laser cutting and applications of artificial intelligence tools in laser cutting. There are reviewed in this chapter.

2.2 Experimental Investigations in Laser Cutting: A Brief Review
Many researchers have investigated experimentally the effect of various process parameters on the different quality characteristics in the laser cutting of different categories of materials. These investigations are discussed below:

2.2.1 Laser Cutting of Conventional Materials
The conventional materials are cut easily by several conventional machining methods but stringent design requirement, intricate shape and unusual size of the workpiece restrict the use of the conventional machining methods hence needed to develop the unconventional machining methods. Nowadays, many unconventional machining methods are used in the industries such as beam machining process (laser beam machining, electron beam machining, plasma beam machining), electro discharge machining, ultrasonic machining, electro chemical machining, jet machining processes (water jet machining, abrasive jet machining, abrasive water jet machining), etc. However, laser beam machining (LBM) is
widely used among these processes. LBM can be categorized in different categories like laser cutting, laser grooving, laser drilling, laser turning, laser milling, laser scribing, laser cleaning and hybrid machining process. Laser cutting of conventional materials has become a reliable technology for industrial production. Currently, it is considered as a feasible alternative to mechanical cutting and blanking due to its flexibility and ability to process variable quantities of sheet metal parts in a very short time with very high programmability and minimum amount of waste. Laser cutting does not need special fixtures or jigs for the work piece because it is a non-contact operation. Additionally, it does not need expensive or replaceable tools and does not produce mechanical force that can damage thin or delicate work pieces. The effect of different gas compositions on the cutting speed in the laser cutting of 3 mm mild steel sheet has been investigated by Chen (1998). Different aspects such as machined geometry, surface quality and metallurgical characteristics of laser cutting are discussed as follows.

**Machined Geometry**

The geometrical kerf quality characteristics of laser cut specimens mainly depends upon two important parameters, i.e. hole diameter/cut width (kerf width) and taper formation (kerf taper). For getting a better quality cut and a better utilization of materials both quality characteristics should be minimized up to acceptable range by a proper selection of the process parameters. Due to converging-diverging shape of the laser beam profile taper formation is always possible on laser cut specimen.

Rajaram et al. (2003) have found the influence of laser power and feed rate (cutting speed) on the kerf width in the laser cutting of 1.27 mm thick 4130 steel. The laser power has a major effect on kerf width while the feed rate effect is secondary. As the laser power increases, the kerf width also increases and smallest kerf width is obtained at the lowest value of laser power and moderate feed rate. Yilbas (2004) has also obtained similar results for the laser cutting of 1 mm and 2 mm thick mild steel sheets. They have observed that the kerf width increases by increasing the laser power and decreases by increasing cutting speed as shown in the Figure 2.2. The effect of workpiece thickness on cutting speed is not significant; in that case, the kerf width increases slightly with increasing thickness. Karatas et al. (2006) have found that the Kerf width can also be changed by varying the focal position of laser beam and thickness of the workpiece. For the workpiece thickness of 1.5 mm in laser cutting of steel sheet, the minimum kerf width is obtained at nominal focus setting of focusing lens (nominal beam waist position) but as
the thickness of workpiece increases from 1.5 to 3.5 mm, the focus setting for minimum kerf width changes, i.e. the nominal beam waist position of the focusing lens moves into the workpiece. Lamikiz et al. (2005) have discussed the effect of beam waist position for the laser cutting of less than 1 mm and more than 1 mm thick sheets of advanced high strength steel (AHSS). They have demonstrated that in both cases of thin and thick sheets, the optimum focal position has been established near the under surface of the sheet and if the laser beam is focused on the surface of the sheet or even above the sheet, the results show poor quality of cut.

![Figure 2.2: Effect cutting speed on kerf width (a) 1 mm thick mild steel sheet; (b) 2 mm thick mild steel sheet; and effect of laser power on kerf width of (c) 1 mm thick mild steel sheet; (d) 2 mm thick mild steel sheet [Yilbas et al. (2004)]](image)

*The plot Figure 2.2 has been reproduced from [Yilbas et al. (2004)]. Professor Yilbas has been kind enough to reproduce this figure for the thesis.*

Yilbas et al. (1997) have observed that micro cracks have been found on the cut edge on increasing the gas pressure during the laser cutting of stainless steel and mild steel sheets. Shape memory alloys such as nitinol (NiTi) are of increasing interest due to their outstanding properties such as ability to remember its shape, ability to accommodate high elastic deformation, high mechanical strength, high efficiency in converting thermal
energy into mechanical energy and high biocompatibility. The mechanical machining of these materials is very difficult due to their low thermal conductivity and low elastic modulus. Laser cutting process can be effectively used for the cutting of these materials due to its non-contact, precise and localized energy input. Pfeifer et al. (2010) have applied the laser cutting process for the cutting of 1 mm thick NiTi shape memory alloys and the effects of cutting speed, spot overlap, pulse width and pulse energy on kerf geometries (top and bottom kerf widths) have been discussed. They have shown that the top and bottom kerf widths decrease linearly with increasing cutting speed or decreasing spot overlap. The top kerf width is marginally affected with pulse width but bottom kerf width decreases by increasing pulse width.

The stainless steel is widely used engineering material. However, it is difficult to cut by oxy-fuel method due to high melting point and low viscosity of the formed oxides. It can be cut by the laser cutting process. Ghany and Newishy (2005) have compared both modes of operation (pulsed and continuous) and shown that the maximum cutting speed of 8 m/min is obtained in the continuous wave Nd:YAG laser cutting of 1.2 mm austenitic stainless steel sheet. The effects of laser power, pulse frequency, cutting speed, focus position and types of gases on the kerf width have been investigated. Kerf width is decreased by increasing the pulse frequency and cutting speed while it is increased by increasing the laser power, focus position and gas pressure. Compared to oxygen, nitrogen gives brighter and smoother cut surface with smaller kerf but it is not economical as compared to the oxygen.

Laser cutting process has also been applied for the cutting of Malaysian wood. Yusof et al. (2008) have found that at all cutting speeds, the kerf width increases by increasing the laser powers while sideline length and percentage over length decreases by increasing laser power.

Surface Quality

Surface roughness (SR) is another key parameter to represent the quality of the cut. For all powers, the SR generally increases by increasing cutting speed in the CO₂ laser cutting of 4130 steel sheet [Rajaram et al. (2003)]. Ghani and Newishy (2005) have found that the nitrogen gas produces brighter and smooth surface as compared to the oxygen at pressure 9 bar and 11 bar for the pulse and continuous mode Nd:YAG laser cutting of 1.2 mm thick austenitic stainless steel sheet, respectively.
Increasing the cutting speed in pulsed mode led to rough surface and incomplete cutting while in CW mode, increasing the cutting speed with equivalent increase in power, led to better quality and smoother cut surface up to 8 m/min cutting speed. The SR also increases by increasing the peak power, gas pressure, pulse frequency and duty cycle. The surface roughness of the cut specimen can also be changed by changing spot overlap and pulse width. A minimum SR is obtained at an intermediate spot overlap for the pulsed Nd:YAG laser cutting of 1 mm thick NiTi shape memory alloy [Yusof et al. (2008)].

