A Review on Laser Beam Cutting

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Abstract
Laser beam cutting is one of the important advanced machining processes. It is gaining importance over conventional machining methods due to its superior characteristics. However, significant future attempts are still required to overcome the challenges as regards to use laser beam cutting in different environment and for various materials. This paper provides a review on laser beam cutting where introduction, salient features, and past work are discussed. It starts with an introduction to the process where laser system and its components, working principle and mechanism, and important process parameters are discussed. Review of past work under various categories on laser beam cutting is followed. Paper ends with summary and important future research directions to establish the field further.

Keywords
Laser beam cutting, Modelling, Optimization, Surface quality, Micro-part

1. Introduction
LASER is basically the abbreviation of Light Amplification by Simulated Emission of Radiation. In other words, laser is a monochromatic, coherent and cohesive electromagnetic radiation beam with wavelengths ranging from ultraviolet to infrared. The use of a laser beam for cutting, trimming and drilling holes has been around for more than five decades and since then has evolved into an extensively used method of material removal with cost effective solutions for manufacturing processes.
The history of laser started in 1960 at Hughes Research Laboratories when T.H. Maiman successfully achieved simulated optical emission, followed by the development of first CO_2 laser in 1963 by Kumar Pateland by 1967 pressurized oxygen passing through a nozzle was used as an assist gas to cut through a 1 mm sheet of steel (Hilton 2007). Since then, laser cutting systems have been diversified and perfected to provide a reliable technology extensively used in industry for cutting of metals efficiently, with great precision and high cut quality.
Laser beam cutting (LBC) is the prevalent application of laser machining processes from macro to micro-machining scale. The process mechanism is based on the use of the intense energy laser beam localized on a small spot on the surface of the material to be cut (Hilton 2007; Wandera 2010). The material absorbs and converts the energy into heat that melts or vaporizes the material while an assist gas, released through a nozzle coaxially with the laser beam, removes the molten metal from the cut zone.

1.1 Laser system and components
The laser beam in any laser system is generated using the three main parts: a pump source, a gain medium and a resonant system as seen in Figure 1. 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. A mirror is placed at each end of the cavity, one being partially reflective and the other, totally reflective mirror. These mirrors form the optical resonator of the laser system. The resulting amplified light is delivered via reflective optics (mirrors) or optic fibers

to the cutting head. This is a complex device that delivers the laser output beam and incorporates the focusing lens, the tracking system and the nozzle together with assist gas delivery system. The movement of the laser beam along the path of the geometry to be cut is achieved by CAD/CNC controls of the cutting head and/or the machine working table. Auxiliary equipment of a complete laser cutting system consists of power supply, cooling system, control system and assist gas delivery system.

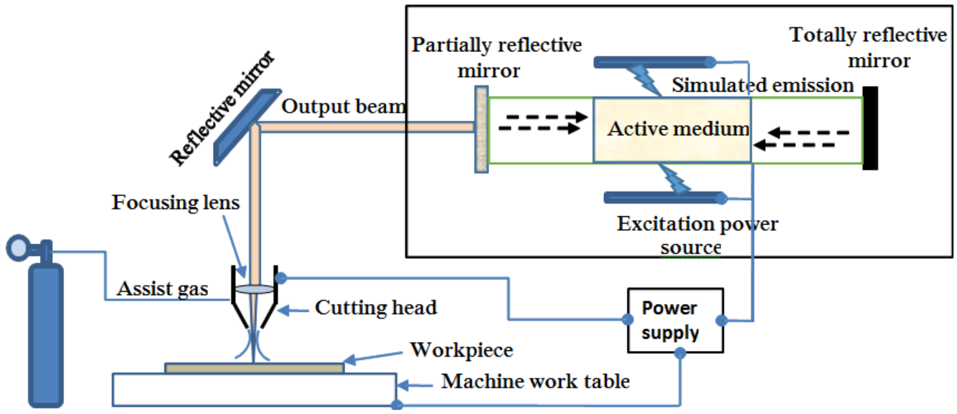

Figure 1. Schematic of laser system

Amongst the commercial lasers available in the market used in metal processing, the Nd:Yag wavelength of 1064 nm belongs to near infrared electromagnetic spectrum, while the CO_2 laser with 10600 nm wavelength is a far infrared radiation. For that, the Nd:Yag laser are suitable for highly reflective metals such as silver and their laser light can be focused to a smaller spot size than CO_2 laser and may be delivered through optical fibers.

1.2 Laser system types

The laser systems can be continuous wave, mostly used for macro-machining with powers outputs up to several kW or pulsed beam systems where the power is delivered as a short burst of high energy for a very brief period of time. Their average power is below one kW and these systems are mainly used for micro-machining.

