



A comprehensive review of studying the influence of laser cutting parameters on surface and kerf quality of metals

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Abstract

Sheet metals such as titanium alloys, steel alloys, and aluminum alloys are significant materials due to their importance among everyday life products as well as high-strength applications in aircraft, ships, automobiles, construction, military, and marine purposes. Recently, laser cutting is one of the best and fastest non-conventional methods to cut sheet metals, so it is necessary to understand how laser cutting parameters affect cutting quality. A comprehensive review was presented to investigate how laser cutting parameters affect the cut surface and kerf quality and which parameters affect cutting quality the most. An overview of the advantages of laser cutting when compared to other methods of machining was presented. In addition, a description of the laser cutting method and the different sources of laser were presented with clearing the range of thicknesses of the cut material for each source and their advantages. Also, a description of the properties and the applications of the studied materials were discussed. The performance parameters of cutting were illustrated in detail by graphs and equations. The research analysis and discussion were discussed in such organized details by tables and graphs which show the full classification of the studied papers. It was found that the best conditions to obtain low surface roughness, small HAZ width, small kerf width, and small kerf angle are using low laser power, high cutting speed, medium gas pressure, high standoff distance, medium pulse frequency, medium pulse width, small nozzle diameter, small thickness, and nitrogen as an assist gas.

Keywords Laser cutting · Titanium alloys · Steel alloys · Aluminum alloys · Surface quality

Nomenclature

Pu	Laser power, W	PE	Pulse energy, J
V	Cutting speed, mm/min	DA	Defocusing amount, mm
P	Assist gas pressure, bar	DC	Duty cycle, %
PF	Pulse frequency, Hz	I	Lamp current, A
PW	Pulse width, mm	ND	Nozzle diameter, mm
FP	Focal position (focal point), mm	NOP	Number of pulses, –
SOD	Standoff distance, mm	T	Thickness, mm
WT	Wait time, S	SR	Surface roughness, μm
		KW	Kerf width, mm
		UKW	Upper kerf width, mm
		LKW	Lower kerf width, mm
		KT	Kerf taper (kerf angle), $^\circ$
		MRR	Material removal rate, mm^3/min
		VH	Hardness, μm
		HAZ	Heat-affected zone, mm
		EHD	Enter hole diameter, mm
		OHD	Output hole diameter, mm
		CD	Cycle duration, ms
		LBC	Laser beam cutting, –
		USC	Ultrasonic cutting, –
		PBC	Plasma beam cutting, –

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AWJM	Abrasive water jet machining, –
TM	Taguchi method, –
ANOVA	Analysis of variance, –
DOE	Design of experiment, –
PP	Pareto principle, –
MCM	Monte Carlo method, –
LMT	Laser machine type, –
AGT	Assist gas type, –
N ₂	Nitrogen, –
O ₂	Oxygen, –
KD	Kerf deviation, –
EE	Energy efficiency, –
E _l	Linear specific energy, –
E _s	Surface specific energy, –
E _v	Volume specific energy, –
Nd:YAG	Neodymium-doped yttrium aluminum garnet; Nd: Y3Al5O12,

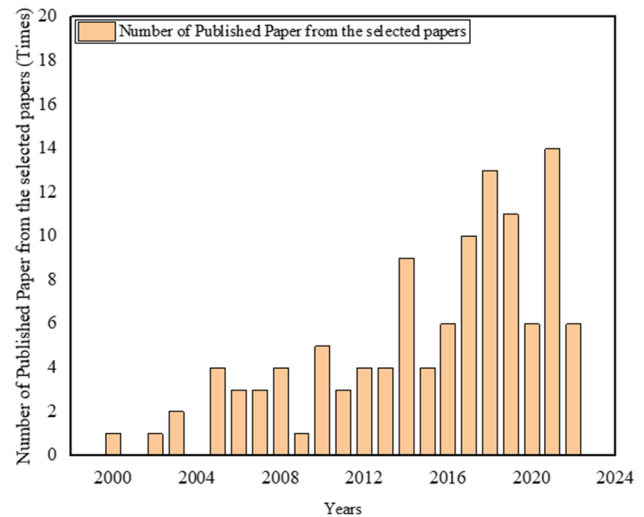


Fig. 1 Number of published papers in laser cutting during the period from 2000 to 2022 based on the papers selected for this review

1 Introduction

1.1 The definition and the applications of the laser cutting process

Laser cutting process is one of the advanced machining processes which use thermal energy for cutting without direct contact with the workpiece. Laser is an abbreviation for “light amplification by stimulated emission of electromagnetic radiation” which is used for producing a monochromatic coherent light beam. Because of its spatial coherence property, which enables lasers to be focused on a small area, they can be utilized for a variety of industrial and medical applications. In the manufacturing industry, it has a wide range of applications starting with drilling small holes, and welding finishing with thick metal sheets cutting with a good value of high accuracy and tolerance. Laser is extensively used in a wide range of fields as there is no need to a specific medium such as gas shielding or vacuum for the purpose of operation [1, 2].

Laser cutting offers a lot of potential for cutting ceramics, metals, polymers, composites, and conductive and non-conductive materials [3]. Moreover, titanium alloys, steel alloys, aluminum alloys, ceramics, and composites are challenging to cut because of their superior mechanical properties [4–6].

1.2 Number of published papers or Reviews in Laser Cutting during the period from 2000 to 2022 based on the papers selected for this review

Figure 1 shows the number of the published papers or reviews in laser cutting during the period from 2000 to 2022 based on the selected papers for this review, which indicate the progressive increase in the use of the laser

cutting techniques in the cutting of the sheet metals of the studied materials as it offers a high level of accuracy of the cut surface. In addition, it reduces the time of machining which achieves a high rate of production and as a result it improves the industrial process. So, laser cutting techniques offer a high level of advantages with a little disadvantage when compared to other advanced techniques and traditional methods of metal cutting which will be discussed later in detail. Also, it shows that the laser machining techniques moved from investigating the cutting of the medium hard materials to hard materials as this thing will lead to a high efficiency of cutting by saving time and faults which happen by traditional ways beside the high accuracy when comparison with other nontraditional machining. Also, it shows an incredible increase in studying the method of laser cutting during the period from 2017 to the early of 2022, which represent 60 papers in only 5 years compared to 42 papers in 17 years during the period from 2000 to 2016. From the above information, the laser cutting techniques provide an image about the future trend which expected to be studied more and more.

1.3 Laser cutting process description

Laser cutting process considers a thermal-cutting procedure which uses a laser beam for cutting materials and is frequently used in industrial manufacturing. This is accomplished by using a LBC machine, which is shown in Fig. 2, by directing a high-power, coherent, monochromatic laser beam with wavelengths ranging from ultra-violet to infrared onto the surface of a workpiece. The workpiece absorbs the energy coming from the laser beam, causing a quick increase in the material temperature at the focused spot. Beside the

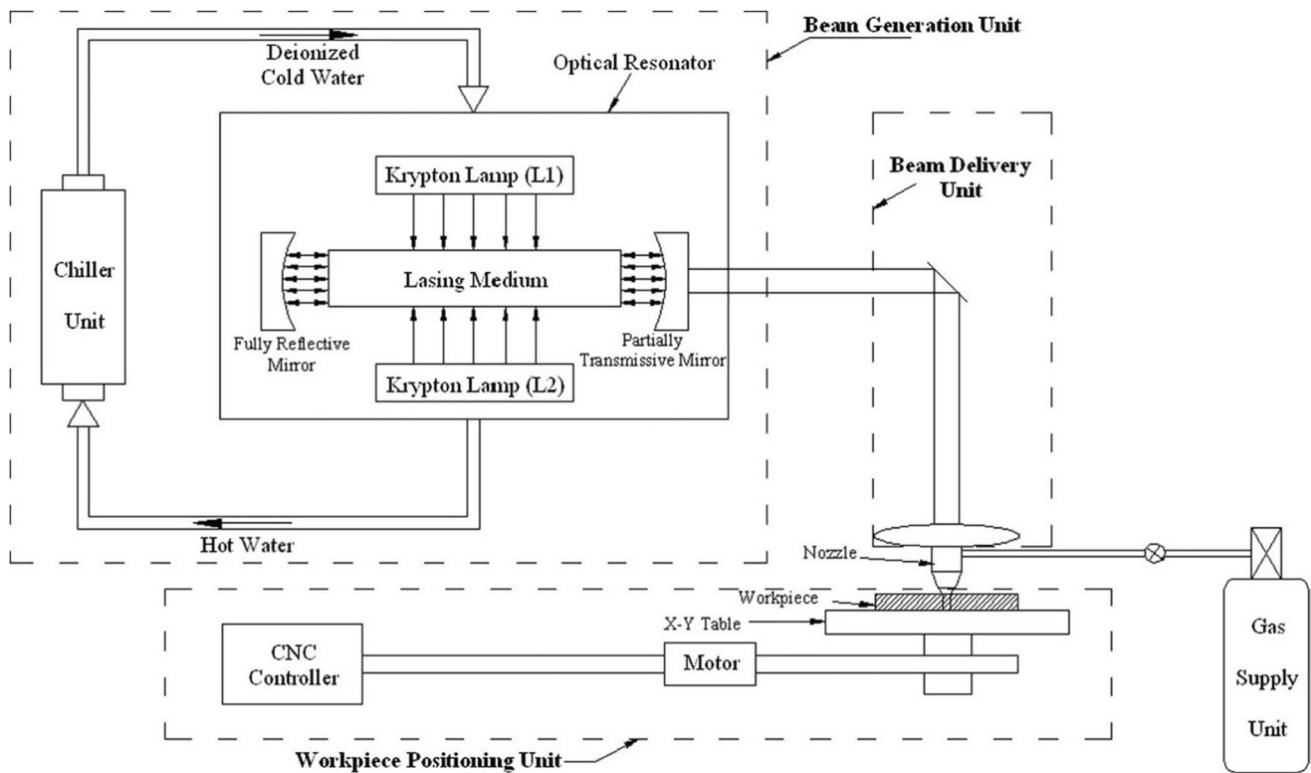


Fig. 2 Schematic diagram of laser cutting machine [14]

high value of temperature, the properties of the cut material and the beam intensity cause added effect on the cut surface, which cause a high concentrated spot of a high amount of heat. As a result, the material melts and vaporizes; also chemical transformation may happen before being evacuated using a high-pressure support gas [7–13].

1.4 Laser-assisted machining and laser cutting process advantages and disadvantages when compared to other conventional machining methods

The laser cutting process has a wide range of advantages in comparison to using the conventional cutting machines such as turning, milling, and drilling. These advantages are delivering good cut quality, minimizing the material loss during the cutting process, and achieving high accuracy of the cut surface [1]. Because of the high mechanical characteristics of the studied materials such as titanium alloys and steel alloys, these materials are difficult to machine using conventional cutting methods [15, 16]. The machinability characteristics suggest many challenges for the machining, such as increased machining force, irregular size, increased machining temperature, reduced tool life because of tool wear [17], and low surface quality. So, it is considered a problem

for cutting efficiency [16, 18]. However, some studies try to help in cutting titanium alloys by preheating the alloy before cutting, which helps in decreasing cutting problems and time [19]. Then studies started to use the laser source as a heat source to increase the cutting quality and life of the tool by decreasing the cutting force [20, 21]. Laser-assisted technique was also used for milling of Inconel 718, where it was observed that the melting area is proportional to the cutting speed and inversely proportional to the laser beam power [22]. Moreover, this technique was again used for milling of Inconel 718 to predict the surface roughness values in milling process [23]. Then some studies presented a comparison between conventional and laser-assisted machining, which added more assurance that laser-assisted machining is better than conventional methods [9, 24].

However, the ease of automation, the laser cutting method, has considerable disadvantages such as the high cost of the machine itself and the high operating cost, and the cut quality is greatly influenced by the input factors. Thus, it is necessary to optimize the process parameters to get high cut quality which differs based on material properties. Also, monitoring the change of the microstructure in the cut material surface is necessary as the quick cooling may produce undesirable effects that could cause failure [25].

1.5 Laser cutting process advantages and disadvantages when compared to other non-conventional machining methods

As a result, some studies focused only on using non-traditional machining methods such as laser machining (LM) [26], abrasive water jet machining (AWJM) [27], ultrasonic machining (USM) [28, 29], and abrasive water jet–assisted laser machining (AWJALM) [30], which are examples of alternative machining processes that are more efficient and faster than conventional methods. But laser cutting machining is preferred over abrasive water jet machining and plasma machining with many advantages, such as low operation time and low operation energy, and there is no need to harden the metal before cutting [31]. Table 1 shows that laser beam machining (LBM) is better than plasma beam machining (PBM) and abrasive water jet machining (AWJM) in many aspects, so it is preferred to use LBM over the other non-conventional methods.

1.6 Types of lasers cutting sources and the applications of each type

1.6.1 CO₂ laser

One of the most well-known types of lasers utilized in the mechanical industries for cutting metallic materials is the CO₂ laser as shown in Fig. 3. It can cut metals of various thickness values, with high cut quality [34]. The CO₂ laser is the dominant type of laser sources in laser cutting applications due to their good quality of the laser beam, the high values of temperature, and high output power [10, 35, 36].

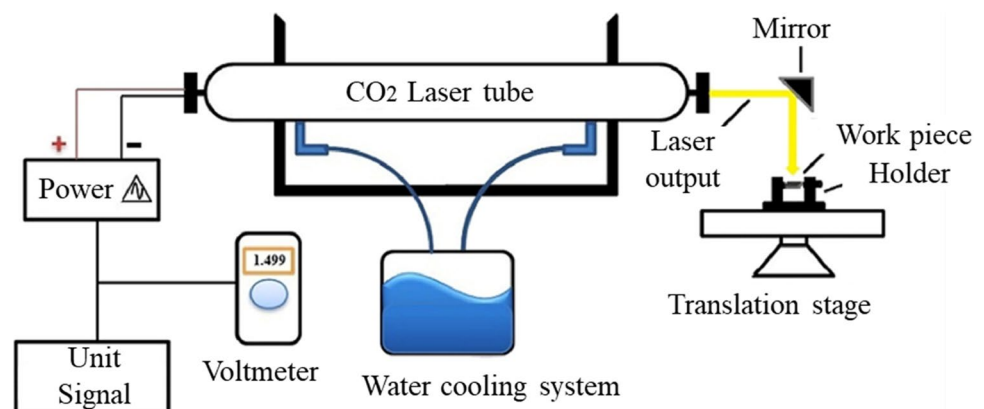
1.6.2 ND:YAG pulsed laser

The solid-state pulsed Nd-YAG machine is shown in Fig. 4, which has a wide range of uses in cutting of sheet metal; besides cutting the thinner sheet metal, it has the ability to even cut the thicker materials due to its higher peak power and shorter pulse

Table 1 Comparison between LBC, PBC, and AWJM [8, 27, 31–33]

Cutting method	LBC	AWJM	PBC
Speed of cutting	Fast	Slow	Fast
Thermal deformation	Yes, small area	lack	Yes, wider area
Machining cost	lower	Topmost	lower
Material thickness	Thin and medium	Thick and thin	Medium and thick
Accuracy of cutting	Higher	High	Good
Hardening of material	Yes	No	Yes
Size details	Small and large	Small and large	Large
Shapes	Complex	Complex	Simple
Formation of burr	Yes	Minimal	Yes
Composites cutting	No	Yes	No
Kerf width	≤ 1 mm	– 2.5 mm	> 1 mm
Production level	High level	Medium to low level	Medium level
Operating energy	Small value	Medium to low values	Medium values
Output surface roughness	1 to 10 μm	2 to 6.5 μm	> 6.5 μm
Process type	Thermal	Mechanical	thermal

Fig. 3 CO₂ LBC diagram [37]



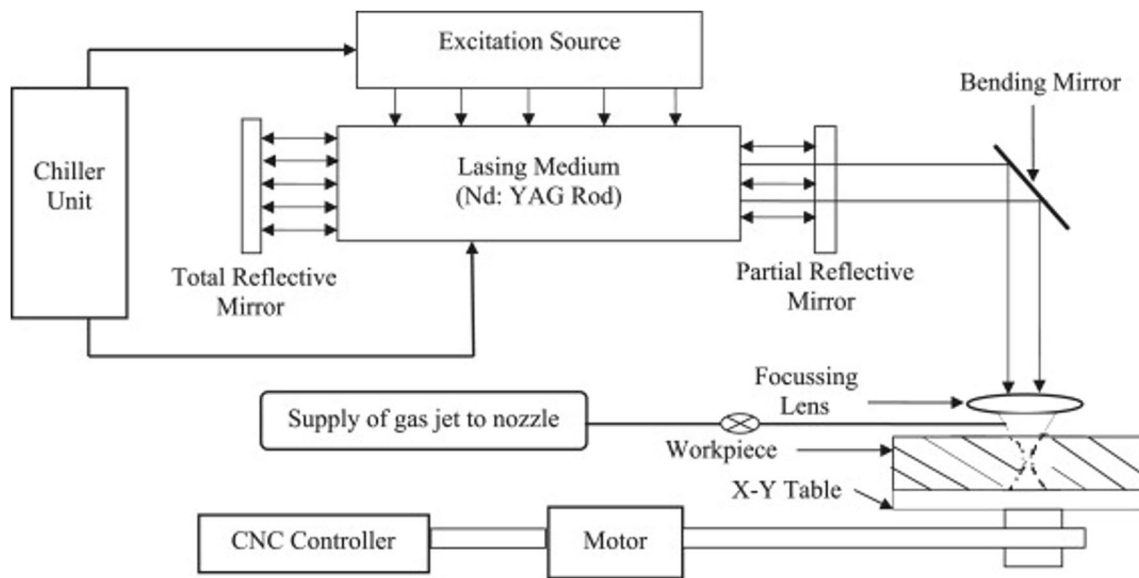


Fig. 4 Nd:YAG LBC diagram [41]

duration [38]. Also it is applicable for the process of microwelding like small electromechanical component seam welding, the welding, and fine cutting of thin sheet metals [39, 40].

