

# Laser Drilling of Superalloys and Composites



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## Nomenclature

$A$	Material absorptivity
$A_s$	Cross-sectional area of the laser spot ( $\text{mm}^2$ )
$D_{Max}$	Maximum hole diameter (mm)
$D_{Min}$	Minimum hole diameter (mm)
$D_{ent}$	Entrance hole diameter (mm)
$D_{ex}$	Exit hole diameter (mm)
$D_p$	Pulse duration (s)
$E_{abs}$	Energy absorbed by the material (J)
$F_l$	Focal length (mm)
$H_c$	Hole circularity
$P$	Applied laser power (W)
$P_d$	Laser power density ( $\text{W}/\text{mm}^2$ )
$P_e$	Pulse energy (J)
$S_d$	Spot diameter (mm)

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$t$	Material thickness (mm)
$\theta$	Taper angle
$\emptyset$	Beam divergence (angle)

## 1 Introduction

Aircraft engine components usually operate under elevated temperature (above 1000 °C) and high-pressure conditions (more than 1 MPa) [42]. Materials with outstanding thermo-mechanical properties are required for effective performance in such hot sections of an aeroengine. Superalloys are the ideal candidate for use in aforesaid extreme operating conditions because of excellent corrosion and wear resistance, and high creep strength properties [71]. Superalloys are majorly classified into four categories, (Ni) nickel-based, (Ti) titanium-based, (Co) cobalt-based and (Fe) iron-based alloys. A significant portion (70%) of superalloys is used by aerospace industries and approximately 50% of the aerospace components are manufactured using Ni-based superalloys [24]. The characteristics of high strength, excellent thermal and fatigue resistivity enabled these alloys to be used in various applications, such as aeroengine components, space shuttles, nuclear reactors and tooling.

Composite materials have become popular in a wide range of industries due to their enhanced properties, including high strength to wear ratio, lower weight, and better corrosion and high-temperature resistance. Metal matrix composites (MMCs) are a comparatively new class of material structured by embedding high-strength ceramic fibres into a tough metal matrix [38]. These composites have superior properties comparable to superalloys and are used in both commercial and industrial applications especially in the aerospace sector [2, 35].

Conventional machining of these materials is challenging because of higher tool wear and the low material removal rate [3, 60]. The significance of using non-conventional machining processes (electrical discharge machining (EDM), laser machining and water-jet machining) for superalloys and MMCs has been discussed by Bains et al. [5] and Majumdar and Manna [47]. It is noted that non-conventional machining processes produce high quality products with better surface characteristics. Of all the available non-conventional machining processes, laser processing is a fast and flexible machining process specifically when drilling of aerospace components is considered [48].

There are different ways to drill a particular hole geometry. They can be divided based upon drilling processes such as single-pulse, percussion and trepanning. For a particular process, there is a range of parameters involved which control the material removal, hole quality and manufacturing cost. Furthermore, there are different factors which influence the laser drilling manufacturing cost. All of these aspects are discussed in this chapter.

## 2 Drilling in the Aerospace Industry

Advancements in aeroengine efficiency are associated with an enhancement of exhaust gases and combustion temperatures in aircraft gas turbines [52]. Although superalloys can sustain these elevated temperatures, supplementary cooling of components is necessary for effective engine performance. This can be achieved through drilling multiple cooling holes in hot-section components. Hole dimensions as well as the number of holes vary in different components as shown in Table 1.

Different methods are available to drill these holes. These include electrochemical machining (ECM), electrodischarge machining (EDM) and laser drilling. The latter method has an advantage over ECM and EDM because of the following reasons [20, 21, 46, 54, 92]:

- i. There is no direct contact with the material surface and therefore no tool wear or breakage is involved.
- ii. Proper design of the motion-control system and beam delivery facility enables the achievement of high precision and repeatability.
- iii. The laser beam can be focused precisely on the defined area, which allows drilling of holes of various shapes and sizes.
- iv. It is easy to program and automate the laser drilling process.
- v. A wide range of materials can be operated on including composites, plastics, silicon, rubber or metals.
- vi. The process duration is shorter as compared to EDM and ECM techniques.
- vii. Some of the laser machines are versatile and it is possible to perform multiple functions using the same laser, such as welding or cutting.

However, there are some limitations of laser drilling which must be considered; these are provided below [20, 21, 46, 54, 92].

- i. High capital cost is needed to buy a laser drilling setup.
- ii. Laser drilling is associated with some inherent defects, such as hole taper, circularity, recast layer thickness (RLT), heat affected zone (HAZ), surface roughness, spatter and microcracks.
- iii. Appropriate laser safety precautions need to be implemented.

**Table 1** Hole dimensions of gas turbine components [53]

Components	Wall thickness (mm)	Diameter (mm)	Angle to the surface (°)	Number of holes
Nozzle guide vane	1.0–4.0	0.3–1.0	15	25–200
Turbine blade	1.0–3.0	0.3–0.5	15	25–200
Baseplate	1.0	0.5–0.7	30–90	10,000
Afterburner	2.0–2.5	0.4	90	40,000
Cooling ring	4.0	0.78–0.84	79	4200
Seal ring	1.5	0.95–1.05	50	180

iv. Optical setup needs regular maintenance.

Therefore, this chapter is focused on the laser drilling process taking into consideration both cost and quality aspects.

### 3 Laser Drilling

Laser drilling is a non-traditional machining process, which is extensively used in the aerospace industry for the machining of high strength and high-temperature resistant metals and alloys. Recently, the application of laser drilling for producing holes in aluminium matrix/silicon carbide reinforcement (Al/SiC) MMCs has been reported by researchers [49, 51, 93]. This technique is preferable compared to other manufacturing processes, especially in the drilling of aerospace components [52, 73]. It has been extensively adopted for producing cooling holes for aerospace gas turbine components, in particular combustors, nozzle guide vanes and high-pressure turbine blades [6].

In the laser drilling process, a high power laser beam is directed on the surface of the workpiece, where the optical energy of the laser beam is thermalized and rapidly heats the base material and converts it into its molten state as a result of thermal diffusion. Some of the energy is lost due to scattering and reflection of the laser beam. Depending on laser intensity material is removed in both the liquid and/or vapour states. The process of hole formation during laser drilling is shown in Fig. 1. If the laser intensity is high enough, the vaporisation will generate plasma and recoil pressure which helps in the ejection of molten metal and results in the formation of a hole cavity (Fig. 2a) [83]. To make the liquid metal removal more efficient high pressure assist gas can be used, as presented in Fig. 2b. Kinetic energy of the assist gas is used to expel liquid metal where the process doesn't need to rely on the vapour pressure. Assist gas pressure together with plasma and recoil pressures control material expulsion in the laser drilling process [66, 82].

Different types of methods are available for the laser drilling operation, which include single-pulse, percussion and trepan laser drilling. The following section outlines the description of these methods.

### 4 Methods of Laser Drilling

Laser drilling can be performed using different methods and laser types. Depending on the required applications, a particular method and laser are selected as indicated in Fig. 3.

