Recent Developments in Laser Cutting of Metallic Materials

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Abstract

Laser cutting has become an extensively used method of material removal with cost effective solutions for complex manufacturing processes. An extensive research has been going on worldwide where researchers and industry experts are focusing on maximizing the productivity and reducing the cost while maintaining a high quality during laser cutting of engineered parts. Laser cutting, as the prevalent application of laser beam machining (LBM), offers a competitive advantage over conventional cutting processes in terms of material savings due to narrow kerf width, less heat affected zone and minimum distortions. The process offers high precision and good surface quality, with no tool wear and easy automation. The current paper aims to present an overview on the recent research on laser cutting of metallic materials, in terms of process monitoring and control as well as modeling and optimization, and to summarize the past five years of research on the topic.

Keywords
Kerf, laser, optimization, productivity, surface roughness.

1. Introduction

Laser beam machining (LBM), with capabilities to cut, trim, drill holes and weld in a wide range of materials have become the most widely used thermal energy process. The process is applicable from a macro-machining scale to micro and nano-machining. With a growing automotive industry and increase demand for precision and accuracy in aerospace, electrical and electronics sector, laser cutting, have gained advantage over traditional cutting processes such as oxy-fuel cutting, plasma cutting, sawing and punching. Laser cutting is a thermal process without contact, capable to produce accurate profiles with high cutting rates in a variety of materials, and to easily adjust to meet the requirements of new products. For more than two decades researchers embarked on to study closely the interaction between the process parameters and to optimize the processes for better quality and faster production. In laser cutting, research has been conducted around the influence of the process parameters on the quality of the laser cut (Pavlica, 2015). The criteria for evaluating the quality of the cut surface as well as the dimensional tolerance are given in standard EN ISO 9013:2000. Evaluation of the quality of the cut is based on surface of the cut, geometry of the cut, burr formation and the characteristics of material in the cut zone. The geometry of the cut evaluation is based on kerf profile (taper) and kerf width, perpendicularity and slant tolerance.
Most cut quality characteristics evaluated in previous research are the cut surface roughness, kerf width and HAZ (heat affected zone), while the most input parameters considered are the laser power, cutting speed and gas pressure (Radanovic, 2011).
This paper aims to present an overview on the recent research on laser cutting of metallic materials, in terms of process monitoring and control as well as modeling and optimization, hence to summarize past few years of research on the

topic. The metallic materials under consideration are those with commercial and industrial importance and include ferrous and non-ferrous alloys.

2. Laser cutting

Laser cutting is the prevalent application of lasers in metal processing due to its competitive advantage over conventional cutting processes in terms of material savings, high precision and good surface quality, no tool wear and easy automation. The focused laser beam allows for a tool free cut with great accuracy, narrow kerf and minimal heat affected zone (HAZ).
Laser cutting is a thermal process whereas an intense energy laser beam is focused in a very localized spot on the surface of the material to be cut. The energy is absorbed by the material and converted into heat such that the material melts or vaporize throughout its thickness, while assist gas help eject the molten material away from the cut. As laser cutting is having a large number of parameters with nonlinear and complex interaction between them, efforts are constantly made to understand the process and model it for best cut quality and faster cutting speed.

2.1 Methods of metal laser cutting

Depending on the amount of energy supplied and the type of assist gas used there are three methods to cut metals, namely: fusion cutting, flame cutting and sublimation cutting. Laser fusion cutting requires enough power to melt the material throughout its thickness. It uses reaction inhibiting Nitrogen or Argon as the assist gas. The gas is blown coaxially with the laser beam at pressures between 2 and 20 bar (Pavlica, 2015) and has the role of expelling the molten metal from the cutting zone, cooling the material and shield the cut preventing edges from oxidation. Laser flame cutting or laser burn cutting uses oxygen as the cutting gas. The gas is blown into the cutting joint at pressures up to 6 bar (Pavlica, 2015), and reacts chemically with the material being cut, with release of large amounts of energy, considerably increasing the input energy. Due to chemical reaction between O_2 and the constituents of the base material, an oxide layer forms on the cutting edge that influences the cut quality. This method is used in high speed cutting of thick metal sheet where a good edge quality is not a requirement. Laser sublimation cutting or vaporization cutting uses nitrogen, argon or helium as the process gas at low pressures of 1 to 3 bar. The gas serves only to shield the cut. The method involves vaporization of the material with as little melting as possible therefore requires high laser power and it is slower but produces high quality cuts. The method is not commonly used in sheet metal fabrication.