**Metallurgical Characteristics**

Most of the heat is utilized in melting and vaporizing the metallic material and is then carried away by the flow of assist gas because laser cutting is a thermal process. The rest of the heat is transmitted to the matrix and changes the microstructure of the surface material resulting in the formation of heat affected zone (HAZ) layers. HAZ, recast layer, oxide layer, and morphological changes are the main attributes which affect the metallurgical quality characteristics of cut in the laser cut specimen. Salem et al. (2008) have investigated experimentally to evaluate the CW Nd:YAG laser cutting parameters: laser power (337-515 W), scanning speed (700-1500 mm/min), the oxygen gas pressure (3.5-6 bar) for 1.2 mm thick ultra-low carbon steel sheets (C% < 0.0012). They have investigated the effect of the cutting parameters on the cut quality by proper monitoring the variation in hardness, oxide layer width and micro structural changes within the heat affected zone (HAZ). They have found that the HAZ width increases with increasing the laser power and decreases with increasing scanning speed and gas pressure. The oxide layer width increases by increasing the laser power due to the excess heat input and decreases by increasing the scan speeds due to the decrease in exposure time that allow the oxidation. The oxide layer width is not affected by the energy density input but affected by the oxygen gas pressure due to exothermal energy reaction. Rajaram et al. (2003) have shown that the laser power and cutting speed are the two important parameters which affect the HAZ width during the CO\textsubscript{2} laser cutting of 4130 steel sheet. HAZ generally decreases with decreasing laser power and increasing cutting speed. At high power levels, increasing cutting speed led to slight increase in the HAZ. Li et al. (2005b) have shown that the minimum HAZ width is found at lower values of current and higher values of cutting speed for the Nd:YAG laser cutting of QFN packages. Muhammad et al. (2010) have compared the of dry and wet fibre laser profile cutting on thin 316 L stainless steel tubes. They have used four process variables (peak pulse power,
pulse frequency, pulse width and cutting speed) with N\textsubscript{2} assisted gas in pulsed mode and found that the heat affected zone (HAZ), kerf width, surface roughness and dross deposition have been improved when the water introduced in the tube.

### 2.2.2 Laser Cutting of Advanced Engineering Materials

The different technologically advanced industries such as spacecraft, automobile, nuclear, etc., are continuously demanding such types of materials having better performance characteristics as high strength to weight ratio, better hot hardness, better corrosion resistance and better mechanical properties. The researchers are performing more research the material science area and continuously trying to develop such type of materials like superalloys, high strength temperature resistance (HSTR) alloys, ceramics, satellite, cubic boron nitrides, poly crystalline diamond (PCD) and composites. The cutting methods are also needed to be developed for such types of materials. The complex shape production, better surface finish, low value of tolerance, higher production rate, automated data transmission, miniaturization, etc., in these materials using conventional cutting methods, are still not possible. To achieve this target under the unconventional machining processes, laser cutting process can be applied on the advanced engineering materials by the proper selection of the different control parameters.

#### Machined Geometry

To minimize the different geometrical kerf quality characteristics in the laser cutting of advanced materials, the researchers are trying to investigate the effect of different process parameters in the laser cutting of these materials. In pulsed laser cutting, the spot overlap is a crucial factor for deciding the quality of the cut [Thawari et al. (2005)]. They have experimentally investigated the effect of spot overlap in pulsed Nd:YAG laser cutting of nickel based superalloy (Hastelloy X). They have observed that both top and bottom kerf widths increase while surface roughness decreases by increasing spot overlap as shown in Figure 2.5. They have also found that lower pulse energy gives higher kerf taper. At shorter pulse duration, the kerf has lower taper as compared to that in longer pulse duration. Moreover, at the longest pulse duration (2 ms), the entry kerf width is significantly higher than the exit kerf width.

Quintero et al. (2006) have studied the aerodynamic features of the gas flow inside the cut kerf by means of flow visualization using Schlieren technique. They have concluded that the sum of the gap between the nozzle and workpiece plus thickness of the workpiece
should be lower than the supersonic length (in this case 15 mm) and the nozzle inclination angle should be adjusted according the Mach number of nozzle used so that the formation of normal and detached shock waves can be avoided.

The kerf width varies with the reinforced materials in laser cutting of metal matrix composites. Yilbas et al. (2010a) have observed that 7050 aluminium alloy reinforced with 20% Al₂O₃ particles results in relatively large kerf width as compared to the 7050 aluminium alloy reinforced with 20% B₄C. The percentage of top as well as bottom kerf width variations for the laser cutting of 7050 aluminium alloy reinforced with 20% Al₂O₃ composite was observed to be more for the 7050 aluminium alloy reinforced with 20% B₄C composite, with laser power for different pulse frequencies and duty cycles as shown in the Figure 2.3 and Figure 2.4, respectively.

*The plots Figure 2.3 and 2.4 have been reproduced from [Yilbas et al. (2010a)]. Professor Yilbas has been kind enough to reproduce these figures for the thesis.*
Ahn et al. (2010) have investigated experimentally the effect of cutting parameters (laser power, cutting speed and cut material thickness) on 1 mm thick Inconel 718 superalloy sheet. They have found that the kerf width for high power CW Nd:YAG laser (2.8 kW) cutting of sheet by using oxygen assist gas lie in the range 0.53 – 0.61 mm. The kerf width increases with increasing the cutting speed when the cutting speed is greater than the critical cutting speed. The effect of laser power intensity on the kerf width in the CO$_2$ laser cutting of 64 layered carbon/carbon multi-lamelled plain weave structures have been investigated. They have observed that the kerf width increases with increasing the laser power [Sulaiman et al. (2006)]. An off-axis nozzle with a de Laval nozzle design to inject a supersonic assist gas jet and to avoid the recast layer formation and dross inclusions at the laser cut edges in pulsed Nd:YAG laser fusion cutting of 4 mm thick alumina composite.

![Figure 2.5: (a) Effect of spot overlap on surface roughness and kerf width (b) Effect of spot overlap on cut edge profile [Thawari et al. (2005)]](image)

*The plots Figure 2.5 have been reproduced from [Thawari et al. (2005)]. Professor Thawari has been kind enough to reproduce these figures for the thesis.

