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CO_2 Laser Cutting of Different Materials – A Review

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Abstract - *Laser cutting is one of the most widely used thermal energy based non-contact type advance machining process which can be applied for almost whole range of materials. The width of laser cut or kerf, quality of the cut edges and the operating cost are affected by laser power, cutting speed, assist gas pressure, nozzle diameter and focus point position as well as the work-piece material. This review paper aims at presenting the state of the art in the field of CO_2 laser cutting of various engineering materials with special emphasis on experimental investigations that dealt with analyzing process parameters that affect the cut quality characteristics. In addition it reports about the most used types of experimental plans used.*

Key Words: plasma, kerf width, beam, layer, duty cycle

1. INTRODUCTION

Laser, which is stands for Light Amplification by Stimulated Emission of radiation, is an electrical-optical device that produces coherent radiation. Simply put, a laser is a device that creates and amplifies a narrow, intense beam of coherent light. Nowadays, laser is widely applied in today's industry. Lasers are widely used in industry for cutting and boring metals and other materials, in medicine for surgery, and in communications, scientific research, and holography [1]. They are an integral part of such familiar devices as bar code scanners used in supermarkets, scanners, laser printers, and compact disk players. One of the laser systems that dominate the commercial laser industry is CO_2 laser systems. It has its own strengths in various cutting and marking applications.

1.1 CO_2 laser systems

A CO_2 laser is a type of gas laser. In this device, electricity is run through a gas-filled tube, producing light. The ends of the tube are mirrors; one of which is fully reflective and the other which lets some light through. The gas mixture is generally comprised of carbon dioxide, nitrogen, hydrogen and helium. Light produced by CO_2 lasers is invisible, falling in the far infrared range of the light spectrum [2]. When stimulated by electric current, nitrogen molecules in the gas mixture become excited, meaning they gain energy. Nitrogen is used because it can hold this excited state for long periods of time without discharging the energy in the form of photons, or light. The high-energy vibrations of the nitrogen in turn excite the carbon dioxide molecules. At this point, the laser achieves a state called population inversion, the point at which a system has more excited particles than non-excited ones. For the laser to produce a beam of light, the nitrogen atoms must lose their excited state by releasing energy in the form of photons. This happens when the excited nitrogen atoms contact the very cold helium atoms, which causes the nitrogen to release light. The light produced is very powerful compared to normal light because the tube of gases is surrounded by mirrors, which reflect most part of the light traveling through the tube. This reflection of light causes the light waves being produced by the nitrogen to build in intensity. The light increases as it travels back and forth through the tube, only coming out after becoming bright enough to pass through the partially-reflective mirror.

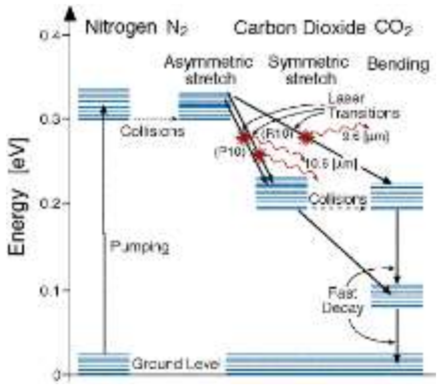

Fig -1: Energy Level Diagram of CO_2 Laser

Light from a CO_2 laser is powerful enough to cut many materials, including cloth, wood and paper; the most powerful CO_2 lasers are used for machining steel and other metals. Although the highest-powered CO_2 lasers run over 1,000 W, those used for machining are generally between 25 and 100 W; by comparison, laser pointers are a few thousandths of a watt. Because it's in the infrared, it has a very long wavelength, around 10.6 micrometers; it is much longer than visible light, which runs between about 450 and 700 nanometers. As continuous lasers go, the CO_2 type is the most powerful in production.

1.2 Laser Cutting

The laser cutting process works by having a focused and precise laser beam run through the material that you are looking to cut, delivering an accurate and smooth finish. Initially, the laser is used to pierce the material with a hole at the edge, and then the beam is continued along from there. The laser being used essentially melts the material away that it is run over, so is more like melting than cutting. This means that it can easily cut light materials such as cloth up to tougher metals and gemstones such as diamonds [4–7]. You can use either a pulsed laser beam or a continuous wave laser beam, with the former being delivered in short bursts while the latter works continuously. You can control the beam intensity, length and heat output depending on the material you are working with, and can also user a mirror or special lens to further focus the laser beam. Laser cutting is a highly accurate process, thanks to this high level of control that you are offered. Thanks to this, slits with a width as small as 0.1mm can be achieved when using the laser cutting process.