2.2 Laser systems

All laser systems have three main parts: a pump source, a gain medium and a resonant system. The pump source may be electrical discharge, flash or arc lamps, or chemical reactions. The gain medium, where suitable excitation and population inversion occurs, may be liquid, solid or gaseous. The gain medium is contained in a chamber called cavity. At each end of the cavity there is a mirror, one is a partially reflective and the other totally reflective mirror (see Fig. 1). These mirrors form the optical resonator of the laser system. The output beam is delivered to the workpiece as a small spot of high energy after passing through a focusing lens. Laser systems used for macro-machining are in general continuous-wave with laser beam power of up to several kW, while for micro-machining, pulsed beams systems with average power below one kW are used. For cutting metallic materials the most common industrial laser machines used are CO_2 and NdYAG and fiber. The CO_2 laser, although it is one of the earliest that have been developed, it is currently the highest power continuous wave laser available. The gain medium is a mixture of gases (CO_2, Nitrogen, Helium and in small percent, hydrogen and/or xenon) that is either water or air cooled. It is electrically pumped and radiates at 10.6 μm wavelength.
The gain medium in Nd:YAG laser is neodymium-doped yttrium aluminium garnet and the energy source is supplied by a bank of diodes or flash lamps. Output light beam is then collimated and focused by a lens on the material to be cut. The light is produced far more efficiently and is delivered in a much simpler system than the CO_2 laser.
This optically pumped solid state laser that works at a 1.06 μm wavelength allows cutting of materials with higher reflectivity. The fiber laser working principle is similar with NdYag laser except that the gain medium is an optical fiber doped with rare elements like ytterbium, erbium, neodymium, etc.

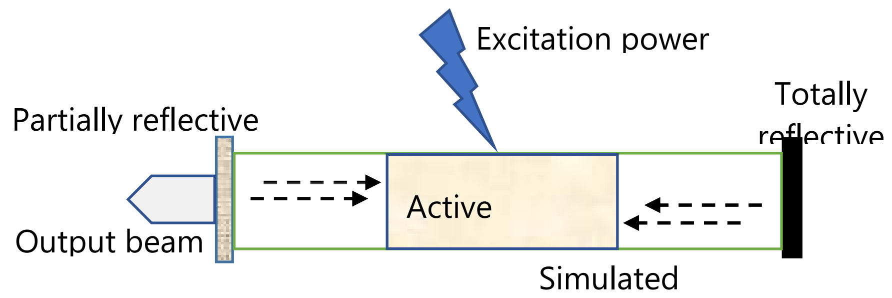

Figure 1. Diagram of main parts of a laser system

Factors to be considered when choosing the appropriate laser system are the type of material to be cut, the thickness of the material and the reflectivity/absorptivity of it, the accuracy required, edge quality and number of components.

2.3 Laser cutting parameters

Laser cutting is a complex process governed by a multitude of factors with difficult to predict interaction. The parameters of laser cutting process can be classified as system parameters, the workpiece parameters and process parameters as illustrated in Figure 2.