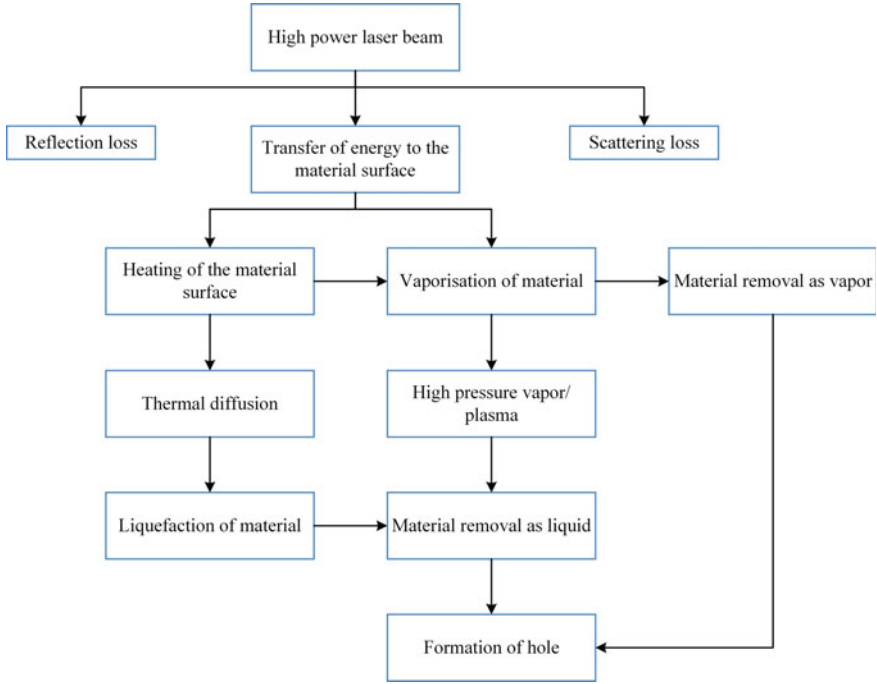


Fig. 1 Hole formation physical mechanism in the laser drilling process [56]

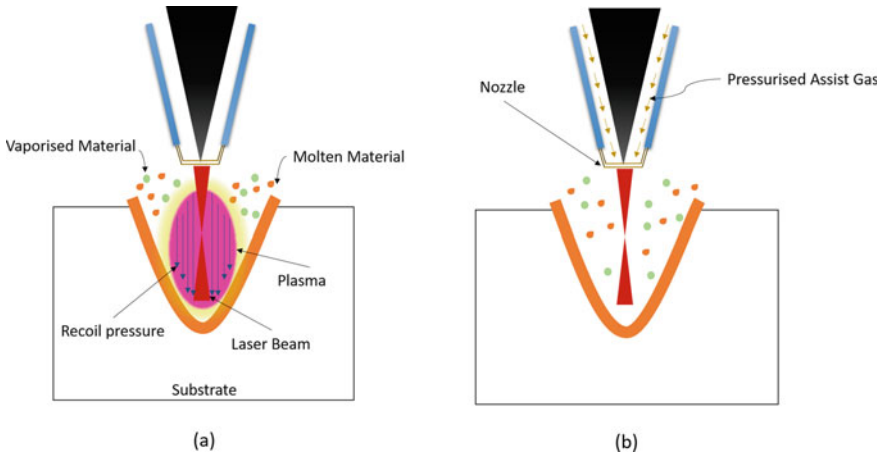
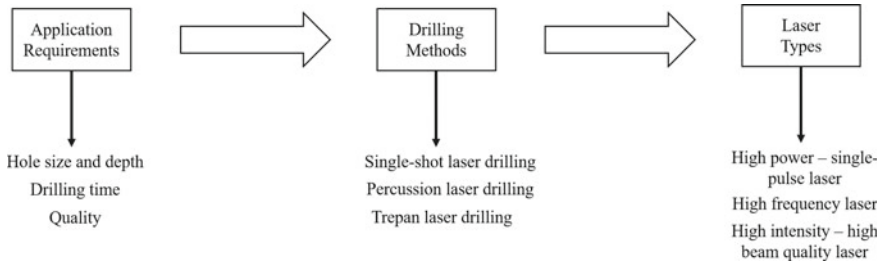


Fig. 2 Schematic of the laser drilling process: a vapour driven melt expulsion, b assist gas melt expulsion



**Fig. 3** Laser drilling methods and their application requirements

### 4.1 *Single-Pulse Laser Drilling*

Single-pulse laser drilling, also known as single-shot laser drilling is a simple method of drilling holes. It involves the use of a single pulse with high energy to create a hole throughout the material thickness. The maximum thickness of material that can be drilled is limited by the pulse energy of the laser. The hole size and quality depend on material thickness and spatial as well as temporal profiles of the laser beam [70].

Using this method, a large number of holes can be produced in a relatively short amount of time. This depends on laser frequency and the speed of the motion system. Single-pulse drilling is a better choice when productivity is the priority compared to quality [79]. It is to be noted that above certain thickness very high pulse energy lasers are required which are expensive, therefore this method is suitable for producing holes in thin sheet materials.

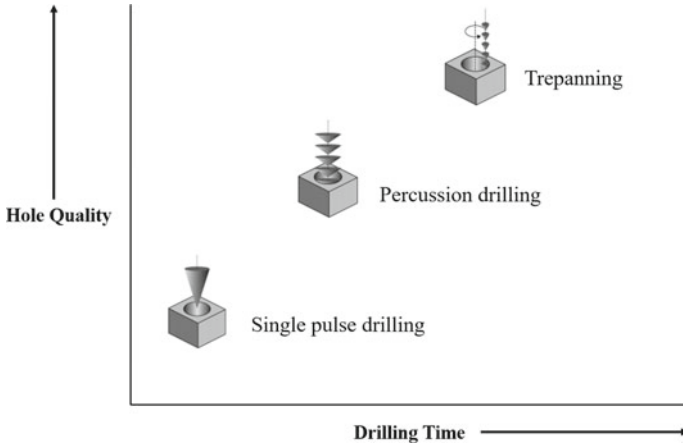
### 4.2 *Percussion Laser Drilling*

Percussion laser drilling involves a series of laser pulses fired at a particular spot of a material where each pulse generates a proportion of the hole. The productivity of this process is a function of pulse energy (edge depth per pulse) and pulse frequency.

Better hole quality can be attained with percussion drilling which depends on laser beam quality and its intensity profile; however, this process is slower in comparison to single-pulse drilling and requires more energy to drill a hole [79].

### 4.3 *Trepan Laser Drilling*

Trepan laser drilling or trepanning is employed to drill large diameter holes. This process begins by piercing a central hole into the material similar to percussion drilling; the laser beam is then moved in a spiral configuration using a motion control system to cut the required size hole. A significant benefit of this method is the delivery



**Fig. 4** Correlation between hole quality and drilling time for different laser drilling methods. *Source* Gautam and Pandey [25]

of good quality holes but it takes a more time compared to other methods [48]. Figure 4 shows hole quality and drilling time associated with various laser drilling methods. It is evident that trepanning is the best choice when hole quality is the priority. In trepanning, hole quality depends on the accuracy of the motion system [55].

## 5 Performance Measures

Performance of the laser drilling process depends upon efficient removal of (molten) material, hole quality and manufacturing cost. These performance measures are described in the following sections.

### 5.1 Material Removal Volume

Material removal is a key feature of the machining process. Laser drilling process involves the removal of molten material to produce a hole cavity. Material removal volume (MRV) indicates the volume of material removed per unit time when it is correlated with the process time, specified as  $\text{mm}^3/\text{s}$  [79]. It helps the users to calculate the speed of the drilling of any arbitrary hole by knowing the volume of material needed to be removed per hole. It also defines the energy efficiency of the process that is associated with the amount of material removed per unit joule of energy, usually measured in  $\text{mm}^3/\text{J}$  [23]. Energy consumption is also an important

cost driver of the laser drilling process, therefore it is reasonable to achieve higher MRV with lower energy consumption.

