Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2015, 2(10): 70-76

Research Article ISSN: 2394 - 658X

Laser Beam Machining: A Literature Review on Heat affected Zones, Cut Quality and Comparative Study

Chithirai Pon Selvan M, Nethri Rammohan and Sachidananda HK

School of Engineering & Information Technology, Manipal University, Dubai
mcpselvan@yahoo.com

ABSTRACT

Laser beam machining is a form of non-traditional machining that can machine almost any known materials. It is thermal, non-contact process, which does not induce any mechanical stresses in the work-piece. This paper presents a review on the conclusions of the various research papers available on laser beam machining on the various properties that affect the quality of the process such as heat affected zone formed in the work-piece, laser cut quality and why laser beam machining is more advanced than the other machining processes.

Key words: Laser Beam Machining, Laser Cutting, Heat Affected Zones, Kerf Width, Assist Gas

---

INTRODUCTION

Acroynam of laser is 'Light amplification by stimulated emission of Radiation'. The light produced is a coherent, monochromatic and collimated beam which can be focused to small spots of diameter of 0.002 mm. The laser beam is traversed along the work piece for cutting. Material is removed in laser beam machining by a combination of melting and evaporation [1].

In [2], Kumar et al explained the formation of a photon as follows: In the model of atom, negatively charged electrons rotate around the positively charged nucleus in specified orbital paths. Each orbital electron is associated with a unique energy level. At absolute zero temperature an atom is said to be at ground level. The electrons at ground state can be excited to higher state of energy by absorbing energy from external sources: increasing the electronic vibration at elevated temperatures, through chemical reaction, and also by absorbing energy of a photon. Then the electron moves from a lower energy level to a higher energy level. Once the higher energy level is attained, the electron reaches an unstable energy band. Therefore it comes back to its ground state by releasing a photon, in a small duration. Photons are the main source of energy in laser beam machining. According to Meijer [3], light is used for everything ranging from eye surgeries to telephone technologies. One important property of photons is that they have no volume and no charge. Therefore they do not repel each other like electrons, when concentrated in the form of a beam at particular point. When they encounter with matter, the photons behave like particles of energy.

Madic and Radovanovic [4] state that among the various advanced machining processes, laser beam machining (LBM) is one of the most widely used thermal-based processes applied for processing a wide variety of materials. In LBM the material is melted by focusing the laser beam on the work-piece surface. It is a high energy process that works quickly on complex shapes and is applicable to almost all materials. This process generates no mechanical stress on the work-piece, reduces waste, provides an ecologically clean technology, and can be modified to work in the micro range.

TYPES OF LASERS

Lasers can be classified into two groups based on the state of the lasing medium:

- Solid state lasers (Ruby, Nd-YAG)
- Gas lasers (CO_2 Laser and Argon Laser)
- Liquid lasers (Nitrobenzene)

CO_2 and Nd-YAG lasers are the most commonly used lasers in the industry as they give a power output of about 1 kW [1, 9]. Based on the review done by Dubey and Yadava (2008) CO_2 lasers, a gas laser, has a wavelength of 10 mm in the infrared region. It has a high average beam power, better efficiency and good beam quality. It can be utilised for the fine cutting of sheet metal at high speeds [7]. Carbon lasers are the highest-power continuous wave lasers that are currently available. They are also quite efficient. The ratio of output power to input pump power is around 20% [2].

Nd:YAG lasers, a solid laser, have a low beam power but when operating in pulsed mode, high peak powers enable it to machine even thicker materials. Also, shorter pulse duration suits for machining of thinner materials. Due to shorter wavelength of 1 mm, it can be absorbed by high reflective materials which are difficult to machine by CO_2 lasers [7].

Even though CO_2 is more commercially used, the Nd-YAG lasers offer certain benefits that are particular to them. Based on the experimental results published in literature, Dubey and Yadava (2008) found that Nd-YAG has some unique characteristics. Though the beam power of Nd-YAG laser is low, the beam intensity can be relatively high due to smaller pulse duration and better focusing behavior. Smaller kerf width, micro-size holes, narrower heat affected zone (HAZ) and better cut edge kerf profile can be obtained in Nd-YAG laser beam machining [8].

