Laser Beam Cutting of Steels – An Overview

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ABSTRACT

Laser beam cutting (LBC) is one of the most widely used thermal energy based non contact type advance machining process which can be used for almost any range of materials. Laser beam is focused for melting and vaporizing the unwanted material from the base material. It is suitable for geometrically complex shape machining and making miniature drills in sheet metal. In the recent years, researchers have explored a number of ways to improve the performance of LBC process by analyzing different factors that affect the quality characteristics. The experimental and theoretical studies shows that process performance can be improved significantly by proper selection of laser parameters, material parameters and operating parameters. This paper presents the detailed literature overview in the area of LBC.

Keywords***: Laser beam cutting, experimental models, analytical models.***

1. INTRODUCTION

Laser beam cutting (LBC) is a thermal energy process in which the material is removed by melting, vaporization, sublimation and chemical degradation. When a high energy density laser beam is focussed on material surface the thermal energy is absorbed which heats the work piece and transforms the work piece into a molten, vaporized or chemically changed state that easily removes material by the flow of high pressure assist gas jet (which accelerates the transformed work piece material and ejects it from machining zone) studied by Majumdar (2003). Laser cutting in general is successful process to reduce production and manufacturing costs. This is due to the advantage of high production rates as well as the fact that lasers can be automated, computer controlled and included into assembly lines. Many industries have been revolutionized by the application of laser equipment in their production lines. This is because of the high quality and low distortion characteristics of the cutting action which can be achieved. LBC deals with machining and material processing like heat treatment, alloying, cladding, sheet metal bending, cutting, drilling, milling, etc. Such processing is carried out utilizing the energy of laser beam. It mostly converts thermal energy upon interaction with most of the materials. Nowadays, lasers are also finding application in regenerative machining or rapid prototyping investigated by Rozzi (2014). Development of advanced engineering materials, intricate design requirements, complex shape and unusual size of workpiece does not allow the use of conventional machining methods Chryssolouris (2015). Hence, it is needed to develop some non conventional machining methods called as advanced machining processes (AMPs). Now-a-days many AMPs are being widely used in the industry such as electro discharge machining (EDM), laser beam machining (LBM), electron beam machining (EBM), ion beam machining (IBM), plasma beam machining (PBM), electrochemical machining (ECM), chemical machining processes such as (chemical blanking or photochemical machining), ultrasonic machining (USM), and jet machining processes such as abrasive jet machining (AJM), water jet machining (WJM) and abrasive water jet machining (AWJM), but these processes have their own advantages and limitations regarding workpiece material, shapes, sizes, etc. studied by Dubey et al. (2008). LBC is one of the most widely used AMPs which are used for shaping almost whole range of engineering materials, Meijer (2004). The laser beams are widely used for cutting, drilling, marking, welding, melting, sintering and heat treatment (Pham et al., 2014). The laser beam is also used to perform turning as well as milling operations but major application of laser is mainly used in cutting of metallic and non-metallic sheets discussed by Tsai (2013). Fig. 1 shows the LBC process in which laser beam passes along with assist gas on the workpiece for different cutting operations.