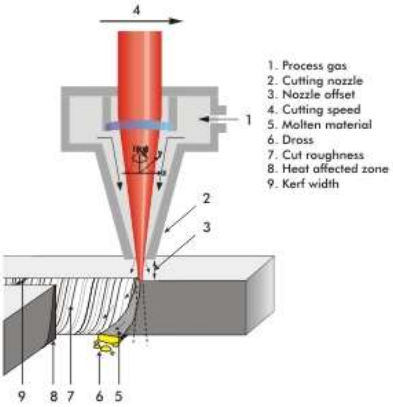

Fig -2: Principle of laser cutting

Laser cutting can be:

- Sublimating — the material is removed primarily by evaporation due to the high intensity of the laser radiation in the cut area;
- Melting — the material is melted by a laser beam in the cut area and blown away by an auxiliary gas. Mainly metallic materials are cut using this process;
- Burning— a laser beam heats the material to its ignition temperature, so it can then burn in an exothermic reaction with the reactive gas (e.g., oxygen), and the slag is removed from the cutting area by an auxiliary gas. Titanium, low carbon and corrosion resistant steels can be cut this way.

2. LASER CUTTING OF DIFFERENT MATERIALS

Laser beam cutting is most commonly used for the cutting of different categories of materials because it is superior to any cutting method due to material versatility, no tool wear or change of tool, high material utilization and production flexibility, precise cuts with narrow kerf, faster cutting process, better accuracy and cut edge quality. A lot of experimental and theoretical investigations have been performed on the laser cutting of different categories of materials such as ceramics, composites, advanced engineering materials (superalloys), difficult-to-laser-cut materials.

2.1 Laser cutting of metals

Laser cutting of metals including steels and stainless steels has been the main aim of many investigations since steel and its alloys are in massive demand in many industries such as automobile and power plant industries. The nature of the LBC process, and the effect of process parameters on the quality of the cut sections were studied by many researchers.