LASER BEAM MACHINE SET-UP

Dubey and Yadava [8] explained that the LBM process is a thermal energy based machining process in which the material is removed in the following order [8]:

- Melting
- Vaporization
- Chemical bond breakage

When a high energy density laser beam is focused on work surface the thermal energy is absorbed which heats and transforms the work volume into a molten, vaporized or a chemically changed state that can be easily removed by flow of high pressure assist gas jet which in turn removes the materials form the machined surface [8].

The setup consists of a cylindrical ruby/Nd-YAG crystal in the case of solid laser [1] or cylindrical vessel filled with gas in the case of gas lasers [2]. One end face of the cylinder is partially reflective and the other end is fully reflective (full silvered). A flash tube containing inert xenon gas is placed around the outside of the cylindrical lasing medium. The flash tube converts the electrical energy into light energy which is imparted to the lasing medium in the form of thousands of flashes per second. The imparted light energy excites the atoms in the cylindrical lasing medium to a higher energy level. The excited atoms then return back to their original state, during which they radiate the energy which was absorbed from the flash tube, in form of photons. This energy is seen in the form of red fluorescent light called laser [1, 2]. A schematic setup of the entire laser machining process is given in Dubey and Yadava (2008); an optical delivery/feedback system is also present. Cooling mirrors and mirrors for guiding the beam and provisions for manipulating the position of the target are also important in the setup as shown in figure 1 [7].

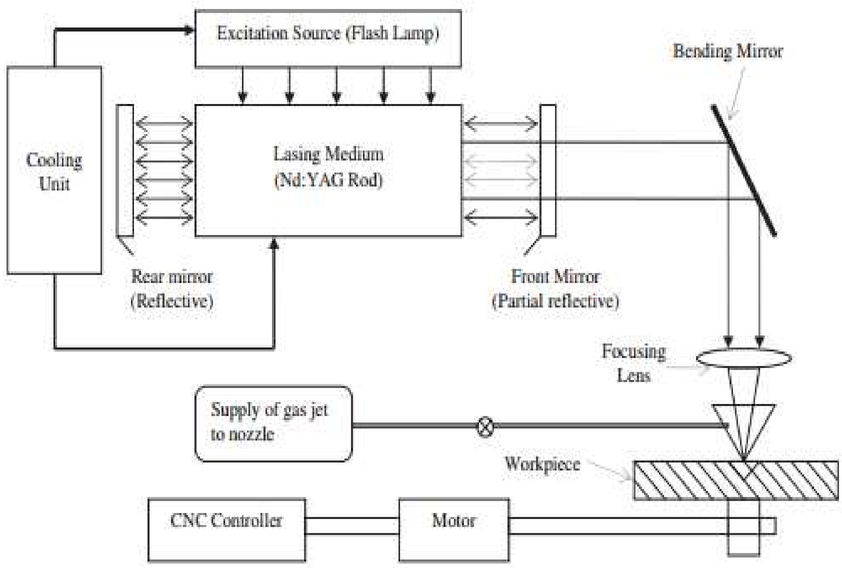

Fig. 1 Schematic Representation of Nd-YAG Laser Beam Machining (Dubey and Yadava [7])

HEAT AFFECTED ZONES & CUT QUALITY OF WORK-PIECE

Abedin and Kalla [6] state that LBM being a non-contact process that has several advantages over other non-traditional processes. The main advantages being that there is no tool wear/damage or any contact force induced problems. Laser cutting involves thermal process and it does not depend on the strength and hardness of the work piece, thus making it ideal for cutting non-homogeneous material.

Radovanovic and Dasic [5] state that the cut quality is a characteristic of the LBM that ensures an advantage over other contour cutting processes based on experimental research conducted to determine the surface indicators. Laser cutting, due to the narrow kerf width results in a superior quality, higher accuracy and greater flexibility [9]. Heat affected zones (HAZ) and laser cut quality are the two important factors in LBM. Laser cutting is performed these days with an assist gas such as oxygen or air. In gas assisted laser cutting, the gas is usually introduced coaxially with the focused laser beam into the cutting zone. The gas cools the cut area, thus lowering the HAZ, and also removes molten dross from the cut [5, 9]. Figure 2 gives a schematic representation of gas assisted laser cutting.