1.6.3 Fiber laser

The fiber laser machine is illustrated in Fig. 5, which offers better cutting characteristics and allows for faster, more

precise cutting of thin sheets, such as steel sheets with thickness up to 4 mm. But for the thicker sheets, the cut surface quality of fiber laser is lesser than CO₂ laser cutting quality at the same speed of cut of thicknesses higher than 4 mm as shown in Fig. 6, which shows an image of the cut surfaces of the AISI 304 material obtained by using the fiber laser and CO₂ laser sources for cutting different thicknesses higher than 4 mm. The surface roughness is

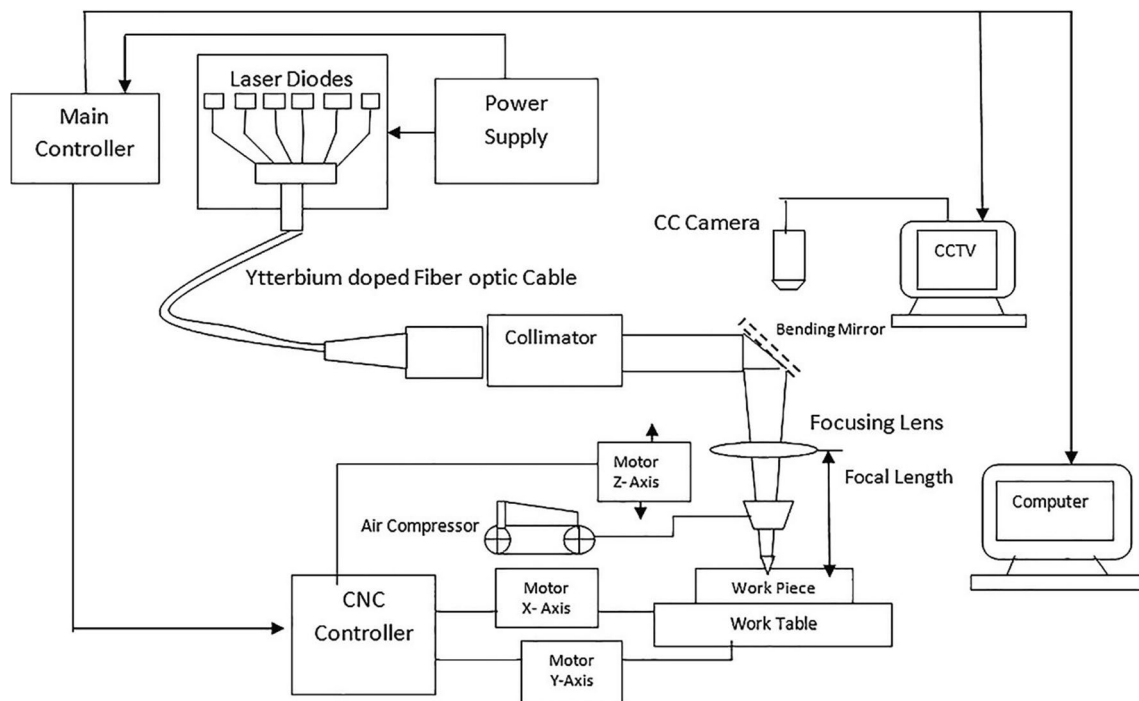


Fig. 5 Fiber LBC diagram [44]

the representation of that mentioned cut quality [34]. As a result, fiber laser is not a favorable method for thick section cutting, as it gives low absorption at the surface of the metal [42]. The fiber laser high focus ability leads to a thin kerf width; because of this, the assist gas flow separation occurs inside the kerf close to the lower cut surface. This causes flow instability close to the lower cut surface. This enhances the uncontrolled burning and removal of molten material close to the bottom surface, leading to the bad quality of the cut surface and the thicker of the bottom kerf width [43].

1.7 A summary of existing review papers and what is new in current one

Table 2 shows the contribution of existing review papers and information added in this review paper.

1.8 The aim of this study

Many experimental studies have been conducted recently with the goal of enhancing the effectiveness of the laser cutting process. So, in this study, a comprehensive review has been

introduced to study how laser cutting parameters affect the metals surface quality and which parameters are affecting the most on the studied surface qualities. Also, brief sections have been introduced to show the number of published papers during the last 22 years and an overview of the advantages of laser cutting when compared to other methods of machining. In addition, a description of the laser cutting method and the different sources of lasers have been presented with clearing the range of thicknesses of the cut material for each source and their advantages. Also, a description of the properties and the applications of the studied material has been discussed. The process, the beam, and the performance parameters of the laser cutting method have been illustrated in detail by graphs and equations. The research analysis and discussion have been showed in such organized details by tables and graphs which shows the full classification of the studied papers by authors, year of publication, studied material, material thickness, assist gas, type of laser source, input parameters, performance parameters, and the key findings of each paper. The discussion section has been illustrated in points to show the effect of the different cutting parameters on the performance of the cutting method represented in the performance parameters such as surface roughness, heat-affected zone, kerf width, kerf taper, and dross height.

2 Materials and their properties

Figure 7 shows the percent of the studied papers based on material type in the selected papers for this review. The figure shows that papers which concentrate on studying the steel alloys are the most in the field of laser cutting because of the high range of the applications that depends on steel. The chart below also shows that titanium alloys are the future field to study with laser cutting because it has been less studied compared to steel and aluminum alloys, which are new to that field because of the difficulties of cutting titanium alloys using laser cutting method. Aluminum alloys are also common when using laser cutting techniques because they are common in that field and have fewer cutting challenges compared to harder materials such as titanium and steel alloys.

2.1 Titanium alloys

Titanium alloys, notably Ti-6Al-4 V, exhibit extraordinary properties in mechanical and chemical sides, like exceptional resistance to corrosion, oxidation, and high temperature. Also, they have high strength-to-weight ratio, high tensile strength, and high value of toughness. Due to this, they are used in common industries such as automobiles, biomedicine, chemicals, petrochemicals, offshore oil and gas, desalination of water, power generation, and aerospace [15, 16, 46–50]. They are generally manufactured using CNC machining after casting or from wrought bar stock.

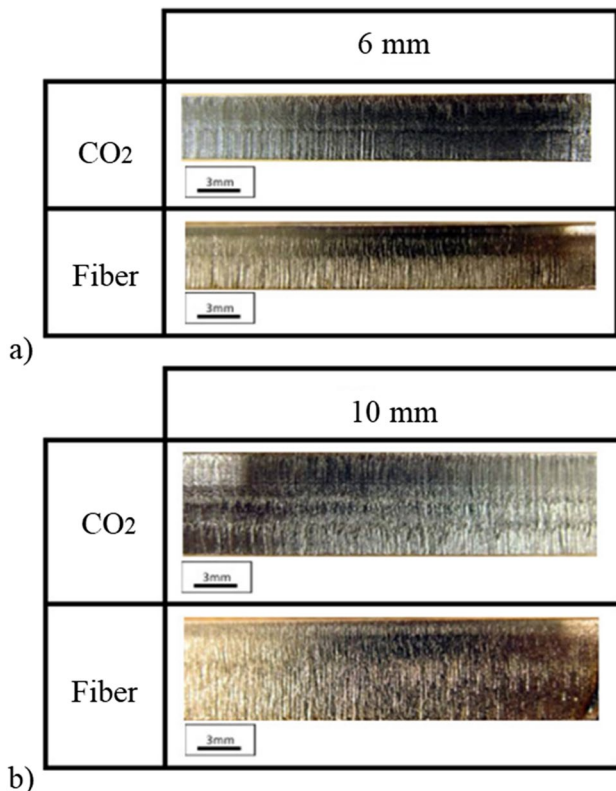
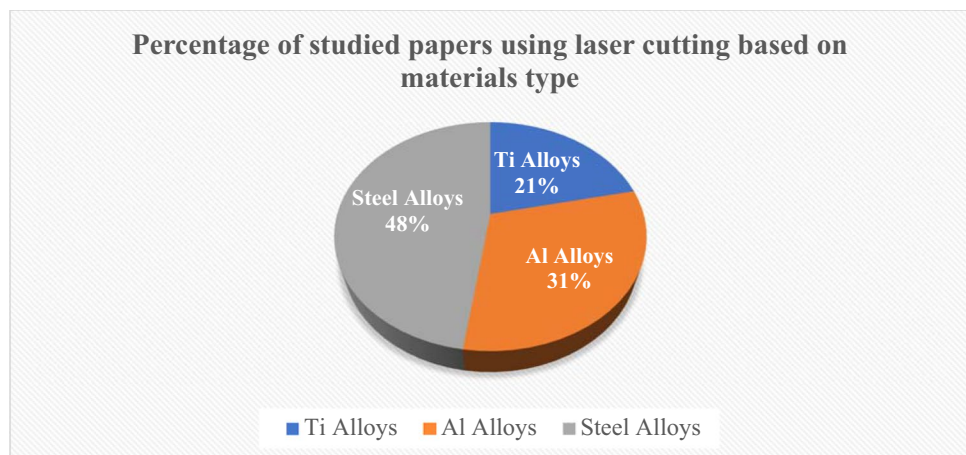


Fig. 6 Images of the cut surfaces of the AISI 304 material obtained by using two different laser sources such as CO₂ and fiber laser for different thicknesses: **a** 6 mm thick; **b** 10 mm thick [45]

Table 2 Comparison of the contribution of previous review papers and this review paper

Reference	Summary	Current contribution
[6, 11]	The study focused only on different steel alloys and their effects when machined using a CO ₂ laser beam. Numerous factors and their impacts were indicated in the studies presented, which were evaluated by several researchers. Thickness, material, and other optimization approaches used by many researchers were also displayed	A full table of steel alloy studies has been added with detailed information and full discussion. In addition, this review focused on three different types of alloys: titanium alloys are high strength alloys, steel is in the middle category in terms of mechanical properties, and aluminum alloys are at the bottom of the mechanical properties of metals. Therefore, three different categories of metals are discussed in this review
[9]	It concentrated on the different mechanisms of material removal rate. In addition, laser cutting of titanium alloys, nickel alloys, and ceramics which are hard materials for conventional machining	The mechanisms of material removal rate are introduced as a performance parameter in the discussion part to show the effect of cutting parameters on MRR. Also, the studied alloys here are different and introduced on a large scale of information and discussion
[10, 36]	The purpose of these studies was to discuss the machining of different engineering materials such as metals, ceramics, plastics, polymers, and woods using CO ₂ laser cutting type. It focused on studies that investigated the effect of cutting parameters on the performance of cutting	Metal alloys have only been discussed here but in detail and using further studies. The input and output parameters are presented in more detail. Many figures and graphs are also provided to enhance the texts
[12]	It concentrated on the history and laser-assisted machining, besides the applications of laser beam machining. The effect of input parameters on output parameters was also studied in some categories such as mechanical properties and metallurgical properties. The effective parameters of the laser cutting method are also presented	More recent studies are presented in this review. More information and details were also entered using tables to make the studies clearer, and many figures and graphs were also provided to improve the quality of the information provided
[14]	It focused on studying the ND-YAG laser method for cutting complex geometries and the research that used this method in its experimental studies. The mechanisms of material removal rate are also discussed	The ND-YAG laser method and MRR mechanisms are presented here in small sections to show their contribution to the field of laser beam manufacturing and get the reader ready for the main part. The review focuses on the contribution of cutting parameters to cutting quality for three different types of materials
[37]	The study focused on various aluminum alloys, their problems during their manufacture using CO ₂ laser beam, and appropriate solutions for them. Numerous factors and their effects have been pointed out in the studies presented	A full table of aluminum alloy studies has been added with detailed information and a full discussion of these studies. In addition, this review discusses the effect of laser beam input parameters using any type of laser sources not only CO ₂

Fig. 7 Laser cutting process based on materials type for the studied papers



However, in the mentioned desirable characteristics of Ti alloys in the practical applications, the tool damage mostly will happen because of the temperature rise, the stress, and the vibration in the region of machining [51, 52]. In addition, Ti alloy machining is extremely difficult because of their high strength, low thermal conductivity (approximately 80% lower thermal conductivity than that of steel), and the chemical reaction with tool materials (at high temperatures) which lead to hazards to cutting tools, causing a substantial decrease in tool life. Furthermore, the relatively low Young's modulus of titanium alloys causes chatter and spring-back, which lowers the quality of the cut surface [53, 54].

2.2 Steel alloys

Several elements, including silicon, boron, vanadium, chromium, nickel, manganese, and molybdenum, are alloyed with steel to create alloy steel. These components are alloyed together to improve the toughness, wear resistance, and hardness. The alloying percentages of the elements can range from 1 to 50%. There are two groups of alloy steels: low alloy and high alloy. It is widely acknowledged that a 5% alloying element marks the distinction between low alloy and high alloy steel. In the field of oil and gas, alloy steel essentially refers to low alloy steel [55]. Also, steel alloys are hard to cut because of the following reasons [9, 56]:

1. During the machining process, the cutting tool fractured because of the high strength and hardness.
2. High dynamic shear strength of steel alloys, abrasive saw teeth, and localized stress are often developed during cutting process.
3. The tool can conduct heat much more quickly at high levels of temperatures close to 1000 °C.
4. When used at high temperatures, most tool materials react with steel alloys, accelerating tool wear.

2.3 Aluminum alloys

Aluminum alloys are employed in many different industries, including the manufacturing of aero planes, machinery, automobiles, and food. The weight-saving qualities of aluminum were increasingly important in the creation of fully electric vehicles. Another benefit is that aluminum can absorb energy in a collision, making these vehicles safer than those made of traditional steel. Compared to cutting steel, cutting aluminum presents a variety of difficulties because of the following reasons [57–62]:

1. Aluminum has a thermal conductivity that is 4 times higher than that of steel at 205.0 W/mK compared to 50.2 W/mK respectively. Rapid heat dissipation is the result, and the heat-affected zone absorbs laser energy. Due to these factors, cutting is done superficially and by vaporization.
2. The increased reflectivity of aluminum. Aluminum alloys are renowned as highly reflective materials that require greater laser power to cut through their poor laser beam energy absorption.
3. Cutting area oxidation and alumina formation (aluminum oxide Al_2O_3). Alumina is a 2072 Co. oxide with a very high melting point. Thermal isolation has another adverse impact; alumina thermal conductivity is 30 W/mK. Heat is not transferred to the aluminum plate because of the limited thermal conductivity.

Most industrial laser sources which are used to cut aluminum are fiber lasers and continuous wave sources which mean the laser power at the output is constant. In addition, nitrogen is utilized as an assist gas [59].

Fig. 8 Schematic of laser cutting with indicated parameters

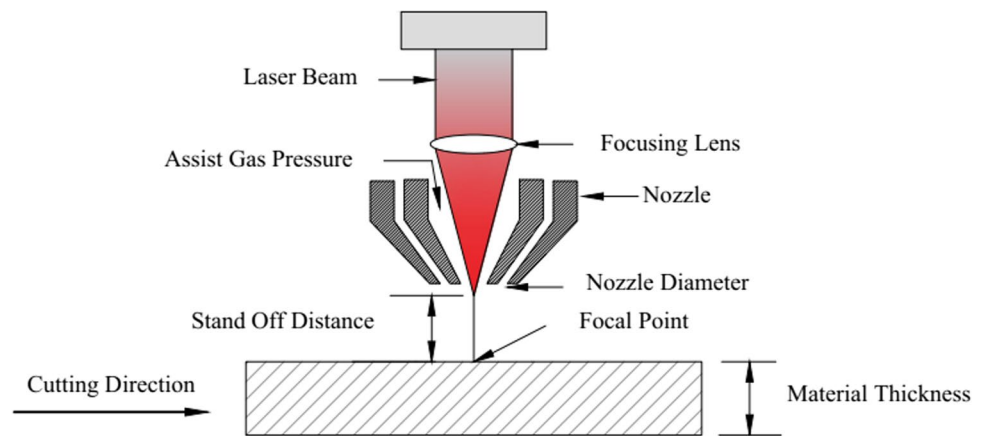


Table 3 Classification of laser cutting parameters

Laser cutting parameters	
Beam Parameters	Process parameters
Wavelength	Focusing of laser beam
Power intensity and spot size	Process gas and pressure
Pulsed laser power	Nozzle diameter
beam polarization	Stand of distance
Types of beams	Cutting speed

3 Laser cutting parameters

As shown in Fig. 8 and Table 3, the laser cutting input parameters of laser beam cutting are categorized into two major sections: beam and process parameters [7, 8, 63].

