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Laser cutting of various materials: Kerf width size analysis and life cycle assessment of cutting process

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ABSTRACT

Laser cutting of various materials including Ti-6Al-4V alloy, steel 304, Inconel 625, and alumina is carried out to assess the kerf width size variation along the cut section. The life cycle assessment is carried out to determine the environmental impact of the laser cutting in terms of the material waste during the cutting process. The kerf width size is formulated and predicted using the lump parameter analysis and it is measured from the experiments. The influence of laser output power and laser cutting speed on the kerf width size variation is analyzed using the analytical tools including scanning electron and optical microscopes. In the experiments, high pressure nitrogen assisting gas is used to prevent oxidation reactions in the cutting section. It is found that the kerf width size predicted from the lump parameter analysis agrees well with the experimental data. The kerf width size variation increases with increasing laser output power. However, this behavior reverses with increasing laser cutting speed. The life cycle assessment reveals that material selection for laser cutting is critical for the environmental protection point of view. Inconel 625 contributes the most to the environmental damages; however, recycling of the waste of the laser cutting reduces this contribution.

1. Introduction

Laser cutting of sheet metals offers significant advantages over the conventional cutting methods; some of these include precision of operation, high speed processing, and low cost. Laser cutting involves with high temperature processing of materials including solid phase heating, melting, and evaporation. In the case of metallic materials processing, assisting gas is used to reduce the oxidation reactions in the cutting section. Since the oxidation reactions gives rise to excessive heating in the cutting section via high temperature exothermic reactions, the resulting section suffers from cutting asperities such as sideways burning, dross attachments, and thermal erosion [1]. The proper controlling of the laser cutting process through appropriate selection of the cutting parameters minimizes the defect sites along the cut sections. However, further investigations are needed for net shaping of the materials, which involve with high thermal conductivities and low fracture toughness such as titanium alloys and alumina. On the other hand, a care must be taken during the cutting process from the perspective of the energy consumption. This is because of the fact that a laser as a machine tool uses the electrical energy to generate irradiated power in the cutting section. Since the efficiency of the lasing devices is low, which in the order of 30% [2], the electrical energy consumption increases the cost of machining and contributes to the environmental degradation. This is due to the electrical energy generation from turbines, particularly gas and steam turbines, which have adverse effect on the environment. Consequently, investigation of the laser cutting process from the environmental perspective via life cycle assessment becomes essential.

Laser cutting process and the assessment of cutting parameters on kerf size and geometry are important aspects of the quality evaluation of the end product. Optimization studies on laser cutting offers improved process control and securing of the end product quality. Modelling and optimization study for the assessment of the cut quality of a thin aluminum-alloy was carried out by Sharma and Yadava [3]. They introduced the entropy measurement methodology for the calculation of weight corresponding to each quality characteristic. They indicated that the hybrid approaches for modelling and optimization of the laser cutting process provided reasonably good accuracy. Optimization of multiple quality characteristics in laser cutting of titanium alloy sheet was examined by Pandey and Dubey [4]. They identified important control factors related to the quality characteristics for kerf tapering and surface roughness. Jet impingement onto a laser produced kerf and the effect of kerf wedge angle on heat transfer rates and