**Surface Quality**

Surface roughness is one of the parameter which affects the quality of the cut. The experimental investigation in the CW Nd:YAG laser cutting (maximum power 2.8 kW) of Inconel 718 sheet (1.0, 1.6, 2.0 mm thick and 9 specimens) shows that the surface roughness of the cut section is mainly affected by the cutting speed and its value decreases with increasing cutting speed. The maximum and average value of the surface
roughness lies in the ranges of $1.4 - 5.7 \, \mu m$ and $8.2 - 29.1 \, \mu m$ respectively [Ahn and Byun (2009)].

To an extent, the surface roughness also depends upon the spot overlap and it can be decreased by increasing the spot overlap [Ghany and Newishy (2005)]. The surface roughness for the ultra violet (UV) laser cutting of aluminium nitride ceramic, increases with increasing spot overlap upto 70% and remains constant for spot overlap between 70 – 85% with the values ranging between $1.24 \, \mu m - 2.17 \, \mu m$. For near infra red (NIR) laser cutting, the surface roughness remains almost constant upto 85% spot overlap and after that it increases quickly, reaching to maximum surface roughness (15 \, \mu m) at 95% spot overlap [Gilbert et al. (2007)].

Kuar et al. (2005) have observed that the optimum value of surface roughness falls in the range of pulse frequency (6 – 8.5 Hz), cutting speed (17 – 22 mm/s) and lamp current (22-27 amp) for the laser cutting of silicon nitride ceramics. The surface roughness of thick ceramic tiles during CO$_2$ laser cutting, has been found affected by ratios of the power to cutting speed, material composition and its thickness, gas type and its pressure [Black et al. (1998b), Black and Chua (1997)]. The use of nitrogen as assist gas in laser cutting of composite fiber gives better surface finish by minimizing the sideways burning and edge irregularities in the cut section [Sulaiman et al. (2006)]. The surface roughness for the laser cutting of high performance polyethylene depends upon the laser power, cutting speed and focal position. It decreases with increasing laser power and focal point position, and with decreasing cutting speed [Eltawahni et al. (2010)].

**Metallurgical Characteristics**

The metallurgical quality characteristics of laser cut surface is mainly represented by the heat affected zone (HAZ). This is also one of the main quality characteristics to change the microstructure of the surface material. HAZ width can be controlled by proper selection of the laser cutting process parameters. In laser cutting of ceramics (Mullite alumina), the HAZ depends upon the pulse frequency, laser power, cutting speed and assist gas pressure. The HAZ width decreases with increasing cutting speed and pulse frequency, and with decreasing laser power. In the pulsed Nd:YAG laser cutting of 4 mm thick Mullite – alumina, it has been observed that the specimen processed at lower cutting speed (2.5 mm/s) have wider HAZ than those obtained at higher cutting speed (5.0 mm/s) [Quintero et al. (2004)]. Paulo Davim et al. (2008) have found almost similar results, i.e.
HAZ width increases with laser power and decreases with cutting speed, in laser cutting of polymeric materials. The HAZ width also depends upon the types of lasers and their power density applied for the cutting of materials. Zhang et al. (2007) have used two types of lasers (Nd:YAG laser and KTP/Nd:YAG laser) for the cutting of polycrystalline diamond compacts (PDC) and have concluded that more HAZ and heat checking has been obtained with Nd:YAG laser than KTP/Nd:YAG. KTP/Nd:YAG has been found superior to the Nd:YAG laser in terms of quality of PDC cutting. The quality of laser cut specimen has also been affected upto some extent by the striation formation, dross and micro cracks. Yilbas and Akhtar (2012) have found striations and sideways burning in laser cutting of Kevlar laminates. The formation of striation has been attributed to the air trapped during the manufacturing of kavlar laminates. The trapped air is released during the laser cutting process. The fibers in the Kevlar laminate burns and adhere to the cut edges. Yan et al. (2012) have found that the striation formation depends upon the laser power, cutting speed, pulse frequency, gas pressure and stand-off distance for the laser cutting of 1 mm thick alumina sheet. They have obtained striation free cutting at the optimum parameter settings as; average laser power of 360 – 420 W, pulse energy 23.7 – 34.1 mJ, pulse repetition rate of 12 -15 kHz, pulse duration of 50 – 55 ns, cutting speed of 120 – 270 mm/min, focal plane position of 0 – 0.5 mm and nozzle standoff distance of 0.5 – 1 mm with 1 – 1.5 bar assist gas pressure.

2.2.3 Laser Cutting of Difficult-to-Laser-Cut Materials
The materials which have non favorable optical and thermal properties like high reflectivity and very low or high thermal conductivity are difficult to cut by laser. Highly reflective materials like aluminium (Al) and its alloys reflects most of the incident laser beam energy and hence reduces the available energy for melting and/or vaporization. High thermally conductive materials like copper and its alloys transfer most of the thermal energy to the region adjacent to cutting zone and hence less heat energy is available for raising the temperature of the desired zone upto melting or vaporization. Materials having very low thermal conductivity such as Ti and its alloys have tendency to accumulate most of the heat in very narrow region (somewhat equivalent to beam spot diameters), hence give extreme rise in temperature that can cause local burning of material rather than melting and/or vaporization. The reflectivity problem can be overcome to some extent by selection of suitable laser from a wide range of wavelengths, e.g. aluminium and its alloys better absorb the Nd:YAG laser as compared to the CO2
laser. Further, coatings of non-reflective materials can be provided to enhance the absorptivity. Pulsed laser beams have been found suitable for the cutting of highly thermally conductive materials because pulsed laser supply gives high peak powers with reduced interaction time. But materials like Ti and its alloys, having very low thermal conductivity and high chemical reactivity at elevated temperature pose problems in achieving satisfactory quality cuts even by using pulsed lasers. A number of researchers have studied the laser cutting performance of Ti alloys in different conditions. When these alloys are cut with oxygen assist gas, at even low pressure, the uncontrolled burning of cutting front starts that results in wide kerf and poor surface quality. Shanjin and Yang (2006) have investigated the Nd:YAG pulsed laser cutting of titanium alloy sheet (1 mm thick) and the influences of laser cutting parameters (pulse energy, pulse rate, cutting speed, gas type, and gas pressure) on laser cut quality factors such as heat-affected zone (HAZ), surface morphology and corrosion resistance. For air assisted laser cutting, the reaction of titanium with oxygen and nitrogen produces a thin layer of hard and brittle oxides and nitrides, and generates much thicker HAZ in comparison to that of nitrogen or argon. They have found that the HAZ thickness decreases with increasing pulse rate, cutting speed and assist gas pressure while with pulse energy, it first decreases, then remains almost constant for a range of 1.5 – 2.5 J and after that increases with increasing pulse energy. Air and nitrogen assisted laser cutting of titanium alloys leads to micro cracks and reduced surface quality due to formation of oxides and nitrides at the cut edge surface. Hitachi S- 4700 SEM instrument has used for measuring surface quality and analysis of HAZ.