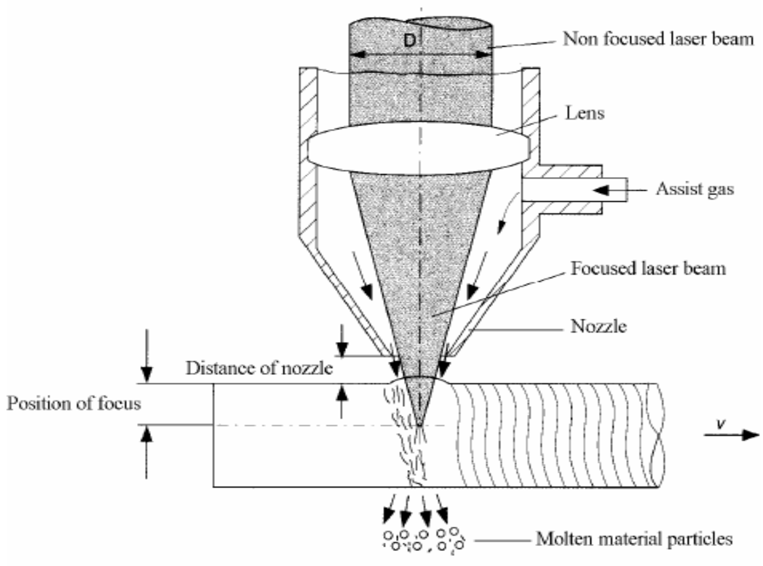

Fig. 2 Gas assisting Laser Cutting (Radovanovic and Dasic [5])

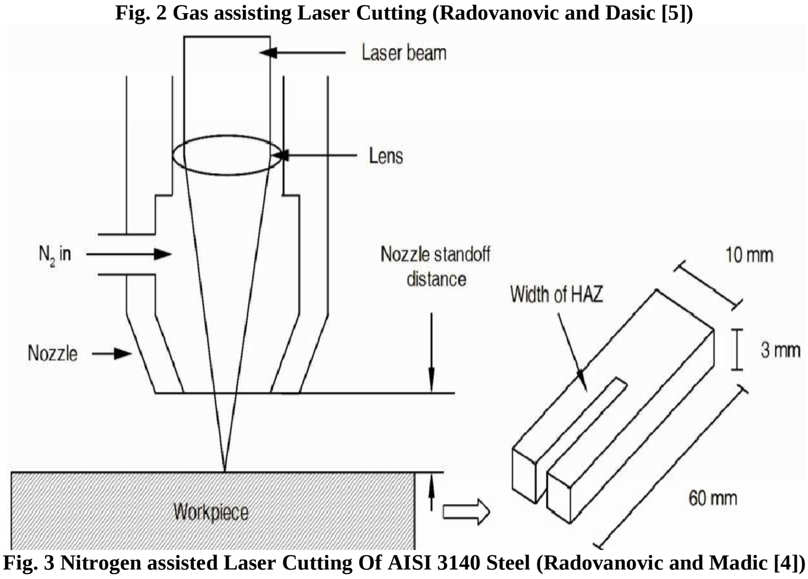

Fig. 3 Nitrogen assisted Laser Cutting Of AISI 3140 Steel (Radovanovic and Madic [4])

In the experimental study conducted by Madic and Radovanovic [4] to analyze the effect of the laser cutting parameters on the width of HAZ in CO_2 laser cutting (using nitrogen as the assisting gas) of AISI 304 stainless steel. The analysis was done by developing an artificial neural network (ANN) mathematical model with laser power, cutting speed, assist gas pressure, and focus position as the input parameters. The developed ANN model was derived from 27 sets of experimental data using the gradient descent with momentum algorithm and tested by 6 extra experimental data sets. From the analysis of the effect of the laser cutting parameters on the width of HAZ the following conclusions were drawn:

- The width of HAZ is highly sensitive to the selected laser cutting parameters and their interactions.
- The dependence between the width of HAZ and the laser power, cutting speed and focus position is highly non-linear, whereas in the presence of an assist gas pressure this dependence is nearly linear.
- The effect of a given laser cutting parameter on the width of HAZ must be considered through the interaction with other parameters.
- Cutting speed has maximum influence on the width of HAZ followed by the laser power, focus position and assist gas pressure.

Figure 3 shows the experimental setup of the nitrogen assisted CO_2 laser cutting and the dimensions of the work piece [4]: The response surface methodology is a widely adopted tool for the quality engineering field. The response surface methodology is a collection of mathematical and statistical techniques that are useful for modeling, analysis and optimizing the process in which response of interest is influenced by several variables and the objective is to optimize this response. Response surface methodology uses quantitative data from appropriate experiments to determine and simultaneously solve multi-variable equations [10-11].