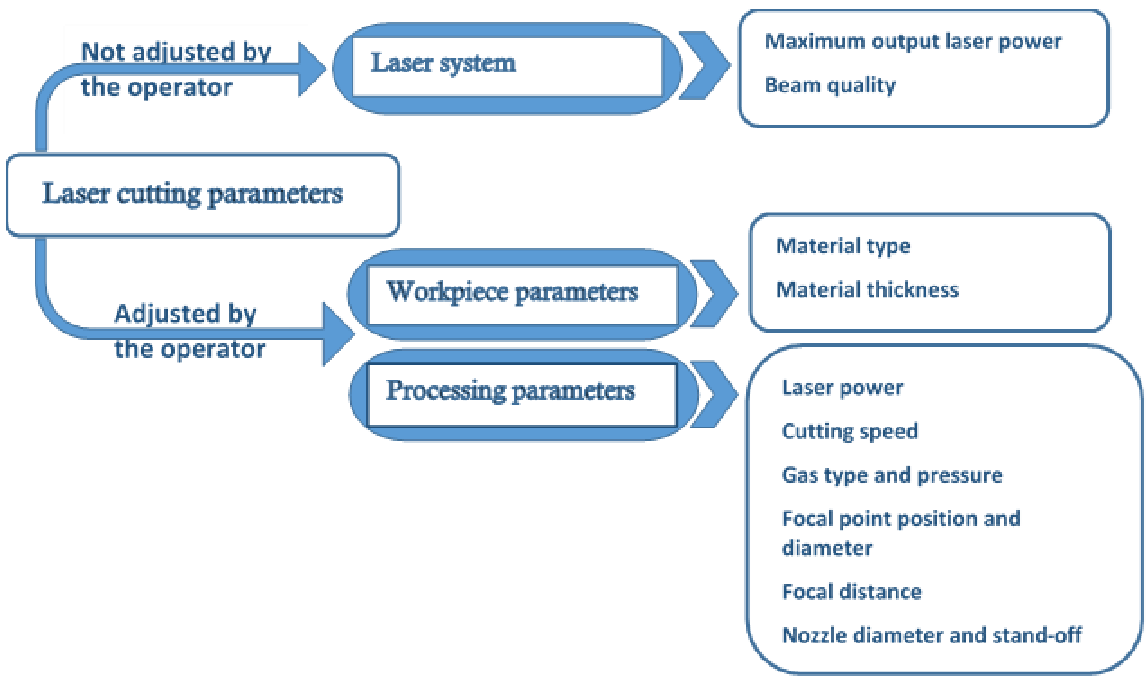

Figure 2. Laser cutting parameters

2.3.1 Workpiece parameters

Metals are characterized by high melting point, thermal conductivity and optical reflectivity. When referring to metallic materials the ones with lower reflectivity and thermal conductivity are most suitable for processing with laser. Both CO_2 and Nd:YAG laser machines have excellent capabilities for cutting the most common material used in manufacturing industries which is steel in all variants: mild steel, stainless steel, tool steel or alloy steel. Aluminium, titanium and nickel-based alloys (prime candidate materials for aircraft industry) are also fairly good processed by

both laser systems. However, materials which are highly reflective like copper and its alloys, gold and silver etc. are difficult to cut. Most used material type in recent research is mild steel and stainless steel. Varkey (2014) and Solanki (2016) conducted investigation on Ti6AlV4 and Ti grade II respectively, while Parthiban (2015) and Leonea (2015) used 6061-T6 aluminium alloy. Tungseten alloy was used by Hajdarevic (2017) and Klancnik (2014), and Ni-based alloy was used by Sharma (2015).
The thickness of the piece to be cut influences the power required to melt or vaporize the material and the cutting speed. For thicker materials, slower cutting speed and higher power is needed. Orishich (2016) investigated the utmost thickness of a low carbon steel sheet using fibre and CO_2 laser and O_2 as the assist gas. He found a maximum thickness of 40-50 mm that can be cut with CO_2 laser with a good cut quality. However, the method of determination of the maximum thickness could not be applied to fibre laser cutting. The thickness of the sheet metal used in recent research varies between 1 and 10 mm. Tamura (2015) studied the cutting of thick steel plates and simulated steel components using 30 kW high power fibre laser. He successfully cut carbon steel and stainless steel up to a thickness of 300 mm proving that the process can be used in decommissioning of nuclear plants.

