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MATERIAL PROCESSING: FOCUS ON LASER CUTTING

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ABSTRACT

Light Amplification by Stimulated Emission of Radiation (laser) is among the fastest growing technologies in the engineering world and has a vast range of applications. It involves focusing photons of lights on a single spot of a workpiece with considerable accuracy, so as to transfer energy into the workpiece in a measure that is adequate to melt or achieve a particular material process. The technology is extremely broad, hence this review will focus on using laser for cutting applications which is one of the most popular, recently developed and emerging laser material processing techniques. This review utilizes relevant and recent literature to discuss material cutting by laser, the attributes of laser cutting, laser cutting parameters optimization as well as the trends in development of the process.

KEYWORDS: Laser, Material processing, cutting, Gas Assist Lasers & Waterjet Guided Lasers

1. INTRODUCTION

One of the most vital inventions of mankind is Laser technology. Currently, it is one of the upsurging technologies of the 21st century, providing conventional optical science rejuvenation and also bringing into being a new industry (Liu, Duan, & Peng, 2014). Due to its performance properties, the laser is used in many applications, including medicine (medical diagnosis and therapy /surgery), measurement technology (length, speed, roughness measurement), in manufacturing, in weapon systems, in optical communication / computing, at higher and lower divergence angles, more attractive homochromaticity, brief light pulse along with steady adjustable spectrum output compared to other light sources (Dutta Majumdar & Manna, 2003; Liu et al., 2014). However, the technology is difficult to describe because it covers a wide range of applications and also because of its continuous development. The laser uses the energy that is emitted when an electron moves from an elevated energy orbit or level inside an atom to a sub energy orbit or level. The source of heat or energy in laser treatment of materials refers to the laser beam. The homochromatic and electromagnetic propagated beam with a wavelength from ultraviolet to infrared is emitted to a substrate with an interaction / pulse time through a medium (10^{-3} to10^{-15} s) (Dutta

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Majumdar & Manna, 2003; Paulo Davim, 2013).

In the manufacturing industry, the beam generated from the laser is many a time regarded as a beneficial provenance of intense heat for diverse utilization such as to cutting, welding, surface treatment, punching, micromachining, surface structure fabrication, etc. This is possible because the beam has a very high energy concentration attributed to the fact that it has reasonable divergence, homochromatism, consistency and stability unlike normal light sources (Paulo Davim, 2013).

Lasers are normally classified based on the medium used for their action; thus, gas lasers, solid-state lasers, liquid-dye lasers, free-electron lasers, and semiconductor (diode) lasers (Paulo Davim, 2013). Major commercial lasers applied in material processing practices include the Nd-YAG laser, the carbon dioxide (CO_2) laser, the laser doped etheric disc (Yb), the ytterbium doped fiber (Yb) laser, high power diode laser, and laser excimer (Schopphoven, Gasser, & Backes, 2017; William M. Steen & Mazumder, 2010; Wandera & Niyibizi, 2018).

Several studies have been carried out on the treatment of materials with lasers, in particular Dutta et al. (Dutta Majumdar & Manna, 2003), Steen (W. M. Steen, 2003),and Steen et al. (William M. Steen & Mazumder, 2010). The goal was to use lasers to machine, shape, assemble, surface process, clean, bend, and mark materials. However, there is little information about laser cutting, cutting parameters and optimal operating conditions, and optimization methods or models for laser cutting. This article, which describes material processing via laser, its developments and future prospects, also discusses some models to optimize the laser cutting process. To the best of the authors' knowledge, this information has not been discussed in the existing literature.

2. LASER CUTTING

One of the best-known applications of the laser beam, which, due to its operational precision, low costs and local processing, constitutes almost 80% of industrial laser devices in operation is laser cutting (WM Steen, 2003; Yilbas, 2012). Laser cutting is one of the best-known applications of the laser beam, which, due to its operational precision, low costs and local processing, constitutes almost 80% of industrial laser devices in operation (WM Steen, 2003; Yilbas, 2012). The cutting beam maybe focused on the workpiece with a clear or reflective lens. Schematic diagrams of laser assisted gas cutting are as shown in Figure 1.

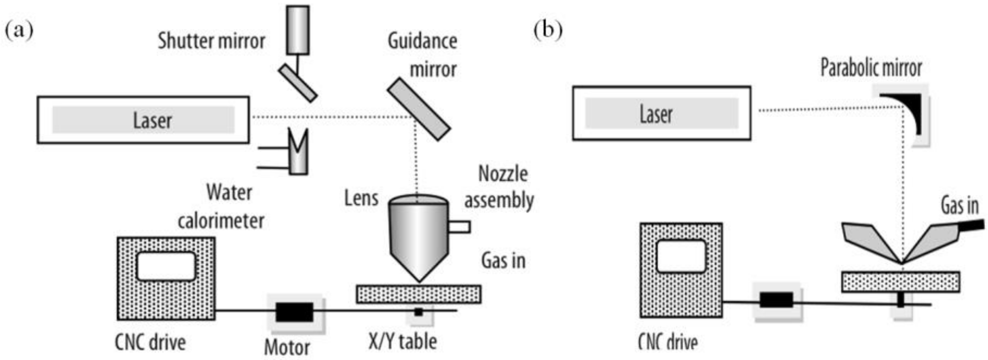


Figure 1: Illustrations of cutting with Laser (a) Transmissive Optics (b) Reflective Optics (William M. Steen & Mazumder, 2010)

Transmissive optics lasers are mostly CO_2 (GaAs, ZnSe, or CdTe) and YAG or excimer lasers (quartz) (William M. Steen & Mazumder, 2010). The selection of optics for laser application is based on considerations related to beam power vis-à-vis thermal stress limit and operational safety (Dutta Majumdar & Manna, 2003). Transmissive optical lasers which are prevalent, are cooled incidentally, by water cooling near the optics mountings whereas reflective optics may operate superior levels of heat, and the reason they are popularly used for high-powered executions.

Lasers can cut in several different ways such as evaporative, melt and blow, melt and blow in a responsive gas, melt-stress cutting for brittle materials, mechanical snapping and scribing, cool cutting (W. M. Steen, 2003). In which way, the photon energy ionizes the material near the cutting edge causing it to fly apart because of Coulomb forces. In the course of cutting with laser, material adjoining the cutting edge undergo hash thermal cycles when the laser beam passes over. The cutting edge or the heat affected zone (HAZ) experience rapid heating and cooling which leads to an induce microstructural changes (Al-Mashikhi, Powell, Kaplan, & Voisey, 2011). A gas squirt is recommended to aid the cutting operation on one hand and to safeguard the optics from speckle in gas as illustrated in Fig. 2.