Uslan [7] has utilized CO_2 lasers to cut high-strength low alloy steel and to investigate the influence of laser power and cutting speed variations on the kerf width size. It was found that increasing the laser power intensity increases the kerf width size and this is more pronounced when the cutting speed is reduced. It was reported that a small variation in laser power results in a large variation in the kerf size. He reported that the influence of the cutting speed was less than that corresponding to the laser power. Also, he mentioned that when using an unfocused laser beam, which in turn reduces the laser power density, the kerf width increases. Gonsalves et al. [8] have investigated the interdependence of the laser parameters on the cut width when cutting thin sheet of 302 stainless steels. It was demonstrated that the cut width decreases with increasing cutting speed. Also, they verified that only some of the available power is utilized. The effect of process parameters on the kerf width during CO_2 laser cutting has also been studied by Yilbas [9]. It was found that increasing the laser power and the energy coupling factor increases the kerf width size. It was reported that even slight variations in laser power, cutting speed and energy coupling factor modify the kerf size remarkably. It was mentioned that at low cutting speed and high laser power, increasing the energy coupling factor increases the kerf width as a result of increasing the size of the melt zone in the kerf. On the other hand, any increase in the cutting speed reduces the kerf width. However when the cutting speed decreases, then the rate of energy available at the surface increases and this in turn, increases both the melt size and the striation size. He reported that laser power has a highly significant effect on the kerf size. A theoretical model has been derived by Chen [10] to investigate the effect of the manufacturing parameters on the three-dimensional cutting front and cut kerf cross-section using a CO_2 laser working on mild steel. He analysed the effects of oxide files, polarization, cut front shape, cutting speed and laser power. It was reported that very small levels of impurity in the oxygen would significantly affect the cutting performance. Also, it was mentioned that the kerf width was significantly decreased from 1.86 to 1.66 mm and the maximum kerf depth was considerably reduced from 73.91 to 34.73 mm when laser power decreased from 1500 to 750 W. Moreover, he stated that a higher laser power makes the cut kerf larger and the cut-through performance better. In addition to that he found that the kerf width produced using pure oxygen is larger when compared with the kerf produced using an inert gas. Finally, he reported that the tendency of the experimental results of many previous researchers agrees with the predictions of his theoretical model. Yilbas [11] has also presented a study to examine the effect of laser cutting parameters on cutting quality when cutting mild steel. The parameters he investigated were workpiece thickness assist gas pressure, cutting speed and laser power. He extended the study by monitoring the surface plasma, which in turn affects the formation of striations and cutting quality. It was concluded that self-burning occurs at very low cutting speed and increases with increasing oxygen pressure. Also he reported that once the jet velocity reaches sonic velocity, the critical cutting speed drops due to the cooling effect of the jet. Furthermore, it was found that at high oxygen pressure a substantial amount of surface plasma occurs, which in turn may partially block the incident laser beam, resulting in less energy from the laser beam reaching the surface. This plasma then expands due to the pressure differential in the plasma. As a result, more incident energy reaches the surface, which in turn increases the removal rate of molten metal from the kerf, causing more surface plasma. This process occurs periodically and leads to the development of strias around the kerf edge. Yilbas et al. [12] have conducted a study to assess cut edge quality in terms of waviness and flatness of stainless steel with different thicknesses. They considered cutting speed, oxygen pressure and workpiece thickness as working parameters. They extended the study to detect the light emission from surface plasma. It was found that the cut quality is mainly affected by the oxygen pressure and cutting speed. However, they reported that flatness depends significantly on the thickness. Also, they reported that as the oxygen gas pressure increases the waviness increases. Evaluating the optimum laser cutting parameters for cutting samples of austenitic stainless steel with a thickness of 1.2 mm, has been investigated by Abdel Ghany and Newishy [13]. It was shown that all the process input parameters have an effect on the cut quality. They reported that the optimal cutting conditions are: power 210 W, frequency from 200 to 250 Hz, speed 1.5 m/min, focus position from -1 to -0.5, nitrogen pressure from 9 to 11 bar and oxygen pressure from 2 to 4 bar. It was found that increasing the frequency and cutting speed cases a decrease in the kerf width and the roughness of the cut surface, while increasing the power and gas pressure increase the kerf width and roughness. It was mentioned that when nitrogen is used as an assist gas, it produces brighter and smoother cut surfaces with smaller kerf. It was reported that when using the CW mode, the cutting speed could be increased to 8 m/min with the same power and gas pressure setting mentioned above. The effect of high-pressure assistant-gas on CO_2 laser cutting of 3 mm thick mild steel samples has been investigated by Chen [14]. It was shown that an acceptable