2.3.2 Process parameters

The laser power, known also as the heat input is dependent of the type of material to be cut, its thickness and the desired cutting rate. Materials such as stainless steel and aluminium require about 1000 W of heat input for cutting 1 mm thick sheet while mild steel and titanium of the same thickness, around 400 W of heat input.
Laser cutting is most efficient process in terms of its feed rate. Maximum cutting speed can be used when matched with the appropriate level of power and assist gas pressure to successfully cut a given thickness with good cut quality. Golyshev (2015) studied the maximum cutting speed as a result of the laser beam polarization. He found that the maximal cutting speed is reached when the field vector coincides with the cutting direction. Jarosz (2016) investigated the effect of the cutting speed on surface quality and HAZ when cutting AISI 316L of 10 mm thick with CO_2 laser using nitrogen as assist gas. It was observed that cutting speed is influencing the width of HAZ and the presence of dross and burnt material. As the cutting speed is decreased from a maximum recommended value, the width of HAZ was observed to increase and at 50% of the maximum recommended speed, the lower part of the cut becomes visibly damaged.
Typically, the assist gas used in laser cutting may be an inert gas such as nitrogen, argon and helium, or a reactive gas such as oxygen. The main role of the assist gas is to aid in the ejection of the molten metal from the cut zone. The pressure of the assist gas has an influence on the dross and striation formation on the cut surface. Stainless steel and Ni-based alloys are commonly cut with nitrogen as assist gas, whereas for titanium alloy argon is the choice. The other function of the inert gas is to provide cooling of the cut edge and help reduce the HAZ. Oxygen is generally used for cutting mild steel if the cut quality is not important. When using oxygen as an assist gas, this reacts with the constituents of the steel resulting in release of energy that adds to the energy provided by the laser beam. The process results in an oxide layer that may need removal. Chekic (2015) conducted an investigation of the cut quality of two high alloy steel using oxygen and nitrogen as assist. He concluded that when higher productivity is required, oxygen assist gas is suggested but for better cut quality the nitrogen assist gas is recommended. Focal point and diameter are in fact the minimum diameter beam spot where the laser beam is focused after being passed through a focusing lens. This focal point has the highest power density and can be positioned above the surface of the material to be cut, on the surface, or below it somewhere along the thickness of the material. The focal length is the distance between the focusing lens and the focal spot with minimum diameter. Longer focal lengths are required for cutting thick sections, while for thin sections a lens with shorter focal length is suggested (Eltawahni 2016).
Laser beam diameter along with laser power and cutting speed has been investigated by Miraoui (2016). He reports that the laser beam diameter is the input parameter with the least influence on the HAZ. However, it shows to have the most influence, together with laser power, on the melting zone (MZ). The depth of the melting zone increases with the laser beam diameter. The nozzle has the role to guide the assist gas in a coaxial fashion with the laser beam, and their good alignment plays a role in the cut quality. When misaligned, the gas may flow on the surface of the workpiece, creating undesirable burning or spatter of the molten metal resulting in a poor-quality cut. The stand-off distance is the distance between the nozzle and the top surface of workpiece and is usually between 0.5 to 1.5 mm to minimize turbulence (Eltawahni 2016). There are few standard nozzles designs used in industry like parallel, conical, convergent, convergent-divergent nozzle, etc. Marimuthu (2017) designed supersonic laser cutting nozzle assembly that can deliver oxygen at high velocity and mass flow rate. The evaluation of the developed nozzle revealed good gas flow characteristics inside and outside the nozzle, uniformity in pressure and no shock waves. The nozzle was used to successfully cut 50 mm carbon steel, with 1kW CO_2 laser. That is an effective way to cut thick steel using a low-power laser source.

2.4 Laser cutting process performance

The performance of laser cutting process is determined by the cut quality features. These features, as presented in Figure 3, and are specific to the geometry and surface of the cut, mechanical and metallurgical characteristics of the cut. In the current research, the process performance have been mostly evaluated in terms of average surface roughness Ra and HAZ, kerf width and kerf tapper. Occasionally, the microhardness of the cut was also considered (Chekic, 2015; Miraoui, 2016). Li (2018) investigated striation formation and developed a strategy to suppress striations based on the power modulation. Striation free cutting surface was theoretically predicted by the model using laser power exponential temporal distribution. However, in practice, the power modulation on actual laser cutting machine is difficult to be achieved. Experimental work of Patel (2016) on SS304, showed that the material removal rate is maximum when using maximum laser power, cutting speed and gas pressure. The HAZ increases with increase in power and gas pressure levels, and decreases when cutting speed is increased. Pocorni (2015) employed a high speed camera to observe the melt flow on the cut front when cutting stainless steel with a fiber laser and nitrogen assist gas. From the HIS (high speed imaging) observations, he concluded that the cut front presents bumps covered in a thin layer of liquid that are moving down, the bumps were at an average speed of approximately 0.4 m/s and the liquid flow at an average speed of approximately 1.1 m/s.