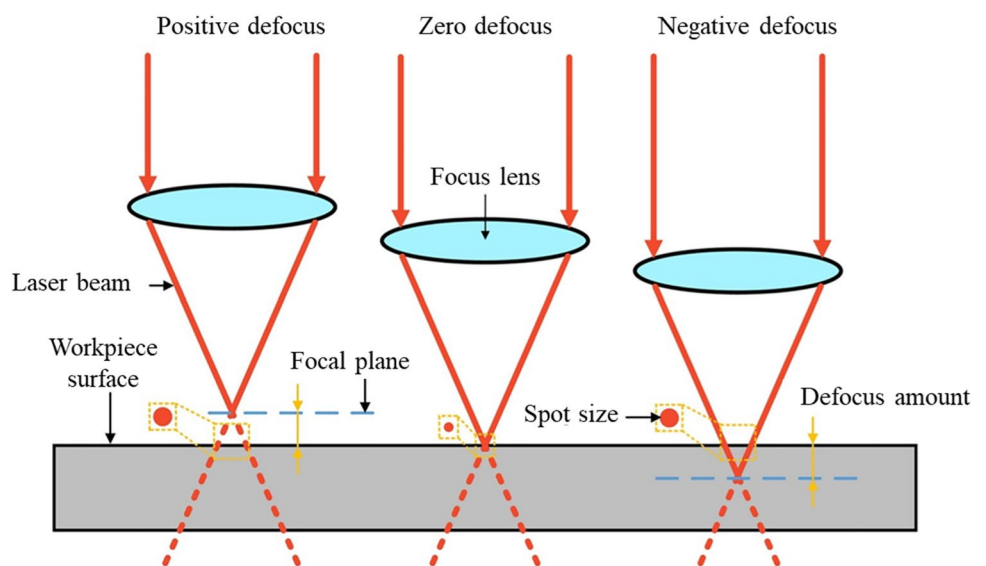
3.1 Beam parameters

Parameters describe the laser beam properties that consist of the power intensity, wavelength, spot size, beam polarization, continue wave pulsed power, types of beams, characteristics of beams, and beam mode.

3.2 Process parameters

The laser process parameters are focal position, which is shown in Fig. 9, focusing on laser beams, dual focus lens, nozzle diameter, assisting gas and pressure, stand-off distance, cutting speed, and alignment. Most of the researchers prefer to control the laser beam power, cutting velocity, and assist gas pressure, as they can control them easily and they are the most effective parameters for most of measured surface quality outputs.

Fig. 9 Focal position representation diagram [64]



4 Laser performance parameters

In this section, the performance parameters as shown in Fig. 10 have been discussed as they are the indication of surface quality. From previous studies, it has been found that surface roughness is the most studied parameter followed by kerf width as they are the most used parameters which indicate the surface quality. So, eight measured parameters have been discussed as follows.

4.1 Surface roughness

It is measured by how far an actual surface deviates towards the direction of its normal vector from its ideal form. The surface is characterized as rough if these variations are considerable and smooth if they are minimal. So, it is an indication for surface quality, and it shows if the surface needs more surface finish or not. They have

found that the laser beam power and cutting speed have the greatest influence on the roughness of the cut surface, as high power at low speed leads to more melted material which leads to bad surface finish. Also using argon as an assist gas helps to get the best surface quality over other assist gas types. Figure 11 shows the smooth and rough surface using SEM.

4.2 Kerf width

The width of the cut path after laser cutting happens is called a kerf width which is shown in Fig. 12. It has two parameters which are the top and bottom kerf width of the cut surface cross-section. The upper kerf thickness is bigger than the bottom kerf thickness as the power is bigger at the top face than the lower face. It is the second performance parameter in the list of discussed parameters in the reviewed papers. The reviewed papers show that the kerf thickness is

Fig. 10 Schematic of laser performance parameters

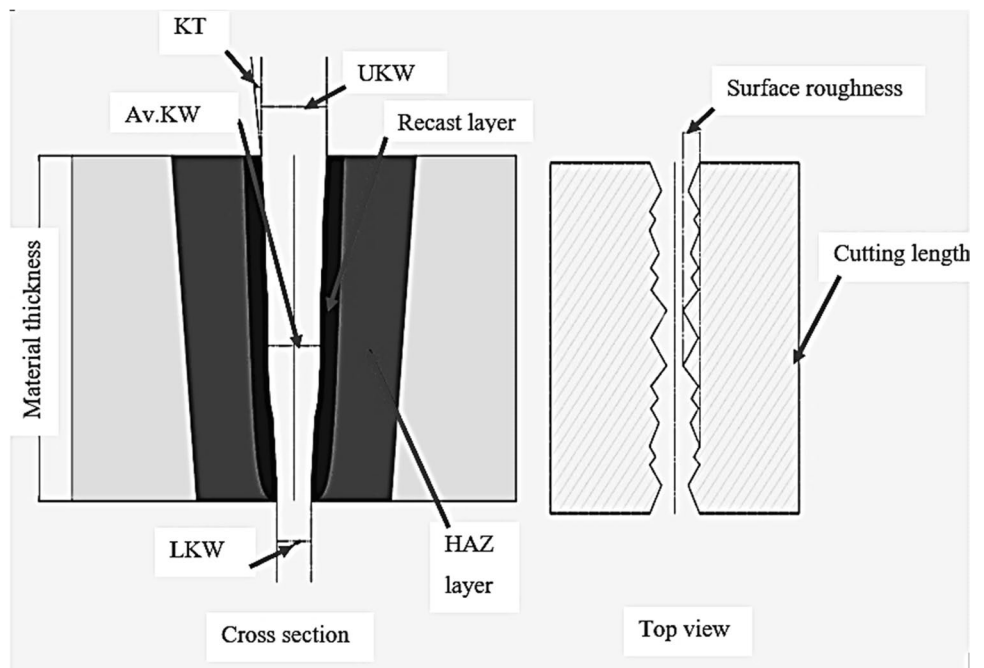
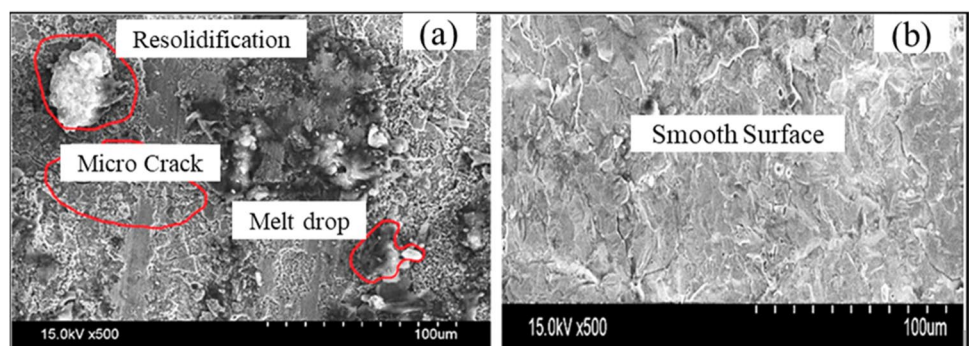


Fig. 11 Difference between rough and smooth surface of titanium alloy using SEM [65]



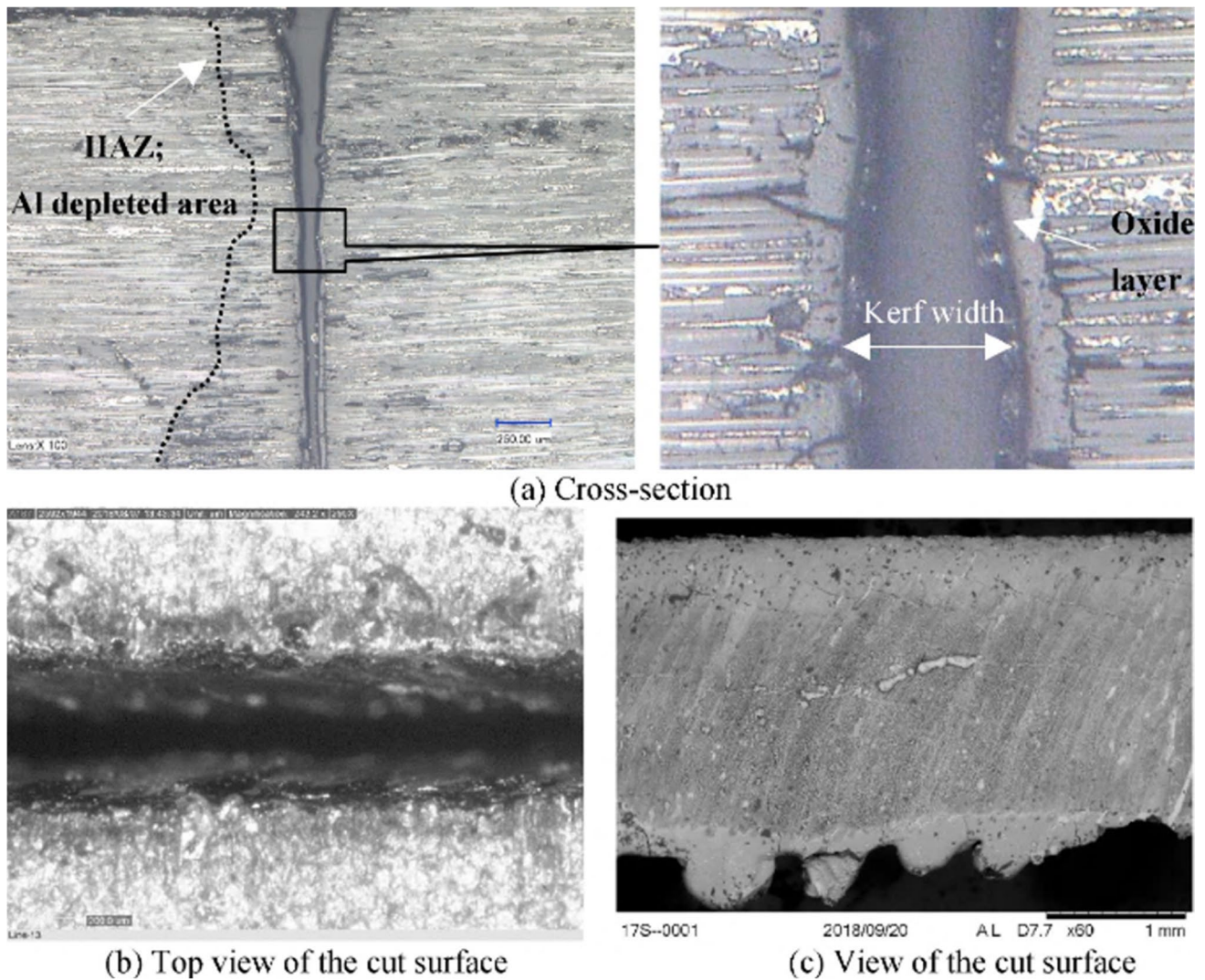


Fig. 12 Kerf width representation of a sample cut by laser beam [66]

proportional to laser beam power and inversely proportional with the cutting speed.

4.3 Kerf taper

Kerf taper in radian is the division of the difference between the upper and lower kerf widths over double of the thickness as shown in Eq. (1) [44], which is shown in Fig. 13. It is the third performance parameter in the list of discussed parameters in the reviewed papers for steel and aluminum alloys, but it is in the fourth place for titanium alloys. The results show that kerf taper is proportional with power and inversely proportional with cutting speed.

$$KT = [(UKW - LKW) \times 180] / (2 \times \pi \times T) \tag{1}$$

where UKW is the upper kerf width, LKW is the lower kerf width, and T is the thickness.

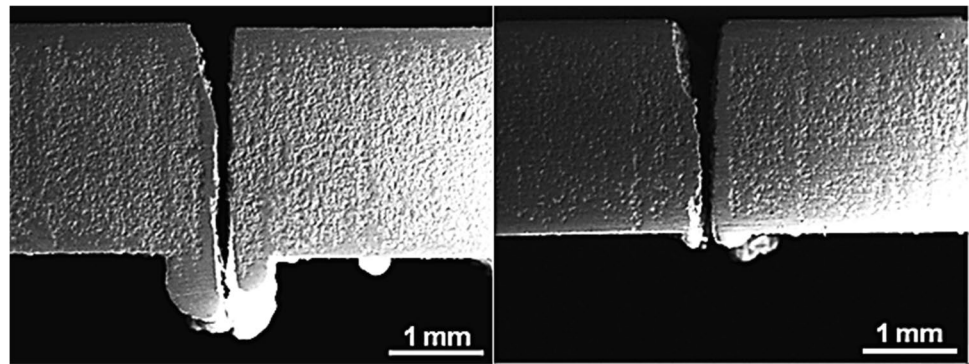
4.4 Heat-affected zone

It is the region whose microstructure changed but did not melt, and its thickness gives an indication of how much the properties of the material have changed during the laser cutting process as shown in Fig. 14. It is in the third place on the list of discussed parameters in the reviewed papers for steel alloys, but it comes in the fourth place for titanium and aluminum alloys. The results show that the width of heat-affected zone (HAZ) is proportional to laser power and inversely proportional to cutting speed.

4.5 Hole profile

The hole profile is like the kerf profile, but the difference is kerf width dealing with linear cutting, but hole profile is dealing with circular profiles as shown in Fig. 15. So, it has the kerf width and kerf taper as the linear profile. Hole kerf width is based on the upper- and lower-hole diameters. The hole kerf taper in radian can be measured as the division of the difference between the upper and lower diameters over double of the thickness. Also, it is affected most with laser power and cutting speed. So, the low power with high speed leads to good hole kerf quality.

Fig. 13 SEM images for kerf taper and drosses representation during laser cutting with conventional and modified way [67]



4.6 Kerf deviation

The difference between maximum kerf width and minimum kerf width over the distance of cut is known as the kerf deviation [38], so the deviation of the kerf width is the representation of the kerf deviation as shown in Fig. 16. The upper kerf width is bigger than the lower kerf width as it is close to the heat source. It also depends on the pulse frequency and the assist gas pressure as studied in the reviewed papers.

$$\text{Kerf deviation (KD) (mm)} = (\text{Avg. Max. TKW} - \text{Avg. Min. TKW}) \quad (2)$$

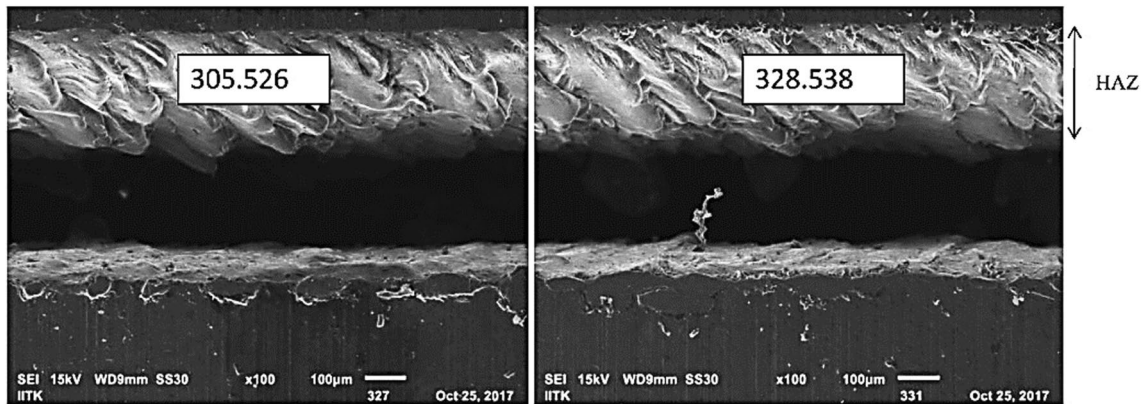


Fig. 14 HAZ boundary after cutting a sample with laser beam [68]

Fig. 15 The entrance and output holes representation during a laser beam drilling [69]

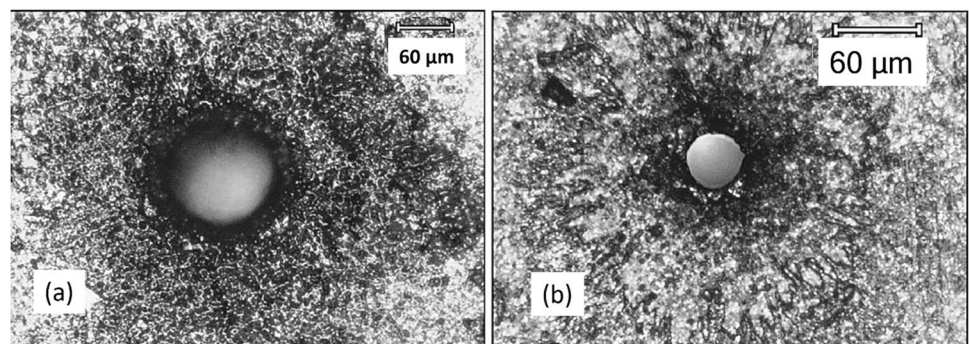
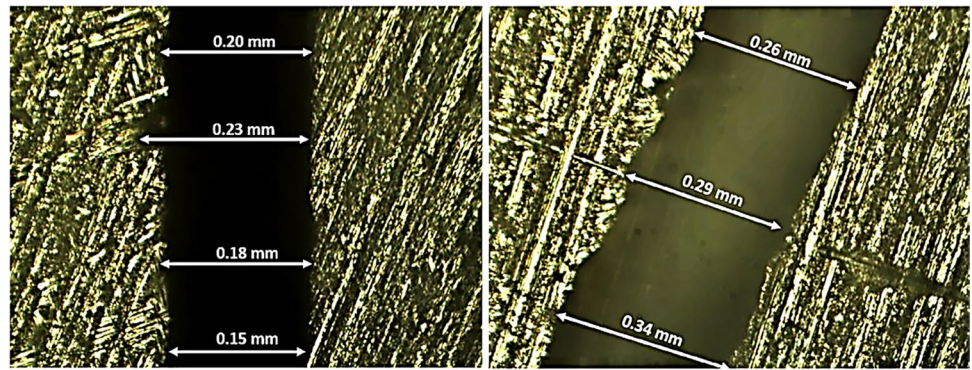


Fig. 16 The representation of the kerf width deviation along the cut path by laser beam at different parameters [70]



where Avg. Max. TKW is the average maximum taper kerf width, and Avg. Min. TKW is the average minimum taper kerf width.