Rao et al. (2005) have used nitrogen (N\textsubscript{2}), argon (Ar) and helium (He) assist gases for the pulsed laser cutting of 1 mm pure titanium sheet. They have observed straight and parallel cuts with Ar and N\textsubscript{2} assist gases while use of He gave wavy cut surface. Laser cutting with high frequency and low duty cycle pulsed mode operation produces dross-free cut surfaces with noticeable HAZ. Helium produces laser cut with narrow HAZ and low dross as compared to the Ar because He provides high heat convection and better ability to generate high shear stress.

Almeida et al. (2006) have performed factorial designed experimentation on Nd:YAG laser cutting of Ti and its alloy sheets. They have observed that use of nitrogen assist gas increases surface hardness from 2 to 3 times due to the formation of TiN while a mixture of He and Ar gases reduces the irregular edges and also eliminates the nitride formation.
CO₂ laser has poor absorptivity due to greater wavelength 10.6 µm so that the use of CO₂ laser is not common in practice for the cutting of highly reflective and thermally conductive materials like aluminium and its alloys. High reflectivity of these materials require high laser power when cut with CO₂ laser and there is possibility to damage laser cavity, cavity optics or beam delivery optics due to reflected laser beams. Further, high thermal conductivity of aluminium alloys tends to produce large heat affected zone (HAZ), wider kerf and oxides on the molten materials in the cutting front. Stournaras et al. (2009a) have experimentally investigated the effect of laser power, scanning speed, pulse frequency and gas pressure on the kerf width, the edge roughness and the size of HAZ for the laser cutting of aluminium alloy 5083 sheet. They have observed that laser power and cutting speed are most important factors for cut edge quality due to the fact that their combination determines the amount of heat that enters the cutting regime. Kerf width and HAZ are mostly affected by laser power and cutting speed parameters. Higher values of laser power, in combination with lower values of cutting speed, results in extended dimensions of the kerf width and HAZ. Pulse frequency and assist gas pressure also play an important role on the surface roughness and lower values of the pulse frequency, with the same scanning speed, gives decrease in the laser spot overlaps and consequently increases the undulations on the cutting edge surface. Adelmann and Hellmann (2011) have proposed fast laser cutting optimization algorithm for the fiber laser cutting of 1 mm thick aluminium sheet and optimized burr height and kerf width. They have observed that the best quality is obtained at optimum parameter levels of velocity 90 mm/s, gas pressure 12 bar, focal position -0.3 mm and nozzle diameter 2.0 mm. Ceramic sheet cutting with the pulsed Nd:YAG laser has shown the heat affected zone (HAZ) increases with increases the pulse energy and feed rate but decreases slightly with increase in the pulse frequency [Zhang et al. (1996)]. Araujo et al. (2003) have shown the micro-structural changes due to heat affected zone in aluminium alloy (Al 2024 T3) during CO₂ laser cut hole. They have observed that the HAZ extension is lower than 5 µm.

Different experimental investigations reviewed here show the effect of process parameters on different quality characteristics. But while studying the effect of process parameters only one parameter has been varied at a time. Only, few research papers have been found for the experimental investigations of difficult-to-laser-cut materials such as aluminium, copper, titanium and their alloys. Hence, it can be concluded that a scientific
approach is required to study the effects of process parameters and an in-depth study of process behavior in the laser cutting of difficult-to-laser-cut materials.

2.3 Theoretical Investigations in Laser Cutting: A Brief Review

The process of laser cutting is complex in nature due to involvement of many process parameters. The quality characteristics of laser cutting process are required to be predicted precisely. For the prediction of quality characteristics, it is required to represent the input and output relationship by mathematical equations. The representation of input and output relationship through a set of equations is nothing but mathematical modeling of the process. These models are further used for simulation, design, analysis, optimization and prediction of performance and behavior of the system. Analytical, mathematical, mechanistic and artificial intelligence (AI) are the most commonly used approaches for the modeling of the process behavior. Analytical models are most versatile and can be used for different conditions, i.e. the validity ranges if larger. For analytical modeling, there is no need of conducting the experiments. The models are based on the principles and laws of physics, i.e. basic laws and principles of the process so the mathematical equations obtained are quite complicated [Dubey and Yadava (2008b)]. In order to solve these equations, some assumptions are made to simplify these equations. The main limitation of the analytical models is that the results obtained by these models are away from the real situations due to these assumptions. On the other hand, the models based on the experimental study, are more realistic and suitable for newly developed study process. In this approach, statistical method such as regression analysis is used to model the input and outputs. Regression methods are frequently used to analyze the data from planned and unplanned experiments. It requires less effort and computational efficiency. However, these models are not used for the prediction of non-linear problems accurately and are valid only within a certain range of parameters.

Nowadays, a third type of study known as mechanistic modeling, is frequently used. It is a combination of experimental and analytical modeling which harnesses the advantages of both the techniques and avoids the limitations of both. AI based methods such as artificial neural network (ANN), fuzzy logic (FL), and neuro fuzzy are most commonly used to model the non-linear, uncertain and complex problems. ANN, with their remarkable ability to derive meaning from complicated or imprecise data, can be used to extract patterns or detect trends that are too complex to be noticed by either humans or
other computer techniques. A trained neural network can be thought of as an “expert” in the category of information it has been given to analyze. Fuzzy logic is a perfect means for modeling uncertainty and imprecision arising from mental phenomena. Numerical modeling techniques are finite element method (FEM), boundary element method (BEM), finite difference method (FDM), finite volume method, etc., for solving the complex equation [Dubey and Yadava (2008b)].

A lot of theoretical investigations have been carried out for the laser cutting of different materials. These theoretical investigations can be broadly categorized into two main categories: exact solution based analytical models and numerical solution based analytical models. Many researchers have used exact solution based analytical models to find machined geometry (kerf width, kerf depth and kerf deviation), surface quality (surface roughness), metallurgical characteristics (melt thickness and HAZ) during laser cutting of different materials.

**Machined Geometry**

Many researchers have developed theoretical models for geometrical kerf quality characteristics such as kerf width, kerf depth and kerf deviation. Caprino and Tagliaferri (1988) have developed theoretical model for prediction of depth of kerf in CO\(_2\) laser cutting of glass fiber reinforced plastic composite. Kaebernick et al. (1999) have developed analytical model to predict the kerf width during the pulsed Nd:YAG laser cutting of 0.5 and 0.9 mm thick mild steel and stainless steel sheets. For developing the model, the shape of the laser pulse is taken as rectangular, with the peak power being constant for the duration of the pulse. Cenna and Mathew (2002) have developed theoretical models for kerf width at entry and exit sides, material removal rates and energy transmitted through the cut kerf by considering the spatial distribution of laser beam, interaction time between the laser and the work material, absorption coefficient of the laser beam and thermal properties of the material. Yilbas (2004) has developed a kerf width model based on lumped analysis for the CO\(_2\) laser cutting of 1 and 2 mm thick mild steel sheet. He has also included the contribution of high temperature oxidation reaction due to assist gas in his analysis.