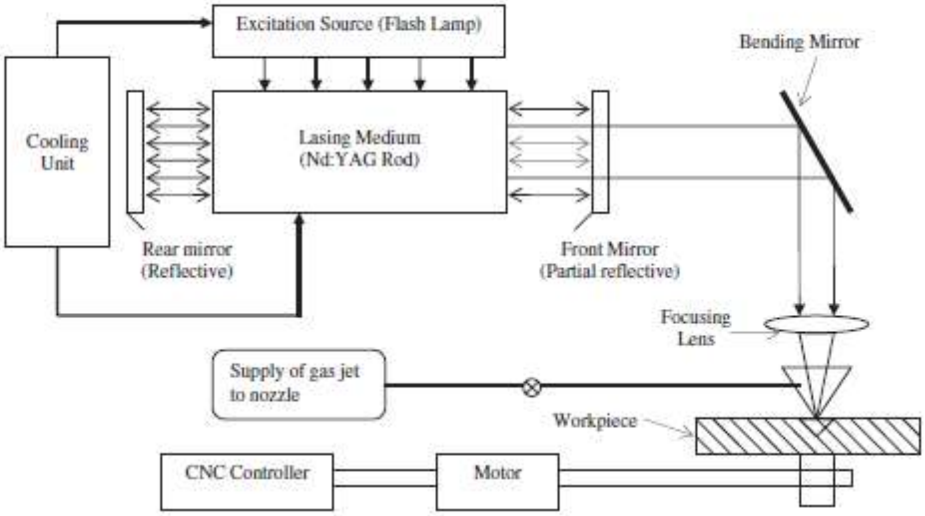

Fig-1: Nd-YAG Laser beam cutting process (Dubey, et al. 2007)

2. LITERATURE REVIEW

This paper provides a overview on the various research activities carried out in LBC process. Major research works in the category of different materials, experimental models and analytical models are described as follows.

2.1 LBC for different materials

Shang (2000) investigated the importance of exothermic reaction of CO_2 laser cutting and effects of gas composition on high power CO_2 laser cutting of mild steel. Non-linear interacting factors are responsible for laser cutting process performance. The effects of gas composition variation and the gas pressure on the cut quality are found out, with particular reference to small variations in gas composition. Chen (2001) has developed a model for the prediction of surface profile using neural network and future trend are also introduced. Yilbas et al. (2005) found that laser cutting of wedge surfaces cannot be avoided in sheet metal processing and the quality of the end product defines the applicability of the laser cutting process in such situations. In their study, CO_2 laser cutting of the wedge surfaces as well as normal surfaces was considered and the end product quality was assessed using the international standards for thermal cutting. Laser melting of thick mild steel material is considered and effect of cutting parameters on the percentage of kerf width variation is examined by Yilbas (2005). The cutting parameters considered include laser output power, cutting speed and oxygen assisting gas pressure. In the two dimensional analytical model developed by Lee et al. (2005) power absorption over the cut front, effect of oxidation and melt film thickness are studied in the model. The surface profile and surface roughness of a machined workpiece are two of the most important product quality characteristics and in most cases a technical requirement for mechanical applications. Chen et al. (2006) have studied the effect of not vertical cutting with laser beam in order to avoid interference during 3D laser cutting of thin metal. A laser head cannot be kept vertical to the surface of a work piece. In such situations, the cutting quality depends not only on typical cutting parameters but also on the slant angle of the laser head. Powell et al. (2007) have studied the effect of conductive losses in CO_2 laser cutting. Their studies have shown that in oxygen assisted laser cutting of steel the oxidation reaction is the major contributor for cutting at higher thickness material. For a particular laser power, the power of oxidation during cutting exceeds that of laser. Jorgensen et al. (2008) have studied on-line quality detection during CO_2 laser cutting. Fourier Analyses and statistical analyses of the signals have been carried out and from these analyses they have estimated the surface roughness in the cut kerf, dross attachment at the backside of the work piece and the penetration of the laser beam. Cheng et al. (2009) have used a perturbation method to study the linear stability behaviour of a thin molten layer in laser cutting. A theoretical model for high velocity laser cutting of metals assuming that the light absorption occurs as per the classical Fresnel formulae has been given by Schulz et al. (2009). Yilbas et al. (2010) has given a statistical method based on factorial analysis to identify the influence of cutting parameters on the resulting cut quality by using International standards for thermal cutting process. The effect of assist gas pressure on the material removal rate in laser cutting has been found by Farooq and Kar (2010). Markus (2011) in his paper concentrates only on exothermic reactions of the melt material with the assist gas while neglecting other important physical mechanisms for modelling the laser cutting process. Hsu and Molian (2011) have used a dual gas-jet, laser-cutting technique involving coaxial and off axial oxygen gas flows to cut 6.35mm thick AISI 304 stainless steel plates with a 1200 W CO_2 gas transport laser at a cutting speed of 12.7 mm/sec. Tirumala and Nath (2012) have correlated the cut surface quality and the melt film thickness. They have estimated that optimum pressure required for melt ejection under laminar flow regime. An experimental study of the benefits of using an annular jet in conjunction with the standard cutting jet was made during CO_2 laser cutting trials to examine the validity of the theoretical calculations. Role and effect of oxygen purity in laser cutting of mild steel is also studied by Powell et al. (2012). Asano et al. (2013) have shown that the range of processing conditions for laser cutting is determined by the energy input per unit area of the work piece. Yousef et al. (2014) have developed a neural network model using the experimental data. Using mean depth and diameter of the crater as inputs, and pulse energy, variance of depth and diameter as output parameters. Their study has shown that the proposed neural network approach is useful and beneficial in understanding the behaviour of the cutting process during laser machining to a high degree of accuracy. Tani et al. (2014) have studied the striation and dross formation on the basis of an analytical model by considering mass, force and energy balances. The narrowing of the kerf width with increasing cutting speed is explained by heat conduction. Uslan (2015) has investigated the effect of laser power and cutting speed variations on the kerf width size. Design and characteristic effect of supersonic nozzles for high gas pressure laser cutting was studied by Man et al.(2015) and dynamic characteristics of gas flow inside a laser cut kerf under high cutting assist gas pressure was also studied by Man et al.(2012). Lee et al. (2015) have developed a two-dimensional, analytical model placing special stress on the effect of laser parameters such as power, cutting speed and spot sizes. Power absorption over the cut front, effect of oxidation and melt film thickness predicted in the experimental model. Chen et al. (2016) have given a physic -mathematical model for the phenomenon of formation of periodic striations in oxygen laser cutting of mild steel material.