4.7 Hardness

Hardness is the material resistance to localized plastic deformation. Hardness varies from extremely hard materials like diamond, boron-carbide, ceramics, hard metals to soft metals, and down to plastics and soft tissues. Microhardness is proportional with power and inversely proportional with cutting speed for C45 steel alloy as mentioned in reference

[71], but it did not affect power or cutting speed in Al alloy as mentioned in reference [72].

4.8 Material removal rate

Material removal rate is the division of the weight difference of the cut material to the required time for cutting that material [73]. Laser cutting has a machining different mechanisms [6] which is shown in Fig. 17. Unlike the other performance parameters, this performance parameter needs to be high for increasing the efficiency of cutting by reducing the cut time which reduces the cut cost. So, high power with low speed is preferred as laser cutting parameters for this

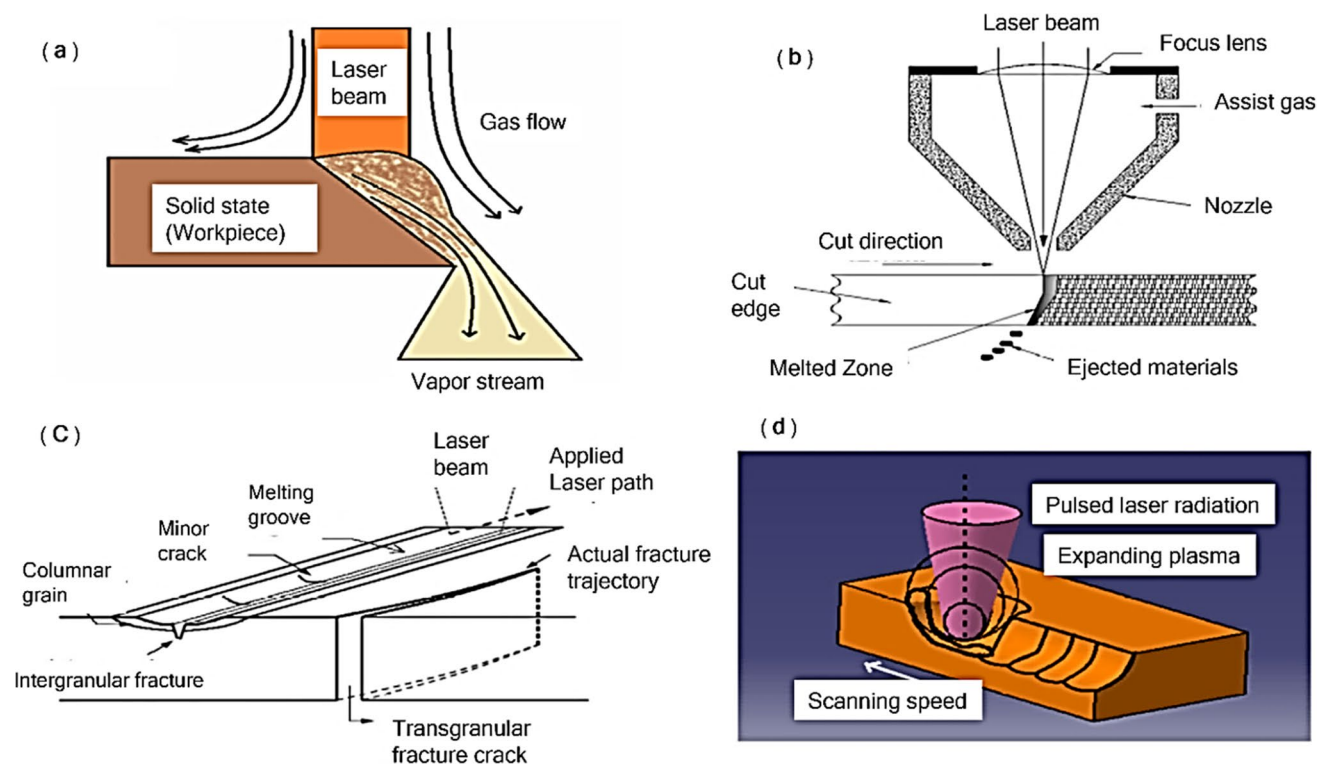


Fig. 17 Laser cutting different mechanisms: **a** laser ablation cutting [74], **b** laser fracture cutting [4], **c** laser fusion cutting [5], and **d** laser vaporization cutting [31]

performance parameter. Also using oxygen as an assist gas is preferred as it adds more heat by the interaction with the material which leads to high material removal rate.

$$MRR(kg/min) = (W1 - W2)/t \quad (3)$$

where $W1$ (kg) is the workpiece weight before cutting, $W2$ (kg) is the workpiece weight after cutting, and t (s) is the cutting time.

5 Research analysis and discussion

Research on laser cutting has been ongoing to enhance the essential properties that are required to be in the cut product, like surface finish, hardness, heat-affected zone, kerf width, kerf taper, kerf deviation, and dross. The cut quality primarily relies on laser power, cutting velocity, assist gas pressure, gas type, laser beam diameter, pulse frequency, focal length, standoff distance, nozzle diameter, etc. From the literature, it is important to optimize the cutting parameters to get the desirable quality of the cut surface [25, 75, 76].

Table 4, Table 5, and Table 6 introduce the reviewed papers with its year of publication, the studied alloy, the thickness of the alloy, the type of the assist gas they used, the laser source they chose to use, the statistical method they used for analysis and optimization, the control parameters they used, the measured parameters they measured, and the results they obtained. Also, all units have the same unification for easy comparison.

6 Discussion

In the following discussion, it is necessary to examine the surface quality in terms of surface roughness, HAZ, hardness, and kerf quality in laser beam machining. Most of the study has been done on sections with relatively thin thicknesses (up to 5 mm), for which other approaches could also be used. But machining with a laser beam demonstrates their ability to cut those materials with better surface quality than other types that cut the same thickness.

Most of the done experimental studies based on laser beam cutting of hard-to-cut materials are primarily intended to investigate the impact of changes in input process parameters, such as laser power, cutting speed, assist gas pressure, standoff distance, nozzle diameter, pulse width, pulse frequency, lamp current, and focal point on output quality characteristics like HAZ, surface roughness, hardness, kerf width, kerf taper, roundness, and deviation where the experiments are carried out based on Taguchi, factorial, artificial neural network, or generic algorithm method.

In addition, there are many points which have been covered in this review paper such as the most recent papers in this field based on the study of three popular metals (titanium alloys, steel alloys, and aluminum alloys) which are used in most of the applications in the industrial field like aerospace industries, spaceship industries, automotive industries, sheet metal works, weldments work, hydraulic industries, and ship industries. On the other hand, the studied papers have been introduced in a way that makes the information easy to read, as they are arranged in a way which makes each point clear and complete to help the researchers get the information in an easy way.

Table 4 shows the effect of the input parameters on the response parameters for titanium alloys in detail by providing the thickness of the cut sheet, the assist gas type, the laser source, the input parameters, the output parameters, and the key factors for the selected papers. It illustrates that when a set of cutting speed, laser beam power, and gas pressure are used as an input parameters, the quality of the cut surface of Ti6Al4V alloy is depending on the speed of cut and the power of the laser beam with values equal 3000W and 2400 mm/min [77]. Also, it shows that the pulse width influences the improvement of the kerf width and kerf deviation with an overall value of 27.39% and the optimized kerf thickness and kerf taper values were discovered to be 0.033 mm and 0.001 mm, respectively, when used beside the power of laser and the speed of cut to machine Ti6Al4V alloy [78].

Table 4 also shows, when using different types of assist gas such as argon, nitrogen, and air to compare their effect on the surface roughness and HAZ of the cut surface, that argon is better than other types to get good surface roughness and small width of HAZ of TC1 alloy and to get thinner HAZ layer and use high pulse rates, medium pulse energies, high cutting speeds, and high-pressure values with argon as an assist gas [4]. The wait time was found to have the biggest effect for material removal rate (MRR) while laser power and pulse frequency are the dominant parameters for taper when these sets of parameters are used to cut Ti6Al4V alloy to see their effect on material removal rate and the taper of the cut kerf, which shows that due to increased thermal energy and better molten metal ejection in the machining area, increased pulse width and gas pressure result in increased material removal rate. Increased non-cutting time throughout the machining time span causes MRR to decrease as pulse interval time increases. Because of the rise in thermal energy and additional metal removal, further taper is caused by an increase in pulse power and frequency [79].

Table 4 also shows that if the speed of cut or the power of laser beam was used separately in a set of cutting parameters, it will be the dominant parameter for the quality of the cut surface. For example, using the speed of cut and the pressure of the assist gas as input parameters to see their effect

Table 4 Laser cutting of titanium alloys

Ref	Year	Material	T (mm)	Gas type	Laser type	Input parameters	Measured parameters	Key factors
[77]	2021	Ti6Al4V	3	Azote	CO ₂	Pu = 1000, 2000, 3000 W V = 480, 1440, 2400 mm/min/P = 2, 8, 14 bar	SR	Laser beam power and the speed of cutting
[78]	2018	Ti6Al4V	1.6	Air	Nd:YAG pulsed	V = 300, 600, 900, 1200, 1500, 1800 mm/min P = 5, 6, 7, 8, 9, 10 bar PW = 1.4, 1.6, 1.8, 2, 2.2, 2.4 mm Frequency = 6, 8, 10, 12, 14, 16 Hz	KW	Cutting speed
[4]	2005	TC1	1	Argon N ₂ Air	Nd:YAG pulsed	V = 30, 60 mm/min/P = 2, 8 bar/F = 10, 20, 25 Hz/PE = 0.5, 1, 2 J	HAZ SR	Use high pulse rates, medium pulse energies, high cutting speeds, and high-pressure values with argon as an assist gas to get thinner HAZ layers
[79]	2019	Ti6Al4V	2	Air	CO ₂	Pu = 300, 500, 700, 900, 1100 W P = 10, 12, 14, 16, 18 bar F = 600, 700, 800, 900, 1000 Hz WT = 0.1, 0.15, 0.2, 0.25, 0.3 s	MRR KT	The wait time has the biggest effect for MRR while laser power and pulse frequency are the dominant parameters for taper
[80]	2020	Ti6Al4V	5	N ₂	CO ₂	V = 480, 1440, 2400 mm/min/P = 2, 8, 14 bar	SR	Cutting speed
[81]	2020	Ti6Al4V	3	O ₂	CO ₂	Pu = 1000, 2000, 3000, 4000 W/P = 2, 3, 4, 5 bar/F = 0.7, 0.9, 1.2, 1.5 Hz/FP = -2, -1, 1, 2 mm	Roundness	Power of the laser beam
[82]	2017	Pure VT1-0	2	Argon	Fiber laser	Pu = 700, 800 W/V = 1500, 2000, 2500, 3000 mm/min/DA = -3, -1.5, 1.5, 3	SR KW	The cutting speed and the laser beam power
[83]	2012	Ti6Al4V	1.4	N ₂	Nd:YAG pulsed	V = 15, 20, 25 mm/min/P = 4-9, 6.87, 8.83 bar/ PW = 1.4, 1.8, 2.2 mm/F = 6, 10, 14 Hz	SR, KW KT	Cutting speed and pulse frequency are the key factors affecting surface roughness, while assist gas pressure and pulse width are for kerf taper
[84]	2021	Pure Ti	2	N ₂	CO ₂	Pu = 2000, 3000, 4000 W/V = 480, 1440, 2400 mm/min/P = 2, 8, 14 bar	SR	Cutting speed
[85]	2021	Pure Ti	3	N ₂	CO ₂	Pu = 2000, 3000 W/V = 480, 1440, 2400 mm/min/P = 2, 8, 14 bar	KW	The speed of cut and the power of laser beam
[86]	2017	Ti6Al4V	2	N ₂	CO ₂	Pu = 500, 1500 W/V = 3000, 6000 mm/min	SR KW	The speed of cut and the power of laser beam
[87]	2013	Ti6Al4V	1.4	N ₂	Pulsed Nd:YAG	V = 900, 1200, 1500 mm/min/P = 5, 7, 9 bar PW = 1.4, 1.8, 2.2 mm/F = 6, 10, 14 Hz	SR KW	Cutting speed and pulse frequency are the key factors affecting surface roughness, while assist gas pressure and pulse width are for kerf taper
[69]	2014	Gamma-titanium aluminide	0.38 0.48 0.58 0.68 0.78	Air	Pulsed Nd:YAG	P = 0.5, 1, 1.5, 2, 2.5 bar F = 0.4, 0.8, 1.2, 1.6, 2 Hz LC = 19, 20, 21, 22, 23 A	KW KT	Lamp current is the dominant parameter on outputs. Pulse frequency influences hole diameters
[38]	2018	Ti6Al4V	1	N ₂	Pulsed Nd:YAG	V = 10, 14, 18 mm/min/P = 6, 7.5, 9 bar PW = 1.5, 1.75, 2 mm/PE = 2.5, 4, 5.5 J	MRR KD	In both single- and multi-objective optimization, the SA algorithm method performs better than GA

Table 5 Laser cutting machining of steel alloys

Ref	Year	Material	T (mm)	Gas type	Laser type	Input parameters	Measured parameters	Key factors
[88]	2017	22MnB5 ultra high strength steel	1.7	N ₂	CO ₂	Pu = 750, 1750, 2750 W/V = 1500, 2500, 3500 mm/ min/DC = 50, 75, 100	KW HAZ	High cutting speed and low value of the power of laser beam give small kerf width; thicker HAZ layer was formed by using a high laser power and low cutting speed
[89]	2017	AISI 316L	2	N ₂	CO ₂	Pu = 2000, 3000, 4000 W/V = 3500, 4500, 5500 mm/ min/P = 7, 8, 9 bar	KW	Cutting speed
[90]	2020	Strenx 900 steel plate	5	N ₂	CO ₂	Pu = 500, 600, 700 W/V = 800, 850, 900 mm/min/P = 6, 8, 10 bar	SR	The power of the laser beam
[91]	2017	AISI 304	3	N ₂	CO ₂	Pu = 1800, 2000 W V = 2000, 3000 mm/min P = 9, 10.5, 12 bar FP = -0.5, -1.5, -2.5 mm	SR KW HAZ KT MRR	The PSI approach is ineffective when there are numerous alternatives with characteristics that are very similar to the chosen. Since the proposed approach contains straightforward, simple-to-understand, and easy-to-implement processes, it is proven to be quite useful in actual manufacturing environments
[64]	2022	Mild steel	25	O ₂	Fiber laser	V = 1050, 1100, 1150, 1200, 1250 mm/min/P = 0.9, 0.95, 1, 1.05, 1.1 bar/SOD = 0.3, 0.35, 0.4, 0.45, 0.5 mm/DA = 10, 10.5, 11, 11.5, 12	KT	Cutting speed
[92]	2021	SS304	5	N ₂	CO ₂	V = 2000, 2500, 3000 mm/ min/P = 9, 10.5, 12 bar/ FP = -0.5, -1.5, -2.5 mm	SR	The focal point location
[93]	2022	SS304	5	N ₂	CO ₂	Pu = 1800, 2150, 2500 W/V = 600, 800, 1000 mm/min/P = 0.9, 1.1, 1.3 bar/F = 1500, 1750, 2000 Hz	SR	The laser beam power and the speed of cut

Table 5 (continued)

Ref	Year	Material	T (mm)	Gas type	Laser type	Input parameters	Measured parameters	Key factors
[94]	2018	SS316	2	N ₂	CO ₂	Pu = 1000, 1250, 1500 W/V = 1000, 2000, 3000 mm/min/P = 10, 12.5, 15 bar/FP = 0, -1, -2 mm	SR KW	The two main factors affecting surface roughness are laser power and focal point position. Cutting speed has the most influence when determining upper kerf width, followed by assist gas pressure. Lower kerf width is mostly affected by laser power followed by cutting speed
[95]	2020	AISI 304	1 3 6	N ₂	CO ₂	V = 2300, 5200, 8900 mm/min/P = 4.5, 9 bar/FP = -2.5, 1, 1.5 mm/ND = 1.4, 1.7, 2.3 mm	SR KW KT	The workpiece thickness has an impact on the top kerf width. Material type, gas pressure, and thickness all had an impact on the bottom kerf width. The taper angle is influenced by material type. Material type and cutting speed have an impact on the surface roughness
[96]	2013	AISI 304	2.5 5 6	O ₂	CO ₂	V = 3300, 3700, 5200 mm/min/P = 0.7, 0.8 bar/FP = 0.5, 2.5 mm/ND = 0.8, 1 mm	SR KW	Surface roughness increases in fiber laser between 4- and 6-mm thickness. Surface roughness increases in CO ₂ laser cutting between 8 and 10 mm thickness
[86]	2017	AISI 304	2	N ₂	CO ₂	Pu = 500, 1500 W/V = 3000, 6000 mm/min	SR KW	Kerf width is inversely proportional with cutting speed and proportional with power. Cast layer thickness is proportional with power and inversely proportional with cutting speed
[97]	2014	AISI 304	3	N ₂	CO ₂	Pu = 1600, 1800, 2000 W/V = 2000, 2500, 3000 mm/min/P = 9, 10.5, 12 bar/FP = -0.5, -1.5, -2.5 mm	SR KW HAZ MRR	The cutting speed and the power of laser beam
[5]	2005	Stainless steel	1.2	N ₂ or O ₂	Pulsed Nd:YAG	Pu = 900, 1100 W/V = 1000, 2000 mm/min/P = 9, 11 bar/F = 200, 250 Hz/FP = -0.5, -1 mm	KW SR	The speed of cut and the laser beam power with argon as an assist gas
[98]	2019	Hardox 400 Hardox 450	10 12			P = 4100, 4200, 4300 W V = 1200, 1600 mm/min Pu = 3700, 3800, 3900 W V = 1450, 1650 mm/min	KW E ₁ E _s E _v	Laser power and cutting speed have the largest influence on LSE. Thickness is the most effective parameter for SSE