**Cutting Speed or Feed Rate**

In the laser cutting process, the cutting speed or feed rate is also an important parameter which decides the heat input in the cutting front and interaction time of laser beam-
workpiece. Some researchers have tried to develop theoretical models for the prediction of cutting speed in the laser cutting process. Black (1998a) has developed four empirical models for the prediction of cutting speed during the laser cutting of decorative ceramic tiles by using different approaches, i.e. Rosenthal’s moving point heat source model and the heat balance approach of Powell, Steen and Chryssloouris. Li et al. (2007) have proposed a theoretical model to predict the critical cutting speed for striation free cut surface during the fiber laser cutting of 2 mm thick annealed EN43 mild steel sheets. It has also found that at cutting speeds above the critical cutting speed, striation reappears and surface roughness increases with the cutting speed.

**Other Quality Characteristics**

Researchers have also developed theoretical models for the prediction of material removal rate (MRR), surface roughness (SR) and striation formation during the laser cutting of different materials. Pietro and Yao (1995) have developed a theoretical model for the prediction of surface roughness and striation formation in the CO₂ laser cutting of 1.2 mm thick, cold rolled mild steel. Tani et al. (2004) have analyzed striation and dross formation by means of an analytical model by considering mass, force and energy balance. It evaluates the 3-D geometry at the cutting front and temperature fields in the melt film. Wee and Li (2005) have developed 2-D models for the prediction of melt film thickness by considering mass, force and energy balance equations. Xie et al. (2008) have developed 3-D energy-coupling model for an evaporative laser cutting of a non-metallic material high absorptivity.

**Numerical Solution based Modeling**

For providing real solution to the problems, most of the analytical models, use numerical solution based methods such as FEM, BEM, FDM. Among the different numerical solution based methods, FEM is most commonly used [Dubey and Yadava (2008b)]. Many researchers have applied numerical methods in the laser cutting process of different materials. The chronology of development of numerical solution based modeling of laser cutting process is shown in Figure 2.6. Li and Sheng (1995) have developed a hybrid modeling approach of crack initiation where kerf width has been determined through analytical solution and temperature and stress distributions have been determined through a numerical plane stress model. Sheng and Joshi (1995) have developed 2-D transient numerical model to predict the extent of HAZ during the laser cutting of stainless steel.
The results obtained through the laser cutting experiments are in good agreement with the numerical estimates of HAZ. Yu (1997) has done 3-D FEM of laser cutting of copper plate. Prusha et al. (1999) have developed mathematical models to predict the conduction heat loss rate, temperature in the HAZ and cutting speed in the laser cutting of thick materials. Kim (2000) has developed 2-D transient numerical model by using BEM to analyze the evaporative material removal process using a high energy Gaussian wave laser beam. Kim and Zhang (2001) has developed an unsteady heat transfer computational model to predict the amount of material removal and groove smoothness by considering Gaussian wave laser beam in pulsed mode. The laser intensity has been assumed to be sufficiently high to cause direct evaporation of material from the surface of the medium. Kim (2004) has applied 2-D time-dependent boundary element method based on transient convective heat transfer equation to analyze the evaporative material removal process using temperature and heat flux distribution. Kim (2005) has developed 3-D computational model to predict the temperature distribution in HAZ and groove shape by considering laser beam as continuous wave Gaussian beam. The temperature distribution has shown that the HAZ is not limited close to the laser position. Gross (2006) has developed 3-D fully coupled model for the laser cutting process to analyze the complete physical phenomena by considering the momentum transfer in the melt, surface tension, advection, Navier-Stokes stresses, Marangoni forces, viscous forces of melt by whole using assist gas jet and including the effect of gravity. Arif et al. (2009) have developed a new methodology for dross free cutting during the laser cutting of silicon steel sheet by employing newly developed cyclone slag separator. The slag separator has been located under the workpiece to form rotating gas flow for controlling the direction of the flowing slag gas. The gas flow acting under the workpiece is simulated by using FEM. Guo et al. (2009) have developed numerical modeling of supersonic jet impinging on a plate with a hole to analyze the gas jet-workpiece interaction. The model has been able to make predictions of the mass flow rate and axial thrust with a standoff distance and exit Mach number. The mass flow rate and average axial thrust have been obtained from numerical models by using computational fluid dynamics (CFD) solver, with standoff distance and Mach number during the laser cutting of 1.5 mm thick sheet. Nishar et al. (2009) have analyzed the cut deviation at the cutting edge during the chip-free diode laser cutting of glass by using controlled fracture technique. Cut path deviation has been analyzed by simulating stress
fields with the application of finite element simulation during the laser cutting of soda-lime glass sheet.

<table>
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<tr>
<th>Authors</th>
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<tr>
<td>Li and Sheng</td>
<td>1995</td>
<td>Numerical simulation based model for temperature and stress;</td>
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<td>Sheng and Joshi</td>
<td>1995</td>
<td>Numerical simulation based transient model to predict the kW and HAZ</td>
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<td>Yu L.M.</td>
<td>1997</td>
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<td>Kim M.J.</td>
<td>2000</td>
<td>BEM based 2-D transient heat conduction model for material removal</td>
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<td>Kim and Zhang</td>
<td>2001</td>
<td>FEM based computational model for MRR and groove smoothness</td>
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<td>Gross</td>
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<td>BEM based computational model for groove shape, and temperature distribution</td>
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<td>Arif et al.</td>
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<td>2009</td>
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<td>Yilbas</td>
<td>2010b</td>
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<td>Yang et al.</td>
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<td>FEM based theoretical model for separation of 2-layer glasses</td>
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<td>Nishar et al.</td>
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<td>Yilbas et al.</td>
<td>2011</td>
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<tr>
<td>Hu et al.</td>
<td>2011</td>
<td>FVM based 3-D axial symmetrical model for laser cutting</td>
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<tr>
<td>Scintilla and Tricarico</td>
<td>2012</td>
<td>Numerical simulation based 3-D semi-stationary model to predict HAZ</td>
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**Figure 2.6:** Development in numerical solution based modeling of laser cutting process.
Yilbas et al. (2010b) have used finite element method (FEM) to predict temperature and stress fields during the laser cutting of 5 mm thick mild steel sheet. The magnitude of the residual stress has been 90 MPa at the sharp corners while maximum von Mises stress has been in the order of 280 MPa, which occurred away from the sharp corners. Yang et al. (2010) have developed a theoretical model for the separation of two layer glasses by using thermal laser shock method during the Nd:YAG laser cutting of soda-lime glass with controlled fracture technique. Nishar et al. (2010a) have developed 3-D transition model to determine the temperature distribution, which has been used as an input for the developed model to find thermal stress during the diode chip-free cutting of glass sheet. Nishar et al. (2010b) have used finite element modeling to simulate the transient effects of the moving and predict thermal fields and stress distributions. Qin et al. (2010) have developed an axisymmetric mathematical model to predict temperature and thermal stress for the long pulsed Nd:YAG laser heating of 2024 aluminium alloy sheet by considering the laser beam as Gaussian laser beam. Yi et al. (2011) have developed 3-D transient process model in ambient dry air and water film and water using FEM by considering thermo-mechanical parameters. Melhem et al. (2011) have developed 3-D mathematical model to analyze the flow field in the kerf and its surrounding, and heat transfer rates from the kerf wall using the control volume approach. Yilbas et al. (2011) have analyzed the thermal stresses at the cutting section using finite element software ABAQUS. Hu et al. (2011) have developed 3-D axial symmetrical model of laser cutting. FEM based numerical simulation has been used by them to investigate the flow field of shield gas in cutting slots by adopting N-S equation. Scintilla and Tricarico et al. (2012) have developed 3-D semi stationary numerical model to predict average cutting temperature in the HAZ and conduction losses for inert gas fusion cutting 1, 5 and 8 mm thick 90MnCrV8 sheet with disk and CO$_2$ laser beam. They have observed that the 3-D semi stationary simplified model showed a good agreement between numerical simulation and experimental data.