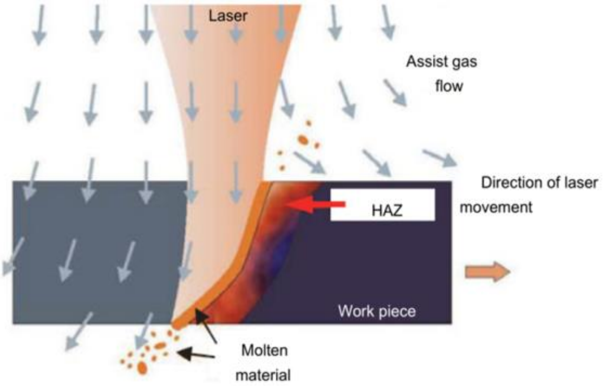


Figure 2: Gas assist Laser cutting (Boyu Sun, Qiao, Jibin Zhao, Ying Lu, & Guo, 2018)

The parameters controlling the laser cutting operation are laser power, beam diameter, material thickness, gas composition, thermo-physical properties, reflectivity, and traverse speed. Laser cutting has been applied to cut a variety of engineering materials of varying thickness vis-a-vis strength. A typical application is in airframe manufacture where Titanium alloys cut in an inert atmosphere. Fabrication of cardiovascular stents from thin stainless steel tubes and cutting stencils for electronic industry, photolithography or OLED mask are other applications of laser cutting. Aluminum alloys, radioactive material, wood, plastics, rubbers, composites, cloth, ceramics have been successfully cut in literature at varying laser parameters. The results proved more accurate cuts and at significant speeds compared to traditional methods.

Table 1 summaries some materials in literature that were successfully cut using a laser.

Table 1: Brief of Assorted Researches on Materials Cutting by Laser

Year	Material	Laser Type	Parameters	Results	Ref
2018	IOL copolymer	Nd:YVO4 laser	0.35 mm thick plate, 1030 nm Wave length, 3.5W output power, 1 MHz Frequency, pulse duration of 350fs ,	high-speed cutting were attained for Ps and fs pulsed laser	(Heberle, Häfner, & Schmidt, 2018)
2018	Carbon Fibre Reinforced Plastic	Nd:YAG (Starcut 150 by ROFIN)	1 mm thick plate,1064nmwavelength, 150W output power, 0.03/2.5 pulse duration, pulse frequency k3Hz	laser could cut CFRP plate at most 12mm/s	(Leone & Genna, 2018)
2018	Stainless Steel (SS) sheet (ASTM 304)	YLR-500” ytterbium fiber laser	3 mm thick plate, 10.6 µm Wave length, 500W output power, 50-60 Hz Frequency, 1.5 mm maximum beam diameter	Laser power as well as the speed of cutting resulted in highest kerf width.	(Kotadiya, Kapopara, Patel, Dalwadi, & Pandya, 2018)
2017	Ti-6Al-4V alloy	CO 2 laser (LC-ALPHAIII)	2 mm thick plate, 10.6 µm Wave length, 2000W output power, 1500 Hz Frequency, 0.25 mm maximum beam diameter, Nitrogen assisting gas	Raising laser power output or reducing the speed of cutting leads higher kerf widths and size	(Yilbas, Shaukat, & Ashraf, 2017)
	Inconel 625				
	Alumina				
2008	ultra-low carbon steel	CW ND:YAG laser	1.2 mm thick sheets, 337–515W output power, oxygen assisting gas	337W laser power, and 1000-1500mm/min speed is recommended for cutting 1.2mm thick ultralow carbon steel when 5bars pressured oxygen is applied as an aid gas.	(Salem, Mansour, Badr, & Abbas, 2008)

2001	Cu-clad glass fiber reinforced epoxy laminates	CO 2 and YAG (frequency multiplied)	2.5 mm thick plate, Five wavelengths 1060, 1064, 532,355 ,266 nm	LM is beneficial for a smooth scale direct drilling and patterning	(Illyefalvi-Vitéz, 2001)
1996	Al–Li + SiC metal matrix composite	Pulsed Nd:YAG	0.35 mm thick plate, pulse duration(t) between 0.6 and 5.0 ms, 120W output power, 10-40Hz Frequency, 0.25mm maximum beam diameter, compressed air or argon	Optimized laser parameters reduced HAZ, enhanced the cut quality as well as efficiency	(Yue & Lau, 1996)
1995	Mild steel and stainless steel	CO, laser of 500 W	0.8 mm and 1.2 mm thick plate, oxygen assisting gas	Cutting consists of reaction /evaporation. It excludes the effects of shock effects while the speed (30 mm s^{-1}) was accurate for the analytical model	(Yilbaş & Sahin, 1995)

The advantages of laser cutting present greater prospects for laser utilization and research. The major setbacks, however, have to do with the high thermal effect on material, the evolution of microns on the heat affected surface area which affects the material performance and lifetime and the spawning of poisonous fumes and smog whilst the cutting is performed(Happonen, Stepanov, & Piili, 2015; Sealy, Guo, Liu, & Li, 2016).

The use of waterjet laser to cut is somewhat new way of using pressure guided waterjet laser to cut materials especially on aircraft. This method has shown a remarkable depletion in heat in the cutting area with good cutting precision devoid blurring alongside less contamination. The water jet serves as an optical surface that reflects the beam of the laser completely into the room (see Figure 3). This happens due to the dissimilar reflection coefficients of air and water.

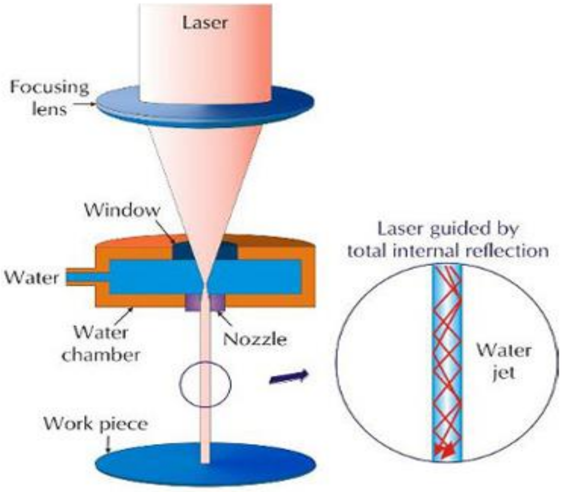


Figure 3: Laser Guided Water Jet (Brian Pfluger & Jacques Coderre, 2016)

An original laser beam is aimed at a focusing lens. The most widely used Nd: YAG lasers among commercially available waterjet cutting lasers are wavelengths of 1064nm (infrared) or 532nm (green light) (Perrottet, Boillat, Amorosi, & Richerzhagen, 2005; Tabie, Koranteng, Yunus, & Kuuyine, 2019). To use a laser for water jetting, the wavelength of the laser need to invert the relay spectrum of the water. This an outstanding limitation in the use of water jet lasers (Perrottet et al., 2005). The power of the laser appears in the form of a steady wave or surged light. (Dobrzański & Drygała, 2007; C. F. Li, Johnson, & Kovacevic, 2003; Perrottet et al., 2005). Pulse lasers with width of pulse calibrated in femtoseconds or picoseconds, have recently received more attention for use with water jets compared to continuous waves, as a better finish is achieved when the jet cools the material during the pulsation period (C. F. Li et al., 2003; Perrottet et al., 2005). The beam is then focused via a permeable window into a faucet located at the underside of a narrow water-filled chamber. Filtered, pure de-ionized, and degassed water is pumped into the water-filled chamber at a pressure between 50 and 600 bar based on the faucet's diameter. Larger faucets diameters require smaller water pressure. Typical nozzle diameters range from 20 to 150μm.