In another study conducted by Singh et al [10], response surface methodology is used to investigate the relationship between laser machining parameters and HAZ dimensions for Polymethyl methacrylate material. The cutting parameters studied were laser power, cutting speed and gas pressure. It was found that when high power laser beam strikes the work material and transfers energy to it, the work piece surface gets heated and it creates a heating zone in cutting area resulting in the HAZ. After increasing laser power, more energy transfer to work material resulting increasing in HAZ hence HAZ is directly proportional to laser power and indirectly proportional to cutting speed. The effect of laser power on the HAZ is more as compared to the effect of cutting speed and therefore it is the most important factor that controls the HAZ.

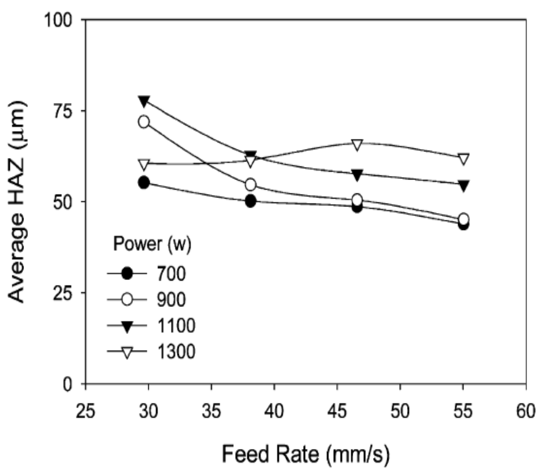

Fig. 4 Variation of HAZ width with power and feed rate (Rajaram et al [12])

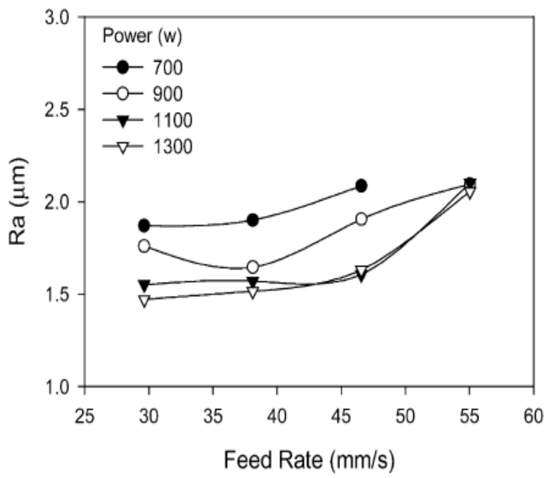

Fig. 5 Variation of surface roughness with power and feed rate (Rajaram et al [12])

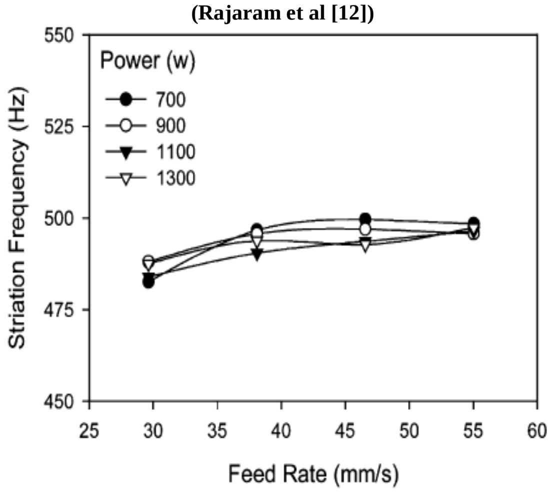

Fig. 6 Variation of striation frequency with power and feed rate (Rajaram et al [12])

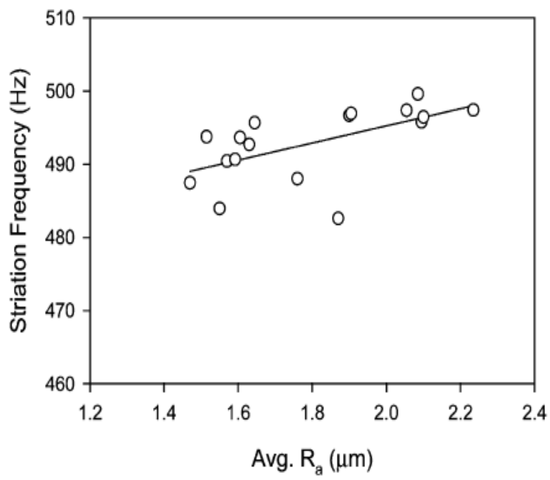

Fig. 7 Correlation between striation frequency and surface roughness (Rajaram et al [12])