## 5.2 Hole Quality

Hole quality is of supreme concern in the aerospace industry. Several characteristics are used to judge the quality of laser drilled holes i.e. geometrical features (hole circularity, hole taper and surface roughness) and metallurgical features (microcracks, recast layer, spatter and heat affected zone) [25]. Detailed quality attributes are provided in the following sections.

### 5.2.1 Hole Circularity

Hole circularity defines the roundness of a hole. It varies with the deviation of the hole diameter across the circumference of a drilled hole as shown in Fig. 5. It is always important to increase hole circularity, which can be calculated by the following relation (1). In single-pulse and percussion drilling, hole circularity depends on the roundness of the laser spot and laser beam intensity profile. Whereas in trepanning it is influenced by the accuracy of the motion system.

$$H_c = \frac{D_{Min}}{D_{Max}} \quad (1)$$

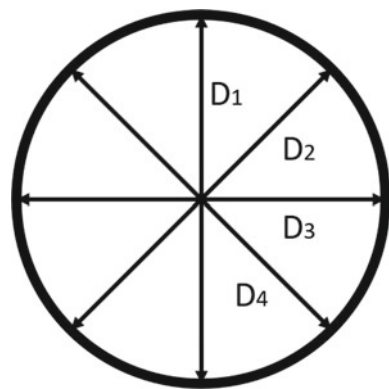
where:

$H_c$  = Hole circularity.

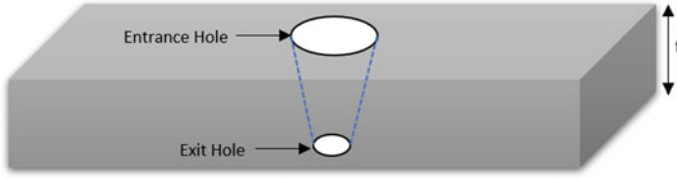
$D_{Min}$  = Minimum hole diameter (mm).

$D_{Max}$  = Maximum hole diameter (mm).

**Fig. 5** Measurement of hole circularity







**Fig. 6** Schematic representation of a (positive) hole taper

**5.2.2 Hole Taper**

Taper formation is an inherent characteristic of laser material processing. It is an important attribute which significantly influences drilled hole quality [4]. Near-zero hole taper is always desirable specifically in aeroengine components where close tolerances and high quality are strict requirements [7].

Hole taper angle is based on the entry and exit hole diameters of the drilled hole and can be calculated using the following relation (2).

$$\tan \theta = \frac{D_{ent} - D_{ex}}{2 \times t} \tag{2}$$

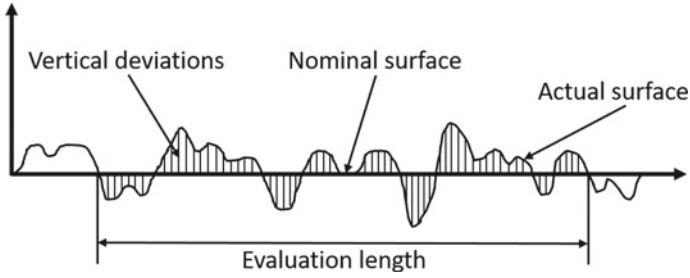
where:

- $\theta$  = Taper angle.
- $D_{ent}$  = Entrance hole diameter (mm).
- $D_{ex}$  = Exit hole diameter (mm).
- $t$  = Material thickness (mm).

Taper angle can be positive or negative depending upon entrance and exit hole diameters. Figure 6 shows the position of hole taper where the exit hole side is smaller than the entry side (positive hole taper). The major cause of this drawback is the diffraction of the laser beam inside the hole cavity.

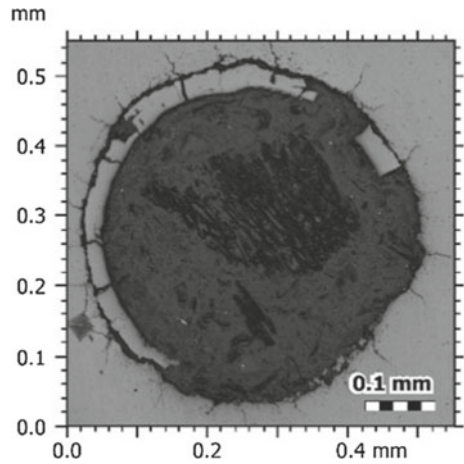
**5.2.3 Surface Roughness**

Surface roughness is one of the important factors considered for quality evaluation of laser drilled parts [86]. It refers to surface irregularities formed on the inner side of the hole which is a product of recast layer. It also reflects the dynamics of the liquid film prior to solidification and local reflectivity of the laser beam. It is usually measured as the arithmetic mean of absolute values of the vertical deviations of the actual surface from the ideal or nominal surface profile over the defined evaluation length, as presented in Fig. 7. A small deviation presents a smooth surface and if the deviation is large the surface obtained is rough. A smooth and uniform surface is required to ensure smooth airflow and avoid turbulence specifically for turbine blades [33]. Surface roughness is majorly influenced by laser intensity, laser power and prepan speed [86, 88].



**Fig. 7** Average surface roughness (Ra) representation [91]

**Fig. 8** Microcracks formation around a drilled hole (0.5 mm thick yttria-stabilized zirconia) [22]



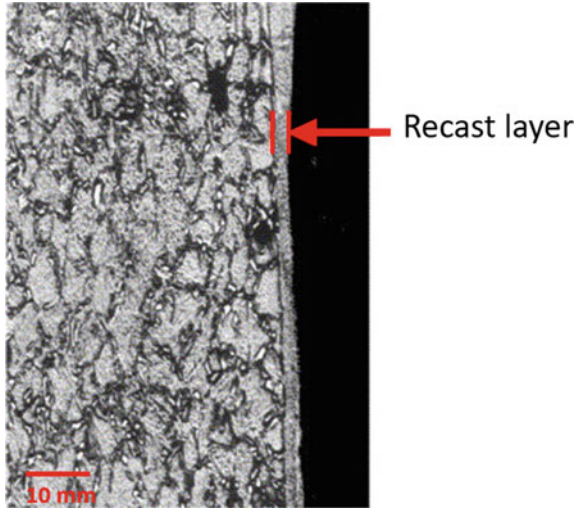
#### 5.2.4 Microcracks

Rapid drilling induces a high cooling rate in the material and in some cases may lead to the formation of microcracks [25]. Microcracks normally arise when drilling is performed in brittle or hard materials. The propagation of these cracks in operation affects the fatigue life of components leading to failure [59]. Figure 8 indicates microcracks formed on the laser drilled surface. Microcracks can be avoided by minimising thermal input into the material.

#### 5.2.5 Recast Layer

During the laser drilling operation, some of the melted material is not removed appropriately and is re-solidified along the walls of the hole. This is known as a recast layer [25]. This layer has contrasting properties compared to the parent material. Sometimes, microcracks are also formed in the recast layer which adversely affect the component's integrity and its lifespan [59]. Therefore, recast layer formation

**Fig. 9** Recast layer in a percussion drilled hole (4 mm thick IN 718) [7]



must be avoided. Figure 9 shows the recast layer in a percussion drilled hole. For a given material, recast layer depends on laser beam intensity. Higher the laser beam intensity more efficient is the material removal which ultimately reduces the chances of recast layer formation.