With the water pressure and nozzle diameter, the force delivered by the water jet is however inconsequential, as the material endures any scattering when revealed to the naked jet (not more than 0.1 N). Conversely, mechanical force delivered by assist gas jet in conventional laser cutting typically ranges between 1 and 5 N, which is 10 times higher than the water jet guided laser (Perrottet et al., 2005; Tabie et al., 2019).

3. ATTRIBUTES OF THE CUTS FROM LASER

The quality of cut, which is determined by the amount of material removed vis-a-vis the substrate material is normally described by the width of the kerf, surface roughness, cut edges perpendicularity, dross attachment and size of the heat-affected zone (HAZ) (Madhukar, Mullick, & Nath, 2016; Yilbas et al., 2017). Substantial researches involving experiments and mathematical models were carried out to evaluate the factors that influence cutting quality. The most relevant and popular laser cutting parameters include speed of cutting, laser power, and fluid pressure. These are often optimized for operating costs and / or efficiency (Salem et al., 2008). Good control of the laser cutting process through proper selection of cutting variables and the evaluation of these variables for slot geometry and size are cardinal aspects of quality assessment in the cutting process by laser (Yilbas et al., 2017). Fig.4 illustrates the effect of laser power on the HAZ width. It shows an increase in HAZ width as the laser power increases. This is as a result the high rate of heating. The fluctuation shown in the HAZ width is related to the laser beam's penetration on the surface of the workpiece.

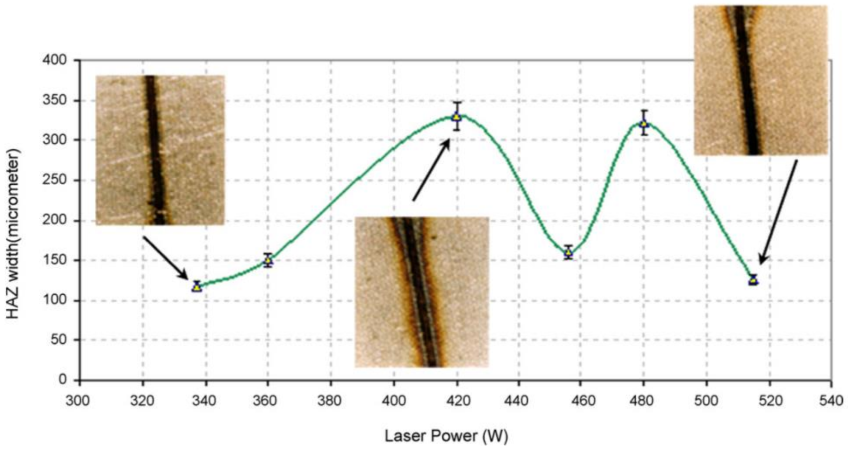


Figure 4: Effect of the laser power on the HAZ width at scan speed of 1500mm/min and gas pressure of 5-bar and their corresponding SEM images (Salem et al., 2008)

A decline in the speed of cutting by 40% was however observed to raise the width of the HAZ in accordance with the total cut's depth by 20% (Jarosz, Löschner, & Niesłony, 2016). This is illustrated in Fig.5. Similar effects were observed by Madic et al. (MADIC & RADOVANOVIC, 2012) using CO_2 laser to cut stainless steel type AISI 304. Fig.6 shows the synergetic consequences of the laser cutting variables on the HAZ's width from their experiments.

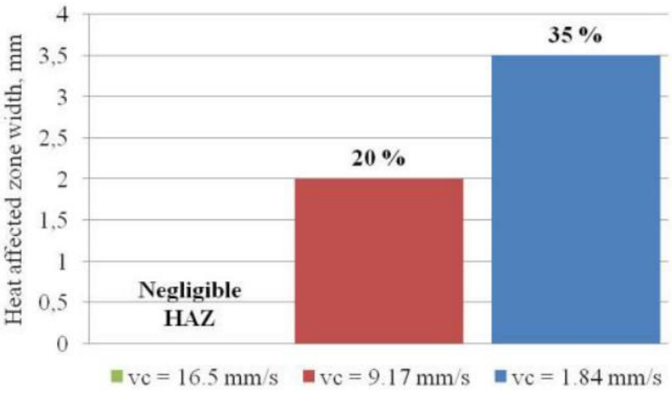
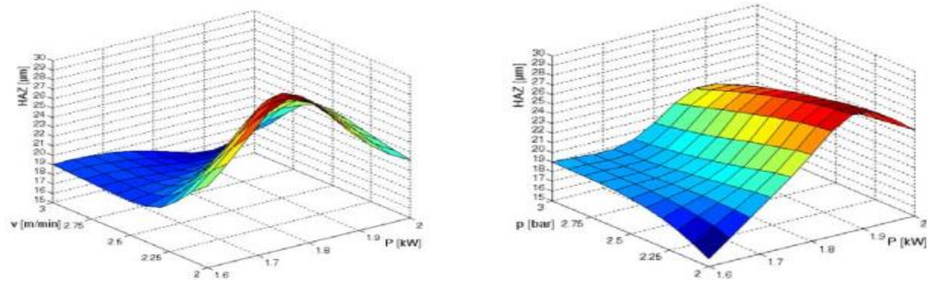
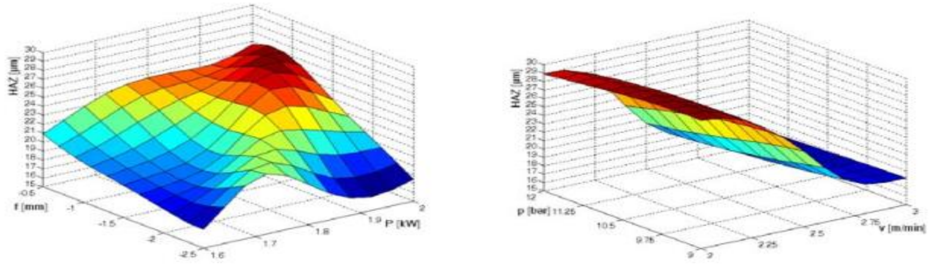


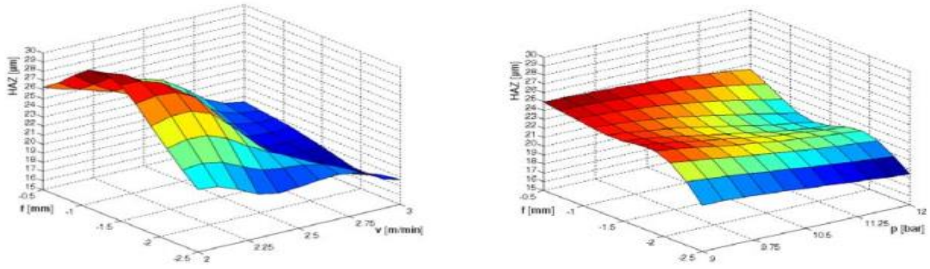
Figure 5: The Cutting Speed's Effect on HAZ's width with reference to the Sample's Thickness (Jarosz et al., 2016)