Lasers can be solid state and fiber lasers, gas lasers, excimer lasers or dye lasers based on the gain medium that can be solid, liquid or gaseous. In the solid state lasers, the lasing material is a solid crystal such as ruby or Nd:Yag (Neodymium doped yttrium aluminium garnet) or an optic fibre (Yb:Yag) while in gas lasers, the gain medium consists of a mixture of gases such as carbon dioxide, nitrogen, hydrogen and helium.

For industrial applications there are two main types of lasers used, namely the CO_2 lasers and the Nd:Yag lasers. The CO_2 laser is a continuous wave system, electrically pumped that radiates at 10.6 µm wavelength. The system has good beam quality and high output power that makes it suitable for thick section metal cutting.

The Nd:Yag is a diode pumped system that can work in continuous wave or pulsed mode and radiates at 1.06 µm wavelength. This system, by comparison has a lower overall efficiency and beam quality (Wandera 2010). Nd:Yag laser is preferred when thin section and highly reflective material such as copper or silver alloy is to be processed. The comparison between the two systems under discussion is presented in Table1.

1.3 Methods of laser cutting

The laser cutting mechanism depends on the type of material to be cut, its thickness and the required cut quality. These methods are vaporization, fusion, reactive fusion and controlled fracture cutting.

In laser vaporization cutting the high power and energy density applied in a very short time brings the temperature of the workpiece to the boiling temperature point causing the material to change phase to vapour. The assist gas, nitrogen, argon or helium, is delivered at low pressures of 1 to 3 bar and serves only to shield the cut. It is mainly applicable to non-melting materials and is also called sublimation cutting.

Table 1. Comparison between CO_2 and Nd:Yag laser system

	CO_2 Laser	**Nd:Yag Laser**
Pumping method	Electrically pumped	High power light diode
Gain medium	Mixture of gases: CO_2, N_2, He and H_2	Solid crystal
Beam delivery	Via mirrors usually in continuous wave (CW) mode	Via mirrors or via optic fiber, in CW or pulsed mode
Wavelength	Longer, not suitable for highly reflective materials;	Shorter, capable to process copper, brass, silver
Applications in metal processing	Drilling, cutting, welding, on steel, stainless steel, aluminium,	Etching and marking metals Steel heat treatment Cutting and welding thin steel sheet,

In fusion cutting, the power supplied is enough to melt the material and a reaction inhibiting gas, such as nitrogen or argon, is used as the assist gas. The gas is blown in the cut zone at pressures between 2 and 20 bar (Pavlica et al. 2015) and has the role to cool the material, to expel the molten metal and to prevent the cut edges from oxidation. Figure 1.11 depicts the process of fusion laser cutting mainly applicable to metallic materials.

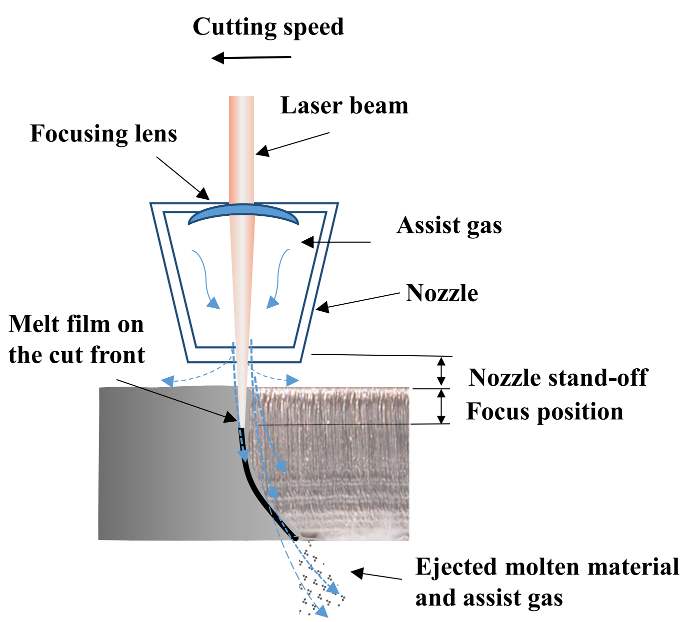

Figure 2. Schematic representation of laser beam fusion cutting

The reactive fusion is similar to the fusion laser cutting process except that the assist gas used is oxygen. The gas is blown into the cutting zone at pressures up to 6 bar (Orishich et al. 2016) and will react chemically with the constituents of the material being cut. The reaction will result in release of energy that will contribute to the input energy provided by the laser beam, considerably increasing the total energy available at the cut zone. Also, the reaction will result in an oxide layer on the cutting edge that influences the cut quality. This method is mostly used in high speed cutting of thick metal sheet.

1.4 Laser beam cutting process 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. The system parameters are inherent to the particular laser system used while all other parameters may be changed to meet desired outputs.

The workpiece parameters refer to the material type and thickness to be cut. Materials 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, which are increasingly used in the aircraft industry, are also fairly good processed by both laser systems. However, materials that are highly reflective like copper and its alloys, gold and silver, are difficult to cut. 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 laser power is required.