Table 5 (continued)

Ref	Year	Material	T (mm)	Gas type	Laser type	Input parameters	Measured parameters	Key factors
[99]	2013	AISI 304	1	Diode laser CO ₂ Fiber laser		V=9000, 12,000 mm/min/P=8, 20 bar/F=1.5, 2.4 mm/ SOD=0.5, mm/ND=1, 2 mm	SR	Diode is less bright than fiber laser in thin metals. Diode quality is less than fiber in thin metals but good as fiber in thick metals
[100]	2018	AISI 304 St37-2	1 2 3 4	N ₂ and O ₂	CO ₂	Pu=1000, 2000, 3000 W/P=16 with N ₂ , 5 with O ₂ /FP=170, 190 mm	KW SR	N ₂ as an auxiliary gas gives a good surface quality compared to O ₂ but cut thinner parts than O ₂ , also O ₂ leads to bigger kerf width than N ₂
[101]	2021	Hardox 400	8	O ₂	CO ₂	Pu=4900, 5000, 5100 W/V=1700, 1800, 1900 mm/min/P=0.45, 0.5, 0.55 bar	KW	The cutting speed and the power of laser beam
[102]	2018	AISI 304	2.5	N ₂	CO ₂	Pu=2000, 3000, 4000 W/V=3500, 4500, 5500 mm/min/P=7, 8, 9 bar	KW	The cutting speed and the power of laser beam
[103]	2018	Mild steel	3	N ₂	CO ₂	Pu=800, 900, 1000 W/V=1300, 1400, 1500 mm/min/P=0.05, 0.15, 0.25 bar	KW KT	Laser power and speed of cut
[104]	2016	AISI316L	10	N ₂	CO ₂	V=110.4, 550.2, 990 mm/min	SR HAZ	Surface roughness, the size of the heat-affected zone, and dress are all directly impacted by cutting speed
[1]	2003	4130 Steel	1.7	N ₂	CO ₂	Pu=700, 900, 1100, 1300 W V=1776, 2286, 2796, 3300 mm/min	KW HAZ SR	Low laser power and high cutting speed lead to a small kerf width, width of HAZ, and minimum roughness
[105]	2007	EN43	2	O ₂	Fiber laser	Pu=600, 1000 W/V=1800, 5100 mm/min/P=0.5, 3 bar/FP=-5, 13 mm/SOD=1, 2 mm	SR	The laser beam power and the speed of cut
[106]	2020	AISI 304	1.5	N ₂	Fiber laser	Pu=420, 450, 480 W/V=60, 72, 90 mm/min/P=8, 10, 12 bar/DA=-1, 0, 1 mm	KW SR	Cutting speed, defocusing, laser power, and assist gas pressure all have an impact on kerf width. Cutting speed, then laser power, has an impact on surface roughness
[107]	2005	ZStE260P ZStE260+Z100 ZStE260+ZE DP750 GXE 450B	1	O ₂	CO ₂	Pu=200, 600 W/V=2000, 8000 mm/min/P=3, 8 bar/FP=1, 1.5 mm	SR	The cutting speed and the laser beam power

Table 5 (continued)

Ref	Year	Material	T (mm)	Gas type	Laser type	Input parameters	Measured parameters	Key factors
[71]	2017	C45	6	N ₂	CO ₂	Pu = 3000, 4000, 5000 W V = 560, 1400, 2240 mm/min	SR HAZ Hardness	HAZ layer thickness and roughness values are inversely proportional with cutting speed and proportional with power. Microhardness is proportional with power and inversely proportional with cutting speed
[108]	2014	S355J2G3 EN 10025	2	O ₂	CO ₂	Pu = 700, 900, 1100, 1300, 1500 W V = 3000, 4000, 5000, 6000, 7000 mm/min P = 3, 4, 5, 6, 7 bar	SR	Surface roughness has a proportional relation with the pressure of the assist gas, and it has inversely proportional relation with laser power and cutting speed
[109]	2013	AISI 304	1	Air	Fiber laser	No. of. pulses 1–2–3–4–5–6–7–8–9–10	KW KT	MRR decreases with each pulse, as the laser beam defocusing when the hole comes deeper
[110]	2016	SS-304	5	N ₂	CO ₂	Pu = 1300, 1500, 1700 W V = 2000, 2100, 2200 mm/min P = 0.5, 0.6, 0.7 bar	SR	The power of laser beam
[3]	2008	high silicon- alloy steel	0.5	O ₂	Pulsed Nd:YAG	V = 25, 50, 75 mm/min/P = 1.5, 2.5, 3.5 bar/F = 20, 24, 28 Hz/ PW = 1, 1.2, 1.4 mm	KW MRR	KW is significantly influenced by cutting speed, pulse width, the square of the pulse width. MRR is significantly influenced by cutting speed, frequency, pulse width, and the square of cutting speed
[45]	2015	AISI 304	6 10		Laser type = fiber laser, CO ₂		SR	Industrial practice agrees that CO ₂ has a superior cut quality than fiber lasers when cutting sheets that are 6 mm thick. However, in the case of 10 mm thickness, neither technology stands out to demonstrate superior quality
[111]	2014	1.4828 (X15CrNiSi20-12) 1.4571 (X6CrNiMoTi17-12-2)	3 4	N ₂	CO ₂	V = 550, 725, 900, 1075, 1125 mm/min/P = 7.5, 10, 12.5, 15, 17.5 bar/FP = -2, -1, 0, 1, 2 mm/SOD = 0.5, 0.75, 1, 1.25, 1.5 mm	SR HAZ	For minimum surface roughness and small width of HAZ use high cutting speed and focus position above the cut surface with nitrogen as an assist gas

on the roughness of the cut surface, it has been found that the speed of cut is the dominant parameters on the roughness of the cut surface when cutting a Ti6Al4V alloy. Also, when laser beam power is used with the assist gas pressure, the frequency, and the focal point as an input parameter to check their effect on the roundness of the cut path when cutting Ti6Al4V alloy, it has been found that laser power is the dominant parameter on the output [80, 81]. Also, when the speed of cut, the power of laser beam, and the defocusing amount have been used as an input parameters, to see their effect on the roughness of the cut surface and the width of the kerf of cut by cutting the pure VT1-0 alloy by fiber laser source, it has been found that cut at the highest cutting speed was between 100 and 200 Hz for optimal cutting. Gas pressure ought to be between 10 and 12 bar when cutting materials are up to 2 mm thick, and the focal spot should be positioned on the material's surface [82]. Cutting speed and pulse frequency are the key factors affecting surface roughness, while assist gas pressure and pulse width are for kerf taper when Ti6Al4V alloy was cut. So, it is recommended to use lower values of frequency and pulse width, greater values of cutting speed, and a moderate nitrogen gas pressure to achieve satisfactory cutting quality in Ti6Al4V [83, 87]. When cutting a pure titanium and Ti6Al4V alloy by using a set of the power of laser beam, the speed of cutting, and the assist gas pressure as an input parameter to see their effect on the width of the kerf of cut, it was found that for both materials kerf width is inversely proportional with cutting speed and proportional with laser power [85].

Table 4 also shows that cast layer thickness is proportional with power and inversely proportional with cutting speed; also, kerf width is inversely proportional with cutting speed and proportional with power when Ti6Al4V alloy was cut using the power of the laser beam and the speed of cutting as an input parameters to see their effect on the quality of the cut surface and the width of the cut kerf [86]. It also shows when a set of assist gas pressure, pulse frequency, and lamp current are used to machine a different small thicknesses of Gamma-titanium aluminide alloy to investigate their effect on the width and the taper of the kerf of cut, lamp current was found the dominant parameter on outputs. Pulse frequency influences hole diameters. Thickness and assist gas pressure influence the exit hole diameter and hole taper [69].

Table 5 reveals the effect of the input parameters on the response parameters for steel alloys in detail by providing the thickness of the cut sheet, the assist gas type, the laser source, the input parameters, the output parameters, and the key parameters for the selected papers. For example, when a set of laser beam power, the velocity of the cutting, and defocusing amount are used to machine a 22MnB5 ultra-high-strength steel alloy to investigate their effect on the width and the HAZ of the kerf of cut, laser power and speed of cut were found the dominant parameters on outputs. Optimum

values for minimum kerf and HAZ happened at 895W, 1923.44 mm/min at 100% of duty cycle. Minimum kerf taper happened at 779W, and 2268.65 mm/min at 100% of duty cycle [88]. Also, when a set of laser beam power, the velocity of the cutting, the pressure of the assist gas, and the defocusing amount are used as an input parameters to machine a set of different steel alloys to investigate their effect on the roughness of the cut surface and the width of the cut kerf, it has been found that cutting speed, defocusing, laser power, and assist gas pressure all have an impact on kerf width. Cutting speed, then laser power, has an impact on surface roughness. For minimum kerf width, optimum values were 420 W for laser power, 90 mm/min for speed, 10 bar for pressure, and – 1 mm for defocusing. For minimum surface roughness, optimum values were 420 W for laser power, 60 mm/min for speed, 8 bar for pressure, and – 1 mm for defocusing [106]. Also, when a set of laser beam power, the velocity of the cutting, the pressure of the assist gas, and the focal point are used as an input parameters to machine a set of different steel alloys to investigate their effect on the roughness of the cut surface, it has been found that the high quality of cutting happens at 0.7–0.8 mm of sheet thickness at high cutting speeds, low power with medium cutting speeds, medium power with high cutting speed, and medium assist gas pressure, and the focal position ought to be near the sheet lower surface [107].

Table 5 also reveals when a set of an AISI beam power, the velocity of the cutting, and pressure of the assist gas are used to machine a AISI 316L alloy to investigate their effect on the width of the kerf of cut, the speed of cut was found the dominant parameter on output. Optimum values for minimum value of surface roughness happened at 600W, 900 mm/min, and 6 bar [89]. But when the alloy has been changed to Strenx 900 steel plate alloy and the same set of laser beam power, the speed of cut, and the pressure of the assist gas were used, it was found that the laser power has the most influence on surface roughness over the other parameters, and the optimum values for minimum value of surface roughness happened at 600W, 900 mm/min, and 6 bar [90].

Furthermore, it also shows that when cutting Hardox 400 alloy by using oxygen as an assist gas with laser power, speed of cut, and pressure of oxygen as an input parameters to see their effect on the width of the cut kerf, it has been discovered that using a laser with a power of 5000 W, an auxiliary gas pressure of 0.50 bar, and a constant cutting speed of 1900 mm/min gets a fine cut. Kerf width depends on the amount of heat which is based on laser power and cutting speed, so low power and high cutting speed will lead to small kerf width [101]. It also shows that when cutting AISI 304 alloy using nitrogen as an assist gas with laser power, speed of cut, and pressure of nitrogen as an input parameters to see their effect on the width of the cut kerf, it has been

discovered that using a laser with a power of 2571 W, an auxiliary gas pressure of 8.99 bar, and a constant cutting speed of 5498 mm/min gets a fine cut. Kerf width depends on amount of heat which is based on laser power and cutting speed, so low power and high cutting speed will lead to small kerf width, so cutting speed and laser power are the dominant parameters for small and fine kerf width [102].

Table 5 also displays that, as it has been mentioned in titanium alloys, when the power of laser beam or the speed of cutting is used separately with a set of other parameters, it becomes the most effective parameters of cutting over the other parameters. For example, when the speed of cut, the pressure of the assist gas, the focal point, and the pulse width are used as input parameters to see their effect on the width of the kerf of cut and the material removal rate by cutting high silicon-alloy steel, it has been found that using hybrid TMRSM makes an improvement in both MRR and kerf width (KW) over Taguchi method. KW is significantly influenced by cutting speed, pulse width, the square of the pulse width, and the interplay between the pulse frequency and the cutting speed. MRR is significantly influenced by cutting speed, frequency, pulse width, and the square of cutting speed [3]. Another trial happened when the speed of cut, the pressure of the assist gas, the standoff distance, and the defocusing amount are used as input parameters to see their effect on the taper of the kerf of cut for cutting mild steel; it has been found that the cutting speed is the effective parameter over defocus amount, stand-off distance, and assist gas pressure. For thick mild steel plates, the oxygen-assisted laser cutting process window is comparatively small [64].

Moreover, when the speed of cut, the assist gas pressure, the focal point, and the standoff distance are used as an input parameters to see their effect on the roughness of the cut surface and the width of the HAZ layer by cutting two different materials which are 1.4828 (X15CrNiSi20-12) and 1.4571 (X6CrNiMoTi17-12-2) alloys with nitrogen as an assist gas, it has been found that nitrogen gives a better surface quality. For minimum surface roughness, use high cutting speed with focus position above the cut surface. The optimum values of parameters are 1000 mm/min, 15 bar, and +1 for focus position for 1.4828 alloy. Surface quality is achieved better in small thickness and also cutting speed is inversely proportional with thickness [111]. But one of the set which were velocity of cut, the pressure of the assist gas, and the focal point to cut a SS304 presented a different result which was that the focal point is the dominant parameter on surface roughness not the cutting speed and the optimum values for minimum value of surface roughness happened at 2400–2600 mm/min, 11.5–12 bar, and pulse frequency – 2.2 and – 2.5 mm [92].

Table 5 also shows, when a set of the power of laser beam, the speed of cut, the pressure of the assist gas, and the focal point as an input parameters to see their effect on

the roughness of the cut surface and the width of the kerf of cut by cutting SS316 alloy, that the two main factors affecting surface roughness are laser power and focal point position. Cutting speed has the most influence when determining upper kerf width, followed by assist gas pressure, and lower kerf width is mostly affected by laser power followed by cutting speed [94]. Also, it shows that when a study has been done on AISI 304 and St37-2 with different sheet thicknesses by using a set of parameters to see their effect on the roughness of the cut surface and the properties of the kerf of the cut, it was found that the workpiece thickness has an impact on the top kerf width. Material type, gas pressure, and thickness all had an impact on the bottom kerf width. The taper angle is influenced by material type. Material type and cutting speed have an impact on the surface roughness [95].

Table 5 also shows, when a set of cutting speed and laser power were used to cut AISI 304 to see their effect on surface roughness and the width of the kerf of cut by using two different sources of laser which are CO₂ and fiber laser to cut a range of thicknesses from 1 to 10 mm, that surface roughness increases in fiber laser between 4- and 6-mm thickness. Surface roughness increases in CO₂ laser cutting between 8- and 10-mm thickness. Max. cutting speed was around 7000 mm/min. There is some difference in kerf profile [96]. Also, when a set of cutting speed and laser power were used to cut Hardox 400 and Hardox 450 alloys to see their effect on the width of the kerf of cut, longitudinal, surface, and volume energies by using two different thicknesses, it has been found that laser power and cutting speed have the largest influence on LSE. Thickness is the most effective parameter for SSE. Low thickness, high speed, and medium power are the effective mix for VSE [98]. Also, when a set of the power of laser beam and the speed of cut are used to investigate the roughness of the cut surface, the width of HAZ layer, and the width of the cut kerf of 4130 steel alloy, it has been found that low laser power and high cutting speed lead to a small kerf width, width of HAZ, and minimum roughness. Cutting speed is the next most important factor in determining kerf width after laser power. Cutting speed is the dominant parameter on surface roughness followed by laser power [1].