In most of the theoretical studies whether exact or numerical solution based, the researchers have investigated the effect of process parameters on the quality characteristics for laser cutting process. In exact solution based studies, the researchers have analyzed geometrical kerf properties such as kerf deviation, kerf width, kerf depth and other quality characteristics like surface roughness, dross and striation formation and material removal rate (MRR). But only a few researchers have focused on the
metallurgical quality characteristics like heat affected zone (HAZ), recast layer thickness and oxide layer. As per the author’s knowledge, the exact solution based theoretical models for the prediction of mechanical properties have not been found. Most of the research papers based on numerical solution are mainly devoted to the temperature and thermal stress simulation with simple assumptions. Some researchers have only focused in depth study of laser cutting process. Very few researchers have performed numerical simulation of recast layer formation, change in mechanical properties at the cutting front for laser cutting of materials. Very few research papers have been found an analytical modeling of difficult-to-laser-cut materials like aluminium and its alloys, titanium and its alloys etc.

2.4 Modeling and Optimization Tools in Laser Cutting: A Brief Review

In order to improve the quality with minimum manufacturing costs, timing, process safety and higher productivity, the setting of the process parameters are required to be selected in the best possible way. Nowadays many manufacturing industries are using fully automated and computer-controlled machines to fulfill the requirement of the competitive market. The success of the manufacturing process mainly depends upon the appropriate selection of the process parameters. These optimum parameters play a very important role to ensure the product quality, increase productivity and reduce the manufacturing cost in fully automated manufacturing process [Rao (2011)]. Modeling and optimization of process parameters of many manufacturing process is usually a very difficult task where the knowledge about the manufacturing process, machine specifications, empirical equations to develop realistic constrains, development of an effective optimization criterion and knowledge of numerical and mathematical optimization techniques have to be required. Researchers have developed in large number of optimization techniques and solved the various types of parameter optimization problems. The various types of optimization problems are shown in Figure 2.7.
There are two types of optimization techniques: conventional and non-conventional. Conventional optimization techniques give a local optimum solution or absolute optimal solution. Non-conventional optimization techniques, based on extrinsic or objective function developed, provide an appropriate solution or near-optimal solution. The conventional optimization techniques can be further divided into two categories- Design of Experiments (DOE) based technique and iterative mathematical search technique. Taguchi methodology (TM), response surface methodology (RSM) and factorial design (FD) are DOE based techniques where as linear programming (LP), non-linear programming (NLP) and dynamic programming (DP) are iterative mathematical search techniques [Mukherjee and Ray (2006)]. Non-conventional, meta-heuristic search-based techniques, which are sufficiently general and extensively used by researchers in recent times, are based on genetic algorithm (GA), simulated annealing (SA), Tabu search (TS), particle swarm optimization (PSO), ant-colony optimization (ACO), artificial bee colony optimization (ABCO), artificial immune optimization (AIO), shuffled frog leaping algorithm (SFLA) and harmony search algorithm (HAS). The classification of optimization techniques are shown in Figure 2.8.
The Figure 2.8 shows different techniques those are used in the machining processes but design of experiment is the superior technique for the optimization of the quality characteristics because it is a systematic and scientific way of planning the experiment, collection and analysis of data with limited use of available resources [Lin (2012), Mukherjee and Ray (2006)].

Figure 2.8: Classification of optimization techniques [Lin (2012), Mukherjee and Ray (2006)]