Alloy carbon steel of 40-50 mm thickness may be cut with CO_2 laser and oxygen as the assist gas, with a good cut quality (Orishich et al. 2016), while the same system was used to successfully cut steel and stainless steel up to a thickness of 300 mm (Tamura et al. 2016).

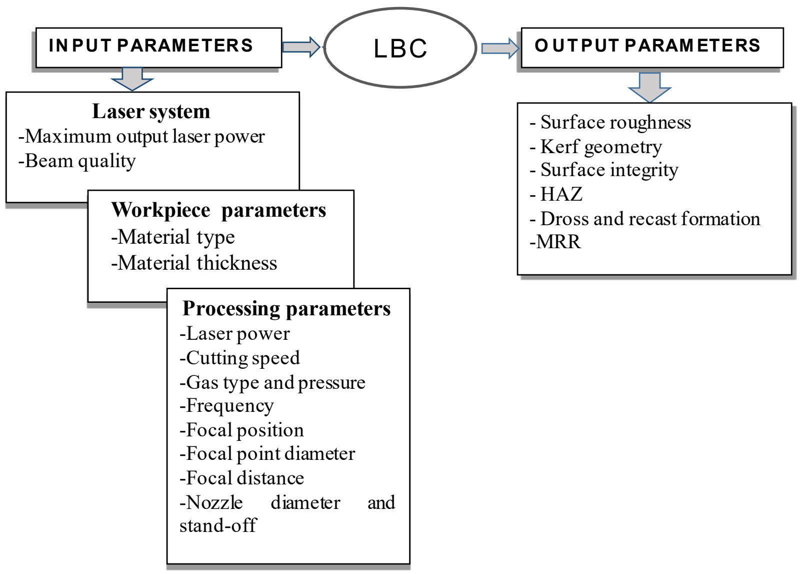

Figure 3. Laser beam cutting process parameters

Laser power also known as the heat input, is dependent of the type of material to be cut and its thickness, and the desired cutting rate. Materials like stainless steel and aluminium will 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.

Cutting speed is the rate at which the laser beam travels on the path to be cut. Laser cutting is the 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. The cutting speed influences the width of HAZ, the formation of dross and burnt material at the bottom of the cut and the surface quality.

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, an oxide layer will be formed on the cut surface that may need removal. For better cut quality, nitrogen assist gas is recommended while for higher productivity oxygen assist gas is suggested (Klacnik et al. 2015).

Focal point diameter refers to the minimum diameter of the 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. This parameter has an influence on the melting zone (MZ) as a higher diameter will result in increased depth of the melting zone.

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 et al. 2016).

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 distance between the nozzle and the top surface of workpiece to be cut is called the stand-off distance and ranges between 0.5 and 1.5 mm to minimize turbulence during cutting (Eltawahni et al. 2016).There are few standard nozzles designs used in industry like parallel, conical, convergent, convergent-divergent nozzle, etc. The nozzle diameter should be selected function of the type and thickness of the material and must deliver a good gas flow with uniformity in pressure and no shock waves that may adversely influence the cut quality.

The process performance is measured by output parameters (i.e. cut surface quality in terms of surface roughness and integrity, kerf geometry, and material removal rate MRR) as presented in Figure 3. MRR is an indicator of the process productivity. Surface quality can be measured in terms of surface roughness and geometrical errors (Gupta and Jain 2013) Geometric error in laser is kerf. Heat affected zone is yet another output indicator in laser cutting type thermal process (Anghel et al.2018). Laser machining offers significant productivity advantage over other advanced manufacturing methods owing to its high cutting speed rates, however due to the dynamic nature of the process parameters interaction, the process productivity has to be carefully tuned with the desired cut quality.

1.5 Advantages and limitations of laser beam cutting

Following are the significant advantages of laser beam cutting process (Eltawahni et al. 2016; Gupta and Jain 2013; Anghel et al.2018):

- As LBC is a non-contact process that does not require tools, therefore there is no tool wear or tool change to consider nor any tooling associated costs.
- The process is fast and flexible, fully CNC controlled with no requirements for special clamping or jigging therefore easy to switch from one cutting job to another.
- The system is stable, reliable and very accurate; intricate profiles can be cut with cutting precision of about +/_0.05 mm.
- Same system may be used to cut a variety of materials.
- Minimum material waste as the cut width (kerf) is extremely narrow.
- Suitable for mass production with high efficiency and accuracy when product replicas are required.
- Each system used for laser beam cutting has its own advantages. The CO_2 lasers works better with thicker materials, has high efficiency, and provides good edge quality with very small HAZ.
- The Nd:Yag system is great with thinner sections, and can cut highly reflective materials, such as aluminium, copper, and brass etc.
- Laser cutting process is computer program controlled hence less human intervention except for observation and maintenance which reduces the risk of accidents and injuries.
- Low running costs.
- Short set-up time as each job is planned initially in a CAD environment with minimum material wastage and easily exported to the machine computer interface.
- It requires lower power consumption than other cutting processes.