(a) Max. width of HAZ = 30.7 µm, min. width of HAZ = 16.37 µm (b) Max. width of HAZ = 27.11 µm, min. width of HAZ = 15.79 µm



(c) Max. width of HAZ = 26.38 µm, min. width of HAZ = 16.55 µm (d) Max. width of HAZ = 30.31 µm, min. width of HAZ = 17.39 µm



(e) Max. width of HAZ = 30.57 µm, min. width of HAZ = 18.46 µm (f) Max. width of HAZ = 24.95 µm, min. width of HAZ = 17.39 µm

Figure 6: Synergetic consequences of the Laser Cutting Variables on the HAZ's width (MADIC & RADOVANOVIC, 2012)

Eltawahni et al. (Eltawahni, Hagino, Benyounis, Inoue, & Olabi, 2012) also observed that the width of the upper enlargened when the power of the laser, pressure of the gas pressure and the faucet's diameter were augmented but declined as the speed of cutting and position of the focus were increased. Nevertheless, the speed of cutting is the major factor that influence the upper kerf width. Fig. 7 illustrates his results.

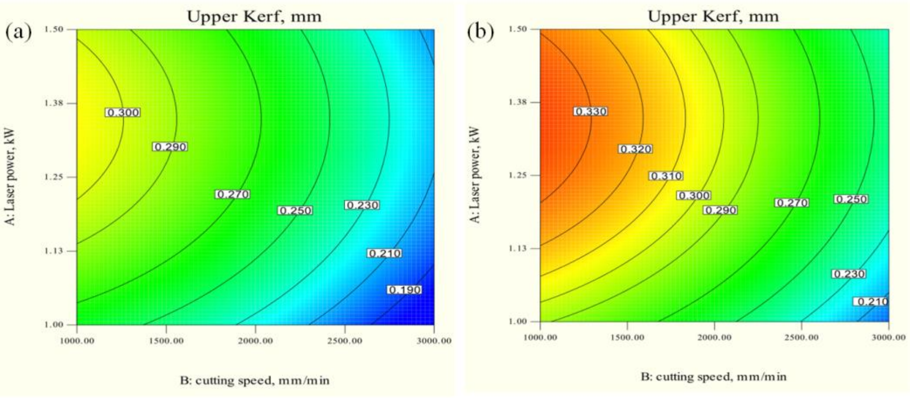
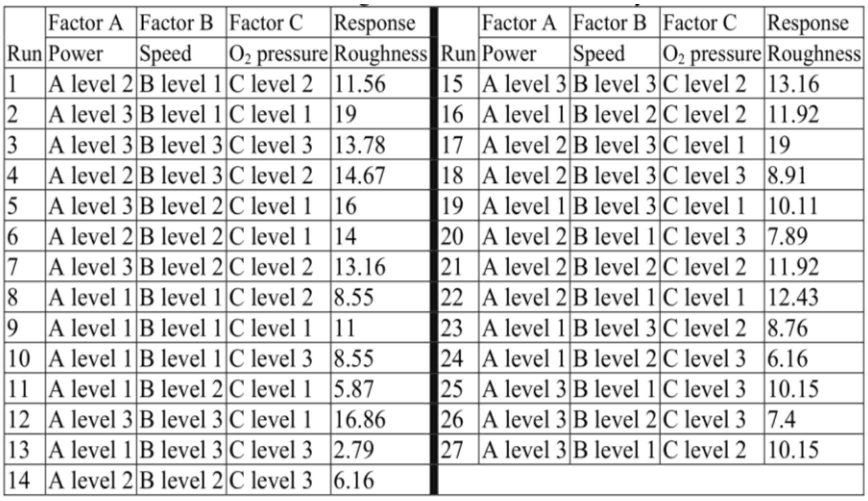


Figure 7: Contours showing the influence of power of the laser and the speed of cutting on the kerf width at different faucet diameters: (a) 1 mm (b) 1.5 mm (Eltawahni et al., 2012)

Figs.8 and 9 and Table 2 are results obtained Amal et al. (Amal, Eman, & Mona, 2016) on the roughness properties for cutting in different conditions of stainless steel 307.The least defined striations were produced at high power and speed and at low gas pressure. Increasing gas pressure leads to non-uniform striations (higher Rv and Rp). The optimum striation in the cutting-edge was found when using low power, speed, and gas pressure also when using high power and speed, and low gas pressure. Using the right balance between crosswise cutting speeds with power and applying a low pressure of gas led to a uniform surface.

Table 2: The Design Data used in ANOVA Analysis(Amal et al., 2016)



	Factor A	Factor B	Factor C	Response		Factor A	Factor B	Factor C	Response
Run	Power	Speed	O_2 pressure	Roughness	Run	Power	Speed	O_2 pressure	Roughness
1	A level 2	B level 1	C level 2	11.56	15	A level 3	B level 3	C level 2	13.16
2	A level 3	B level 1	C level 1	19	16	A level 1	B level 2	C level 2	11.92
3	A level 3	B level 3	C level 3	13.78	17	A level 2	B level 3	C level 1	19
4	A level 2	B level 3	C level 2	14.67	18	A level 2	B level 3	C level 3	8.91
5	A level 3	B level 2	C level 1	16	19	A level 1	B level 3	C level 1	10.11
6	A level 2	B level 2	C level 1	14	20	A level 2	B level 1	C level 3	7.89
7	A level 3	B level 2	C level 2	13.16	21	A level 2	B level 2	C level 2	11.92
8	A level 1	B level 1	C level 2	8.55	22	A level 2	B level 1	C level 1	12.43
9	A level 1	B level 1	C level 1	11	23	A level 1	B level 3	C level 2	8.76
10	A level 1	B level 1	C level 3	8.55	24	A level 1	B level 2	C level 3	6.16
11	A level 1	B level 2	C level 1	5.87	25	A level 3	B level 1	C level 3	10.15
12	A level 3	B level 3	C level 1	16.86	26	A level 3	B level 2	C level 3	7.4
13	A level 1	B level 3	C level 3	2.79	27	A level 3	B level 1	C level 2	10.15
14	A level 2	B level 2	C level 3	6.16					

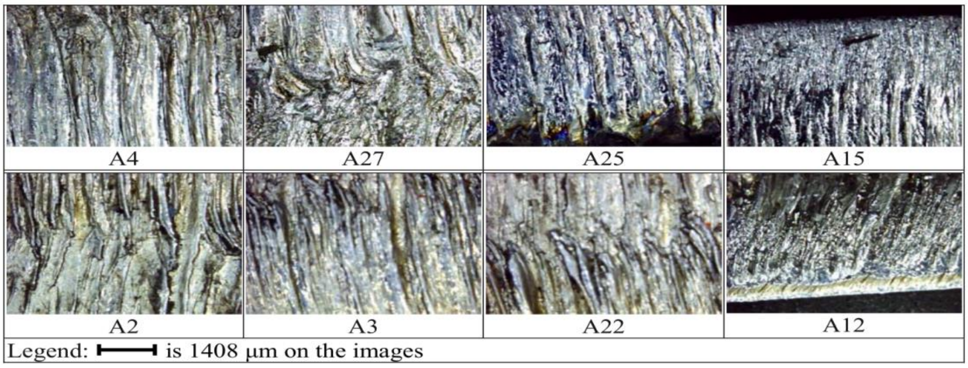


Figure 8: Cutting surface for some samples at different conditions(Amal et al., 2016)