Table 5 also shows, when using two different types of assist gas which are nitrogen and oxygen to compare the effect of them on the surface roughness, and the width of the kerf of the cut by cutting the stainless-steel alloy, that for minimum surface roughness and kerf width, use low values of laser power, high cutting speed, high frequency, and low assist gas pressure. For smooth cut and small kerf width, using N₂ is preferred over using O₂, but it is not economical [5]. It also shows when using two different types of assist gas which are nitrogen and oxygen to compare the effect of them on the surface roughness; the width and the taper of the kerf of the cut by cutting the AISI 304 and St37-2 alloys

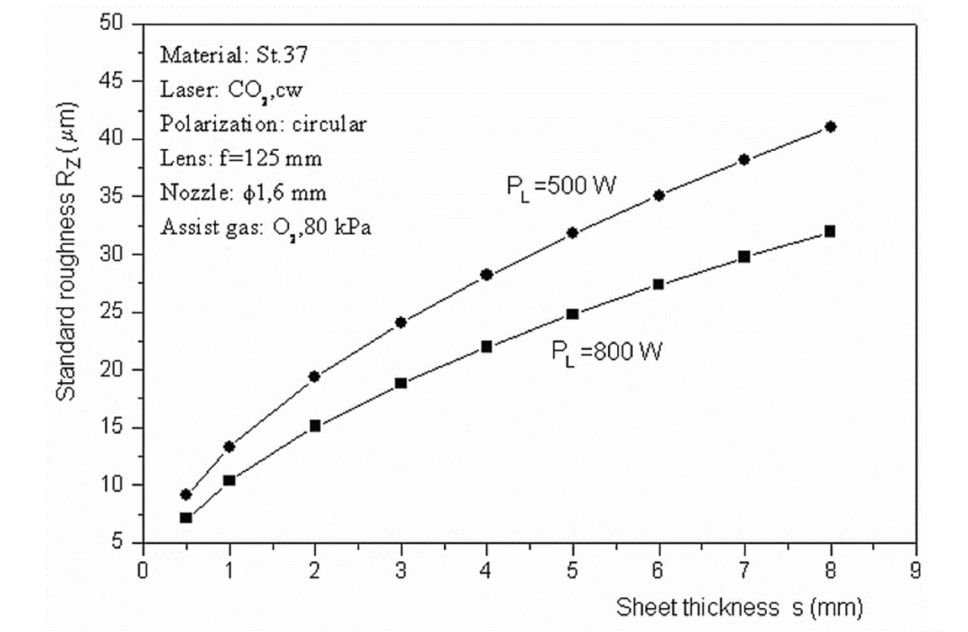
Table 6 Laser cutting machining of aluminum alloys

Ref	Year	Alloy	T (mm)	Gas type	Laser type	Input parameters	Measured parameters	Key factors
[72]	2021	Al-2024-T3	2	N ₂	CO ₂	Pu=1800, 2600, 3400 W/V=3500, 5000, 6500 mm/min	SR HAZ Hardness	HAZ layer thickness and roughness values are proportional with power and inversely proportional with cutting speed, but hardness did not affect by cutting speed or power
[112]	2021	Al 6351	3	N ₂	CO ₂	Pu=3000, 3100, 3200 W/V=7000, 7200, 7400 mm/min/P=6, 7, 8 bar	SR KW	The cutting speed is the effective parameter for the outputs
[113]	2021	Aluminum alloy foil	0.05	Air	CO ₂	Pu=20, 30, 100 W/V=4200, 6000, 12,000 mm/min/P=0.5, 0.7, 0.9 bar	SR	The speed of cut and the power of laser beam
[114]	2017	Al-2024-T3	3	CO ₂	CO ₂	Gas type = argon, N ₂ , O ₂ , air	SR HAZ	Argon is the best choice as an assistant gas for best quality and efficiency
[70]	2021	Al-5052		N ₂	CO ₂	Pu=1000, 1500, 2000 W/V=500, 1500, 2500 mm/min/SOD=0.8, 1.3, 1.8 mm/ND=1.4, 1.7, 2 mm	SR KW	The primary factors for the output values are the laser power and cutting speed
[115]	2022	SiCp/Al Composite	5	N ₂	Fiber laser	Pu=3500, 4000, 4500 W/V=1500, 2000, 2500 mm/min/P=4, 6, 8 bar	KW KT	The cutting speed is the dominant for kerf angle followed by assist gas pressure
[116]	2022	AA2B06		Air	Fiber laser	Thickness = 1.5, 2 mm/Pu=1000, 2000, 3000 W/V=3000, 6000, 9000 mm/min/P=5, 10, 15 bar	SR EE	The laser beam power and the speed of cut
[117]	2015	Al6061/SiCp/Al ₂ O ₃ composite	4	N ₂	CO ₂	Pu=2000, 2500, 3000 W/V=600, 1200, 1800 mm/min/P=8, 10, 12 bar/F=8, 10, 12 Hz	SR KW KT	The cutting speed and the laser beam power
[118]	2009	AA5083	2	N ₂	CO ₂	Pu=1500, 1650, 1800 W/V=2000, 3000, 4000 mm/min/P=10, 12, 14 bar/F=8, 9, 10 Hz	SR KW HAZ	The surface roughness values depend on the assist gas pressure and pulse frequency. HAZ and kerf width is inversely proportional with cutting speed and proportional with power
[95]	2020	AlMg ₃		N ₂	CO ₂	Thickness = 2, 4, 6 mm/V=2200, 4200, 8600 mm/min/P=8, 9, 10 bar/PW=0, -1.5, -7 mm/ND=1.7, 2, 2.7 mm	SR KW KT	The workpiece thickness had the biggest impact on the top kerf width. The type of material, gas pressure, and thickness all had a significant impact on the bottom kerf width. The material type had the biggest impact on the taper angle. Surface roughness affected by material type and cutting speed
[119]	2015	Al 6061-T6	1	N ₂	Pulsed Nd:YAG	Pu=2280, 3330 W/F=150, 659 Hz/CD=0.1, 0.3 ms	KW KT	The kerf width in addition to the taper angle are influenced by the direction of the beam. The down kerf, taper angle, and cross height are all impacted by the pulse duration

Table 6 (continued)

Ref	Year	Alloy	T (mm)	Gas type	Laser type	Input parameters	Measured parameters	Key factors
[86]	2017	Al ₂ O ₃	2	N ₂	CO ₂	Pu = 500, 1500 W V = 3000, 6000 mm/min	SR KW	Kerf width is inversely proportional with cutting speed and proportional with power. Cast layer thickness is proportional with power and inversely proportional with cutting speed
[41]	2012	Aluminum alloy grade 40,800	0.7	O ₂	Pulsed Nd:YAG	V = 8, 10, 12 mm/min/P = 4, 6, 8 bar/F = 10, 12, 14 Hz/PW = 1.4, 1.6, 1.8 mm	SR KT	The cutting speed and assist gas pressure have the most effect on the kerf taper. Surface roughness was influenced by pulse frequency, assist gas pressure, and cutting speed
[120]	2019	Al 6061-T6			CO ₂	Thickness = 1, 3 mm/Pu (1 mm) = 1500, 3000 W/Pu (3 mm) = 2500, 3500 W/V = 2000, 4000 mm/min/P = 5, 6 bar/SOD = -1, 0, 1 mm	SR	The cutting speed and the laser beam power
[121]	2020	AL6061T6				Thickness = 1.5, 3 mm/Pu (1.5mm) = 1500, 2000, 3000 W/Pu (3mm) = 2500, 3000, 3500 W/V = 2000, 3000, 4000 mm/min/P = 5, 6 bar	SR	With increasing laser power, anticipated values for cutting temperature increase while those for surface roughness drop. Higher values of sheet thickness result in higher surface roughness and lower cutting temperature values
[122]	2007	Al alloy	0.9	O ₂	Pulsed Nd:YAG	V = 7.5, 12.5, 17.5 mm/min/P = 4, 6, 8 bar/F = 18, 23, 28 Hz/PW = 0.8, 1, 1.2 mm	KW KD	The assist gas pressure and pulse frequency have the dominant effects on the kerf quality
[123]	2010	Al ₂ O ₃			Fiber laser and CO ₂	Duty cycle = 30, 80%/V = 3000, 9000 mm/min/P = 6, 20 bar/FP = 0, 0.5 mm SOD = 0.1, 0.8 mm	SR	The cutting speed
[124]	2010	2024-T3	3		CO ₂	Gas type = argon, N ₂ , O ₂ , air	SR HAZ	Argon is the best assist gas for best quality of cutting with excluding the cost
[125]	2015	Al alloy	6	N ₂	CO ₂	Pu = 3000, 3500, 4000 W/V = 3600, 4800, 6000 mm/min/P = 10, 12, 14 bar/SOD = 0.7, 0.8, 0.9 mm	SR KW	The surface roughness and kerf width are inversely proportional with cutting speed and standoff distance and proportional with power
[126]	2012	Al alloy	Thin	O ₂	Pulsed Nd:YAG	V = 6, 7, 8, 9, 10 mm/min/P = 4, 5, 6, 7, 8 bar/F = 8, 9, 10, 11, 12 Hz/PW = 1.6, 1.7, 1.8, 1.9, 2 mm	SR KT	GA offers a soft computing method for machining process optimization that is both affordable and effective

Fig. 18 Sheet thickness versus standard roughness [127]



at different thicknesses which are 1, 3, and 6 mm for AISI 304 alloy; and 2.5, 5, and 6 mm for St37-2 alloy, it has been found that the workpiece thickness has an impact on the top kerf width. Material type, gas pressure, and thickness all had an impact on the bottom kerf width. The taper angle is influenced by material type. Material type and cutting speed have an impact on the surface roughness [95]. It also shows, when using the same assist gases which are nitrogen and oxygen to compare the effect of them on the surface roughness and the width of the kerf of the cut by cutting the AISI 304 and St37-2 alloys at different thicknesses which are 1, 2, 3, and 4 mm, that nitrogen as an auxiliary gas gives a good surface quality compared to oxygen but cut thinner parts than oxygen, and also oxygen leads to bigger kerf width than

nitrogen as it adds an extra heat to the cut point. Cut quality is low as well as kerf width is larger when using low cutting speed with O_2 as an auxiliary gas. Also, when employing oxygen as an auxiliary gas instead of nitrogen, the initial hole diameter is greater [100].

Table 5 also shows, when comparing the types of laser sources such as comparing the fiber laser with CO_2 when cutting AISI 304 with 6-mm and 10-mm thickness, that industrial practice agrees that CO_2 has a superior cut quality than fiber lasers when cutting sheets that are 6 mm thick. However, in the case of 10-mm thickness, neither technology stands out to demonstrate superior quality [43]. Also, when comparing the fiber laser with CO_2 and diode lasers when cutting AISI 304 with 1-mm thickness, it has been found that

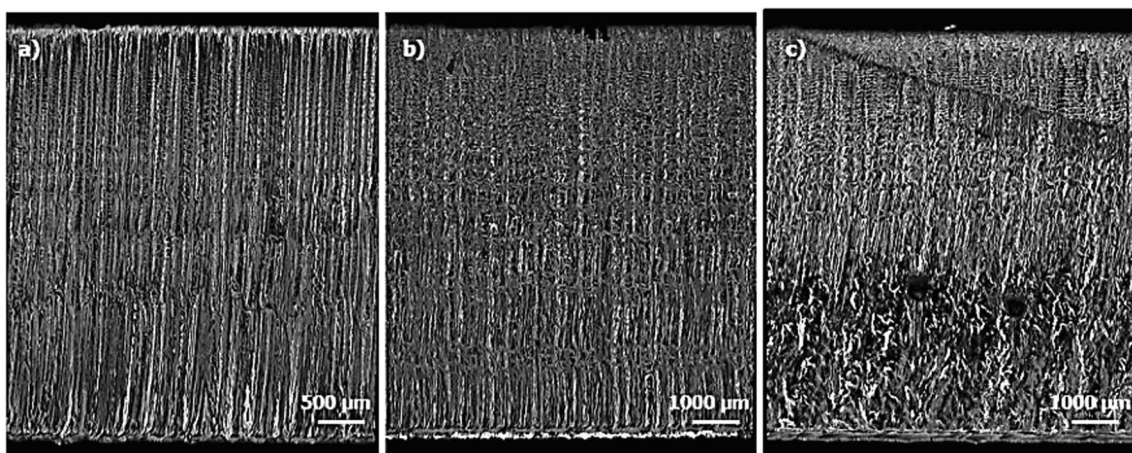


Fig. 19 Increase of the surface roughness with increase of thickness [95]

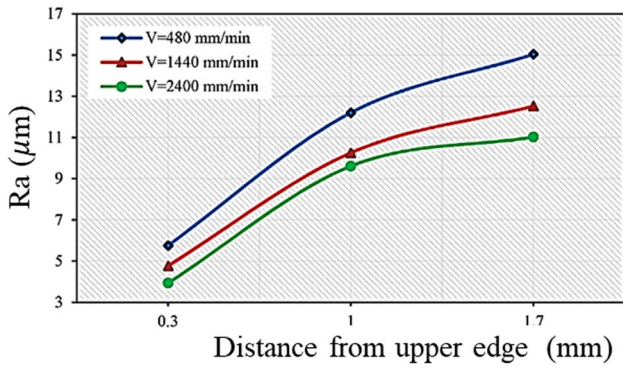


Fig. 20 Measured surface roughness versus increasing the height of measure [84]

diode speed is less than half of fiber laser speed, but higher than CO₂ speed. Diode is less bright than fiber laser in thin metals. Diode quality is less than fiber in thin metals but good as fiber in thick metals [99].

Table 6 displays the effect of the input parameters on the response parameters for aluminum alloys in details by providing the thickness of the cut sheet, the assist gas type, the laser source, the input parameters, the output parameters, and the effective parameters for the selected papers. For example, when a set of laser beam power and the velocity of the cutting are used to machine Al-2024-T3 alloy to investigate their effect on the roughness, the hardness, and the HAZ of the cut surface, the results were introduced as follows: cutting did not happen at 1500W and 3500 mm/min, optimum values for minimum value of surface roughness happened at 2600 W and 5000 mm/min, and HAZ is proportional with power and inversely proportional with cutting speed, but hardness did not affect by cutting speed or power [72]. The same set was used to cut a sheet of Al₂O₃ alloy to investigate their effect on the surface roughness and the width of the kerf of cut. It has been found that kerf width is

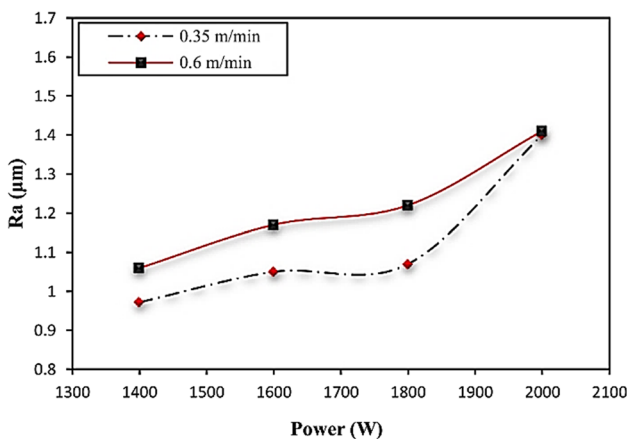


Fig. 21 Laser beam power versus surface roughness [128]

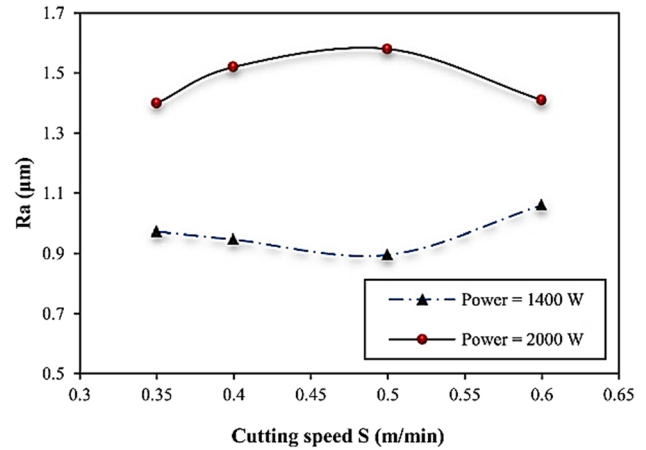


Fig. 22 Cutting speed versus surface roughness [128]

inversely proportional with cutting speed and proportional with power, kerf width increasing percent is low, and cast layer thickness is proportional with power and inversely proportional with cutting speed [86].

The speed of cut was found the dominant parameter on the width of the kerf of cut and the roughness of the cut surface when a set of laser power, speed of cut, and the pressure of the assist gas were used to cut a sheet of Al 6351 alloy; the optimum values for minimum value of surface roughness and kerf width happened at 3200W, 7390 mm/min, and 7.7 bar [112]. The cutting speed was again the dominant parameter when the same set was used to cut SiCp/Al composite alloy to see their effect on the width and taper of the kerf of cut. For efficient MRR, use low cutting speed with 3500W and high cutting speed with 4500W, and the minimum profile contour happened at 4000W, 2500 mm/min,

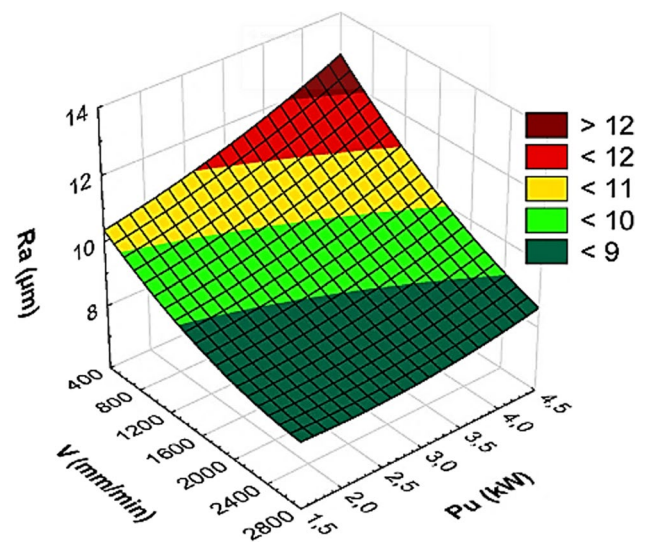
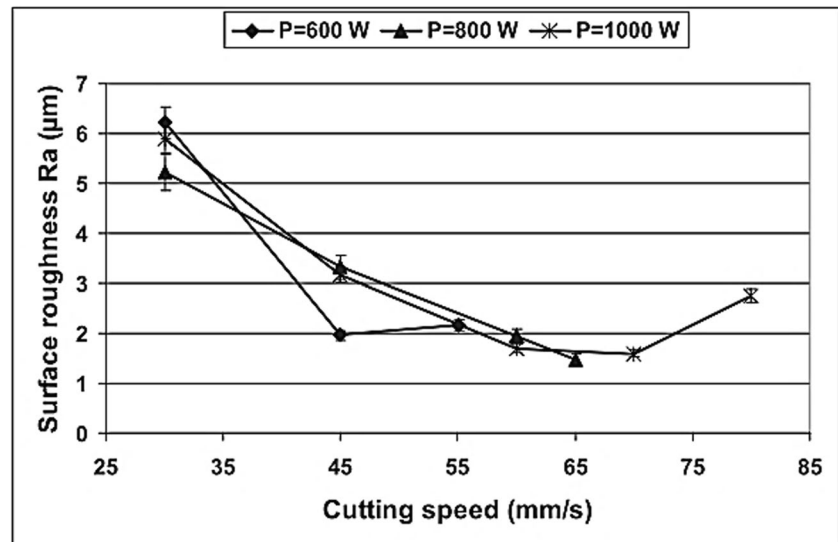


Fig. 23 Effect of cutting parameters on surface roughness [84]

Fig. 24 Cutting speed versus surface roughness [105]



and 8 bar [115]. Also, when the power of laser beam and the speed of cutting is used with a set of other parameters, they become the most effective parameters of cutting over the other parameters. For example, when a set of the power of laser beam, the speed of cut, the standoff distance, and the nozzle diameter are used as an input parameters to investigate their effect on the roughness of the cut surface and the width of the kerf of cut by machining the Al-5052 alloy, it has been declared that the primary factors for the output values are the laser power and cutting speed. Turbulence is produced by larger nozzle diameters, which lowers cut quality. It is evident from the microstructural investigation that turbulence has an impact on the quality of cut materials [70].