To understand laser cut quality, a study was made on laser cut 4130 steels by Rajaram et al [12]. A series of conclusions were made as below –

- Power had a major effect on the kerf width, while feed rate had a minor effect. Decreasing power and increasing feed rate generally led to a decrease in kerf width and HAZ.
- Feed rate has a major effect on surface roughness and striation frequency. Increasing feed rate generally led to increasing surface roughness and striation frequency. An optimum feed rate, for which surface roughness is the minimum, could be identified. Power has a small effect on surface roughness, and no effect at all on striation frequency.

Based on the conclusions, the following graphs were plotted in the study by Rajaram et al [12] to show the correlation between feed rate and the HAZ width and the surface roughness. The points were plotted for different values of power. Graphs were also plotted to show the relation between the feed rate and the striation frequency, as well as the relation between the striation frequency and the surface roughness of the work-piece after the laser cut.

Another experimental study was conducted by Yilbas [13] to assess the cutting quality and validate the kerf width predictions. The schematic representation the experimental setup is shown in Figure 8. A CO_2 laser delivering output power of 1600W was used and ZnSe lens was employed to focus the laser beam. Oxygen was used as the assisting gas which was introduced co-axially with the laser beam through a conical nozzle. Mild steel work-piece was used in the experiment. The laser power intensity, scanning speed (laser cutting speed) of the laser beam, oxygen gas pressure, and work-piece thickness were varied. Width of the cut, out of flatness of the cut edges and waviness of the cut surface (striation patterns) were measured using a reading microscope while microphotography of cut surfaces was carried out using Scanning electron microscope (SEM).

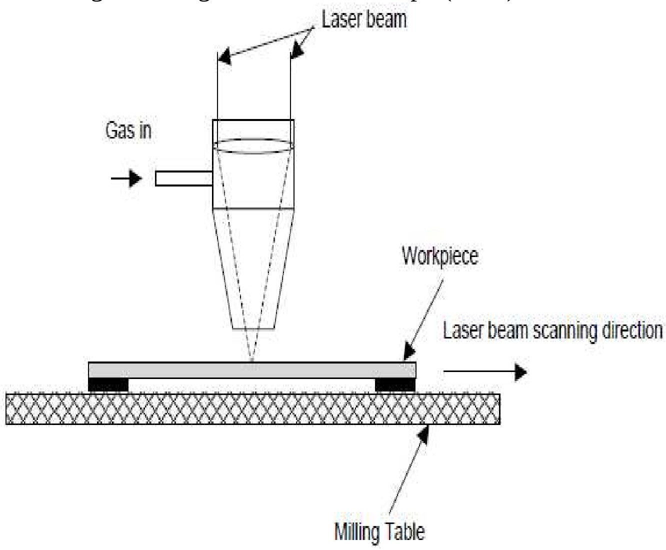

Fig. 8 Schematic view of the experimental set-up (Yilbas [13])

The values of scanning speed (cutting speed), oxygen gas pressure and work-piece thickness were varied as shown in Table-1 [13].The following conclusions were made in the experimental study [13]:

- Kerf width reduces with increasing laser beam scanning speed. Increasing laser output power increases the Kerf width, whereas kerf width increases with decreasing cutting speeds.
- It is observed from SEM micrographs that the cut quality improves as laser beam scanning velocity increases, provided that beyond the limit, cutting stops.

In a theoretical study made by KushalPratap Singh et al [16], using response surface methodology (RSM), in order to study the relationship between laser machining parameters and their results. The process parameters taken in study were cutting speed, frequency and duty cycle [16]. The work-piece material taken in this study is mild steel. It was concluded that the surface roughness was directly proportional to frequency and duty cycle. Whereas, when the cutting speed increased the surface roughness decreased. This relationship using the model equation deduced from RSM.