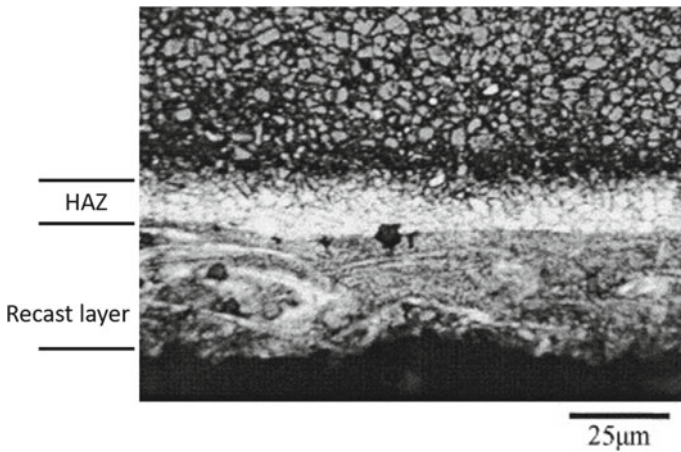
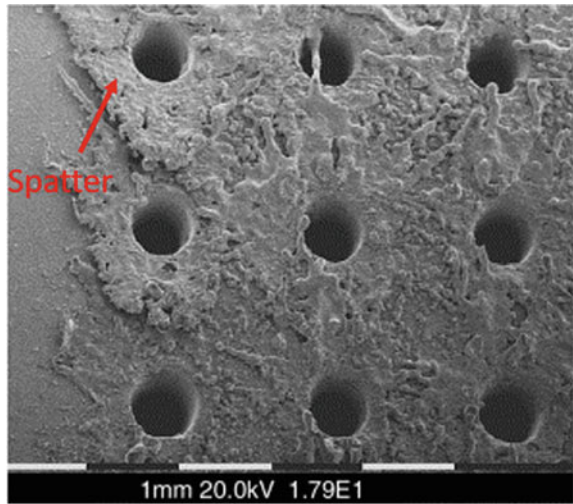
### 5.2.6 Spatter

Incomplete expulsion of melted material occasionally causes the scattering of molten droplets around the edges of the hole, which later resolidify. These droplets get stuck to the hole surface and are known as spatter [32]. It is an innate defect of the laser drilling process and is not desirable especially for effusion cooling applications, whereby the material surface is important for the efficiency and flow of the cooling air [45]. Figure 10 depicts the spatter area formed near the edges of laser drilled holes of a Nimonic sheet.

### 5.2.7 Heat Affected Zone

Laser drilling is a thermal process which involves the interaction of a laser beam with the surface of the workpiece. Higher temperature is involved in the process due to which the (mechanical, physical and chemical) properties of the workpiece surrounding the interaction area are changed. This results in the creation of a distinct zone known as a heat affected zone. The HAZ area is not melted, though lateral heat conduction produces a significant change in the microstructure. The microstructure interface clearly differentiates HAZ from the base material and the recast layer as shown in Fig. 11. HAZ is directly linked to pulse duration and laser beam intensity.

**Fig. 10** SEM image of spatter deposited over the periphery of the holes (2.05 mm thick Nimonic PK 33) [45]



**Fig. 11** HAZ and recast layer in laser drilled hole (8.0 mm thick IN 718) [6]

Low pulse duration allows less time for the energy to dissipate into the material. On the contrary, high laser beam intensity leads to efficient removal of molten material and results in less contact time between the hot liquid and bare material.

### 5.3 Manufacturing Cost

Manufacturing cost of a product plays an important role in its successful design and production. It is used for making several types of decisions for product designing and manufacturing. These decisions include:

- Material type to be utilised for the product
- Manufacturing process type to be used for the product
- Number of products to be manufactured
- Whether to buy or make the part/product
- Product design.

Product manufacturing cost is a major cost element of its selling price i.e. 40% (shown in Fig. 12), which further consists of various elements: labour cost (direct & indirect), material cost, equipment depreciation, energy and plant cost as illustrated in Fig. 13 [81]. It is important to estimate manufacturing cost as it assists the manufacturing companies to evaluate their performance and effectiveness [16].

There are different ways of drilling and each of them has a different quality and associated manufacturing cost which is essential to understand for the user. With single-pulse drilling, manufacturing cost can be reduced but at the expense of hole quality; on the other hand, trepanning gives good hole quality but the manufacturing cost is higher. This shows that there is a trade-off between quality and manufacturing cost. All these factors depend on the process parameters which are discussed in the following sections.

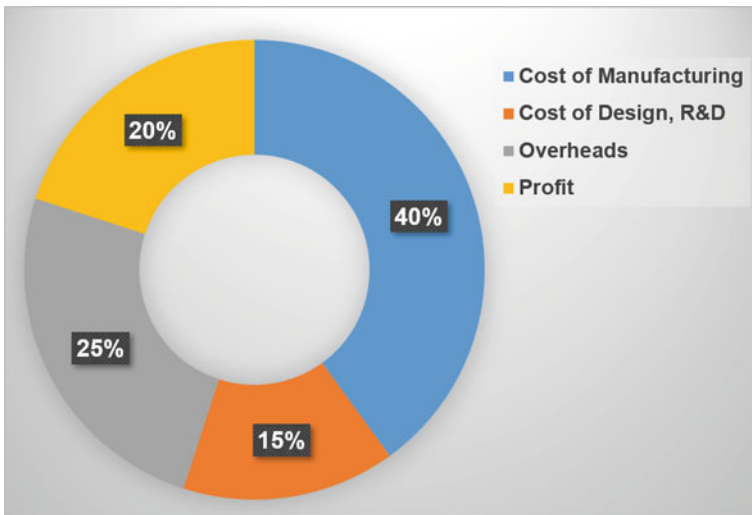


Fig. 12 Product selling price cost elements [81]

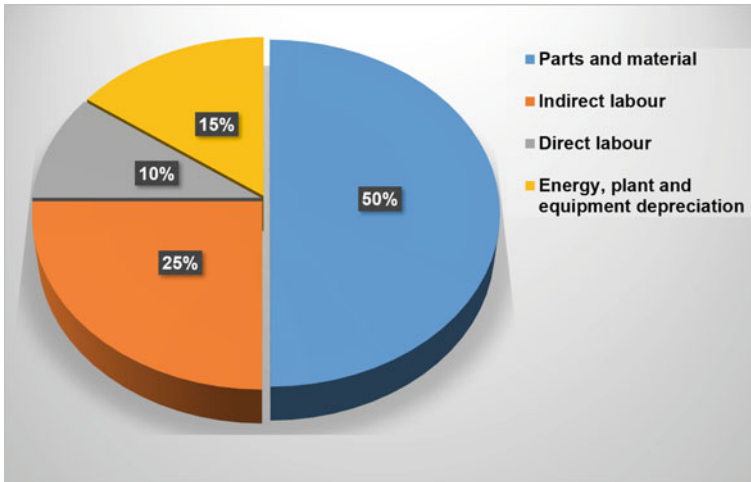


Fig. 13 Manufacturing costs elements [81]

## 6 Laser Drilling Process Parameters

Different parameters are involved in the practical implementation of the laser drilling process. Yeo et al. [92] grouped these parameters into five main categories, as shown in Fig. 14. Laser pulse parameters include pulse energy, pulse duration, pulse frequency and the number of pulses. Environment conditions are the surrounding temperature and humidity level. Material based parameters include material reflectivity, thickness and type of material. Optical setup involves beam shape, intensity profile, focal length and focal position of the laser beam. Assist gas based parameters are gas pressure, nozzle design and the type of assist gas employed. The performance and efficiency of the process depend on an appropriate selection of these parameters.