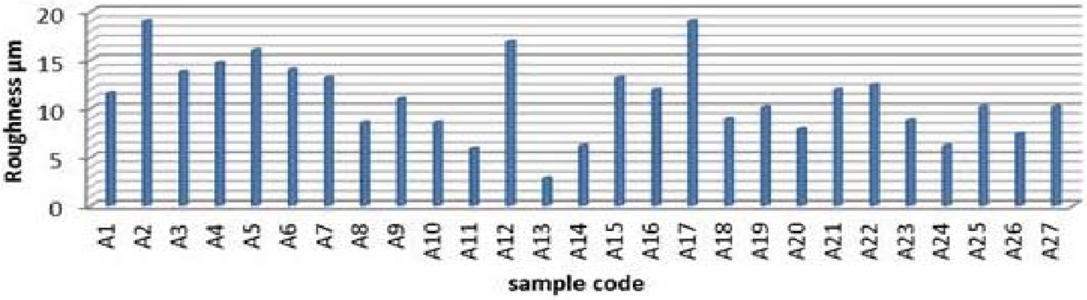


Figure 9: Roughness properties for the Cutting Surface (Ra) at different conditions(Amal et al., 2016)

Radonjić et al.(Radonjić, Kovač, & Mitrović, 2012) suggested an order in which cutting parameters should be adjusted when using gas assisted laser cutting (see Table 3).

Table 3: Order in which cutting parameters should be adjusted(Radonjić et al., 2012)

Step	Cutting withoxygen (O_2)	Cutting withnitrogen(N_2)	Cutting with compressed air(Air)Option
1	Position of Focus	Position of Focus	Position of Focus
2	Power of Laser	Rate of feed ±10% OK	Rate of feed ±10% OK
3	Pressure of gas	Power of Laser	Power of Laser
4	Rate of feed ±10% OK	Pressure of gas	Pressure of gas
5	Nozzle distance	Nozzle distance	Nozzle distance

Some research carried out to investigate the performance of laser cutting under varying parametric conditions include that of Ghany and Newishy(Ghany & Newishy, 2005) which demonstrated that laser cutting quality is dependents on power of the laser, frequency of the pulse, speed of the cutting and position of the focus. The investigation laser beam utilizing pulsed and continuous wave (CW) type Nd: YAG together with nitrogen or oxygen as aided gases to cut 1.2mm austenitic stainless steel sheets. It also observed that the nitrogen assisted cutting produced better-cut surface than oxygen assisted but it is not economically prudent since nitrogen gas is more expensive. The speed could also be increased to more than 8m/min with equivalent power and gas pressure for the limited laser system. Similar studies carried by Lamikiz et al.(Lamikiz et al., 2005) on different AHSS sheet-steels types hypothesized that the power of cutting should be intensified to 300W to evade the consequences of the presence of pitting, which was escalated as the speed of cutting was enhanced. With respect to the pressure of the gas, it was established that once the correct pressure is established, small discrepancies in the pressure do not affect the cut quality. Thus, assisting pressure of the gas can be maintained for different values of cutting speed, power, and position of the focus. The power of the laser, speed of cutting, different gas types, and pressures and focus position on the quality of the cut dross attachment characteristics, width of the kerf, Sand cut roughness of the surface of Zinc-coated steel sheets were also investigated by Ghany et al.(Ghany, Rafea, & Newishy, 2006). It was experimentally demonstrated that the test material could be cut by Nd: YAG applying laser powers not more than 400W with speeds as high as 6m/min. Many other studies have attempted to model the influence of operating variables on the performance characteristics of laser cutting. Some methodologies employed for modeling the laser cutting process include analytical methods, multiple regression analysis (MRA)(Rajaram, Sheikh-Ahmad, & Cheraghi, 2003; Stournaras, Stavropoulos, Salonitis, & Chryssolouris, 2009), response surface methodology (RSM)(Chiang & Chang, 2006; Eltawahni et al., 2012), fuzzy expert systems(Syn, Mokhtar, Feng, & Manurung, 2011), and artificial neural networks (ANNs)(Guo, Chen, & Cheng, 2006). By applying these methods and other traditional optimization algorithms like genetic algorithms (GA), particle swarm optimization (PSO), and simulated annealing(SA), near optimal laser processing conditions were attained but with extensive time, cost and require considerable knowledge in arithmetic modeling, theory of the optimization, artificial intelligence (AI) and statistics (Miloš & Miroslav1b, 2013). The Taguchi method (TM), lacking formulation of any kind of model, is a captivating reserve for determining virtually optimal cutting variables settings in laser cutting and is being increasingly applied. The procedure proved efficient, yet comparatively straightforward and became distinctively popular when applied to diverse performance characteristics. By applying the Taguchi process, industries are able to greatly reduce product development cycle time for both drawings and production, hence reducing costs and enhancing profit (Zhang, Chen, & Kirby, 2007).

The overall Taguchi processes are actually comprised of three distinct phases, which are comprised of design of the system, design of parameter, and the design of tolerance. The planning of experiments with the orthogonal display is, in most cases, efficient compared to numerous statistical designs. While fewer experimental numbers are required to carry out the Taguchi process can be calculated using the DoF approach. A specially designed orthogonal array of Taguchi is used to identify the effects of the whole machining parameters through the minimum experimental number and it takes less time for the experimental identifications.

For example, Taguchi experimental design involving the use of process variables; speed of cutting (A), cutting feed(B), depth of cut(C) for a simplified study by Lokesh et al. (Lokesh, Niresh, Neelakrishnan, & Rahul, 2018) utilized an L9 orthogonal display which has nine various experiments to obtain an optimum feed for cutting with laser. Table 4 shows the level of variables used in the study to optimize the laser cutting variables of composite material by the Taguchi process.