2.2 Experimental models

The most commonly used experimental method which is used to statistically signify the relationship between input parameters and output response is the design of experiment (DOE). Chen and Yao (2000) proposed a hybrid approach to optimize the laser micro cutting process. The initial value of the selected parameters was determined by the energy balance method along with the other information available regarding the interaction time of laser beam with the materials. Sivarao et al. (2010) applied the Taguchi methodology to optimize the process parameters for micro engraving of iron oxide coated glass using Q-switched Nd:YAG laser. The input process parameters are beam expansion ratio, focal length, average laser power, pulse repetition rate and engraving speed and the output response parameter for engraving line width. Biswas et al. (2010) optimize the Nd:YAG laser micro drilling of gamma-titanium aluminide. The effect of lamp current, pulse frequency, assist gas pressure and thickness of job on circularity of hole at exit and hole taper was investigated. Process parameter to obtain square microgrooves on cylindrical wokpiece of aluminium oxide by laser turning process has been determined by Dhupal et al. (2013). Dhupal et al. (2014) developed response surface methodology based mathematical model to optimize the process parameters settings that minimum deviation of both taper angle and depth of microgroove produced on aluminium titanate substrate can be achieved. The input process parameter were lamp current, pulse frequency, pulse width, assist air pressure and cutting speed. Similarly, Kuar et al. (2015) have performed optimal parametric analysis based on response surface methodology to determine the effects of various process parameters such as pulse frequency, pulse width, lamp current and assist air pressure in micro drilling of zirconia (ZrO_2) by pulsed Nd:YAG laser. The primary objective was to obtain the minimum HAZ thickness and taper.