### 6.1 Pulse Energy and Pulse Duration

Pulse energy and pulse duration are the critical process parameters of laser drilling. Pulse energy provides the energy to melt or vaporise a proportion of the material. Pulse duration or pulse width determines the duration at which this energy is applied as shown in Fig. 15. Depending on laser specifications, the ranges of pulse duration and pulse energy can be varied and have a significant impact on the hole characteristics [25].

Both of these parameters are interdependent (see Eq. 3) and define the laser peak power that controls the rate at which pulse energy is applied into the material [48]. To attain the same pulse energy with a short pulse width, higher peak power is required. There is a significant impact of peak power on the material removal process. Higher

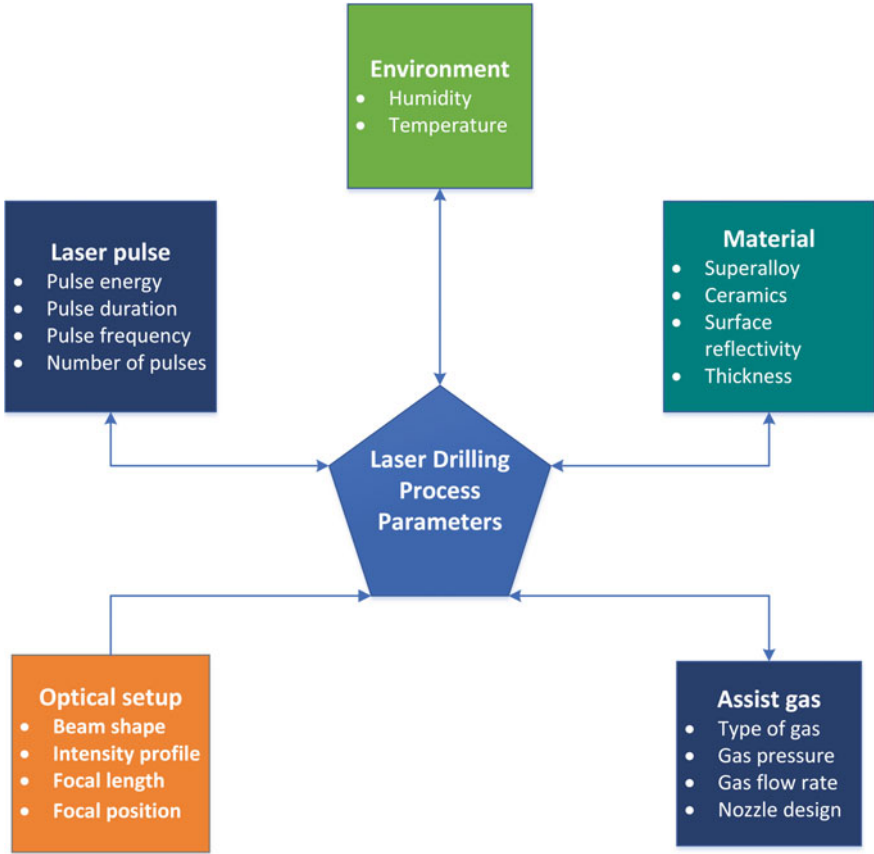


Fig. 14 Classification of process parameters

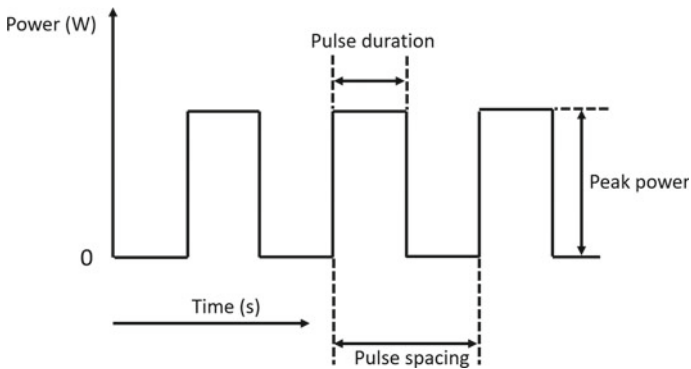


Fig. 15 Laser pulse waveform

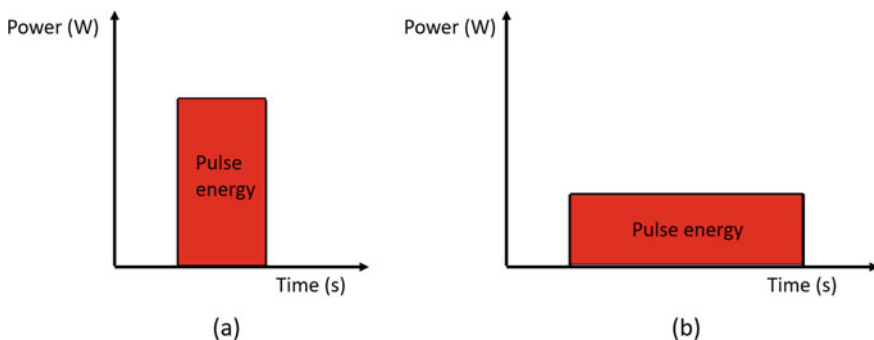
peak power with short pulse duration typically leads to rapid melting and high vapour pressure which subsequently accelerates liquid (molten metal) removal [79]. It has been noted that drilling with high peak power significantly reduces hole taper [31, 57], recast layer thickness [6, 14, 61] and microcracks [59].

$$Peak\ power = \frac{Pulse\ energy}{Pulse\ duration} = \frac{joule(J)}{second(s)} = watt(W) \quad (3)$$

It is clear from Eq. (3) that peak power is directly proportional to pulse energy and inversely proportional to pulse duration. High pulse energy helps to remove the molten material outside the hole cavity and therefore reduces the RLT [14] and microcracking [15]. On the other hand, hole taper increases with an increase in pulse energy [12, 78]. Generally, long pulse duration produces large diameter and deeper hole because of sufficient laser beam-workpiece interaction time [8], however, too long pulse duration is not ideal for laser drilling as it produces a large HAZ [57]. Short pulse duration is found to produce a very small difference between entry hole and exit hole diameters because of the high-power intense laser beam [12, 30] and also reduces microcracking [15]. The above mentioned studies have revealed a significant influence of pulse energy and pulse duration on drilled hole quality, therefore it is important to select a suitable value for these parameters.