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skin friction were investigated by Melhem et al. [5]. They demonstrated that the kerf wall wedge angle had considerable influence on the Nusselt number and the skin friction. Laser cutting of the triangular geometries in aluminum foam and the influence of cut size on thermal stress levels were studied by Yilbas et al. [6]. The findings revealed that small size triangle cuts resulted in relatively higher temperatures around the cut edges as compared to large size triangle cuts; however, opposite was true for von Mises stress levels. This was attributed to the slow cooling rates in the case of the small size triangle cuts. On the other hand, considerable research studies were carried out to examine the laser machining process and environmental impact. Energy related life cycle impact and cost reduction opportunity in laser cutting process was studied by Devoldere et al. [7]. They showed that the CO_2 laser source and the chiller unit were the largest energy consumers during the processing time. In addition, during non-productive time, 12% of the yearly energy consumption was required to keep the chiller and other components active. Environmental assessment of laser assisted manufacturing incorporating the laser shock peening and laser assisted turning was carried out by Zhao et al. [8]. They indicated that the environmental performance of the two laser based processes was significantly better than those of the conventional processes. For the laser shock peening of aluminum, the analysis indicated that this was mainly due to the significant extension of fatigue life of the workpiece being treated. For the laser assisted turning of compacted graphite iron, the improved performance was mainly due to the extended tool life since cutting tool manufacturing was an energy intensive process. In addition, development of high-power laser with a lower wavelength (e.g. direct diode system) could eliminate the use of paint in laser assisted turning. Energy efficiency assessment of laser drilling process was investigated by Apostolos et al. [9]. They presented the laser processing efficiency incorporating two different analyses, which include: (i) considering the entire laser system, and (ii) including only the workpiece – laser beam interactions. Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of composites was studied by Bhushan [10]. He showed that multi response optimization through desirability analysis route reduced power consumption by13.55% and increased tool life by 22.12%. The optimization study for the laser cutting process, incorporating the laser parameters with multi-performance characteristics, was carried out by Caydas and Hascalik [11]. They demonstrated that grey relational grade analysis provided useful information on the laser cutting process; in which case, the laser power had more effect on the cutting quality than that of the cutting speed. Laser-assisted machining of Inconel 718 and the economic analysis was studied by Anderson et al. [12]. They presented the machinability of Inconel 718 under various conditions. They demonstrated that with increasing material removal temperature from room temperature to 620 °C, the benefit of laser assisted machining was demonstrated by a 25% decrease in the specific cutting energy. In this case, 2–3-fold improvement in surface roughness and a 200–300% increase in ceramic tool life over conventional machining were reported. The energy and environmental impact analysis of remanufacturing of turbine blades via laser direct deposition was carried out by Wilson et al. [13]. They demonstrated the effectiveness of laser direct deposition in remanufacturing and its potential to adapt to a wide range of part defects. A Life Cycle Assessment (LCA) on the energy and environmental impacts by remanufacturing was also presented. Energy and resource efficiency of laser cutting processes was examined by Kellens et al. [14]. They provided an overview of the environmental performance in terms of energy. In addition, they derived the resource efficiencies of different types of laser cutting systems and demonstrated the performance improving strategies. Environmental aspects of laser-based and conventional tool for die manufacturing were investigated by Morrow et al. [15]. They indicated that laser-based remanufacturing of tooling could reduce the processing cost and environmental impact simultaneously, especially as the scale of the tool increased.

Laser machining process and life cycle assessment was presented earlier [13], the main focus was to use laser deposition technique to produce parts and the life cycle assessment for the laser cutting of different materials was left for the future study. In the present study, laser gas assisted cutting of titanium alloy, steel, alumina, and Inconel alloy was carried out. The effect of laser output power and cutting speed on the resulting cut geometries, in terms of the kerf width size variation, is studied. The life cycle assessment of the laser gas assisted cutting process was carried out to examine the environmental impact of the laser cutting process.

2. Experimental

A CO_2 laser (LC-ALPHAIII) delivering nominal output power of 2000 kW was used to irradiate the workpiece surface. The laser output intensity was in the form of high frequency repetitive pulses having the frequency of 1500 pulses per second. The wavelength of the laser is 10.6 μm and laser output intensity is Gaussian with TEM_{00} mode. The nominal focal length of the focusing lens was 127 mm and the laser beam diameter focused at the workpiece surface was 0.25 mm. Nitrogen assisting gas at high pressure was introduced coaxially with the laser beam through a nozzle. A computer controlled x, y table was used to mount the workpieces of 2 mm thickness. The laser power intensity was varied in between 500 and 1500 W while the x, y table speed was changed within 5–10 cm/s in the experiment. Nitrogen gas pressure was kept at 550 kPa during the experiments. Table 1 gives the laser cutting parameters used in the experiments.

After completion of the cutting process, the widths of resulting cuts were measured and SEM microphotography of the cut surfaces was carried out. To measure the striation depths and widths, the surface roughness measurement was carried out using a Bendix stylus instrument; in which case, the difference of kerf width size (Δw_k) was obtained. The difference of kerf width size was determined from:

$$\Delta w_{k-P/S} = (w_{k_n})_{P/S} - (w_{k_{n+1}})_{P/S}$$

w_k is the kerf width size, and indices of P and S represents the kerf widths due to laser output power variation and the laser cutting speed, respectively. The kerf width size ratio is determined from the following equation:

$$\%\Delta w_{k-P/S} = \frac{(w_{k_n})_{P/S} - (w_{k_{n+1}})_{P/S}}{(w_{k_{average}})}$$

where $w_{k_{average}}$ is the average of the kerf width size along the cutting edge.

3. Kerf width analysis

Introducing the lumped parameter technique, the overall energy balance for the laser cutting process could be simplified [16]. This relation can be written as [16]:

$$\frac{P}{d} = \frac{\upsilon w_k + A_3\sqrt{\upsilon w_k}}{A_o} \tag{2}$$

where

$$A_o = \frac{A}{a_o};\ A_3 = \frac{1}{a_o}\frac{(w_k + 2wk(T_m T_o))}{2\sqrt{\alpha w w_k}} \quad \text{and}$$

$$a_a = \rho[Cp(T_m - T_o) + L_m + \beta L_b]$$