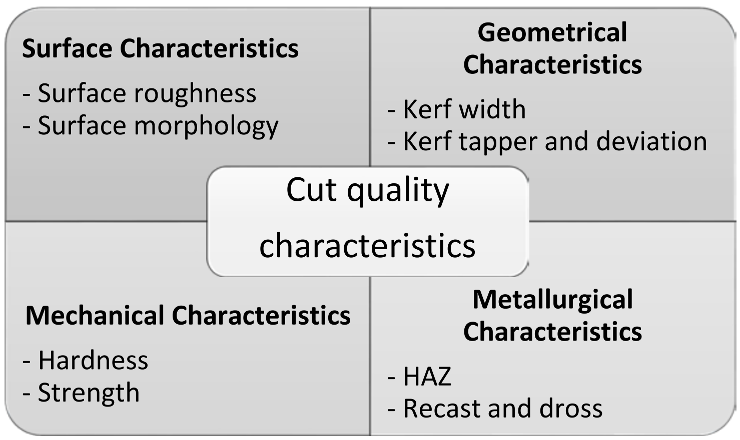

Figure 3. Cut quality characteristics in laser cutting

Miraoui (2016) measured and analyzed the depth of the melt zone (MZ), HAZ and the microhardness beneath the cut surface when cutting low carbon steel plates using high-power CO_2 laser machine. The most significant parameters affecting MZ are laser power and laser beam diameter, while the least significant is the cutting speed. HAZ is affected mostly by laser power and cutting speed and least affected by laser beam diameter. The microhardness is found to increase with the increase in laser power and decrease when cutting speed and laser beam diameter increases. He concludes that the undesirable thermal effects may be reduced by increased cutting speed and decreased laser power and beam diameter. Librera (2014) performed a 3D topography of the cut edge for two types of laser cutting machines, the CO_2 and fiber. For the areal surface roughness measurements he used separate cut-off lengths for the cutting and thickness direction and he found this to be more appropriate representation of the quality of the cut than Ra and Rz. His work presented a possible protocol for analyzing the cut kerf, and visually representing it. The robustness of the method needs to be validated with replication of the cuts, different materials and thicknesses.

3. Modeling and optimization of the laser cutting process

The real physical process in laser cutting is characterized by a large number of parameters and selecting optimum process parameters is crucial for the quality of the product, the productivity and manufacturing costs and research is continuously seeking to optimize the process for improvement of the quality and efficiency characteristics.
The approaches used to determine the optimal laser cutting process conditions for a given applications have been identified by Madic (2017) as: trial and error method, Taguchi method, continual optimization and discreet optimization. The trial and error approach it is based on the experience gained by working with the process and, although is a common approach in the industry due to its simplicity, the possibility of finding the optimal parameter settings is minimal, hence the machine is not used optimally.

Taguchi method is a very popular as this method does not require development of a mathematical model and delivers a near optimal process conditions. It is powerful and simple to implement however does not allow for multiple objective optimization. Continual optimization is the approach where an empirical model is developed, in order to create objective functions that relates the input and output parameters and further optimize the process by using an optimization method. The integration of empirical models and optimization methods results in a continuous single or multi-optimization of laser cutting conditions. The method, although providing the best solution, is time consuming and computationally expensive and its application requires high level of knowledge.

Multi criteria decision making (MCDM) is another method of determining the laser cutting process conditions that uses the performance characteristics as the criteria on which the particular pre-known cutting conditions, or alternatives, are assessed. Design of experiments known as DOE is the name given to several techniques used to guide the choice of the experiments to be performed in an efficient way. Any DOE approach must incorporate the three features namely replication, randomization and blocking as to satisfy the basic principles of statistical methods. Some DOE techniques are: full factorial, fractional factorial, Taguchi, RSM (Response Surface Methodology) with two approaches, CCD (Central Composite Design) and BBD (Box-Behnken Design), etc.