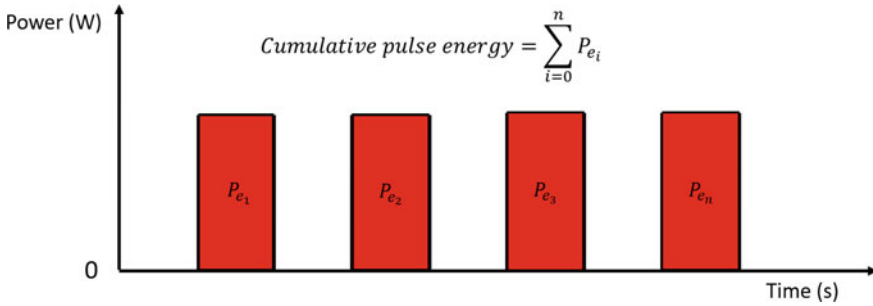
### 6.1.1 Single-Pulse Drilling

Single-pulse drilling employs one high-energy laser pulse to perform the drilling operation. The laser pulse can be of a short pulse duration with high peak power (Fig. 16a) or long pulse duration with low peak power (Fig. 16b), each has a significant impact on hole characteristics. The combination of short pulse width with high peak power is recommended as it improves repeatability of hole diameter [65] and hole circularity [28, 65].



**Fig. 16** Schematic representation of single-pulse drilling regimes: **a** higher peak power, **b** lower peak power





**Fig. 17** Schematic representation of cumulative pulse energy—percussion drilling

**6.1.2 Percussion**

In case of percussion drilling, more than one number of pulses are involved therefore the energy transferred to the material is calculated as cumulative pulse energy i.e. a total sum of energy associated with each pulse, as shown in Fig. 17. Typically, the cumulative pulse energy required to drill a hole is higher in comparison to single-pulse drilling due to pulse off stage in percussion drilling which allows the molten metal to solidify. Laser pulse off time depends on the duty cycle and pulse frequency. This indicates that the number of pulses and pulse frequency are also important parameters. These are explained in the following sections.

**6.2 Number of Pulses**

In laser drilling an increase in the number of pulses helps to remove material from the bottom side of a hole, after the formation of through-hole, and consequently produces lower hole taper [26, 29, 41, 64, 79]. Circularity of holes also improves with higher number of pulses [34]. However, spatter volume can be minimised using a smaller number of pulses [90].

**6.3 Pulse Frequency**

Pulse frequency controls the number of laser pulses fired per second. It also defines the average power of the laser that can be calculated by using the following Eq. (4).

$$\begin{aligned}
 \text{Average power} &= \text{Pulse energy} \times \text{Pulse frequency} \\
 &= (\text{joule}(J)) \times 1/(\text{second}(s)) = \text{watt}(W) \qquad (4)
 \end{aligned}$$

Hole quality is significantly influenced by the change in pulse frequency [63]. At high pulse frequency, the time gap between consecutive pulses is short which reduces the chances of heat loss due to convection and allows sufficient energy to enter into the workpiece material [79]. Lower hole taper with less RLT can be obtained with high pulse frequency [6, 12, 29, 57, 68]. On the contrary, HAZ increases with pulse frequency [57]. High average power (frequency) lasers and high energy lasers are expensive; therefore the type of process and laser used should be carefully selected.

#### 6.4 *Material Properties and Environment*

Material properties have a considerable effect on laser drilling performance. The (reflective) characteristics of a material surface directly influence the amount of energy absorbed during the laser drilling operation. Reflectivity or absorptivity is required to calculate the amount of energy absorbed by the material as indicated in Eq. (5) [74]. Single-pulse drilling is more sensitive to material reflectivity, whereas in percussion drilling there is a preheating effect and absorptivity increases with subsequent pulses.

$$E_{abs} = A \times P \times D_p \quad (5)$$

where:

$E_{abs}$  = Energy absorbed by the material (J).

$A$  = Material absorptivity (1 – Reflectivity).

$P$  = Applied laser power (W).

$D_p$  = Pulse duration (s).

In addition to this, the thermal conductivity of material also affects process efficiency. It is obvious that materials with high thermal conductivity transfer heat quickly throughout the workpiece instead of rapidly heating the targeted zone, therefore more time is needed to reach the melting state [84]. Material thickness is a significant influencing factor related to the geometry and metallurgical features of hole quality. Hole taper decreases with an increase in material thickness. On the contrary, spatter and recast layer increase when thicker material is used [6].

Environmental factors including humidity, mist, dust, ambient temperature and machine vibration also influence laser performance. Moreover, the surface of optical elements should be cleaned and contain no oil vapour or dust particles as these damage the optical system [75].

#### 6.5 *Beam Shape and Intensity Profile*

The temporal profile of a laser beam defines the intensity distribution and material removal capability of a laser pulse [92]. Gaussian beam profile is generally used in

the laser drilling process as it provides a small focused spot and high laser beam intensity which results in efficient removal of molten material [87]. Diameter and roundness of a laser beam directly affect the dimensions of a hole. The size of a hole is directly dependent on beam size. The smallest beam size of a particular laser system is determined by its optics and the optical settings.

### 6.6 Focal Length and Focal Position

Focal length is the distance from the centre of the lens to the focal point (see Fig. 18). Hole characteristics are greatly influenced by a change in focal length since this directly effects the beam spot size that is related with the laser power density, as shown in Eqs. (6) and (7) [1]. High power density is associated with shorter focal length and therefore results in higher melt removal. On the other hand, the spatter area increases with shorter focal length [43].

$$S_d = F_l \times \emptyset \tag{6}$$

$$P_d = \frac{P}{A_s} = \frac{4P}{\pi S_d^2} \tag{7}$$

where:

- $S_d$  = (min) spot diameter (mm).
- $F_l$  = Focal length (mm).
- $\emptyset$  = Beam divergence (angle).
- $P_d$  = (max) Laser power density (W/mm<sup>2</sup>).
- $P$  = Applied laser power (W).
- $A_s$  = Cross-sectional area of the laser spot (mm<sup>2</sup>).

Focal position of a laser beam is divided into three categories based on its position relative to the workpiece surface (see Fig. 19) [34]:

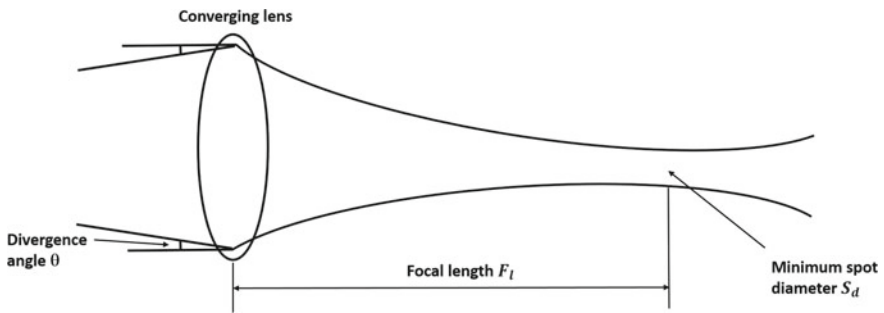
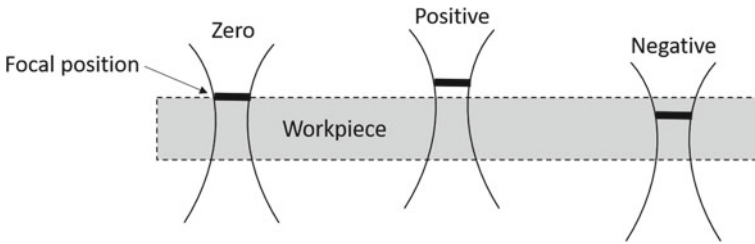


Fig. 18 Focus pattern of a laser beam



**Fig. 19** Schematic diagram showing the variation of focal position [27]

Zero: when the focal position of the laser beam is located exactly at the workpiece surface

Positive: when the focal position of the laser beam is located above the workpiece surface

Negative: when the focal position of the laser beam is located below the workpiece surface.