Table 4: Level of Parameters(Lokesh et al., 2018)

Part	Factors/Variable name	Level A	Level B	Level C
1	Speed of cutting (mm/sec)	225	330	350
2	Cutting Feed(mm/rev)	0.05	0.075	1
3	Depth of cut(mm)	1	2	3

The Taguchi method has also been explored in other ways or combined with other methods such as grey relational analysis (GRA), principal component analysis (PCA), weighted sum method (WSM), and fuzzy logic to optimize laser cutting parameters(Miloš & Miroslav1b, 2013). Dubey and Yadava (Dubey & Yadava, 2008) used a hybrid Taguchi process and response surface technique with multi-performance characteristics to optimize the laser beam cutting process for a thin plate of high class silicon-alloy steel. Lin [22] applied the Taguchi process and GRA to enhance the operations in turning with multi-performance characteristics (tool life, cutting forces and surface roughness). Despite the success in the application of the Taguchi method, it is bridled with some critique in usage such as outlined in (Gadallah & Abdu, 2015; Miloš & Miroslav1b, 2013)

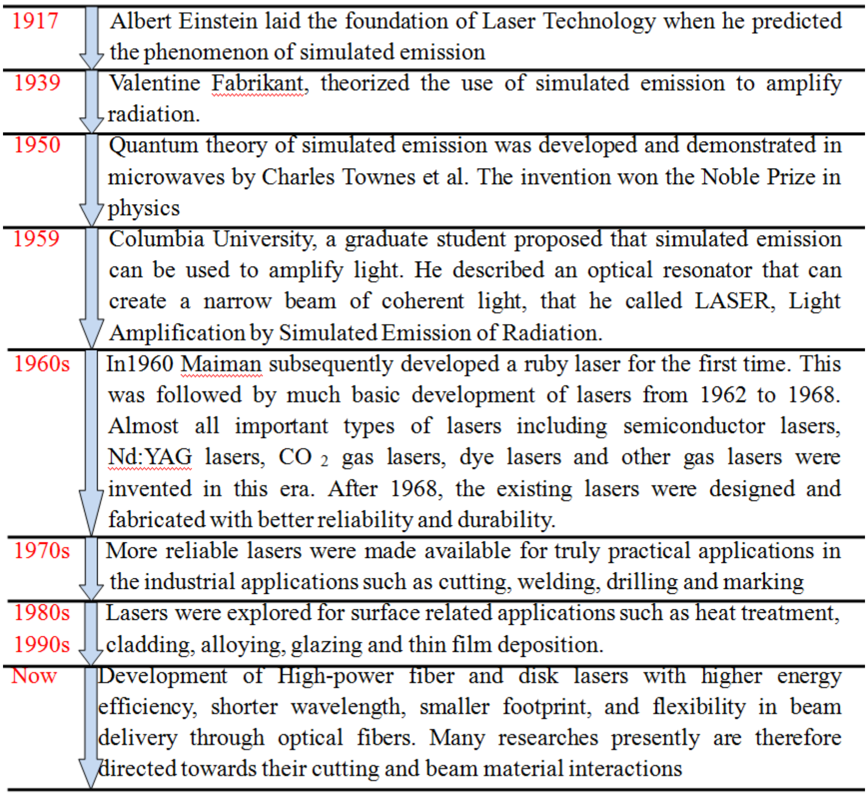
- It leads to duplications of many experiments for just a few interactions.
- There is a need for multi-objective optimization formulation of laser cutting operations.
- Other sources of noise for laser cutting operations need to be identified, modeled and optimized.

4. DEVELOPMENTAL TRENDS IN LASER CUTTING

Laser technology for material cutting is fast developing and growing. It has emerged as an attractive technology with potential application in a wide range of fields. History has it that the foundation for this technology was laid by Einstein in 1917 when he predicted the phenomenon of simulated emission. In 1939, Valentine Fabrikant theorized the use of simulated emission to amplify radiation. Quantum theory of simulated emission was developed and demonstrated in microwaves by Charles Townes et al in 1950. The invention won the Noble Prize in physics. In 1959 at Columbia University, a graduate student proposed that simulated emission can be used to amplify light. He recounted a resonator of optics that can create a tiny but coherent beam of light that he referred to as LASER; Light Amplification by Simulated Emission of Radiation. In 1960, Maiman (Maiman, 1960) subsequently developed a ruby laser for the first time. This was followed by many basic developments of the laser from 1962 to 1968. Almost all important laser types comprising Nd:YAG lasers, semiconductor lasers, dye lasers, CO_2 gas lasers, and various gas lasers got invented in this era. After 1968, the contemporary lasers were developed and fabricated with better durability and reliability. By halfway into the 1970s, more reliable lasers were made accessible for practical applications in the industry including welding, cutting, marking, and drilling. From 1980s to early 1990s, the lasers were investigated for surface related utilizations including heat cladding, heat treatment, glazing, alloying, and thin sheets deposition.

Barely a decade ago, industrial metal sheet cuttings was completely commanded by gas lasers CO_2 types, which have the attributes of extensive wavelength (10 mm) and inferior efficiencies (between 5 and10%) [1]. High-power fiber and disk lasers are becoming popular for material cutting because they have higher energy efficiency (>30%), shorter wavelength (1 mm), compact footprint, and pliability in beam supply via optical fibers(Belforte, 2015; L. Li, 2018). There is a paucity of information on the basic characteristics of these newly emerging lasers. Whereas there are superior for cutting thin materials (<5 mm) to CO_2 gas lasers, the converse holds true for them (L. Li, 2018). Many kinds of researches presently are therefore directed towards their cutting and beam material interactions.

In general, laser cutting technology is currently developed to increase the total energy input, power density by decreasing the spot size whilst easing the removal of molten products by increasing drag and fluidity (W. M. Steen & Kamalu, 1983). Increasing the total energy input requires the use of higher power lasers, making use of additional energy sources and improving the energy coupling of lasers. The high-power laser has been developed and used to cut faster and thicker materials. Chagnot et al. (Chagnot, de Dinechin, & Canneau, 2010) developed a cutting head and used it with an 8-kW Nd: YAG laser to cut stainless steel plates with a maximum thickness of 100 mm. Some studies (Koji Tamura, Ryoya Ishigami, & Ryuichiro Yamagishi, 2016; Tamura & Yamagishi, 2016, 2017) have also been conducted to efficiently cut through a thickness of more than 100 mm using high power lasers. Koji Tamura et al. (Koji Tamura et al., 2016)successfully used a 30-kW high power fiber laser to cut stainless steel and carbon steel plates of up to 300 mm.Fig.9 outlines the timeline of laser cutting developments.



1917	Albert Einstein laid the foundation of Laser Technology when he predicted the phenomenon of simulated emission
1939	Valentine Fabrikant, theorized the use of simulated emission to amplify radiation.
1950	Quantum theory of simulated emission was developed and demonstrated in microwaves by Charles Townes et al. The invention won the Noble Prize in physics
1959	Columbia University, a graduate student proposed that simulated emission can be used to amplify light. He described an optical resonator that can create a narrow beam of coherent light, that he called LASER, Light Amplification by Simulated Emission of Radiation.
1960s	In1960 Maiman subsequently developed a ruby laser for the first time. This was followed by much basic development of lasers from 1962 to 1968. Almost all important types of lasers including semiconductor lasers, Nd:YAG lasers, CO_2 gas lasers, dye lasers and other gas lasers were invented in this era. After 1968, the existing lasers were designed and fabricated with better reliability and durability.
1970s	More reliable lasers were made available for truly practical applications in the industrial applications such as cutting, welding, drilling and marking
1980s 1990s	Lasers were explored for surface related applications such as heat treatment, cladding, alloying, glazing and thin film deposition.
Now	Development of High-power fiber and disk lasers with higher energy efficiency, shorter wavelength, smaller footprint, and flexibility in beam delivery through optical fibers. Many researches presently are therefore directed towards their cutting and beam material interactions