In laser cutting, Taguchi orthogonal array was the most employed DOE (Madic 2014, 2015, 2017; Miraoui 2016; Panu 2014; Gadallah 2015), followed by full factorial design (Nassar 2016; Patel 2016; Leonea 2015). Parthiban (2015) used RSM's Box-Behnken design of experiments techniques to develop linear, 2FI and quadratic models that have been compared with the experimental data. Cekic (2015) used a multiple linear regression analysis to derive sufficient and reliable mathematical equations that defines the effects of relevant process parameters on the cut quality. The mathematical model proved to be consistent with experimental data and can be applied to a group of related steels. Table 1 presents the summary of the past literature on laser cutting of various materials and process parameter optimization by various techniques to get the desirable quality.

In terms of modeling and optimization techniques, Madic (2014) used a hidden single layer ANN (Artificial Neural Networks) trained with Levenberg-Marquardt algorithm to relate machining parameters with cut quality characteristics such as surface roughness, kerf width and HAZ, and material removal rate, and to optimize them. He plotted each performance characteristics operating diagram and trade-off diagrams for improving multiple performance characteristics at the same time. These diagrams can offer multiple solutions that can provide the selection of required laser cutting conditions for the desired cutting performance. The approach was found practical and effective to be used in prediction of the performance characteristics and can be extended to other machining processes. Madic (2015) in addition to ANN modeling, used Monte Carlo method to optimize the laser cutting parameter settings for minimum kerf tapper angle. ANN model could predict the kerf taper with good accuracy. The application of Monte Carlo method resulted in the prediction of optimal settings of laser cutting parameters for minimum kerf tapper angle Another approach used by Madic (2017) was the Preference Index Method for modelling and optimization of laser beam cutting The method is part of MCDM methods, and ranks the alternatives based on linear and quadratic transformations of data contained in the decision matrix. The advantage of the method is that it enables calculations of lower and upper preference selection index values. Although simple and useful in manufacturing field, the method may result in large number of alternative solutions with attribute performances very closed to the preferred ones.

Table 1 Summary of pat literature on use of various modelling and optimization techniques in laser cutting

Sl. No	Researcher (Year)	Material (thickness)	Performance characteristics	Modeling and optimization technique	Findings/outcomes
1	Madic, 2014	AISI 304 3mm	Surface roughness Kerf width HAZ MRR	ANN using the Levenberg-Marquardt algorithm	Developed ANN models can predict the laser cut quality characteristics within the entire experimental space for a given set of input laser cutting parameters. Operating diagrams for each performance characteristic were plotted. From these plots, the optimal laser cutting conditions for each performance characteristics can be easily identified, hence very practical for

					prediction of performance characteristics
2	Cekic, 2015	High-alloyed steel 1.4864 3mm 1.4541 4 mm	Surface roughness HAZ	Multiple linear regression analysis	
3	Madic, 2015	AISI 304 3mm	Kerf taper angle	ANN modelling with Monte Carlo method for optimization	ANN model can predict the kerf taper with good accuracy. The application of Monte Carlo method resulted in the prediction of optimal settings of laser cutting parameters for minimum kerf tapper angle. The combined ANN-Monte Carlo approach is found to be very simple, easy to implement and efficient tool for the optimization of CO2 laser cutting process.
4	Varkey, 2014	Ti6Al4V 2 mm	Surface roughness Kerf tapper	Regression analysis model and multiobjective optimization with customized GA	By the application of the hybrid approach of DoE and GA a set of optimal solutions have been found.
5	Klancnik, 2015	Tungsten alloy 1 mm	Surface roughness Kerf tapper	BP-ANN	The model resulted in smaller prediction error for kerf width than for surface roughness but overall BP-ANN was found suitable for prediction of performance characteristics. When cutting rare or even unknown materials, this provides the means to obtain the input parameters which will result in adequate quality.
6	Chaudhary	Aluminium alloy	Surface roughness Kerf width HAZ	Taguchi-Fuzzy logic model	The computer program, CATFMO (Computer Aided Taguchi-Fuzzy Multi-Optimization) developed for simultaneous optimization of laser cut quality characteristics was found capable to predict optimum values of input parameters in difficult to cut aluminium alloy based on experimental data extracted from literature. It was recommended that advanced fuzzy sets (type -2 fuzzy sets) to be used in future for modeling and optimization.
7	Parthiban, 2015	AA6061-T6 aluminium alloy 2 mm	Surface roughness	Box-Behneken RSM	Three empirical models were developed, a linear, 2FI (two factorial) and quadratic, and compared with experimental data. The linear model had the smallest deviation from experimental data and satisfied all required statistical tests. The proposed methodology may be used to predict other performance characteristics for laser cutting