Focal position significantly affects the quality and geometry of a hole. Minimum RLT was noticed by Marimuthu et al. [48] and Leigh et al. [41] when the focal position of the laser beam was maintained exactly at the workpiece surface. The circularity of holes has also been shown to increase with zero focal plane position [34]. Shin and Mazumder [85] found a significant improvement in the values of hole taper with zero focal plane position.

## 6.7 Assist Gas

In the laser drilling process, an assist gas is employed to facilitate the removal of molten material and to blow out the recast layer and spatter which is deposited inside and on the top of the hole cavity, respectively. Different types of assist gases are utilised for the laser drilling operation. They are broadly classified as reactive gases or inert gases. Reactive gases provide additional exothermic energy as a result of chemical reaction between the molten metal and the gas and subsequently improve drilling efficiency. Oxygen and compressed air are categorised as reactive gases [72]. On the other hand, inert gases only provide kinetic energy to evacuate the molten material from the hole cavity without undergoing any chemical reaction. Nitrogen and argon fall under this category. The quality of the drilled hole is significantly affected by the type of assist gas employed [4]. Low et al. [44] observed lower spatter thickness with weak bonding strength when using oxygen as the assist gas. On the contrary, the drilling edge is oxidised which requires further cleaning [89]. Compressed air is the cheapest option but the disadvantages associated with this gas are the formation of dross and an oxidised surface. Using inert gases (nitrogen and argon), these oxidation scales can be avoided. Marimuthu et al. [49] compared

the quality of laser drilled holes using different assist gases. A regular hole profile with minimum RLT was obtained with argon and nitrogen compared to oxygen and compressed air.

The gas pressure must be enough to overcome the surface tension holding the liquid (molten) metal so that the liquid can be ejected. The value of gas pressure influences hole quality. Higher gas pressure facilitates the removal of molten material along the sidewalls and therefore results in less RLT [14, 48] and lower hole taper [12]. On the other hand, excessive gas pressure is also not desirable as it results in the formation of microcracks due to the phenomena of rapid solidification [14].

The nozzle design also affects hole quality. Biffi and Previtali [10] designed an innovative nozzle and achieved a significant decrease in spatter compared to a standard nozzle. Low values of recast layer were reported by Khan et al. [39] when a small nozzle diameter was used.

Proper control of these process parameters is necessary as they significantly influence performance of the process. Influence of laser drilling process parameters on the selected performance measures is provided below.

## 7 Effect of Process Parameters on MRV

The laser drilling process is associated with the removal of molten material to produce a particular hole geometry. Process efficiency depends on the volume of material removed versus the amount of energy applied. Higher MRV is always desirable with less energy input as it improves process efficiency. Additionally, MRV and process duration define the productivity of the process where higher MRV with less process duration is required for improved productivity.

There are various process parameters which influence MRV in laser drilling. This section covers previous research work conducted by researchers to study MRV in connection with the laser drilling process.

Low et al. [43] examined the laser drilling parameters influencing melt removal during percussion drilling. They concluded that pulse width and peak power directly influence MRV.

Fysikopoulos et al. [23] examined the impact of laser power and pulse frequency on the energy efficiency of the laser drilling process. For energy efficiency, MRV was calculated against the energy applied. It was revealed that increase in laser power and pulse frequency enhances process efficiency.

Panda et al. [68] selected oxygen as an assist gas and studied the variation in MRR. It was found that higher gas flow rate increases MRR. Goyal and Dubey [30] reported that higher gas pressure provides sufficient drag force that facilitates in removing the melt material. Wang et al. [89] analysed the effects of assist gas including oxygen and argon on drilling efficiency. Improved efficiency was reported using oxygen as an assist gas due to its combustible-supportability that generates excessive heat and results in higher MRV.

Sarfraz et al. [79] investigated the effects of laser drilling parameters on IN718 superalloy using three different laser drilling processes. Material removal rate (MRR) was calculated using MRV and drilling time. The results showed that pulse width, number of pulses and trepan speed are the most important parameters that influence MRR.

Biscaia et al. [11] conducted experiments on nickel superalloy using trepan laser drilling to explore the influence of process parameters on MRR. Results indicated trepan speed as the significant parameter influencing MRR. Higher trepan speed produced higher MRV with reduced drilling time.

An investigation was performed by Parthipan and Ilankumaran [69] to examine the material removal rate and surface roughness of laser drilled holes in Cu-Ni-Ti<sub>2</sub> MMC. Response surface methodology (RSM) approach was used to describe the relationship between material removal rate and drilling parameters. Then the optimal process parameters (pulse energy, laser power, gas pressure) were determined for higher MRR and better surface roughness.

## 8 Effect of Process Parameters on Hole Quality

Different experimental studies have been performed by researchers to study the impact of laser drilling process parameters on hole quality. These aim to enhance the quality attributes of the laser drilled holes.

Taper control is the most important issue during the laser drilling process. High value manufacturing industries dealing with aircraft engine components demand holes without any taper. Different factors influence hole taper, the following studies address the significant process parameters.

Bandyopadhyay et al. [7] investigated the hole taper of laser drilled holes produced in titanium alloy and nickel superalloy sheets. Pulse duration, pulse energy and focal position were found to be significant parameters affecting hole taper. Low levels of pulse duration and pulse energy with zero focal position resulted in improvement of hole taper. In another study, Bandyopadhyay et al. [6] found that increase in material thickness caused improvement in hole taper.

Kacar et al. [37] observed the influence of pulse duration and peak power on hole taper using alumina ceramic. An increase in pulse duration and peak power produced an improvement in hole taper.

A study was conducted by Mishra and Yadava [58] on laser drilling of IN 718 sheet. Results showed improvement in hole taper with an increase in pulse frequency. Bathe and Padmanabham [9] reported the influence of laser drilling parameters using TBC (thermal barrier coated) IN 718 as a substrate. Pulse duration produced a significant impact on hole taper. Decreasing pulse duration produced a reduction in hole taper.

Goyal and Dubey [30] investigated the impact of laser drilling parameters on hole taper of laser drilled IN 718 sheet. Hole taper was found to decrease with an increase in trepan speed and pulse frequency. Similar findings were reported by Dhaker and Pandey [18].

Bahar et al. [4] showed the importance of laser power and laser frequency in the laser drilling process. They reported that higher laser power and increased pulse frequency help to improve hole taper. The study also revealed that comparing the effect of compressed air, oxygen and nitrogen on hole taper, improved hole quality was obtained with compressed air and nitrogen. Shin and Mazumder [85] stated that hole taper can be improved when higher laser power is applied with lower trepan speed and zero focal position.

Chatterjee et al. [12] explored studies on laser drilling of titanium alloy. Pulse duration, pulse energy, pulse frequency and gas pressure were varied to observe their effects on hole taper. They stated that increasing pulse frequency and gas pressure resulted in improvement of hole taper. It was also discovered that hole taper was increased by increasing pulse energy and pulse width. Chatterjee et al. [13] conducted another study on stainless steel (AISI 316). Similar results were found for this material except for gas pressure and pulse energy effects due to a difference in material properties.

Sarfraz et al. [79] conducted experiments to investigate the impacts of pulse energy, pulse frequency, number of pulses, pulse duration and trepan speed on hole taper. Pulse duration and pulse energy produced the most significant effect on hole taper.

