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Evaluation of Productivity and Operating Cost of Laser Drilling Process – A Case Study

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Abstract. Laser drilling is a non-conventional machining process which is widely used in automotive, electronics and aerospace sectors to produce holes in diverse range of materials. Different types of lasers and methods are available to produce various hole geometries. Big number of researchers have examined several ways to enhance the performance of this process by investigating different process parameters and drilling methods, that seek improvement of the drilled hole quality. Whereas, productivity and operating cost are also important factors which need to be evaluated along with drilled hole quality. Reducing the drilling time can improve productivity and the selection of a suitable laser can save operating cost which will benefit laser processing industries in this global competitive environment. A case study was performed using different lasers for single pulse and percussion drilling. A significant improvement in productivity was observed with the use of a high power laser that is subject to high operating cost.

Keywords. Laser drilling, operating cost, productivity, drilling time.

1. Introduction

With an advancement in materials along with the need for precise hole geometry and high productivity, different unconventional drilling techniques have been developed such as electro-discharge machining, laser drilling, electrochemical machining, ultrasonic machining and water jet machining, etc. Laser drilling is more suitable than the other techniques due to its applicability for a diverse range of materials and high production rate [1–5]. It is widely used to produce holes for fuel filters, engine cylinder rings or injection nozzles and air-cooling holes in turbomachinery components such as combustors, afterburners, vanes and blades.

Different types of methods are available for laser drilling operation which include single pulse, percussion and trepanning. The latter method translates the laser beam into a circular path to cut the perimeter of a hole and is basically a cutting process [6, 7]. Percussion drilling involves multiple pulses to remove material. A particular amount of material is removed with each pulse, depending on the applied pulse energy, and the

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required hole size is obtained after a certain number of pulses. On the other hand, single pulse drilling is a high-speed process which removes the material completely using a single pulse only [3].

Due to inherent defects of laser drilling such as heat affected zone (HAZ), recast layer, micro cracks and hole taper, selection of suitable process parameters is essential to achieve better hole quality. The transformation of metallurgical characteristics of laser drilled hole particularly depends on HAZ. Hence it is important to minimise the HAZ during laser drilling by controlling the process parameters, where low pulse energy yields smaller HAZ. Bandyopadhay et al [8] revealed that hole taper decreases with the increase in pulse frequency and the thickness of HAZ was found to decrease when lower pulse energy was applied. Yilbas [9] studied the effect of pulse duration, pulse energy, focal position, and material thickness on three materials nickel, titanium, and stainless steel, and observed that hole taper increases by increasing pulse duration and energy. It was also revealed that pulse energy, pulse frequency, pulse width and focal position control the formation of recast layer. It is observed from the previous studies that pulse energy, pulse repetition rate and pulse duration play a significant role in influencing the quality of the drilled hole [9–14].

From the literature review, it was revealed that majority of research work focused on the analysis of hole geometry and quality characteristics. However, very limited work is reported on productivity and operating cost of laser drilling process. In this paper, a case study has been presented to evaluate the productivity and operating cost of the laser drilling process.

2. Materials and Methods

The present study was conducted for drilling of IN718 because of its relevance to gas turbine and aeroengine applications [15]. This material is used for hot section components to enable them withstand high temperature. The operating temperature of aeroengine components varies between 400 to1100°C [16]. In order to improve the operational life of these components, substantial cooling is necessary. Therefore, laser drilling is used to provide a passage for air coolant in hot path components. A cooling film is formed around the component surface as the air passes over it, which provides a protection barrier facing the hot combustion gases. In the last few decades, increased number of cooling holes in turbine design have been observed in order to improve performance and efficiency. For instance, 40000 holes are found in the afterburner of a gas turbine.

2.1. Energy Calculation

In laser drilling process, the material surface is initially melted by using a powerful laser beam; the (melted) particles are then flushed out with the aid of assist gas delivered under high pressure. A particular amount of energy is associated with the removal of a specific volume of material. The reduced input of laser energy into the work part is always favourable as it results in a small heat affected zone [17]. Moreover, hole taper also has a direct relationship with pulse energy and increases linearly with an increase in pulse energy [9]. The minimum amount of energy needed to melt the workpiece material for through hole drilling can be calculated theoretically using the following equation [18]:

$$E_{th} = m(C_p(T_m - T_o) + L_m) \quad (1)$$

Where:
E_{th} = theoretical energy required to melt the work piece material (J)
C_p = specific heat capacity of workpiece ($Jkg^{-1}K^{-1}$)
T_m = melting temperature of workpiece (K)
T_o = initial temperature of workpiece (K)
L_m = latent heat of melting (Jkg^{-1})

In through hole drilling, the mass of material removed (m) after a successful drilling process can be found as:

$$m = \rho \frac{\pi D_h^2}{4} T_h \quad (2)$$

Where:
ρ = material density ($kgmm^{-3}$)
D_h = diameter of hole (mm)
T_h = thickness of workpiece (mm)

It is important to note that E_{th} represents the minimum energy needed to melt the material to produce through hole; the energy needed for melt ejection and vaporisation is not included in Eq. (1). Moreover, solid and liquid phase properties have been considered separately and the variation of thermo-physical properties with temperature is ignored.

2.2. Case Study - Single Pulse Drilling

A case study of multi-hole drilling was conducted using different lasers with single pulse drilling method. Drilling operation was performed on IN 718 plate with different thicknesses (1mm, 2mm, 3mm and 4mm). Figure 1 shows the variation of energy (calculated using Eq. 1) with the removed material volume for different hole sizes. It is apparent that more energy per pulse is needed to remove large material volume which means having a high power laser.