The limitations of laser beam cutting are as follows:

- Not all metals can be cut by laser beam as the reflectivity of the material creates beam reflections issues that affect the optical lens system that focuses the laser beam.
- Parts processed with the high intensity laser beam are exposed to heat that will result in a narrow heat affected zone along the cut edge.
- Improper settings of the machine can cause burns on the material.
- High initial capital cost.

- The thickness of sheet metal to be cut is limited by the laser power of the machine and the cut quality required.
- Safety procedures must be followed strictly.

1.6 Applications of laser beam cutting

Laser beam cutting process has experienced a growing popularity in the automotive industry. In general, lasers are used to process complete vehicle bodies with all the versatility offered by cutting, drilling marking and welding with laser beam. There are a wide range of uses of laser cutting process of components and functional parts, mainly sheet-metal parts required for BIW (body in white) or bumpers, crossbeams and supports, for car interior such as dashboards and consoles, etc. The process is used to cut a wide variety of materials and this are just few examples of the many uses of the process in car manufacturing industry.
The aerospace industry, just like the automotive industry, have found the process to be crucial for cutting of components in various shapes and sizes mainly from high strength aluminium and titanium alloys with high precession, perfect finish and low heat affected zone.
Electronic industry uses this technology to cut small and intricate parts with great accuracy in a variety of materials often with multiple layers. The process is used to cut the plastic and metal component that encases mobile phones, cutting of USB cards, printed circuit boards and microprocessors.
As the process main advantage is to produce clean and highly accurate cuts with smooth finish, this render the process as ideal for fabrication of much smaller products, components and devices. From cutting silicon wafers to creating micro channels for biomedical devices and micro-fluidic applications, stents for coronary arteries etc., laser beam machining proved once more its capabilities and versatility. Laser micromachining processes are micro-drilling, micro-cutting, micro-grooving, micro-milling and micro-turning resulting in very small surface or 3D structures with dimensions ranging in the micron domain. For that, lasers with very short pulse duration of nano, pico even femtosecond are used to minimize thermal effects.

2. Review of Past Work

The review will present research on various other aspects of laser beam machining process. As the research started few decades ago, there is an abundance of reference from which the most relevant and/or recent will be mentioned.
Past research of laser beam cutting was done on various materials from mild and stainless steel to Ti and Ni alloys with thicknesses usually ranging from 1 to 10 mm. Both the type of material and the thickness to be cut are regarded as workpiece parameters.

2.1 Laser beam cutting of engineering materials

Orishich et al. (2016) conducted an experimental investigation to find the utmost thickness of mild steel workpiece that can be cut with a 2 kW Ytterbium fiber laser and an 8 kW CO_2 laser using oxygen as assist gas, with acceptable quality. They establish a criterion for the determination of the maximum thickness of the cut sheet and demonstrated that, for the CO2laser, an utmost thickness of 40-50 mm can be achieved. For the fiber laser system, the criterion could not be applied as the mode of uncontrolled metal burning at low speeds was absent.
Laser cutting process on 1 mm thick 6061-T6 aluminium alloy was explored by Leonea et al. (2015) who used a low power Nd:Yag multimode system that created an elliptical beam footprint. Their investigation showed that the cutting speed is affected by the pulse duration and beam travel direction. An increase cutting speed may be obtained with longer pulse duration and with the focal spot moving along the minor elliptical axis. An almost perpendicular kerf ($<4^0$) is obtained at long pulse duration with a dross height lower than 40 µm.
Parthiban et al. (2015) used CO_2 laser system with nitrogen as assist gas to cut 2 mm thick aluminium alloy AA6061-T6. They varied laser power, cutting speed, focal position and gas pressure on three levels and developed empirical models to predict the surface roughness. The predicted and experimental surface roughness values were 1.6611 µm and 1.6648 µm respectively.
Solanki and Madia (2016) used 1 kW fiber laser machine to cut 2 mm thick super duplex stainless steel and 1.6 mm titanium alloy to investigate process parameters on surface roughness and kerf width. They varied laser power, cutting speed and gas pressure on three levels and concluded that laser power is the most significant factor for the selected performance characteristics and the minimum surface roughness obtained was 1.1 µm for stainless steel and 1.9 µm for titanium alloy respectively.
Varkey et al. (2014) investigated laser beam cutting of Titanium alloy using 5 Kw CO_2 laser. Laser power, cutting speed, gas pressure and focal point position were varied on three levels in order to determine the interaction between all control factors on the responses. They found the cutting speed and laser power as most significant control factors

for the surface roughness while laser power and assist gas pressure were the significant factors for kerf taper. In their 50 possible optimum solutions the minimum value for surface roughness was 8.9517µm and for kerf taper of 1.8903^0.