quality cutting region does not exist for pure oxygen at a pressure of 10 bar, with power ranging from 0.6 to 1.4 kW and cutting speeds from 40 to 120 mm/s. It was recorded that for inert-gas cutting, dross was formed under the cut kerf with most of the cutting parameters. However it was found that a clean cut was obtained with an argon gas pressure of 10 bar at a cutting speed of 25 mm/s. Also, he advised that for this metal oxygen cutting is still the best, although argon and nitrogen may be used instead. Finally, it was mentioned that compressed air is inferior to these gases as an assistant gas. However, the cut surface roughness of 28 μm is better than that of pure oxygen of 110 μm and poorer than that of argon of 14 μm. Assessments of laser cutting quality and thermal efficiency analysis have been carried out by Yilbas [15]. A statistical method based on factorial analysis was introduced to identify the effect of cutting parameters on the resulting cut quality. It was found that increasing laser beam scanning speed (the cutting speed) reduces the kerf width, while the kerf width increases with increasing laser power. It was reported that the main effects of all the parameters employed have a significant influence on the cut quality. Hamoudi [16] has studied the effect of cutting speed and assist gas type and pressure, on kerf width, striation frequency and heat-affected zone in mild and stainless steels. It was reported that for exothermic cutting, a wide kerf size was associated with high roughness and large HAZ, while a narrow kerf occurred with a smooth cut and a small HAZ. It was found that the kerf width and the HAZ decrease with increasing cutting speed but increase with increasing gas pressure. It was mentioned that exothermic cutting of stainless steel produced smaller roughness values as compared with the roughness of fusion cutting. Sheng and Joshi [17] have performed a numerical study on the development of the heat-affected zone during the laser cutting of 304 stainless steel. This numerical model was validated using laser cutting experiments which revealed good agreement. It was concluded that this model is useful as a process planning aid for laser cutting to determine the process parameters that will optimise the material removal rate, the HAZ and the kerf taper. Dilthey et al. [18] have investigated the laser cutting of steel and stainless steel. The results they achieved have revealed that both mild steel up to a thickness of 12 mm can be cut to an excellent quality and stainless up to a thickness of 6 mm can be cut to a good quality using TEM00 up to 1.5 kW. It was mentioned that when cutting stainless steel, it is essential to be able to make exact adjustments of both focus position and gas jet in order to obtain dross free cutting. Also, they reported that corrosion is likely to occur when cutting stainless steel with oxygen or vice versa when cutting stainless steel using inert gas. Cadorette and Walker [19] have investigated laser cutting using new laser equipment in an operational manufacturing environment to explore the conditions under which the equipment performance could be improved. It was concluded that cut quality highly sensitive to changes in the input variables-particularly O_2 purity. Wang and Wong [20] have studied the laser cutting of sheet steels coated with zinc and aluminium with thickness ranging from 0.55 to 1 mm. It was shown that by proper control of the cutting parameters good-quality cuts are possible at a high cutting speed of 5000 mm/min. It was revealed that high laser power above 500 W results in a poor- quality cut. They reported that the kerf width generally increases with increasing gas pressure and laser power, and with a decrease in cutting speed. They recommended a method of setting the parameters to control and optimise the process. Pietro and Yao [21] have conducted an investigation into characterizing and optimizing laser cutting quality. Their aim was to investigate and review the current status of laser cutting and associated quality techniques, including research efforts undertaken in the fields of modelling, regulation, diagnosis and monitoring. They defined the quality of the laser cut in terms of: kerf width, cut edge squareness, inner side slope of the kerf, HAZ extent, dross appearance and surface roughness (striations). It was reported that the arithmetic average roughness parameter Ra was a reliable parameter for characterizing the profile. Also, it was mentioned that a roughness profile can be measured when a complete cut surface is produced. It was reported that the measurements of Ra can only be recorded soon after performing the cut. The combined effects of laser power and cutting speed on kerf width, surface roughness, striation and size of HAZ of 4130 steel have been studied by Rajaram et al. [22]. It was observed that the laser power had a major effect on the kerf width and size of HAZ, while the cutting speed effects were secondary. It was shown that the cutting speed had a major role in determining the surface roughness and striation frequency. It was reported that a low laser power leads to a smaller kerf width and HAZ, while a low cutting speed gives a small surface roughness and a low striation frequency. Yilbas [23] has conducted an investigation to understand the striation formation mechanism and its relationship with the process parameters. It was found that the mathematical model which he introduced represents the physical phenomena well and the prediction of the striation frequency, and striation width agrees with the experimental findings. It was reported that sideways burning, liquid layer oscillation at the surface and variation in the absorbed power due to surface plasma are the