					process or for any other non-traditional machining process.
8	Sharma, 2015	Ni-based superalloy	Kerf deviation Kerf tapper	GRA (Grey relational analysis) coupled with EM (Entropy measurement)	The hybrid approach of GRA coupled with EM modeling was used to obtain the preferred operating parameters during NdYAG laser cutting. The application of this approach showed a reduction in kerf deviation as compared with values obtained from Taguchi L27 OA.
9	Gadallah, 2015	SS 316L 3 mm	Kerf tapper Surface roughness HAZ	Taguchi RSM	The kerf taper and surface roughness both were optimized simultaneously for cutting of SS 304L with NdYAG laser. The models developed are giving good predictions for kerf width, surface roughness and HAZ, as confirmed by further ten verification experiments.

Varkey (2014) performed modelling and optimization using regression analysis and genetic algorithm for kerf taper and surface roughness. The multi-objective optimization resulted in a set of optimal solutions. The required solution may be selected based on the production objectives. Klancnik (2014) developed back-propagation artificial neural network (BP- ANN) model for the analysis and prediction of surface roughness and kerf width cut quality and compared the predicted results with the experimental data. The prediction error of kerf width was found to be less than the prediction error of surface roughness, however the prediction of both process characteristics with BP-ANN model was found suitable. The developed method is especially useful for rare or unknown materials, where the prediction of cut quality based on the input process parameter can be made, before actual machining, to find the parameters that will result in sufficient quality. Chaudhary (2014) developed software CATFMO (Computer Aided Taguchi-Fuzzi Multi-Optimization) for simultaneous optimization of multiple quality characteristics in laser cutting process. The software has been used for multi-performance optimization where kerf width, surface roughness and HAZ for difficult to cut aluminium alloy were the responses. The proposed approach achieved the prediction of optimum values of the input parameters for simultaneous optimization of all the cut quality characteristics for cutting of aluminium alloy. Parthiban (2014) considered a Box-Behnken DoE and used RSM to generate three predictive models: a linear model, a two factorial model and a quadratic model. When compared with the experimental data, the linear model presented the smallest deviation and satisfied the required statistical tests, therefore recommended for prediction of surface roughness in laser cutting process. The methodology may be extended to other laser cutting process characteristics or to other non-traditional processes such as Water jet machining, Electrical discharge machining and Electro-chemical machining. Sharma (2015) obtained preferred laser cutting parameters by using GRA (Gray Relational Analysis) coupled with EM (Entropy Measurement) method. The EM was employed to compute the weights corresponding to each quality characteristic for finding the grey relational grade. The result was a reduction in kerf deviation by 30% from that obtained with Taguchi L27 OA.

4. Summary

The paper presents the basic functioning of laser machine, the two main laser systems used in sheet laser cutting and the process parameters involved in laser cutting. In studying the process, majority of the research used for modelling process parameters such as laser power, cutting speed, gas pressure, and focal position. Regarding the workpiece parameters, few papers explored different thicknesses of the same material or different types of material. Some research gave consideration to beam characteristics like beam polarization, diameter, pulse width and frequency. Apart from the usual output parameters regarding the cut quality such as surface roughness, HAZ, kerf width and tapper, other mechanical and metallurgical cut qualities such as the microhardness, the melt zone and melt flow have been observed. The literature reviewed and presented in this paper show that efforts to better model and optimize the laser beam cutting process are continuing. Although various theoretical and experimental models were used to describe the performance of laser cutting process, Taguchi method remains the preferred DoE method. The application in soft

computing techniques such as GRA, Fuzzy logic, and ANN etc. have also been investigated with some interesting hybrid approaches.
As the interaction of the process parameters and their influence on the cut quality have been extensively studied for mild and stainless steel there is much scope in the further study of Ti and Al alloys. As the thickness of the material in the examined research was between 1 and 10 mm, greater thicknesses still needs investigation. For the validation of the process optimization with hybrid techniques, further research is recommended.

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