Moreover, when a set of the power of laser beam, the speed of cut, the pressure of the assist gas, and the frequency are used as an input parameters to investigate their effect on the

roughness of the cut surface, the width, and the taper of the kerf of cut by machining the Al6061/SiCp/Al₂O₃ composite alloy, it has been discovered that the optimal cutting parameters are 2970.94W, 1196.4 mm/min, 8.42 Hz, and 12 bar, which mean that the power and the speed of cut have the most effect on the output [117]. Also, when a set of the power of laser beam, the speed of cut, the pressure of the assist gas, and the frequency are presented as an input parameters to investigate their effect on the roughness of the cut surface, the width of the HAZ layer, and the width of the kerf of cut by machining the AA5083 alloy, it has been found that the laser power and cutting speed are the dominants for the output values. The surface roughness values depend on the assist gas pressure and pulse frequency. HAZ and kerf width are inversely proportional with cutting speed and proportional with power. Assist gas higher pressure value will lead to high melted MRR [118].

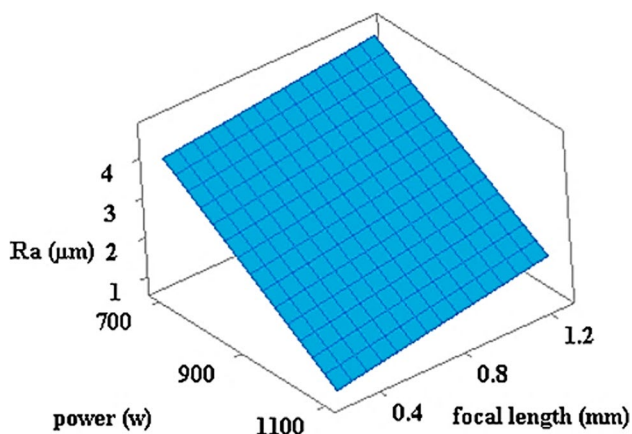


Fig. 25 Response of surface roughness versus power and focal length [129]

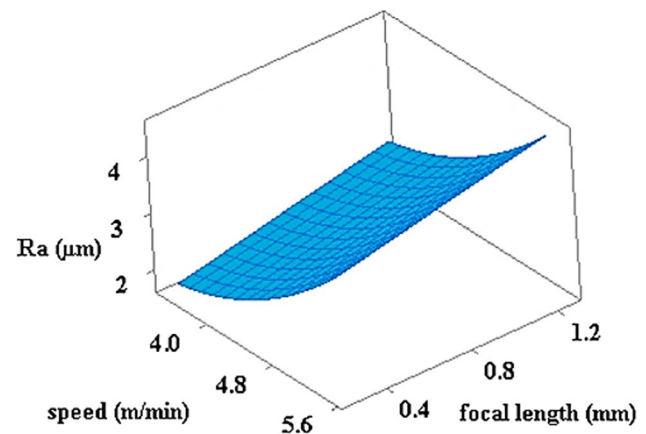
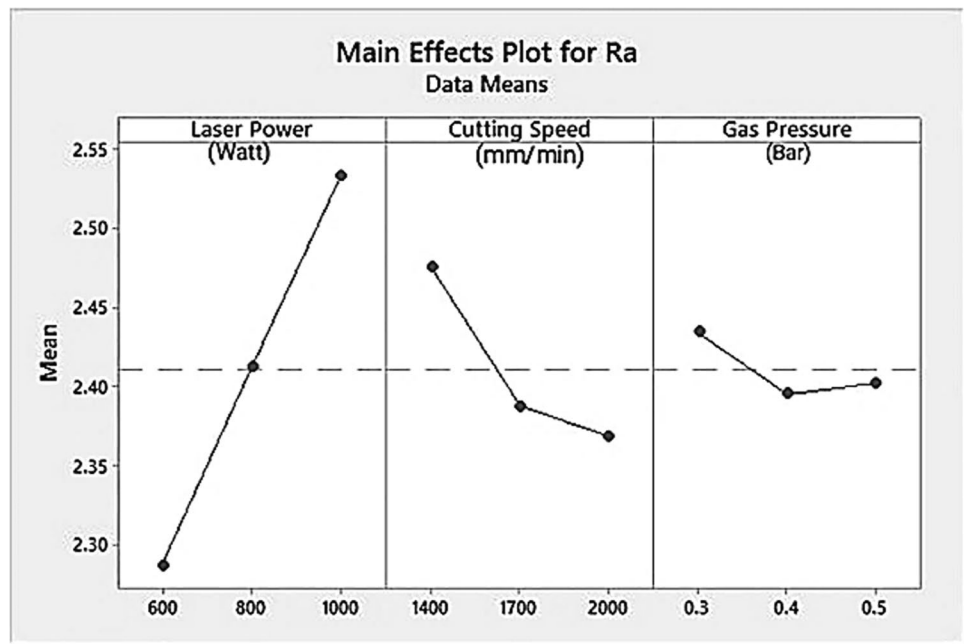


Fig. 26 Response of surface roughness versus power and focal length [129]

Fig. 27 The main effect of cutting parameters on surface roughness [130]



Furthermore, when a set of laser beam power, cutting speed, assist gas pressure, and standoff distance are presented as input parameters to investigate their effect on the roughness of the cut surface by cutting the Al 6061-T6 alloy, it has been found that the minimum surface roughness happened at high speed and low power, as it leads to low temperature [120]. Also, when a set of the power of laser beam, the speed of cut, the pressure of the assist gas, and the standoff distance are presented as an input parameters to investigate their effect on the roughness of the cut surface and the width of the kerf of cut by cutting the aluminum alloy, it has been found that the surface roughness and kerf width are mostly influenced by the laser power, cutting speed, and the standoff distance, whereas assist gas pressure has little bearing on either. The surface roughness and kerf width are inversely proportional with cutting speed and standoff distance and proportional with power [125].

Table 6 also shows when a set of the frequency, cutting speed, assist gas pressure, and pulse width are set as input parameters, the optimal cutting parameters are 1.2 ms, 1500 mm/min, 28 Hz, and 8 bar. The assist gas pressure and pulse frequency have the dominant effects on the kerf quality [122]. Also, it shows that when a study has been done on AA2B06 with different sheet thicknesses by using a set of parameters to see their effect on the roughness of the cut surface and the energy efficiency, it was found that for sample group 1, 2000W, 6000 mm/min, and 15 bar are the ideal values for sheet thickness of 1.5 mm and 2 mm. For sample group 2, the ideal values are 2000W and 9000 mm/min for sheets that are 1.5 mm and 2 mm thick. The ideal pressures are 5 bar for 1.5 mm and 10 bar for 2 mm. Surface roughness and energy efficiency have been improved with significant values [116].

Table 6 also shows that when a study has been done on AL6061T6 with different sheet thicknesses by using a set of parameters to see their effect on the roughness of the cut surface, the results are barely impacted by the cutting speed and gas pressure. With increasing laser power, anticipated values for cutting temperature increase while those for surface roughness drop. Higher values of sheet thickness result in higher surface roughness and lower cutting temperature values [121]. But for Al 6061-T6 alloy, with different thicknesses, it has been found that both the power of laser beam and the speed of cut are the effective parameters [120].

Table 6 also shows, when comparing the types of laser sources such as comparing the fiber laser with CO₂ when cutting a sheet of Al₂O₃ alloy by using the same set of input parameters for both types, that the optimal cutting parameters for fiber laser are 250 W, 6000 mm/min, 0.3 mm for sod, 0.3 mm for focus, and 12 bar. The optimal cutting parameters for CO₂ laser are 180 W, 7200 mm/min, 0.4 mm for sod, –0.25 mm for focus, and 12 bar [123]. It also shows, when using four different types of assist gas which are argon, air, nitrogen, and oxygen to compare the effect of them on the surface roughness and the HAZ width, that O₂, N₂, and air produced a different value of dross, width of HAZ, and a change in microstructure of the AL-CU alloy. Argon is the best assist gas for best quality of cutting with excluding the cost [124].

This review can be concluded in these points:

1. The most set of parameters used as a control parameter are laser power (P_u), cutting speed (V), and assist gas pressure (P), followed by the set of cutting speed (V), assist gas pressure (P), pulse frequency (F), and pulse

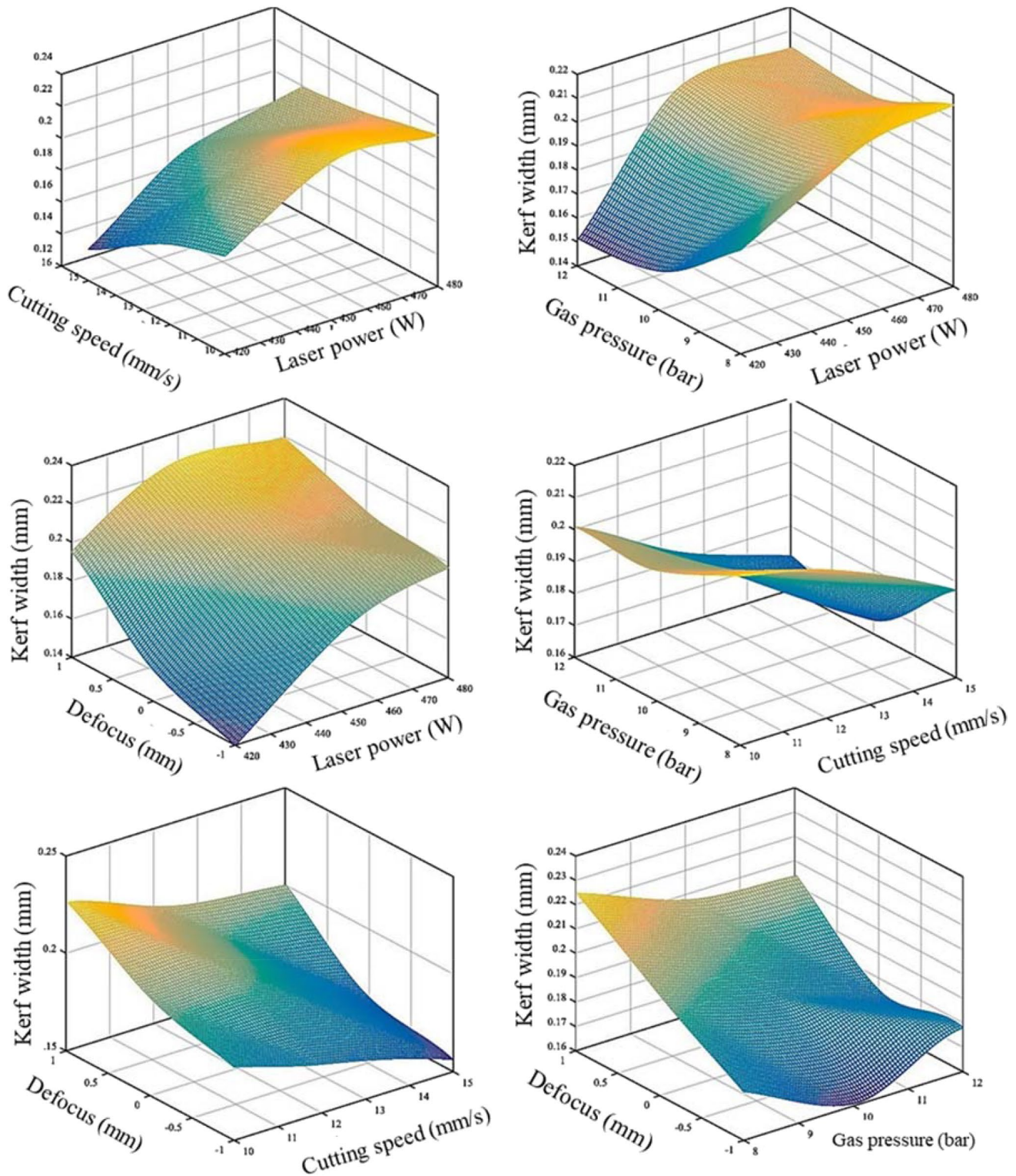


Fig. 28 Kerf width relation with cutting parameters [106]

width (PW), followed by the set of laser power (P_u), cutting speed (V), assist gas pressure (P), and pulse width (PW). So, it is recommended to use the first set, as it gives the best indication for surface quality

depending on changing one parameter of them; also it is easy to control those parameters without complications which will lead to ease of work with those parameters.

Fig. 29 Main effect plot for kerf width values versus cutting parameters [130]

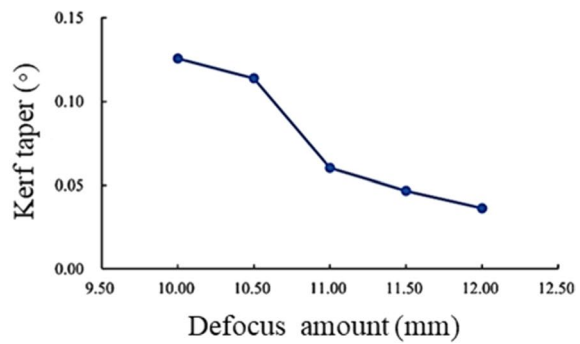
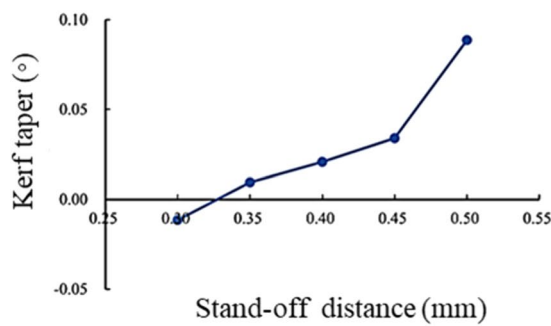
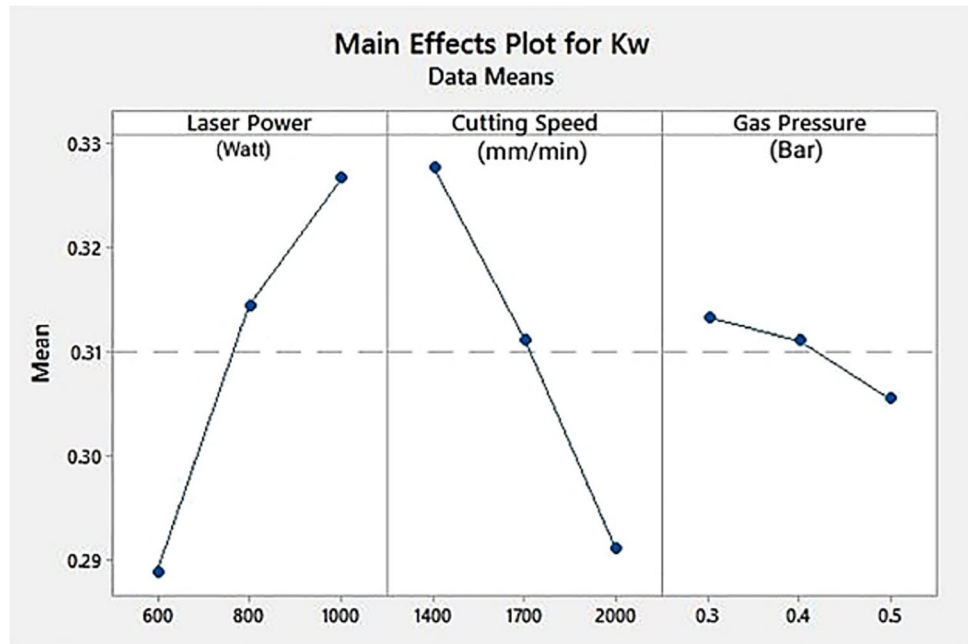


Fig. 30 Kerf taper relation with standoff distance and defocusing amount [64]