main reasons for the striation. Li et al. [24] have reported an investigation into achieving striation-free laser cutting of 2 mm thick EN43 mild steel. A 1 kW single mode fibre laser was used in this work. They proposed a theoretical model to predict the cutting speed at which striation- free cutting occurs. It was indicated that above the critical speed of 33 mm/s striation occurs and the surface roughness increases. Prasad et al. [25] have discussed the laser beam machining of metallic coated steels with the goal of determining the process parameters which have an influence on the outcome of the cutting process. It was found that oxygen is quite effective as an assist gas for cutting coated steels. However, localised overheating and oxidised edges were observed in the case of GALVABOND specimens. This could be eliminated by using nitrogen or helium as an assist gas. It was proven that cutting speed is a function of the input power and that laser processing of these materials is a commercially possible option. A theoretical work has been undertaken by Simon and Gratzke [26] for the purpose of investigating the instabilities in laser gas cutting. It was suggested that these instabilities could be causes of the formation of striations. The effects of gas composition on the CO_2 laser cutting of mild steel have been addressed by Chen [27]. It was found that a high purity of oxygen is required for high- performance CO_2 laser cutting of mild steel as only a tiny oxygen impurity of 1.25% will reduce the cutting speed by 50%. He reported that for 3 mm thick mild steel a good- quality cut was obtained using inert gas with a low pressure (up to 6 bar). It was stated that a good-quality cut would be achieved when cutting 3 mm thick mild steel using pure oxygen with pressure ranged between 0.75 and 2.0 bar, a laser power of 1500 W and cutting speed ranged from 20 to 40 mm/s. It was reported that the energy density at the bottom of the workpiece is decreased by a ratio of ½.44, so that the total input energy may not be sufficient to vaporize the material in the lower part of the cut front within a very short time, although it is sufficient to melt the material. If the pressure of the assistant gas is not enough to quickly blow away the viscous molten material, the high temperature molten material (adhering to the cut surface) continues its oxidation reaction (or burning). This makes the cut surface more irregular, the undercut angle not very sharp and striation on the cut face more curved. In inert gas cutting, the reduction of energy intensity between the top and the bottom of the sample may also have a large effect on the cutting performance (surface roughness, dross adhesion and maximum cutting speed). Therefore, the striation on the upper part of the cut surface is more flat than on the lower part of the cut surface. Therefore, the surface roughness of the upper part is normally smaller. Atansov [28] has performed an experimental and theoretical investigation of high- pressure nitrogen assisted CO_2 laser cutting of Aluminium and stainless steel. It was found that the quality of the cut improved significantly with this combination. He recommended this approach for cutting of Al-alloys and stainless steels with thickness less than 5 mm when the cut quality is of particular importance. Grum and Auljan [29] have investigated the heat effects in the cutting front and its surroundings when cutting both low carbon steel and stainless steel by monitoring the heating phenomena in the specimen material. It was mentioned that the amount of energy input transferred to the cutting front varies due to oscillations in the laser source, changes in the heat released in exothermic reactions and heat losses. The theoretical calculation they made indicates that with a cutting speed of 30 mm/s, power oscillation frequency of the laser source of 300 Hz produces 10 striations per millimetre. They confirmed this theoretical calculation by experimentally measuring the striation widths at the cut surface of low carbon steel. It was assumed that the alloying elements in the stainless steel, especially the chromium, have an influence on the oscillation frequency and therefore on the striation widths at the cut surface. Duan et al. [30] have analysed the effects of laser cutting process parameters on cut kerf quality. It was confirmed that the theoretical predictions could be verified by practical experiments. It was found that the flow field depends strongly on the geometrical shape of the cutting front, which is affected by other laser parameters such as: laser power, cutting speed, focal position etc. It was mentioned that an increase in the nozzle to cut kerf displacement is beneficial in reducing the gas consumption. Finally, it was concluded that the mathematical model can be used to build up an optimal group of cutting parameters in order to obtain a high-quality cut edge. CO_2 laser cutting of Incoloy 800 HT alloy has been studied by Yilbas and Rashid [31]. They monitored the dross ejection from the kerf. The frequency of the dross ejection correlated with the striation frequency and out of flatness. Also, a statistical analysis was conducted to determine the significance levels of cutting speed, laser output intensity, thickness and pulse frequency. It was found that the dross ejection frequency is directly related to the striation frequency. They reported that the overall quality of the cut edge improves within at a pulse frequency of 600 Hz and the rate of dross ejection from the kerf becomes almost steady at this frequency. It was mentioned that the cutting speed and thickness have a significant effect on the out of flatness. They indicate that the cut quality can be improved by varying the