Figure 10: Timeline of Laser Cutting Developments

5. SUMMARY AND CONCLUSIONS

It has been shown that laser cutting is a complicated process resulting from the amalgamated action of optical, chemical, hydrodynamic and thermodynamic phenomena. Despite the fact that the laser cutting technique is well acknowledged and the corresponding relevance of the parameters of the material cutting process is understood and can, accordingly be regulated to match the requirements for optimum speeds of cutting, best quality in the cut with maximum thickness, a particular model or methodology that holds good for a variety of applications and material is still a challenge. There is the need to revise the optimization models notably the Taguchi method to cater to these discrepancies associated in their usage. One way that seems prudent is the possibility of using a novel perspective to multi-objective task optimization, established on the Taguchi process and AI. Nonetheless, sufficient literature has demonstrated there is an explicit limit for the speed of the cutting, while there is no real limit for the maximum thickness and cut quality. Since laser cutting shows considerable advantages juxtaposed to traditional cutting methods, it is foreseeable that laser cutting will substitute more and more conventional processes. That development could accelerate if the present models are revised.

REFERENCES

1. Al-Mashikhi, S. O., Powell, J., Kaplan, A. F. H., & Voisey, K. T. (2011). Heat affected zones and oxidation marks in

fiber laser-oxygen cutting of mild steel. Journal of Laser Applications, 23(4).

2. Amal, N., Eman, N., & Mona, A. Y. (2016). Effect of laser cutting parameters on surface roughness of stainless steel 307. Leonardo Electronic Journal of Practices and Technologies, 15(29), 127-136.
3. Belforte, D. (2015). 2015 Industrial Laser Market Outperforms Global Manufacturing Instability. .Journal of Industrial Laser Solutions 31.
4. Boyu Sun, Qiao, H., Jibin Zhao, Ying Lu, & Guo, Y. (2018). Current status of water-jet guided laser cutting technology. Opto-Electronic Engineering, 44(11), 1039-1044.
5. Brian Pfluger, & Jacques Coderre. (2016). When Precision Matters, Deliver it with Advanced Laser-EDM Combo. Radical Departures, Advanced Techniques in Aerospace Manufacturing, 13, 22-26.
6. Chagnot, C., de Dinechin, G., & Canneau, G. (2010). Cutting performances with new industrial continuous wave ND:YAG high power lasers: For dismantling of former nuclear workshops, the performances of recently introduced high power continuous wave ND:YAG lasers are assessed. Nuclear Engineering and Design, 240(10), 2604-2613. doi: https://doi.org/10.1016/j.nucengdes.2010.06.041
7. Chiang, K.-T., & Chang, F.-P. (2006). Optimization of the WEDM process of particle-reinforced material with multiple performance characteristics using grey relational analysis. Journal of Materials Processing Technology, 180(1), 96-101. doi: https://doi.org/10.1016/j.jmatprotec.2006.05.008
8. Dobrzański, L. A., & Drygała, A. (2007). Laser processing of multicrystalline silicon for texturization of solar cells. Journal of Materials Processing Technology, 191(1), 228-231. doi: https://doi.org/10.1016/j.jmatprotec.2007.03.009
9. Dubey, A. K., & Yadava, V. (2008). Multi-objective optimization of Nd:YAG laser cutting of nickel-based superalloy sheet using orthogonal array with principal component analysis. Optics and Lasers in Engineering, 46(2), 124-132. doi: https://doi.org/10.1016/j.optlaseng.2007.08.011
10. Dutta Majumdar, J., & Manna, I. (2003). Laser processing of materials. Sadhana 28(3-4), 495-562.
11. Eltawahni, H. A., Hagino, M., Benyounis, K. Y., Inoue, T., & Olabi, A. G. (2012). Effect of CO2 laser cutting process parameters on edge quality and operating cost of AISI316L. Optics & Laser Technology, 44(4), 1068-1082. doi: https://doi.org/10.1016/j.optlastec.2011.10.008

12. Gadallah, M. H., & Abdu, H. M. (2015). Modeling and optimization of laser cutting operations. Manufacturing Rev., 2.
13. Ghany, K. A., & Newishy, M. (2005). Cutting of 1.2mm thick austenitic stainless steel sheet using pulsed and CW Nd:YAG laser. Journal of Materials Processing Technology, 168(3), 438-447. doi: https://doi.org/10.1016/j.jmatprotec.2005.02.251
14. Ghany, K. A., Rafea, H. A., & Newishy, M. (2006). Using a Nd:YAG laser and six axes robot to cut zinc-coated steel. The International Journal of Advanced Manufacturing Technology, 28(11), 1111-1117. doi: 10.1007/s00170-004-2468-x
15. Guo, D., Chen, J., & Cheng, Y. (2006, 0-0 0). Laser Cutting Parameters Optimization Based on Artificial Neural Network. Paper presented at the The 2006 IEEE International Joint Conference on Neural Network Proceedings.
16. Happonen, A., Stepanov, A., & Piili, H. (2015). Feasible Application Area Study for Linear Laser Cutting in Paper Making Processes. Physics Procedia, 78, 174-181. doi: https://doi.org/10.1016/j.phpro.2015.11.030
17. Heberle, J., Häfner, T., & Schmidt, M. (2018). Efficient and damage-free ultrashort pulsed laser cutting of polymer intraocular lens implants. CIRP Annals. doi: https://doi.org/10.1016/j.cirp.2018.04.095
18. Illyefalvi-Vitéz, Z. (2001). Laser processing for microelectronics packaging applications. Microelectronics Reliability, 41(4), 563-570. doi: https://doi.org/10.1016/S0026-2714(00)00250-X
19. Jarosz, K., Löschner, P., & Niesłony, P. (2016). Effect of Cutting Speed on Surface Quality and Heat-affected Zone in Laser Cutting of 316L Stainless Steel. Procedia Engineering, 149, 155-162. doi: https://doi.org/10.1016/j.proeng.2016.06.650
20. Koji Tamura, Ryoya Ishigami, & Ryuichiro Yamagishi. (2016). Laser cutting of thick steel plates and simulated steel components using a 30 kW fiber laser. Journal of Nuclear Science and Technology. doi: DOI: 10.1080/00223131.2015.1080633
21. Kotadiya, D. J., Kapopara, J. M., Patel, A. R., Dalwadi, C. G., & Pandya, D. H. (2018). Parametric analysis of process parameter for Laser cutting process on SS-304. Materials Today: Proceedings, 5(2, Part 1), 5384-5390. doi: https://doi.org/10.1016/j.matpr.2017.12.124
22. Lamikiz, A., Lacalle, L. N. L. d., Sánchez, J. A., Pozo, D. d., Etayo, J. M., & López, J. M. (2005). CO2 laser cutting

of advanced high strength steels (AHSS). Applied Surface Science, 242(3), 362-368. doi: https://doi.org/10.1016/j.apsusc.2004.08.039