Padhee et al. [67] examined the impact of number of pulses and pulse width on the taper angle of drilled holes produced on (Al/SiC) MMC. Improvement in taper angle was observed when lower number of pulses and lower pulse width was applied. Moreover, the impact of concentration (wt%) of SiC particulates on hole taper was studied. It was noted that higher concentration of SiC increases hole taper.

Marimuthu et al. [49] studied the characteristics of holes during laser drilling of (Al/SiC) MMC. It was observed that less energy is required to drill holes with acceptable quality in (Al/SiC) MMC in contrast to isotropic metals or alloys. In another study, Marimuthu et al. [50] investigated the water jet guide (WJG) laser drilling of the same material. WJG laser drilling produced better hole quality with less taper, no recast layer and improved hole circularity compared to conventional laser drilling.

## 9 Effect of Process Parameters on Manufacturing Cost

The laser drilling process depends on several process parameters that affect process efficiency and product quality as described above. Sarfraz et al. [76, 78] specified that these process parameters also influence manufacturing cost. These researchers provided a cost breakdown structure of the laser drilling process and identified cost drivers involved in the process. Detailed work has been reported by Sarfraz et al. [80] depicting the laser drilling process parameters impact on manufacturing cost. Pulse duration was reported as the most significant parameter affecting the drilling cost followed by gas flow rate and pulse energy. However, the work was only limited to the single-pulse drilling process.

Besides the laser processing parameters, there are other factors involved which contribute to the laser drilling manufacturing cost. These factors are discussed in the following section.

## 10 Cost of Laser Drilling

Manufacturing cost estimation is essential for companies targeting to become successful in the current competitive scenario. One of the important tasks of cost estimation is to establish a work breakdown structure (WBS). The main purpose of a WBS is to provide a uniform structure incorporating all the elements of the process that will be specified by the cost estimate, where each element represents the cost required to execute that process. When a WBS includes all the cost information, it may serve directly as a cost breakdown structure [62]. The operating costs breakdown structure of a laser drilling process is presented in Fig. 20.

Cost estimation requires an identification of cost drivers i.e. those factors which significantly influence the cost. The total cost is changed with a small modification to a single cost driver. It is possible to generate a comprehensive cost estimate for a particular process only if all of its cost drivers are identified [62].

The main cost drivers relevant to the laser drilling process are provided in Table 2. Equipment running cost, maintenance, material and labour costs are the key drivers in laser drilling cost estimation. It was identified that equipment running cost further consists of equipment depreciation, electrical (power) consumption, components replacement, gas consumption, component handling and overhead costs. When all cost drivers are finalised, a cost is allocated to each driver and the total process cost can be calculated.

The selection of an appropriate laser source is also important as it affects the cost efficiency of the process [19]. Nd:YAG and fibre lasers are the most commonly used laser sources for drilling in the industry. A comparison between these two lasers is

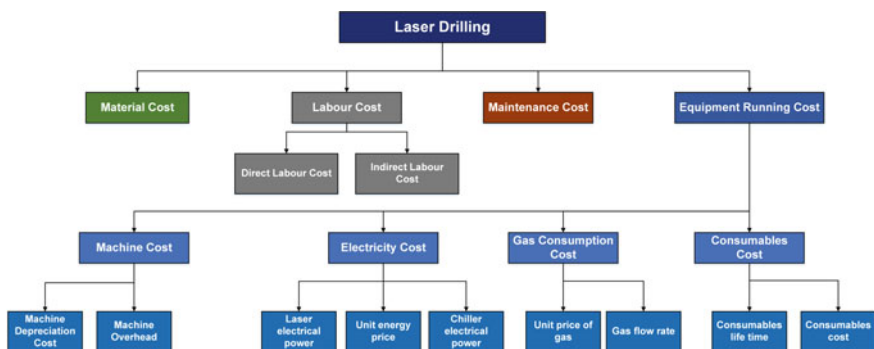


Fig. 20 Cost breakdown structure



**Table 2** Cost drivers of the laser drilling process

Cost drivers	Yeo et al. [92]	Baisev and Powell [8]	Ion [36]	Dahotre and Harimkar [17]	Sarfraz et al. [77]
Equipment running cost	Equipment depreciation	Equipment depreciation	Equipment depreciation	Equipment depreciation	Equipment depreciation
	Electrical consumption	Electrical consumption	Electrical consumption	Electrical (power) consumption	Electrical consumption
	Replaceable components (lenses, flash lamp, filters)	Replaceable components (lenses, laser pumps)	Replaceable components (lenses, flash lamps)		Replaceable components (lenses, flash lamp, filters, nozzle)
	Gas consumption		Gas consumption		Gas consumption
		Component handling		Component handling	Component handling
		Overhead	Overhead	Overhead	Overhead
Maintenance		Equipment maintenance	Equipment maintenance		Equipment maintenance
Material				Material cost	Material cost
Labour		Labour (operator) cost	Labour (laser operators and engineers) cost	Labour cost	Labour cost

provided in Table 3. It is noted that the purchase cost of a fibre laser is higher than Nd:YAG but its running cost is much lower because of higher electrical efficiency and longer operating life. Nd:YAG laser does require periodic maintenance and service for the alignment, cleaning and replacement of optics, on the other hand, a fibre laser is maintenance free. It is important to mention that these laser sources have different beam quality, which ultimately affects hole quality and productivity [19, 40]. Therefore, it is important to evaluate the laser source being used for the drilling.

**Table 3** Fibre laser and Nd:YAG laser comparison

	Fibre laser	Nd:YAG laser
Laser capital cost	Higher	Lower
Laser operating cost	Lower	Higher
Electrical efficiency	Higher	Lower
Operating life	Longer	Shorter
Maintenance	Low	High

## **11 Concluding Remarks and Future Perspectives**

### ***11.1 Conclusions***

Laser drilling is a well-established technology exclusively in the aerospace sector, where this process involves large volume production of holes. In this chapter, single-shot, percussion and trepan laser drilling methods are discussed. Performance measures of the laser drilling process including material removal volume, hole quality attributes and manufacturing cost are explained.

Different laser drilling process parameters are extensively discussed, and the existing literature depicting the attention of several authors towards this advanced machining process is presented. The performance of the laser drilling process can be enhanced when proper selection and control of process parameters are applied. Furthermore, the cost factors of the laser drilling process are explained within this chapter. It is observed that the laser source affects the cost efficiency of the drilling process along with productivity and hole quality.

### ***11.2 Future Research Trends***

Because of their superior properties, metal matrix composites are potential candidate materials for use in aeroengine components. However, limited documented knowledge is available discussing the performance of laser drilling of MMCs. Exploring the behaviour of MMCs against the applied laser drilling parameters is, therefore, necessary to find out the best combination of process parameters for optimum hole quality.

It is noted that the laser drilling process parameters have a substantial impact on the manufacturing cost of the process. Therefore, there is a need to examine the impact of process parameters on the manufacturing cost along with the economic implications of the laser drilling process.

It is also specified that the product quality and the manufacturing cost are interdependent and both depend on the applied process parameters. Consequently, connecting the quality attributes with the manufacturing cost is a knowledge gap that can be covered in a future study.

Different types of laser drilling methods are available to perform the drilling operation. From the available literature, it has been found that there is a lack of research characterising laser drilling methods in terms of economic and quality perspectives. Therefore, a model can be developed to provide a comprehensive understanding for the designers and practitioners to select a suitable laser drilling technique for the required cost and quality attributes.

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