combination of pulse frequency and laser output intensity. Dross formation during CO_2 laser cutting has been studied by Yilbas and Abdul Aleem [32]. It was found that the liquid layer thickness increases with increasing laser power and reduces with increasing assisting gas velocity. It was mentioned that the droplet formed is spherical and the predicted droplet sizes agree well with the experimental results. It was concluded that compounds are formed in the droplets and that the main compound formed in the droplet is FeO. This is due to high temperature oxidation reactions. The surface roughness of CO_2 laser cutting of mild steel sheets has been investigated by Radovanovic and Dasic [33]. It was observed that the cut surface has two zones, the upper zone in the area where the laser beam enters the sample, the lower one in the area where laser beam leaves the sample. The lower zone has a rougher surface. It was reported that the surface roughness increases with increasing the sheet thickness, but decreases with increasing laser power. An investigation into the effect of laser cutting operating parameters on surface quality of mild steel has been carried out by Neimeyer et al. [34]. It was indicated that the average surface roughness may be best at high cutting speed and low assist gas pressure. They confirmed that the workpiece thickness had little effect on the cut surface quality. It was concluded that the profiles of the cut surface of the top and bottom edges yield the same values for average surface roughness, despite the significant visual difference in the striation pattern. The same observation of two striation patterns was reported by Schuocker [35] and Lee et al. [36]. They observed a regular pattern near the upper surface and a less regular pattern nearer the lower. CO_2 laser cutting of wedge surfaces and normal surfaces of mild steel has been considered by Yilbas et al. [37]. They assessed the end product quality using the international standards for thermal cutting. The cut surfaces were examined by optical microscopy and geometric features of the cut edges such as out of flatness and dross height were measured from the micrographs. It was found that the dross height and out of flatness are influenced significantly by the laser output power, particularly for the wedge-cutting situation. Moreover, the cut quality improves at a certain value of the laser power intensity. CO_2 laser cutting of advanced high strength steels has been reported by Lamikiz et al. [38]. They considered the influence of the material and, more importantly, the effect of coating on the quality of the cut. It was demonstrated that there were very different behaviors between the thinnest and thickest sheets. However, the variation in the cutting parameters due to the influence of the material was less significant. They succeeded in determining the optimum cutting conditions. It was mentioned that if a high speed of 8000 mm/min is required, the power should be increased to 300 W. Finally, it was found that the best position for the laser beam is underneath the sheet. The effect of beam waist position and material thickness on the kerf size and striation formation of steel sheets has been considered by Karatas et al. [39]. They modelled the kerf width using group parameters analysis. It was found that the beam waist position has a significant effect on the kerf size especially when the thickness is small. They reported that the minimum kerf width could be achieved for a thicker workpiece when the beam waist position is moved below the surface of the workpiece. It was confirmed that the predictions of kerf width agree well with the experimental data. It was observed that (no specific striation patterns except) the stria width and depth increase with increasing workpiece thickness. The laser micro-processing of a metallic stent (i.e. artificial tube) for medical therapy made from SS316L has been investigated by Kathuria [40]. He described the fabrication of a metallic stent of length 20 mm and diameter of 2.0 mm with from a tube thickness of 0.1 mm. He discussed some characteristics such as HAZ and dross. It was found that the desirable taper and quality could be achieved using a laser short pulses with a high pulse repetition rate. The correct choice of laser cutting parameters is essential in order to minimise the quantity of the heat transferred to a part during the cutting operation. In this way, the part will be cut with the smallest amount of thermal damage. The magnitude of the heat input (contribution of heat) depends on the cutting power and speed. Therefore, the cutting speed should be maximised and the power minimised in order to minimise the thermal damage. Lamikiz et al. [41] have also investigated the laser cutting of a different series of advanced high-strength steels. They studied the influence of the laser cutting parameters on different metallurgical characteristics. It was found that good-quality cuts for sheet thicknesses of 0.7 and 0.8 mm were achieved using a large range of cutting speeds between 2000 and 7000 mm/min. It was reported that a level of power of 200 W was sufficient to working at a speed of 4000 mm/min and 300 W for speed of 8000 mm/min. It was mentioned that a gas pressure of 6 bar was sufficient for all speeds mention above. They found that if the sheet thickness was more than 1 mm, good-quality cuts were achieved by using a speed of 3000 mm/min, a power of 300 W and O_2 pressure of 4 bar. They recommended that the O_2 flow should be reduced as the thickness increases to ensure that the exothermic reaction is not too aggressive and does not damage the cut area. Finally, they indicated that the optimal focal position should be near the under- surface of the sheet.