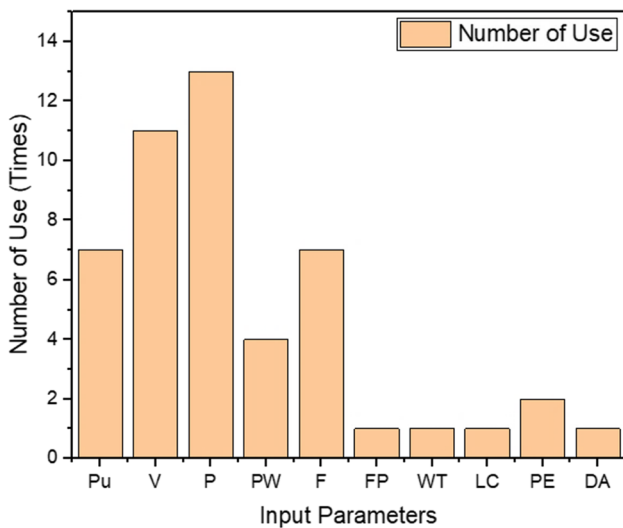


Fig. 31 Number of using input parameters in titanium studies

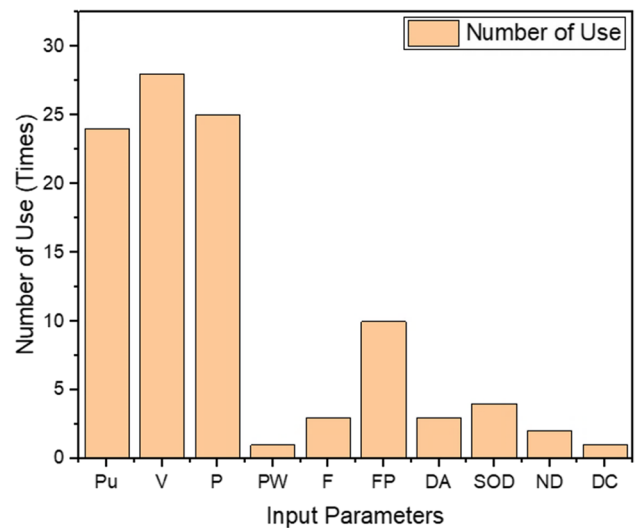


Fig. 32 Number of using input parameters in steel studies

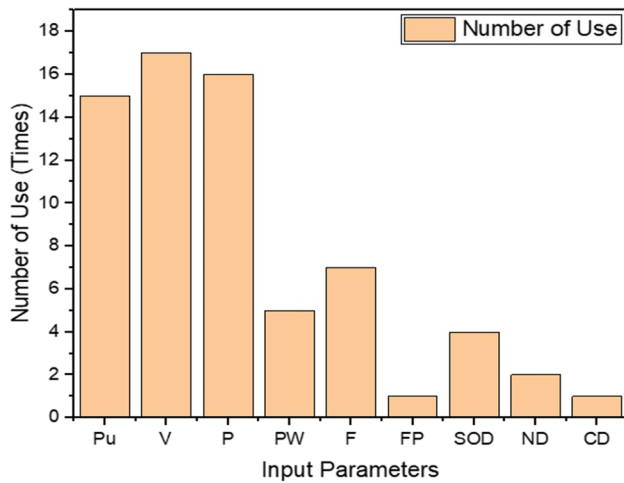


Fig. 33 Number of using input parameters in aluminum studies

- Based on the previous studies, sheet metal thickness has notable effect on the values of outputs, as higher sheet thickness values cause increased values of the surface roughness and kerf taper as those outputs require higher values of laser power at lower values of cutting speed which lead to high concentration of heat. As a result, higher values of surface roughness are produced. As an example, thickness has a high effect on the output parameters such as surface roughness as shown in Fig. 18, Fig. 19, and Fig. 20.
- Most of the cutting parameters have a direct effect on the cut surface quality such as laser power and speed of cutting as the increase of the laser power adds more heat to the cut point which causes bad finish. On the other hand, increasing speed of cut causes a decrease

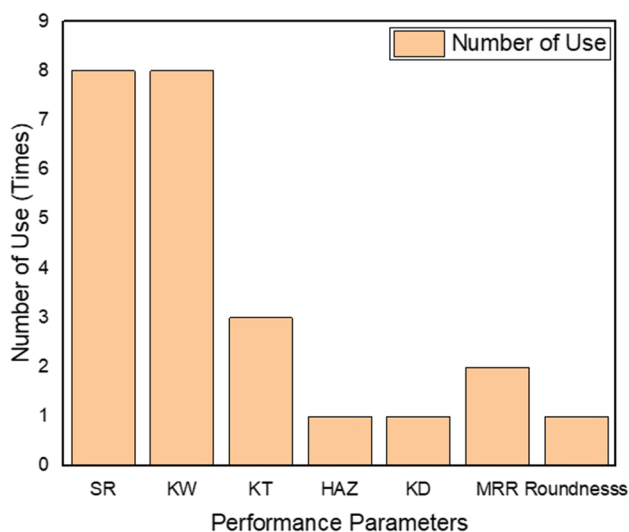


Fig. 34 Number of measuring performance parameters in titanium studies

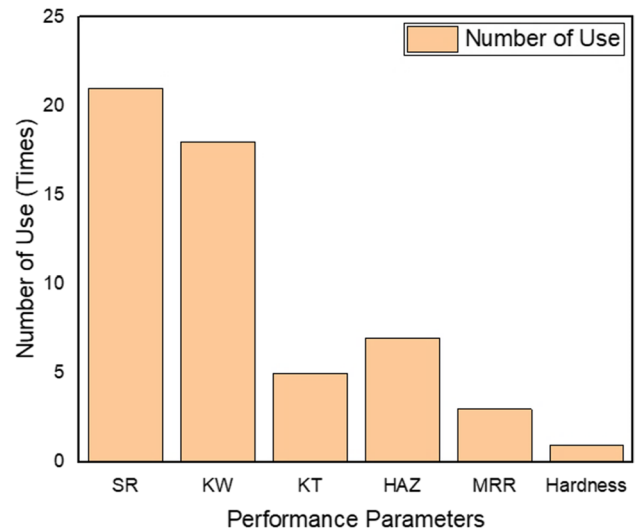


Fig. 35 Number of measuring performance parameters in steel studies

of the concentrated heat which causes good surface finish as shown in Figs. 21, 22, 23 and 24. But increasing the velocity values with a high percentage may cause an increase of the cut surface roughness values as the striation pattern becomes rougher because of changing its shape from strait to inclined; also increasing power may add more stability to surface roughness values as shown in Figs. 25 and 26 which clearly shows that focal length goes proportionally with the surface roughness values. But the most effective parameter for surface roughness is laser power in comparison with the speed of cut and gas pressure as shown in Fig. 27.

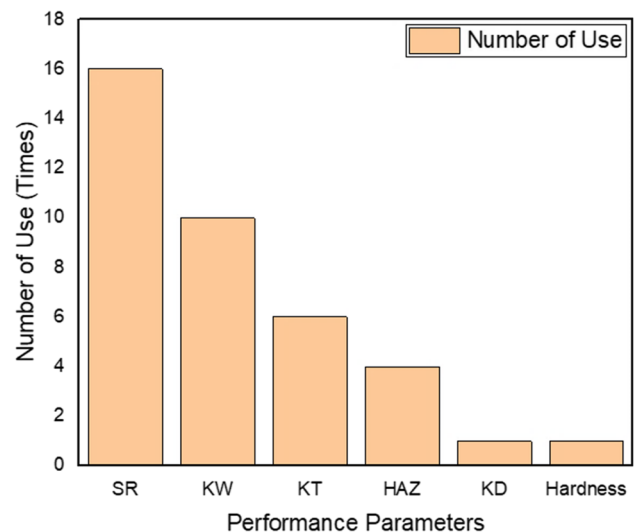


Fig. 36 Number of measuring performance parameters in aluminum studies

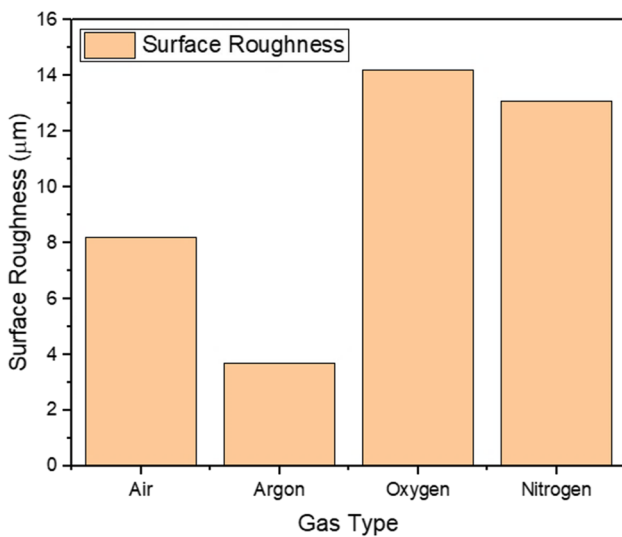


Fig. 37 Surface roughness values of Al-2024-T3 versus different types of assist gas [114]

4. Kerf width is a crucial factor for determining the performance of the laser cutting process, which refers to the quality of the cutting process. It was observed that the width of the kerf is inversely proportional to the cutting speed and proportional to the power. Increasing the power increases the heat in the cutting area, which leads to more molten metal, resulting in a large kerf width if the speed is also low. The assist gas pressure has a little effect on the kerf width. The defocusing amount influences the kerf width as it causes an increase when it has a positive value against a decrease when it has negative values as shown in Figs. 28 and 29.

5. Kerf taper depends on the type of cut material besides its thickness and depends on the assist gas pressure and cutting velocity. Increasing the thickness of the cut metal or cutting material with high mechanical properties will lead to an increase in the taper angle. High pressure and velocity with moderate power will also minimize the taper angle because of the lack of concentrated heat at the cut point. Increasing the stand-off distance and the defocusing amount will cause an increase of the kerf taper as shown in Fig. 30.
6. Dross height is a crucial parameter for detecting the performance of the laser cutting process, as a small dross height indicates that the cutting quality is high due to the use of appropriate cutting parameters. The impact of the different values of the parameters of the laser cutting process on kerf taper values in metals was studied, and it was found that the dross height depends on laser power and cutting velocity, followed by the assist gas pressure value.
7. The most parameter used in titanium alloys papers was assist gas pressure (P), followed by cutting speed (V), followed by laser power (P_u), followed by pulse frequency (F), and pulse width (PW) as shown in Fig. 31.
8. The most parameter used in steel alloys papers was cutting speed (V), followed by assist gas pressure (P), followed by laser power (P_u), followed by focal point (FP), and thickness (T) as shown in Fig. 32, which shows that the most used parameters in steel cutting are P_u , V , and P .
9. The most parameter used in aluminum alloys papers was cutting speed (V), followed by equality between laser power (P_u) and assist gas pressure (P), followed by pulse frequency (F), and pulse width (PW) as shown in

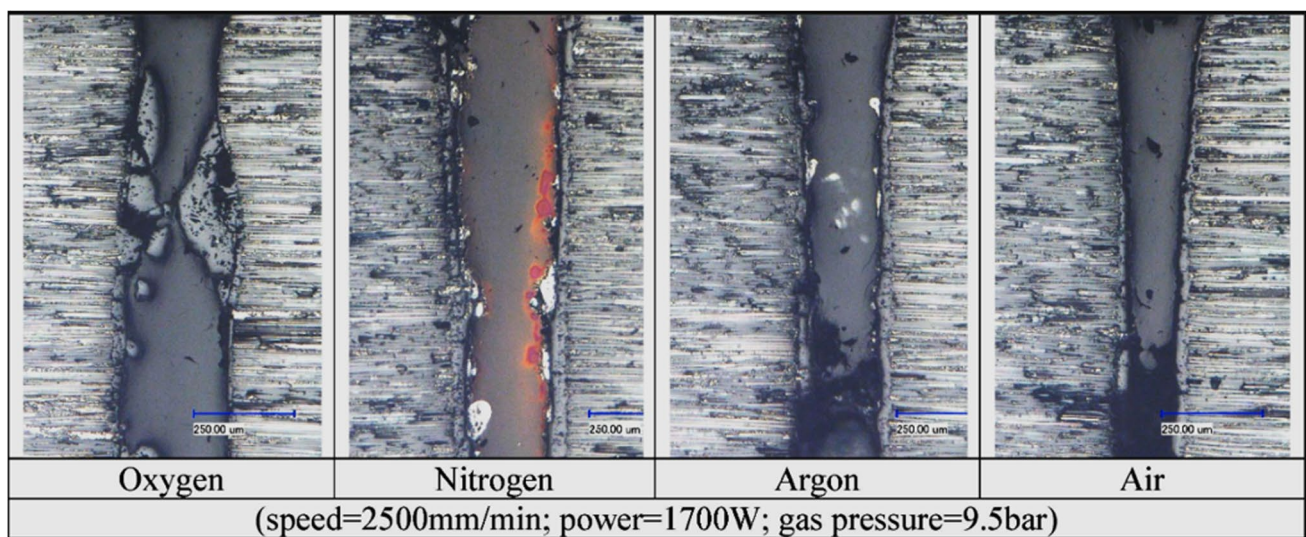


Fig. 38 The effect of the gas composition during a laser beam machining on the thickness of the oxidation layer [66]

Fig. 33, which shows that the P_u , V , and P are the most used parameters in laser cutting of aluminum alloys.

10. The most sets that have been measured to indicate the surface quality are surface roughness (SR) and kerf width (KW), which mostly indicate surface quality and kerf profile, as surface roughness gives an indication about dross formation and dross height. Also, kerf width gives an indication of the shape of the kerf profile and if we measured the kerf width from the upper side and from the lower side with knowing the thickness of the sheet, we can get the taper value.
11. The most measured parameter in titanium alloy papers is SR, followed by KW, followed by kerf taper (KT), and heat-affected zone (HAZ) as shown in Fig. 34, which indicate that surface roughness and kerf width are the most studied as output parameters in cutting of titanium alloys by using laser techniques.
12. The most measured parameter in steel alloy papers is SR, followed by KW, followed by HAZ, and KT as shown in Fig. 35, which confirm that SR and KW are the important performance parameters in laser cutting of steel alloys.
13. The most measured parameter in aluminum alloy papers is SR, followed by KW, followed by KT, and HAZ as shown in Fig. 36, which assure that the surface roughness is the most important performance parameter in laser machining of metals.
14. Assist gas pressure is not the most significant parameter in most of output parameters but it helps in refining the cut surface by removing the molten metal which gives good surface quality, also helps in decreasing the HAZ by decreasing the amount of heat in the material which also affect the kerf angle by decreasing the amount of heat and removing the cut metals.
15. The type of assist gas is very significant as the researchers used about 5 different types which are air, oxygen, azote, nitrogen, and argon. But the most important are three types which are argon, nitrogen, and oxygen. Figure 37 shows the different values of surface roughness versus the different types of assist gas after using laser cutting for machining Al-2024-T3 alloy which clearly shows that the minimum values of surface roughness were taken when argon has been used as an assist gas followed by nitrogen [114]. Also, the composition of used gas affects the thickness of the oxidation layer as shown in Fig. 38. Most of the researchers used nitrogen as an assist gas as it is more economic than argon and gives better surface quality than oxygen. But if the application does not care about surface quality of a thicker material and needs more material removal rate, so it is recommended to use oxygen as an assist gas as it provides more heat which gives a high MRR. But if the application needs a high surface quality for a thin material to be used in precision applications so, it is

recommended using argon as it is the best assist gas pressure in high accuracy.

16. Surface roughness, kerf width, kerf taper, HAZ, and MRR are proportional with power, pulse width, pulse frequency, and inversely proportional with cutting speed and standoff distance. As increasing laser power, pulse frequency, and pulse width with low cutting speed and small distance between the nozzle and cut surface result in increasing the heat on the cut point that cause more melted metal which lead to high dross, big HAZ, high surface roughness, big kerf width, high taper angle, and high material removal rate which are the only advantages of those conditions which can be used if the surface quality is not important as MRR. On the other hand, microhardness is proportional with power and inversely proportional with cutting speed in steel, but hardness was not affected by laser power or cutting speed in aluminum which is not rational as hardness should be affected by the laser power and cutting speed as they lead to a change in the sheet metal properties.

7 Conclusions

Extensive research investigations have been reviewed to study the use of laser beam machining by different researchers. Going through the analysis, the discussion part has been made and the following conclusions can be drawn:

1. Kerf width, surface roughness, kerf taper, HAZ, and MRR are all inversely correlated with cutting speed and standoff distance and are proportional to power, pulse width, and pulse frequency.
2. In steel, microhardness is inversely correlated with cutting speed and inversely proportional to laser power. However, neither of these variables had any effect on aluminum's hardness, which is illogical given that both factors influence the properties of the sheet metal.
3. The most critical aspect of assist gas is its type; although the researchers employed roughly 5 different types, argon, nitrogen, and oxygen are the most crucial. Since it is more affordable than argon and provides a better surface quality than oxygen, most researchers selected nitrogen as an assist gas. But the study advised utilizing oxygen as an aid gas because it adds more heat to the laser heat because of reaction with the material during laser cutting, giving a high MRR, and this can be used if the application does not care about the surface quality of the material and needs higher material removal rate.
4. Finally, it is recommended using low laser power, high cutting speed, medium gas pressure, high standoff distance, medium pulse frequency, medium pulse width,

small nozzle diameter, small thickness, and nitrogen as an assist gas for getting low surface roughness, small width of HAZ, small kerf width, and small kerf angle.

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Declarations

Ethics approval This article does not contain any studies with human participants or animals performed by any of the authors.

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