Table -1 Variation of Parameters (Yilbas [13])

Source of Variation	Level 1	Level 2	Level 3	Level 4
Laser Power, P_o (W)	750	1000	1250	1500
Assisting Gas Pressure, P_g, (kPa)	125	175	225	275
Workpiece thickness, T (mm)	0.75	1.00	1.50	2.00
Laser Beam Scanning Velocity, v (m/s)	1	2	3	4

COMPARATIVE STUDY

An experimental study was conducted by Rasheed [15] to compare material removal rate (MRR), HAZ and dimensions of the holes created in the workpiece by micro-EDM and LBM [15]. A sheet of Ni-Ti shape memory alloy (SMA) of 100µm thickness is used as the work-piece. Electrical Discharge Machining (EDM) is a method of removing material from the work-piece by the formation of sparks between the electrode and the work-piece due to electrical discharge. In the case of material removal rate (MRR), LBM process was found to have a maximum MRR of 0.06 mm3/min, whereas micro-EDM was found to have an MRR under 0.01mm3/min.

Dimensional accuracy was measured by comparing the diameters of the entry and exit micro- holes made by the process. The taper angle and circularity of the micro-holes are also measured. On average calculation, it was observed that the difference in the diameters of the entry and exit micro-holes produced by micro-EDM is about 118µm, whereas the difference in micro-holes diameters produced by LBM is 120.64µm [15]. Similarly, the taper angle of the micro-holes was found to be more in LBM than in micro-EDM. The circularity of the micro-holes produced by micro-EDM was higher than that of the holes produced by LBM process.

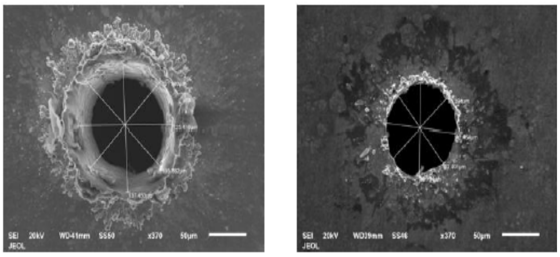

Fig. 9 SEM images of the entry and exit micro-holes produced by LBM (Rasheed (2013), [15])

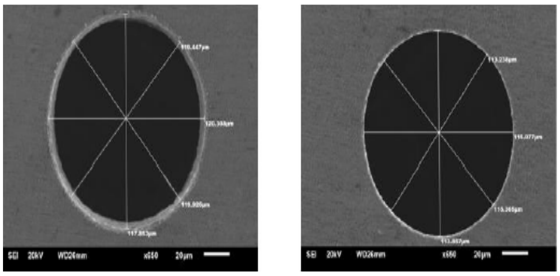

Fig. 10 SEM images of the entry and exit micro-holes produced by micro-EDM (Rasheed (2013), [15])

Another important point of comparison is the surface topography which compares the spatter and HAZ formed around the periphery of the holes. Spatter is the re-solidified molten metal which adheres to the periphery after machining [15]. These are compared by using scanning electron microscope images.

The spatter and HAZ around the micro-holes produced by micro-EDM is lesser compared to EDM. Hence, the quality of the micro-holes produced by micro-EDM was higher than the LBM produced micro-holes.

Cost plays an important role as the machining process must also be suitable economically [14]. An appropriate estimation of manufacturing cost is essential for manufacturers and costumers to make decisions. In the study by Yazdi et al [14], a model was proposed, which took into account:

- Fixed costs: This includes capital cost, cost of interest, insurance, space, and maintenance.
- Variable costs: Cost of assist gas, lens, and nozzle for LBM, in addition to common costs such as cost of labour, material, and electricity.

The model is derived from general calculation formulas used in manufacturing economics. Having each of fixed and variable costs (€/hr) multiplied by total time of cutting for one meter length part, the costs converted to euro per part, and final cost is calculated by summation of all sub costs[14]. The model showed that higher the purity of the cutting gas is, higher will be the cutting speed and lower will be the cost per part. A reduction of 12% in the total cost was observed when cutting speed increased by 20% [14].