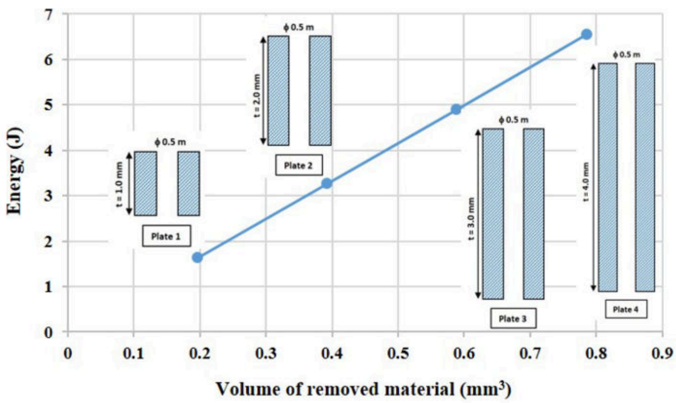

Figure 1. Variation of required energy with respect to volume of removed material

It is obvious that productivity can be improved if the drilling time is reduced to a minimum. On the other hand, in order to remove the same volume of material in lowest possible time higher power laser needs to be used which increases the operating cost. Similar trend is observed when drilling was performed for 100 holes, as shown in Figure 2. It can be observed that laser E and F (high power lasers) reported significant decrease in drilling time than laser C and D. It is also evident that drilling time is higher for plates 3 and 4 because of the large volume of removed material. Laser A and B were not applicable for single pulse drilling because the energy per pulse was too small compared to the required pulse energy (shown in Table 1).

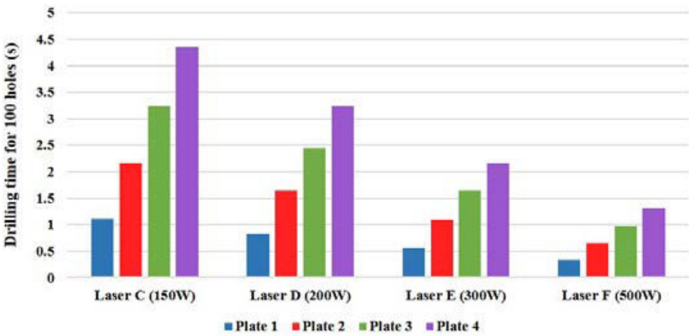

Figure 2. Drilling time values for 100 holes with different lasers

2.3. Case Study - Percussion Drilling

In this case study, multi-hole drilling was considered to evaluate the productivity and operating cost using different lasers with percussion drilling method. IN 718 plate was used as workpiece material with 1mm thicknesses. In percussion drilling, series of pulses is used to drill hole, therefore the energy required for drilling is the cumulative pulse energy i.e. product of energy per pulse and the number of pulses/pulse frequency, which indicates that both pulse energy and pulse frequency influence the performance of this method. Different lasers were used to perform this study. The specification of each laser is given in Table 1. For instance, laser B has the minimum pulse energy with maximum pulse frequency as compared to the other lasers. Similarly, laser F has maximum pulse energy with medium pulse frequency in contrast with other lasers.

Table 1. Specification of lasers used for laser drilling

Parameters	Laser A	Laser B	Laser C	Laser D	Laser E	Laser F
Average power (W)	8.5	100	150	200	300	500
Maximum pulse energy (J)	0.85	.001	50	40	56	120
Maximum pulse frequency (Hz)	10	1000000	500	500	1000	500

Figure 3 shows the productivity and operating cost values of different lasers. A significant variation is observed from laser A to F. Highest productivity is achieved when high power laser (laser F) is used in contrast with low power laser (laser A). Whereas, a remarkable difference in operating cost is found between laser A and laser F.

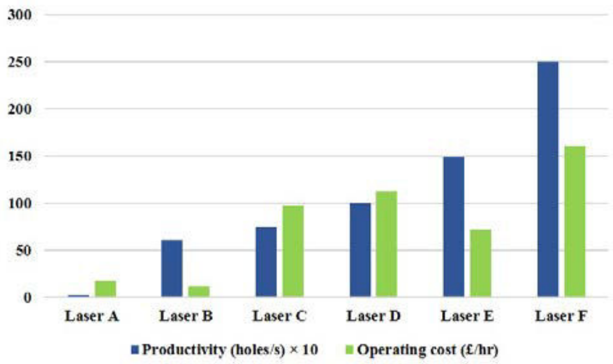

Figure 3. Productivity and operating cost values for different lasers

3. Results and Discussion

In laser drilling, the formation of hole is associated with the amount of material removed which depends on applied pulse energy. High material removal rate is associated with a high power laser and vice versa. It is pertinent to note that knowing the amount of energy associated with a particular volume of material, it would be easy to select a suitable laser drilling facility.

There are different ways to drill a particular hole, either single shot drilling with a single pulse or a multi-pulse percussion drilling. The single pulse drilling requires high pulse energy lasers, which may be expensive but the drilling time is shorter. On the other hand, the percussion drilling requires lower pulse energy lasers but to offer high efficiency rates a high repetition rate is required, which means high average power laser. The trade-off depends on the number of holes and material thickness required. In addition, the quality aspect such as taper angle, size of HAZ needs to be considered as well.

4. Conclusions

High value manufacturing industries are continuously striving to enhance their competitive position through improved productivity at minimum possible cost. Results of the case study show that selection of a suitable laser helps in meditation between productivity and operating cost.

The cost of laser depends on the average power of the laser and this increases with its power. This shows that it is appropriate to use high power laser, for certain applications, only if it is possible to take advantage of high energy or high repetition rate capability, otherwise it will be uneconomical.

In future, experimental studies will be performed to support these results and to make a comprehensive model for laser drilling production of holes which will benefit laser processing industries by providing complete cost and productivity information.

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