Begic-Hajdarevic et al. (2017) varied laser power and cutting speed parameters when cutting 1 mm thick tungsten alloy with CO_2 laser machine. They used control charts to determine the influence of the selected process parameters on the cut surface roughness. From developed charts they found that at lower laser power the increase of cutting speed will deteriorate the process control status. A uniform surface roughness can be obtained at 1500 mm/min or 2000mm/min at 2 kW laser power.

Klancnik et al.(2015) used a CO_2 laser system to cut 1 mm thick tungsten alloy with laser power, cutting speed and assist gas type as input process parameters, aiming to predict cut quality in terms of kerf width and surface roughness. They developed adequate models for prediction of the selected laser cut process performances and concluded that the type of the assist gas affects significantly the quality of the cut, especially the kerf width.

The recent reported studies of the laser cutting process on steel and its variants are presented in detail in the following section.

2.2 Influence of laser beam cutting process parameters

The complexity of laser beam cutting process is mainly due to its large number of process parameters and their dynamic interaction. The important process parameters are laser power, beam frequency, feed rate or cutting speed, focal distance and focal point position, gas type and gas pressure, nozzle stand-off and nozzle diameter. Most researchers varied from two to four of these parameters to study their effect on the cut quality characteristic such as surface roughness, kerf width and kerf taper, HAZ width and occasionally the striations, dross formation or material removal rate.

CO_2 laser cutting machine with nitrogen as assist gas was used by Madic et al. (2014) to cut AISI 304 stainless steel. They used Taguchi L27 to analyze the effects of laser power, cutting speed, assist gas pressure and focus position were on MRR and surface quality. The results showed a minimal surface roughness of 1.254 µm is achieved but all other characteristics have less than optimal values. Similarly, for a minimal kerf width of 0.323 mm the surface roughness is 2.188 µm, or for a minimal HAZ width of 12.29 µm the surface roughness is 2.19 µm. Therefore, they have plotted operating diagrams for each performance characteristic in order to easily identify optimal and trade-off setting for multiple performance characteristics at the same time. Further reported studies of Madic et al. (2014) with same experimental setup, aimed at the investigation and optimization of process parameters for a minimal kerf taper. They found that a combination of low laser power (1.6 kW) and assist gas pressure with high cutting speed (3 m/min) and focal point at about 2/3 of the material thickness will result in an acceptable kerf taper angle.

Miraoui et al. (2014) examined significant variation in HAZ with laser beam diameter (1-2 mm) and laser power (3-5 kW). In Miraoui et al. (2016) further research where the cutting speed was also varied between 600 and 2200 mm/min, the measured responses were HAZ depth, MZ (melting zone) depth and HAZ microhardness. The analysis showed same effects for the HAZ depth as before. The MZ was least affected by the cutting speed and its depth increases with laser power and laser beam. The microhardness in HAZ decreases with increase in laser beam diameter and cutting speed.

Cekic and Begic-Hajdarevic (2015) studied the laser cutting process of high alloy steel with 3 mm thickness when varying cutting speed, assist gas pressure, focus position and nozzle stand- off. They used a 2kW CO2 laser system with oxygen as the assist gas. The process quality was measured in terms of width of cut, HAZ, and average roughness. Based on the experimental data and mathematical models they have achieved a minimum width of cut, HAZ and average roughness at the following input parameter combination: 2 kW power, - 1 mm focal position, 12.5 bar assist gas pressure, 1mm stand-off nozzle distance and 4625 mm/min cutting speed. For smaller values of roughness, a higher cutting speed with the focal position above the workpiece surface is recommended.

Gadallah and Abdu (2015) derived process performance models from experiments conducted on Nd:Yag laser beam machining of 3mm thick stainless steel (316L) sheet. The performance characteristics under their study were kerf taper, surface roughness and HAZ as affected by the following input process parameters: power, assist gas pressure, cutting speed and pulse frequency. In their investigation, kerf quality and surface characteristics were significantly affected by laser power and gas pressure. Low level of process parameters used in the study, except cutting speed, will result in lower value of surface roughness.

Jarosz et al. (2016) investigated the effect of cutting speed on the surface roughness and HAZ when cutting 10 mm thick AISI 316L stainless steel with high power CO_2 laser machine and nitrogen as assist gas. They found a visible effect of the cutting speed on width of HAZ, surface roughness and presence of dross. Out of the three levels of cutting speed used only the two highest are practically applicable. For a cutting speed of16.5 mm/s a good surface roughness and negligible HAZ was obtained while, for a cutting speed of 9.17 mm/s a lower surface roughness but visible HAZ was obtained. A higher or lower cutting speed will then be selected function of the end user requirements regarding surface quality.

Prajapati et al. (2013) conducted experimental research on two materials: mild steel and Hardox-400 of 6, 8 and 10 mm thickness. They used a CO2laser with oxygen assist gas and varied laser power, gas pressure and cutting speed on three levels. When evaluating the surface roughness, cutting speed and material thickness were found most influential. Gas pressure was found to be more influential for mild steel than hardox.