2.3 Analytical models

For the study of process performance of complex process like LBC the analytical models are best tools for preliminary analysis. These models are based on the basic laws and principles of chemical bonds Wills et al. (2010). The variation in ablation rate at high laser effect in several metallic materials having wide variation in the values of electron coupling constant has been explained by Cheng et al. (2011). Zhang et al. (2011) have developed a numerical model to simulate the micro-scale cavity formation of copper under high intensity pulsed laser radiation. Xu et al. (2012) developed one dimensional heat conduction model to compute the heat transfer and phase change process during micromachining of nickel using excimer laser. Schafer and Urbassek (2012) investigated the laser ablation of metals using a hybrid simulation scheme in which the molecular dynamics has been integrated with heat conduction equation to obtain the electron temperature. A 3D transient finite element model was developed by Xiang et al. (2013) to predict the groove shape and temperature distribution on polymer micro- fluidic chip. Paterson et al. (2013) have presented a numerical model for the ablation of microstructure by excimer laser, based on pulse by pulse propagation of the etched surface. The mesocopic model which not only considers the micro structural features but also provides the link between microscopic and macroscopic phenomenon occurring during the laser ablation process was analysed by Stoneham et al. (2014). Fan et al. (2014) developed a time and position resolved moving breakdown model to accurately predict the nature of laser material interaction responsible for optical breakdown.

2.4 Laser Cutting

Lasers have became popular in many applications in industry particularly in materials processing such as the cutting of engineering structures due to their high power density and precision. The power density required for machining metals is normally very high. In laser machining, the laser beam is incident on the upper surface of the material to be machined, resulting in melting and vaporization, depending on the beam intensity and material properties. The molten metal and vapor are then thrown away using an assist gas. Various types of assist gases react either positively or negatively in chemical reactions during the cutting operations (Powell 1998). In laser cutting the machining operation can be classified into various categories depending on the mechanisms involved. Lasers can be used effectively to cut metal plates of thicknesses more than 5 cm. However, the total heat input required for laser cutting is relatively small. This results in a small heat-affected zone size of about 0.1 mm around the cut edge. In addition, the small size of the focused beam results in very narrow kerf sizes. In fact, the diverging nature of the laser beam results in a slightly tapered cut surface. The workpiece thickness that can be cut with parallel sides is determined by the depth of focus. Plates that are thicker than the depth of focus normally result in tapered surfaces. By means of laser cutting both straight and curved cutting of sheet and plates tock in a wide variety of advanced materials can be achieved. Materials that can be machined include metals, plastics, rubbers, wood, ceramics and composites (Kannatey et al., 2009).

3. COMMENTS ON REVIEWED LITERATURE

The conclusion that can be drawn from this literature overview is that, the main strength of LBC process lies in its capability to machine almost all types of materials in comparison to other widely used advanced machining methods. Material removal in LBC is based on high heat flux generated by laser beams which melt and vaporize the work piece material in the focused point. Unique privileges of LBC such as being a non-contact process, automation adaptability, cost reduction, small heat affected zone (HAZ) and resolving the need for finishing operations have made it famous in the manufacturing industry. Researchers have contributed in different directions but due to complex nature of the process and a lot of works are still required to be done in this area. Most of the experimental works presented in LBC are aimed to study the effect of parameter variations on quality characteristics. Only some of the researchers have used the scientific methods under the heading of design of experiments for the study of LBC process. At present, the use of LBC is limited up to complex profile cutting of sheet materials but due to emergence of advanced engineering materials, need is to develop it for cutting of difficult to cut materials. So, these developments in LBC can be an area of future research. Further, very less research work is reported in the literature on LBC of cutting of materials. Therefore, there is need to apply research efforts in this direction.

4. CONCLUSION

This paper provides an overview of LBC process. It is a powerful machining method for cutting complex profiles and drilling holes in wide range of work piece materials.LBC is one of the most advanced manufacturing methods which find application in drilling, cutting, grooving, turning and milling, amongst other non-contact methods. Laser processing provides a valuable and unique capability in high precision materials processing. The performance of LBC mainly depends on laser parameters (e.g. laser power, wavelength, mode of operation), material parameters (e.g. type, thickness) and process parameters (e.g. feed rate, focal plane position, frequency, energy, pulse duration, assist gas type and pressure). The laser beam cutting process is characterized by large number of process parameters that determines efficiency, economy and quality of whole process and hence, researchers have tried to optimize the process through experimental and analytical method.

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