23. Leone, C., & Genna, S. (2018). Heat affected zone extension in pulsed Nd:YAG laser cutting of CFRP. Composites Part B: Engineering, 140, 174-182. doi: https://doi.org/10.1016/j.compositesb.2017.12.028
24. Li, C. F., Johnson, D. B., & Kovacevic, R. (2003). Modeling of waterjet guided laser grooving of silicon. International Journal of Machine Tools and Manufacture, 43(9), 925-936. doi: https://doi.org/10.1016/S0890-6955(03)00063-4
25. Li, L. (2018). 2 - The Challenges Ahead for Laser Macro, Micro and Nano Manufacturing☆ A2 - Lawrence, Jonathan Advances in Laser Materials Processing (Second Edition) (pp. 23-42): Woodhead Publishing.
26. Liu, Q., Duan, X., & Peng, C. (2014). Novel Optical Technologies for Nanofabrication (J. Tang Ed.). Heidelberg New York Dordrecht London: Springer.
27. Lokesh, S., Niresh, J., Neelakrishnan, S., & Rahul, S. P. D. (2018). Optimisation Of Cutting Parameters Of Composite Material Laser Cutting Process By Taguchi Method. IOP Conference Series: Materials Science and Engineering, 324(1), 012054.
28. Madhukar, Y. K., Mullick, S., & Nath, A. K. (2016). An investigation on co-axial water-jet assisted fiber laser cutting of metal sheets. Optics and Lasers in Engineering, 77, 203-218. doi: https://doi.org/10.1016/j.optlaseng.2015.08.003
29. MADIC, M. J., & RADOVANOVIC, M. R. (2012). Analysis of the Heat Affected Zone in CO_2 Laser Cutting ff Stainless Steel. Thermal Science, 16(Suppl 2), S419-S429
30. Maiman, T. H. (1960). Stimulated optical radiation in ruby. Nature, 187, 493–494.
31. Miloš, M., & Miroslav1b, R. (2013). Application of the Taguchi Method for Optimization of Laser Cutting: A Review. Nonconventional Technologies Review, 50-57.
32. Paulo Davim, J. (2013). Lasers in Manufacturing (J. P. Davim Ed.). Great Britain: ISTE Ltd and John Wiley & Sons, Inc.
33. Perrottet, D., Boillat, C., Amorosi, S., & Richerzhagen, B. (2005). PV processing: Improved PV-cell scribing using water jet guided laser. Refocus, 6(3), 36-37. doi: https://doi.org/10.1016/S1471-0846(05)70398-X

34. Radonjić, S., Kovač, P., & Mitrović, A. (2012). Defining New Processing Parameters in Laser Cutting. Paper presented at the 16 th International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology", Dubai, UAE.
35. Rajaram, N., Sheikh-Ahmad, J., & Cheraghi, S. H. (2003). CO2 laser cut quality of 4130 steel. International Journal of Machine Tools and Manufacture, 43(4), 351-358. doi: https://doi.org/10.1016/S0890-6955(02)00270-5
36. Salem, H. G., Mansour, M. S., Badr, Y., & Abbas, W. A. (2008). CW Nd:YAG laser cutting of ultra low carbon steel thin sheets using O2 assist gas. Journal of Materials Processing Technology, 196(1), 64-72. doi: https://doi.org/10.1016/j.jmatprotec.2007.05.013
37. Schopphoven, T., Gasser, A., & Backes, G. (2017). EHLA: Extreme High-Speed Laser Material Deposition. Laser Technik Journal, 14(4), 26-29. doi: 10.1002/latj.201700020
38. Sealy, M. P., Guo, Y. B., Liu, J. F., & Li, C. (2016). Pulsed Laser Cutting of Magnesium-Calcium for Biodegradable Stents. Procedia CIRP, 42, 67-72. doi: https://doi.org/10.1016/j.procir.2016.02.190
39. Steen, W. M. (2003). Laser material processing—an overview. Journal of Optics A: Pure and Applied Optics, 5(4), S3.
40. Steen, W. M., & Kamalu, J. N. (1983). CHAPTER 2 - Laser Cutting. In M. Bass (Ed.), Materials Processing: Theory and Practices (Vol. 3, pp. 15-111): Elsevier.
41. Steen, W. M., & Mazumder, J. (2010). Laser Material Processing (4th Ed.). London Dordrecht Heidelberg New York: Springer
42. Stournaras, A., Stavropoulos, P., Salonitis, K., & Chryssolouris, G. (2009). An investigation of quality in CO2 laser cutting of aluminum. CIRP Journal of Manufacturing Science and Technology, 2(1), 61-69. doi: https://doi.org/10.1016/j.cirpj.2009.08.005
43. Syn, C. Z., Mokhtar, M., Feng, C. J., & Manurung, Y. H. P. (2011). Approach to prediction of laser cutting quality by employing fuzzy expert system. Expert Systems with Applications, 38(6), 7558-7568. doi: https://doi.org/10.1016/j.eswa.2010.12.111
44. Tabie, V. M., Koranteng, M. O., Yunus, A., & Kuuyine, F. (2019). Water-Jet Guided Laser Cutting Technology- an Overview. Lasers in Manufacturing and Materials Processing, 6(2), 189-203. doi: 10.1007/s40516-019-00089-9

45. Tamura, K., & Yamagishi, R. (2016). Laser cutting conditions for steel plates having a thickness of more than 100 mm using a 30 kW fiber laser for nuclear decommissioning. Mechanical Engineering Journal, 3(3), 15-00590-00515-00590. doi: 10.1299/mej.15-00590

46. Tamura, K., & Yamagishi, R. (2017). Observation of the molten metal behaviors during the laser cutting of thick steel specimens using attenuated process images. Journal of Nuclear Science and Technology. doi: 10.1080/00223131.2017.1299643

47. Wandera, C., & Niyibizi, A. (2018). Potential Benefits of adoption of Laser Materials Processing in East Africa's Manufacturing Industry. Paper presented at the 3rd DeKUT International Conference on STI&E NYERI, KENYA.

48. Yilbaş, B. S., & Sahin, A. Z. (1995). Oxygen assisted laser cutting mechanism—a laminar boundary layer approach including the combustion process. Optics & Laser Technology, 27(3), 175-184. doi: https://doi.org/10.1016/0030-3992(95)93638-8

49. Yilbas, B. S., Shaukat, M. M., & Ashraf, F. (2017). Laser cutting of various materials: Kerf width size analysis and life cycle assessment of cutting process. Optics & Laser Technology, 93, 67-73. doi: https://doi.org/10.1016/j.optlastec.2017.02.014

50. Yue, T. M., & Lau, W. S. (1996). Pulsed Nd:YAG Laser Cutting of Al/Li/SiC Metal Matrix Composites. Materials and Manufacturing Processes, 11(1), 17-29. doi: 10.1080/10426919608947458

51. Zhang, J. Z., Chen, J. C., & Kirby, E. D. (2007). Surface roughness optimization in an end-milling operation using the Taguchi design method. Journal of Materials Processing Technology, 184(1), 233-239. doi: https://doi.org/10.1016/j.jmatprotec.2006.11.029