Senthilkumar et al. (2016) varied four laser machine parameters when cutting 3 mm thick mild steel plate with CO_2 laser cutting system and CO_2 as the assist gas. They used Taguchi L16 orthogonal array and varied laser power, cutting speed, gas pressure and nozzle stand-off on four levels in order to establish their influence on surface roughness, machining time and kerf width. They found little variation of the surface roughness with gas pressure and nozzle stand-off distance and a reduction in surface roughness when laser power and cutting speed are increased. The values of roughness for their experimental setup ranged from 0.59 to 2.58 µm. A decrease in power and cutting speed while maintaining a medium gas pressure will result in a minimized value of machining time. The nozzle stand-off distance does not have a significant effect on the machining time. The kerf width can be minimized by using the maximum values of power and cutting speed and laser power; however the variation of gas pressure and nozzle stand-off distance marginally affect the kerf width. Their experimental values of machining time were between 3.967 and 5.922 sec and values of kerf width between 0.62 and 2.16 mm.

Tahir and Rashid (2016) selected 22MnB5, an ultra-high strength steel (UHSS) with 1.7 mm thickness to be cut with a CO_2 laser system and oxygen assist gas. Laser power, cutting speed and assist gas pressure was varied on three levels to determine their influence on cutting quality defined by the top and bottom kerf width and HAZ. In the kerf width formation, they have identified laser power and cutting speed as the influential parameters with a positive relationship for power and negative correlation for cutting speed. Laser power is the input parameter affecting HAZ while, cutting speed and gas pressure have no significant influence on the HAZ formation. A greater HAZ region was obtained as greater laser power was selected.

Librera et al. (2015) investigated SS part quality when cutting by CO_2 and fiber laser systems. Their assessment was based on the use of areal roughness parameters for fixed cutting conditions on AISI 304 with 6mm and 10 mm thickness. The samples cut with both laser systems revealed a similar cut edge, in general smooth and homogenous, for the 6 mm thick samples. However, for 10 mm thick the edge of the sample cut with CO_2 laser was found less homogenous and a coarse central part, while the fiber laser samples were also less homogenous with much rough surface. They have found it more appropriate to use separate cut-off lengths on the cutting and thickness directions when evaluating the areal surface roughness.

2.3 Past work on modeling and optimization of laser beam cutting process parameters

There are various approaches/methods used for modeling and optimization of a process for the improvement of the quality and efficiency characteristics. Various design of experiments (DOE) techniques such as full factorial and fractional factorial (namely Taguchi and Response Surface Methodology- Box Behnken Design 'BBD' and Central Composite Design 'CCD') etc. have been used by researchers in laser beam machining work. However, Taguchi technique has been the most extensively used by researchers worked on laser beam machining.

Madic et al. (2014) used ANN simple hidden layer trained with Levenberg-Marquardt algorithm and obtained performance characteristics operating diagrams and trade-off diagrams that offers multiple solutions in terms of optimum parameters for the desired cutting performance. They found the approach to be effective and practical for the prediction of performance characteristic of laser cutting process or other machining processes. In a subsequent research, Madic et al. (2014) used ANN modeling successfully combined with Monte-Carlo optimization technique to obtain minimum kerf tapper angle. Later on, Madic et al. (2017) applied PIM (Preference Index Method) with the advantage of being simple and practical for manufacturing processes and with possibility of calculating lower and upper performance selection index values. However, a large number of alternative solutions may be obtained that have attribute performances very closed to the preferred ones.

Klancnik et al. (2015) used back-propagation artificial neural network (BP-ANN) to establish a relationship between process parameters and quality of cut, while Partiban et al.(2015) combined a Box-Behnken DOE with RSM and generated three predictive models. They compared the models with the experimental data to find that the linear one has the smallest variation in predicting the surface roughness. The developed methodology is recommended for quality characteristics prediction in laser machining and even for other advanced machining processes such as AWJM and EDM etc.

Varkey et al. (2014) modeled and performed a multi-optimization of the dimensional and surface deviation using regression analysis and GA (Genetic algorithm) obtaining a set of optimal solutions that offers the possibility of selection based on production objectives.

Sharma and Yadava (2015) used GRA (Grey relational analysis) method to obtain the 30 % reduction in kerf deviation during laser machining.