**DOE (Design of Experiments) based**

Nowadays, design of experiments (DOE) based techniques have been used in all sectors of engineering and business application. The DOE based optimization process has included planning of experiments, conduction of experiments and analysis of the experimental data. The planning or designing of the experiments has been the most important phase for the experiment to provide the information. In the FD approach, each complete trail or replication of all possible combinations of the factors such as main effect of individual factors, and all interaction effects among the different factors are investigated. RSM is a collection of mathematical and statistical techniques that is useful for modeling and analysis of a problem in which a response of interest is influenced by several variables [Montgomery (2004)]. It is a dynamic and foremost important tool of DOE wherein the relationships between the response of a process with its input decision
variables are mapped to achieve the objective of maximization or minimization of the response properties [Mukherjee and Ray (2006)]. In this method, a regression model with first order or higher is developed and the developed regression model is optimized with the steepest gradient method. It is suitable for lower-order polynomial equation to establish the relationship between response and decision variables at an early stage of experimentation [Montgomery (2008)]. RSM is not suitable for highly nonlinear systems. Some researchers have used DOE based methods such as FD, RSM and TM for an investigation of the parameter effects and performed parameter optimization and modeling of the laser cutting process. Yilbas (2008) has carried out a factorial analysis to identify the main effects and interactions of the laser power, cutting speed and oxygen assist gas pressure on the kerf width variation. He has observed that the laser output power and oxygen gas pressure have significant effect on the percentage of kerf width variation. Riveiro et al. (2010) have experimentally compared the modes of laser operation during the CO$_2$ laser cutting of 3 mm thick, 2024-T3 sheet using full factorial design for experimentation. They have found that a better cut quality is obtained while processing in CW mode substantially increasing the cutting speed. Almeida et al. (2006) have performed optimization of titanium cutting by factorial analysis in the pulsed Nd:YAG laser cutting of 0.5 mm and 1 mm thick sheet. They have found that the samples originated from the use of He and Ar gases and their mixtures resulted in the reduction of irregular edges. Mathew et al. (1999) have investigated the parametric study on pulsed Nd:YAG laser cutting of carbon fiber reinforced plastic composites using RSM and observed that the gas pressure has the most influencing parameter for kerf width. Choudhury and Shirley (2010) have done central composite design based experiments on the laser cutting of three polymeric materials, each 3 mm thick namely polypropylene (PP), polycarbonate (PC) and polymethyl methacrylate (PMMA) to investigate the effect of laser power, cutting speed, and assist gas pressure on HAZ, surface roughness and dimensional accuracy. They have found that PMMA has less HAZ and better cut edge surface quality than PC and PP. Sivarao et al. (2010) have investigated experimentally on the laser cutting of 6.0 mm thick mild steel sheet using RSM. They have observed that high cutting speed only can produce better surface coupled with high duty cycle, regardless of pulse frequency. Yilbas et al. (1998) have done TM based experimental study and found that the cut quality is mainly influenced by cutting speed and oxygen pressure. Sharma et al. (2010) have suggested optimum parameter levels for optimization of geometrical kerf quality characteristics such as kerf width, kerf taper and kerf deviation.
based on TM during straight and curved profile laser cutting of nickel based superalloy sheet. They have observed that the optimum parameter level for straight cut profile is entirely different from curved cut profile. They reported an improvement on all quality characteristics for straight as well as curved profiles at respective optimum level. Dubey and Yadava (2008c) have investigated the optimization of kerf taper and MRR during pulsed Nd:YAG laser cutting of aluminium alloy (8011) sheet using self developed software namely Computer Aided Robust Parameter Design (CARPD). They have observed a considerable improvement in both the quality characteristics at optimum levels. They have also found that the effect of the process parameters differs from characteristics to characteristics and different quality characteristics have different optimum parameter levels. Modern requirement is to optimize the different quality characteristics simultaneously. Some researchers have used different DOE based optimization techniques to optimize the quality characteristics simultaneously. Simultaneous optimization of kerf taper and MRR using TM during the pulsed laser cutting of aluminium alloy sheet. The results of the multi-objective optimization (MOO) were compared with the single objective optimization and it was found that the kerf taper has increased by 1.6% in MOO while the MRR has the same value. The same methodology has been applied for the single as well as MOO of the kerf width and MRR during the pulsed laser cutting of grain oriented silicon steel sheet and it has been found that the improvement in quality is always possible when moving from single to MOO [Dubey and Yadava (2007)]. Dubey and Yadava (2008d) have investigated the geometrical kerf quality characteristics such as kerf width and kerf deviation during the pulsed Nd:YAG laser cutting of aluminium alloy sheet using TM. They have found that the uncertainty in deciding the weighting factor for individual quality characteristics is a major problem in optimizing multiple quality characteristics using TM.

**Hybrid Approach**

The modeling and optimization tools whether DOE, grey relational analysis (GRA) and principal component analysis (PCA) have their own advantages and limitations. If these methods are integrated together in a logical manner, advantages of individual tools can be incorporated and shortcomings can be removed at the same time. Such hybrid approaches can improve the process performances considerably. Further, the decision on selection of weights for individual quality characteristics has been major challenge during simultaneous optimization of multiple quality characteristics. Quite often, they are
selected on the basis of past experiences and have some uncertainties. As a general practice, equal weights are assumed by researchers. If the weighting factor are decided on the basis of available data and/or rule, the chances of uncertainties are minimized. For example, when TM is integrated with PCA, the uncertainty involved in deciding the weighting factors is minimized and certain improvement in the quality characteristics is observed. Dubey and Yadava (2008e) have used the hybrid approach of TM and PCA for the MOO of geometrical kerf quality characteristics in the pulsed laser cutting of Ni based superalloy sheet. They have found a considerable improvement in kerf deviation as well as kerf taper by using hybrid approach of TM and PCA. Dubey and Yadava (2008f) have also applied the hybrid approach of TM and RSM to optimize kerf width and MRR, simultaneously during the pulsed laser cutting of high Si alloy steel sheet. They have demonstrated a considerable improvement in both the quality characteristics with the hybrid approach of TM and RSM.

From the influence of operating parameters on the performance characteristics, the optimal operating parameters have been very difficult to control. In such complex and multivariate systems, the relationship between factors has uncertainty. The classical statistical procedures can not analyze these systems in an acceptable or reliable manner without large data sets that satisfy certain mathematical criteria. The grey relational theory, on the other hand, can handle both incomplete information and unclear problems very precisely [Dubey and Yadava (2008f)]. The integration of GRA with TM is a hybrid approach (TMGRA), which is used to deal with imprecise, uncertain and incomplete information. Caydas and Hascalik (2008) have applied hybrid approach TMGRA for the optimization of laser cutting process of St-37 steel sheet with multiple performance characteristics. It has shown that the kerf width and width of HAZ have improved effectively through this hybrid approach. Rao and Yadava (2009) have used TMGRA with entropy measurement for the MOO in the pulsed Nd:YAG laser cutting of 0.7 mm thick nickel-based superalloy sheet and found considerable improvements in the kerf width, kerf taper and kerf deviation for both straight as well as curved cut profiles. A considerable improvement in the kerf taper and surface roughness has also been reported during the pulsed laser cutting of Al-alloy sheet by using TMGRA [Sharma and Yadava (2012)]. Dubey and Pandey (2012b) had experimentally investigated multiple quality characteristics optimization simultaneously in laser cutting of titanium alloy sheet (grade
5). They have applied genetic algorithm for optimization. They have developed regression models for the kerf quality, i.e. kerf taper and surface roughness.

2.5 Artificial Intelligence Applications in Laser Cutting: A Brief Review

The conventional methods of modeling require large amount of experimental data to establish the mathematical relationship among the various process parameters and responses. The laser cutting process is highly non-linear and complex process due to involvement of many process parameters. The prediction of process behavior of laser cutting is very difficult and can be better predicted by the artificial intelligence (AI) based methods such as artificial neural network (ANN), fuzzy logic (FL) and genetic algorithm (GA). These methods have easy applicability, ability to detect complex relationship between variables, ability to detect implicit interaction among the variables, better prediction and successfully computational ability as compared to the conventional methods [Ayer et al. (2010)]. The artificial intelligence (AI) based methods have a common objective of developing intelligent systems which can perform tasks and solve problems requiring human intelligence. Fuzzy logic has one additional goal of developing cost effective approximate solutions by exploiting the tolerance for imprecision.