CONCLUSION

LBM is a machining process that can be used to machine almost any known material ranging from soft materials to DTM (difficult to machine) materials. Complex shapes can be machined. LBM process has a very high MRR compared to other non-conventional machining processes such as EDM. Though MRR is very high, the material is removed at the cost surface quality. The surface quality is less due to the formation of spatters and burrs which is unavoidable in the process of LBM. However, the spatter formation and HAZ can be reduced by increasing the cutting speed and by adopted gas assisted LBM. Decreasing the laser power also significantly reduces the HAZ. The kerf width characteristic depends on the input parameters as well. Decreasing the power and increasing the feed rate, decreases the kerf width and the HAZ. As the cutting speed increases, the surface roughness decreases and quality improves when the other operating parameters kept constant.

LBM being a flexible process, the various input parameters can be altered to improve the surface quality, decreased HAZ and other output parameters and is widely used in various industries. Extensive researches and experimental studies are being performed in the field of LBM in to order to improve the process characteristics such are frequency of pulsed beams, beam polarization, feed rate, cutting velocity and surface roughness.

REFERENCES

[1] JP Kaushik, *Manufacturing Processes*, PHI Learning Private Limited, India, **2014**.
[2] Atish Kumar, Navjot Singh Bandeshah, Nripjit, Arun Nanda, Rajbir Kaur Bandeshah and Chandan Gupta, State of the Art of CO_2 Laser Beam Machining, *International Journal of Emerging Technology and Advanced Engineering*, **2014**, 4 (4), 993-999.
[3] John Meijer, Laser Beam Machining (LBM), State of the Art and New Opportunities, *Elsevier Journal of Materials Processing Technology*, **2004**, 149, 2-17.
[4] Milo J Madic and Miroslav R Radovanovic, Analysis of the Heat Affected Zone in CO_2 Laser Cutting of Stainless Steel, *Thermal Science*, **2012**, 16 (2), S363-S373.
[5] Miroslav Radovanovic and PredragDašić, Research on Surface Roughness by Laser Cut, The Annals of University Dunărea De Jos of Galaţi fascicle viii, Tribology, **2006** (12).
[6] F Abedin and Devi K Kalla, Review on Heat Affected Zone (HAZ) in Laser Machining, *Proceedings of the 6th Annual GRASP Symposium*, Wichita State University, **2010**.
[7] Avanish Kumar Dubey and Vinod Yadava, Laser Beam Machining-A Review, *Elsevier International Journal of Machine Tools & Manufacture*, **2008**, 48, 609-628.
[8] Avanish Kumar Dubey and Vinod Yadava, Experimental Study of Nd:YAG Laser Beam Machining-An Overview, *Elsevier Journal of Materials Processing Technology*, **2008**, 195, 15–26.
[9] Miroslav Radovanovic and Milos Madic, Experimental Investigations of CO_2 Laser Cut Quality: A Review, *Nonconventional Technologies Review*, **2011**, 4, 35-42.
[10] Kaushal Pratap Singh, Susheel Kumar Upadhyay, Deepak Kumar Gupta, Sahil Panu and Girish Dutt Gautam, An Analysis the Effect of Process Parameters on Heat Affected Zone in Laser Cutting Using Response Surface Methodology, *International Journal of Emerging Technology and Advanced Engineering*, **2014**, 4 (2), 850-855.
[11] DC Montgomery, *Design and Analysis of Experiments*, John Willey, New York, **2001.**
[12] N Rajaram, J Sheikh-Ahmad and SH Cheraghi, CO_2 Laser Cut Quality of 4130 Steel, *International Journal of Machine Tools and Manufacture*, **2003**, 43, 351–358.
[13] BS Yilbas, Laser Cutting Quality Assessment and Thermal Efficiency Analysis, Elsevier Journal of Materials Processing Technology, **2004**, 155-156, 2106–2115.
[14] Saeed Rismani Yazdi, Abdolrasoul Torkzadeh and Carlo Alberto Biffi, Cost Modeling of Laser and Abrasive Water Jet Cutting Processes, *Proceedings of the 3rd International Conference on Mechanical Engineering and Mechatronics*, Prague, Czech Republic, **2014**.
[15] Mohammed Sarvar Rasheed, Comparison of Micro-Holes Produced By Micro-EDM with Laser Machining, *International Journal of Science and Modern Engineering*, **2013**, 1(1), 14-18.
[16] Sahil Panu, Girish Dutt Gautam, Kaushal Pratap Singh and Gavendra Norkey, Parametric Analysis of Cutting Parameters for Laser Beam Machining Based on Box-behnken Design, *International Journal of Advanced Mechanical Engineering*, **2014**, 4(1),61-68.