2.4 Laser beam cutting of micro-parts, shapes and features

LBC has been used to create micro-channels in Inconel 718 superalloy by Alahmari et al. (2016) using under-water laser. Another important application of under-water nanosecond pulse laser is explored by Wuttisarn et al. (2016) for micro-milling of titanium alloy to create micro-features. Yan et al. (2011) successfully fabricated deep cavities in alumina using CO_2 laser. They found much better quality when machining under water rather in air.
LBC can also fabricate quality mechanical components such as gears. Anghel et al. (2020) conducted a detailed investigation on LBC of miniature gears of stainless steel. After optimization of LBC parameters, they obtained precision surface finish i.e. average roughness-0.43 µm and maximum roughness- 2.06 µmon gear teeth flank surfaces. A group of researchers attempted micro-drilling of stainless steel sheets using fibre laser (Iliescu et al.2014) They found power and cutting speed highly influential to the surface quality and heat affected zone. In a recent work, a picosecond laser is used to make hole in silicon wafer (Singh and Samuel, 2019) A systematic analysis and proper optimization of laser parameters are recommended.

3. Summary and Future Research

Laser beam cutting (LBC) is discussed in the paper with a review of the important past work on LBC of different materials, influence of its process parameters, their modelling and optimization, and fabrication of micro-parts, shapes, and features by this process. Ample investigations on LBC of steel material have been found and indicate that laser parameters are highly influential to the part quality and process productivity, and require optimum solutions to obtain better machinability. As regards to the machining of difficult-to-cut materials such as titanium, nickel, and other hard materials, there is a scarcity of work on LBC. Significant future efforts are required to be made to facilitate machining of such materials using LBC. Both statistical and evolutionary techniques have been found effective for modelling and optimization of laser parameters. LBC is also gaining wider acceptance for machining of micro-products.

Some important future research avenues are as follows:

- Since thermal damages and recast layer formation are the major drawbacks of LBC; therefore some prominent solutions are required to be investigated.
- From the point of view of sustainability, some green ways are required to be found to operate the laser system or conduct the process for reducing harmful effects of emitted particulates and gases.
- High power consumption is yet another drawback; therefore, energy efficiency needs to be on utmost priority for research.
- Hybrid manufacturing, where laser is combined with other conventional or advanced machining techniques needs to be explored for novel ways of machining of different materials.
- Optimization of laser cutting parameters to minimize the trade-off between process productivity and product quality needs to be focused more for future research.

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References

Alahmari AM, Ahmed N and Darwish S., Laser beam micro-machining under water immersion. *Int J AdvManufTechnol*; vol. 83 pp. 1671–1681, 2016.

Anghel C., Gupta K., Mashamba A., and Jen T.C., Recent developments in laser cutting of metallic materials. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, IEOM South Africa, pp. 1881-1891, 2018.

Anghel, C., Gupta, K., and Jen, T.C., Analysis and Optimization of Surface Quality of Stainless-Steel Miniature Gears Manufactured by CO2 Laser Cutting. *Optik - International Journal for Light and Electron Optics*, 203, 1640-49, 2020.

Begic-Hajdarevic D., Vucijak B., Pasic M., and Bijelonja I. Analysis of the influence of cutting parameters on surface roughnessin laser cutting process of tungsten alloy using control charts. *Tehničkivjesnik* 24, Suppl. 2, pp. 339-344, 2017.

Cekic, A., and Begic-Hajdarevic, D., Definition of mathematical models of high-alloyed steel 1.4828 in CO2 laser cutting. *Procedia Engineering*, 100, pp. 435-444, 2015.

Eltawahni H.A., Benyounis, K.Y., and Olabi, A.G., High power CO_2 laser cutting for advanced materials – review. *Reference Module in Materials Science and Materials Engineering*, 2016.

Gadallah M.H. and Abdu H.M., *Modeling and optimization of laser cutting operations. Manufacturing review*, 2, no. 20, 2015.

Gupta, K., and Jain N.K., Deviations in Geometry of Miniature Gears Fabricated by Wire Electrical Discharge Machining*", In Proceedings of International Mechanical Engineering Congress & Exposition (IMECE 2013) of ASME*,, V010T11A047, Nov. 13-21, 2013, San Diego, California, USA.

Hilton P.A., The early days of laser cutting*, 11th Nordic Conference in Laser Processing of Materials*, Finland. August 20-22, 2007.

Iliescu, M., Necşoiu, T., and Stanciu, E. M., Study on Process Parameters in Fiber Laser Micro-Cutting Technology. *Applied Mechanics and Materials*, 657, 211–215, 2014.

Jarosk K., Loschner P., Nieslony P., Effect of cutting speed on surface quality and heat-affected zone in cutting of 316L stainless steel. *Procedia Engineering*, vol 149, pp.155-162, 2006.

Klancnik S., Begic–Hajdarevic D., Paulic M., Flick M., Cekic M., and Husic M.C., Prediction of laser cut quality of tungsten alloy using the neural network method. *Journal of Mechanical Engineering*, vol. 61, no.12, pp.714-720, 2015.

Leonea C., Gennab S., Caggianoa A., Tagliaferrid V., and Molitiernoe R., An investigation on Nd: Yag laser cutting of Al 6061 T6 alloy sheet. *Procedia CIRP*, 28, pp. 64 – 69, 2015.