Only a few researchers have applied AI based methods in laser cutting process. Sivarao et al. (2009a) have used ANN to predict the surface roughness in laser cutting of 3 mm thick pressure vessel plate. They have used different network structures and optimized the networks. The ANN model has been experimentally validated and found that the model has been adequate for predicting the surface roughness. Syn et al. (2011) have experimentally studied the laser cutting quality characteristics by employing Fuzzy expert system and also developed fuzzy model by using fuzzy logic tool box of MATLAB 7.6.0 for the laser cutting of 1 mm thick incoloy sheet. The findings of these papers show that the proposed fuzzy logic model can be used to predict the surface roughness and dross inclusion in laser cutting of incoloy sheet. Tsai et al. (2008) have used multiple regression analysis (MRA) and ANN for modeling of the laser cutting of QFN packages and GA for finding the optimal set of process parameters. The optimal combination observed: current-29 A, frequency-2.7 kHz, and cutting speed-3.49 mm/s. Karazi et al. (2009) have compared ANN and DOE models for the laser cutting of glass micro channels. They have observed that two of the ANN models have shown greater average percentage error than the DOE model while third ANN model has shown an improved predictive capability
than DOE model. Sivarao et al. (2009b) have applied hybrid methodology of ANN and FL, i.e. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) to model the kerf width and surface roughness in the laser cutting of pressure vessel plate. They have reported that that the model developed for kerf width and surface roughness is reliable and adequate. Dubey and Pandey (2012a) had experimentally investigated the laser cutting of Duralumin sheet. They had used a hybrid approach of Taguchi method and fuzzy logic theory for multi-objective optimization. They observed the influence of the four process parameters (gas pressure, pulse width, pulse frequency and cutting speed) on the kerf quality, i.e. kerf width and kerf deviation.

2.6 Conclusions from Literature Review

Based on the literature review, it has been found that most of the experimental studies on laser cutting are based on the one parameter at a time approach (OPAT). Most of the researchers have investigated the effects of different process parameters on different quality characteristics in laser cutting. Different process parameters used during the experimental investigation of laser cutting are laser beam parameters (laser power, pulse width, pulse frequency, modes of operation, pulse energy, wavelength, spot overlap and focal position), material parameters (type, optical and thermal properties, and thickness), assist gas parameters (type and pressure), and processing parameters (cutting speed). The quality characteristics investigated during the experimental investigation of laser cutting process are material removal rate (MRR), geometrical kerf quality characteristics (kerf width, kerf deviation and kerf taper), surface quality (cut edge surface roughness, surface morphology) and metallurgical quality characteristics (HAZ, recast layer, oxide layer and dross inclusions). It has been found that maximum cutting speed is obtained with the help of O₂ assist gas during the laser cutting of metals and alloys. On the other hand this assist gas gives poor cut edge quality as well as wider kerf. Better quality cuts can is obtained by using inert assist gases such as N₂, He and Ar but these gases increase the cost and reduce the cutting speed. It is found that laser power is most significant parameter for the kerf width as well as HAZ and both quality characteristics increase by increasing laser power. Kerf width, kerf taper and recast layer are also affected by the workpiece thickness and as the thickness increases, the kerf width also increases for the focusing of laser beam on the surface of workpiece. During the pulsed mode laser cutting, the pulse
width as well as pulse frequency have been found significant process parameters for the kerf width, kerf taper, HAZ as well as cut edge roughness.

Experimentation methodology is also important consideration during the laser cutting of different materials. Planned methodology reduces the number of experimental runs significantly. Different researchers have used a well planned methodology or design of experiments (DOE) based methods such as TM, FD and RSM for the experimental investigation of laser cutting process. FD is also well established method for the experimentation which includes all interaction effects of process parameters as well as their main effects. FD has been found more efficient than OPAT experiments. It also allows the effect of a factor to be estimated at different levels of other factors, i.e. it is valid over a range of experimental conditions. TM is applied for the single as well as multi-objective optimization of different quality characteristics during the laser cutting process. RSM is also a well established method of experimentation based on the central composite design. This method has also been used by different researchers for the qualitative optimization of laser cutting process. In order to extract the advantages of these methods and to remove the disadvantages, some researchers have combined two or more methods (hybrid methods) and applied for the modeling and optimization of laser cutting process. A considerable improvement has been reported by some researchers with the application of hybrid methods in different quality characteristics during the laser cutting of different materials.

As some uncertainty has been found in the experimental data, however, it can be minimized by the application of AI methods such as ANN, FL and GA. These methods have also easy applicability, ability to detect complex relationship between variables, ability to detect implicit interaction among the variables, better prediction and better computational ability as compared to the conventional methods. These methods have been frequently used for the modeling and optimization of different advanced machining processes such as electrical discharge machining, electro chemical machining and ultrasonic machining but it has been limitedly applied in the laser cutting process. Some researchers have also applied the hybrid approach of DOE and AI based methods to different advanced machining processes. As per the author’s knowledge, a limited number of papers are available on the single objective and multi-objective optimization of the laser cutting of highly reflective and thermally conductive aluminum alloy sheet. This thesis has applied Taguchi methodology, hybrid approach based methods and AI based
method for the optimization and experimental modeling of difficult-to-laser cut aluminium alloy sheet.

The literature review has shown that many researchers have successfully investigated the effect of process parameters on different quality characteristics during pulsed Nd:YAG laser cutting of different categories of materials such as metals, nonmetals, superalloys, ceramics and composites. Pulsed Nd:YAG laser cutting has also been used for the cutting of difficult-to-laser-cut materials such as Al, Cu, Ti and their alloys as pulsed Nd:YAG laser has gives higher peak power with shorter pulse and it is better absorbed by highly reflective materials such as Al and its alloys. Due to shorter wavelength 1.06 µm, it gives better results on micro parts without any thermal damage. Very few research papers have been found on the laser cutting of difficult-to-laser-cut materials such as Al, Cu, Ti and their alloys. Author have observed that most of the experimental works on the laser cutting have studied kerf quality based on kerf width and kerf taper (deviation along depth of cut) only, while minimization of them ensures a narrow kerf. But minimization of kerf deviation or kerf unevenness along length of cut is also an important quality characteristic for obtaining a uniform kerf. Author have found only a limited number of papers where kerf deviation parameter has been taken care off. Author have also not found many papers related to the surface roughness during laser cutting of the aluminium alloy sheet. Optimization and modeling of surface roughness during laser cutting of Al alloy sheet is also an important quality characteristic for obtaining the better quality. Predictive modeling is essential for better understanding and optimization of the laser cutting process.

Author has not been able to find sufficient work related to metallurgical characteristic like HAZ on difficult-to-laser cut materials, though this characteristic is also very important from micro structural accuracy point of view so that AI based modeling and optimization for HAZ of aluminium alloy sheet has also been used.

From the above literature review it has been found that only a limited number of research work has been done on the highly reflective and thermally conductive aluminium and its alloy sheets.