Librera E., Riva G., Safarzadeh H., and Previtalia B., On the use of Areal Roughness Parameters to Assess Surface Quality in Laser Cutting of Stainless Steel with CO_2 and Fiber Sources. *Procedia CIRP*, vol. 33, pp. 532-537, 2015.

Madić M., Radovanović M., Trajanović M and Manić M., Analysis of correlations of multiple-performance characteristics for optimization of CO_2 laser nitrogen cutting of AISI 304 stainless steel*, Journal of Engineering Science and Technology Review, vol.* 7, no. 2, pp. 16 – 21, 2014.

Madića M., Antuchevicieneb J., Radovanovića M., and Petkovića D., Determination of laser cutting process conditions using the preference selection index method. *Optics and Laser Technology*, vol. 89, pp. 214-220, 2017.

Miraoui I., Boujelbene M., and Bayraktar E. Analysis of Roughness and Heat Affected Zone of Steel Plates Obtained by Laser Cutting. *Advance Material Research*, vol. 974, pp. 169-173, 2014.

Miraoui I., Boujelbene M., and Zaydi M., High-power laser cutting of steel plates: heat affected zone analysis, Advances in Material Science and Engineering, Article ID 1242565, https://doi.org/10.1155/2016/1242565, 2016.

Orishich A.M., Shulyatyev V.B., and Golyshev A.A., The utmost thickness of the cut sheet for the qualitative oxygen-assisted laser cutting of low-carbon steel. *Physics Procedia*, vol. 83, pp.296-301, 2016.

Parthiban A., Ravikumar R., Suresh Kumar B., and Baskar N., Process performance with regards to surface roughness of the CO2 laser cutting of AA6061-T6 aluminium alloy. *Lasers in Engineering*, vol. 32, pp. 327-341, 2015.

Pavlica M.J., Petru J., and Cep R., Selection of the optimal parameters for laser cutting. *ActaTechnicaCorviniensis-Buletin of Engineering*, Fascicule 1, Tome VIII, 2015.

Prajapati BD, Patel RJ, and Khatri BC., Parametric investigation of CO_2 laser cutting of mild steel and hardox-400 material. *International Journal of Engineering Technology and Advanced Engineering*, vol. 3, no. 4, pp. 204-208, 2013.

Senthilkumar V., Bharath M., Dhanapal K., DhineshKumaran M., and Gobinath R., Analysis and optimization of laser machining parameters. *International Journal of Innovative Research in Science*, *Engineering and Technology*, vol. 5, no. 8, pp. 33-40, 2016.

Sharma A., and Yadava V., Modelling and optimization of cut quality characteristics for pulsed Nd: Yag laser curved profile cutting of Ni-based superalloy thin sheet. *Lasers in Engineering*, vol. 31, no. 5-6, pp. 351-382, 2016.

Singh S., and Samuel G.L., Laser Micromachining of Semiconductor Materials. In: Dixit U., Joshi S., Davim J. (eds) *Application of Lasers in Manufacturing*. *Lecture Notes on Multidisciplinary Industrial Engineering*. Springer, Singapore, 2019.

Solanki V., and Madia M., Parametric optimization of surface roughness and kerf width of super duplex stainless steel and titanium alloy grade II by using fiber laser cutting. *International Journal of Advance Research and Innovative Ideas in Education*, vol. 2, no. 3, pp. 2610-2620, 2016.

Tahir A.F.M., and Rashid, A.R., Experimental evaluation of CO_2 laser cutting quality of UHSS using oxygen as an assist gas. *JurnalTeknologi* (Sciences & Engineering), vol. 78, no. 7, pp. 69–73, 2016.

Tamura K., Ishigami R., and Yamagishi R., Laser cutting of thick steel plates and simulated steel components using a 30 kW fiber laser. *Journal of Nuclear Science and Technology*, vol. 53, no. 6, pp.916–920, 2016.

Varkey A.P., Kuriakose S., and Unni V.N., Optimization of edge quality during CO_2 laser cutting oftitanium alloy. *International Journal of Innovative Research in Advanced Engineering*, vol. 1, no. 11, pp.110-117, 2014.

Wandera C., and Kujanpää V., Characterization of the melt removal rate in laser cutting of thick-section stainless steel. *Journal of Laser Applicatio*ns, vol. 22, no. 2, pp. 62-70, 2010.

Wuttisarn T, Tangwarodomnukun V and Dumkum C., Laser micro-milling under a thin and flowing waterlayer: a new concept of liquid-assisted laser machiningprocess. Proc IMechE, Part B: J Engineering Manufacture; vol. 230, no. 2, pp. 376–380, 2016.

Yan Y, Li L, Sezer K, Wang, W., Whitehead, D, Ji, L., Bao, Y., Jiang, Y., CO_2 laser underwater machining of deep cavities in alumina. *J Eur Ceram Soc*, vol. 31, pp. 2793–2807, 2011.

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