2.2 Laser cutting of plastics and its composites

It is well know that laser cutting machines have valuable applications in many industries. One of these industries is the plastic industry where lasers are utilized to cut and make engraving in plastics and acrylics with a high degree of precision and to make complex shapes with a superior cut quality. As mentioned earlier because the laser cutting process is characterized as having many advantages (see chapter one), it has attract many researchers to explore the process fundamentals in order to understand the process more completely. The effect of the CO_2 laser cutting parameters on the resulting cut quality for different plastics was reviewed as follows:

Caiazzo et al. [42] have investigated the laser cutting of three different polymeric plastics namely: polyethylene (PE), polypropylene (PP) and polycarbonate (PC) with thickness ranging from 2 to 10 mm. It was found that high cutting speeds do not always lead to good process efficiency.

However, for all three polymers, cutting speeds have the most significant effect on the different aspects of the quality of the cutting edge. It was concluded that in many cases a high power laser is not necessary because 200 Watts may be sufficient to cut these plastics. It was recorded that the quality of the cut edges and faces was much better when working with PP rather than when working with PE. They concluded that the different gases, employed at a constant pressure of 3 bar indicated no significant variations in the quality of the cut edges or the value of the critical speed, except when the cutting was carried out at the lowest power setting, i.e. 200W. Choudhury and Shirley [43] have investigated the CO_2 laser cutting of three polymeric materials (PP), (PC) and Polymethyl-methacrylate (PMMA). They reported that the quality of the cut in the case of PMMA is much better than in the case of PP and PC. It was found that the roughness is inversely proportional to the laser power, the cutting speed and the compressed air pressure. However, they mentioned that the cutting speed and the compressed air pressure have a more significant effect on the roughness than the effect of laser power. It was observed that PMMA has a smaller HAZ, followed by PC and PP and for all the polymers the dimensions of the HAZ is directly proportional to the laser power and inversely proportional to the cutting speed and the compressed air pressure. Davim et al. [44] have evaluated the cutting quality of PMMA using a CO_2 laser. They reported that the HAZ increases with the laser power and decreases with the cutting speed. Also, they found that the surface roughness increases with a decrease in laser power and an increase in cutting speed. It was presented that the dimensions of the HAZ ranged between 0.12 and 0.37 mm and the surface roughness measurements were less than 1 μm. Finally, they reported that the CO_2 laser cutting of PMMA is widely used in industrial applications. Kurt et al. [45] have investigated the effect of the CO_2 laser cutting process parameters on the dimensional accuracy and surface roughness of engineering plastics (PTFE and POM). It was concluded that the cutting speed and laser power must be regulated and optimized in order to obtain the desired dimensions and also, to enhance the surface quality and reduce roughness. It was found that the effect of gas pressure on the dimensions can be negligible. It was reported that the relationship between the cutting speed and the surface roughness is not linear. It was reported that the reason for the surface defects could be high gas pressure and high laser power. The CW CO_2 laser cutting of plastics has been studied experimentally and theoretically by Atanasov and Baeva [46]. They investigated PMMA, Teflon-PMMA- Teflon sandwich structure and Si-rubber. It was observed that a good agreement was achieved between the theoretical predictions and the experimental data. They mentioned that it is possible to predict from the model relationships such as the cutting speed as a function of the substrate thickness or laser power and to use these relationships to determine the optimum setting for the process parameters. Bähr et al. [47] have studied the laser cutting of plastic scintillator and light guide materials. It was found that the optical reflection factor R is a reliable measure for evaluating the quality of a cut surface. It was reported that the light guide materials based on pure PMMA have an average optical factor of 80 – 90% depending on the thickness. It was found that a scintillator with thickness of up to 10 mm can be laser cut with a reflection factor of 80%. It was concluded that all laser cutting parameters should be optimized in order to obtain the required surface optical quality. Davim et al. [48] have presented a preliminary study to evaluate the effect of processing parameters (laser power and cutting speed) on the laser cut quality of polymeric materials with different thicknesses. It was found that the HAZ increases with the laser power and decreases with the cutting speed. It was reported that when cutting samples of PMMA, parts could be made with acceptable dimensions and without burrs. It was mentioned that the CO_2 laser of polymeric composites is widely used in industrial applications. Sheng and Cai [49] have developed a procedure that integrates process models for laser cutting with an interactive scheme for selecting the operating conditions. They succeeded in developing an optimization scheme for laser cutting, which is able to predict the laser power and cutting speed that satisfy the constraints for material removal rate (MRR), entrance taper, exit taper and kerf width. It was shown that the critical criterion (MRR in this case) controls the final cutting conditions. It was concluded that this predictive process planning model will eliminate the trial-and-error procedure that is currently used in laser-based manufacturing. Berrir and Birkett [50] have investigated experimentally and theoretically the effect of laser parameters on the cutting and drilling rate in samples of Perspex. It was verified that the experimental results agree with the theoretical predictions and provide a sound basis for the assessment of laser machining of other materials which behave in a similar manner. It was found that increasing the power, increases the depth of the cut, (i.e. thicker samples can be cut successfully) whereas, increasing cutting speed decreases the depth of the cut. Also, they mentioned that moving the focal plane of the lens towards the top surface of the Perspex increases the depth of the cut. It was proved that the gas pressure has no effect on the cut depth. Romoli et al. [51] have studied CO_2 laser machining in order to create 3D cavities by vaporizing PMMA layer by layer. They used a theoretical model to predict the depth and width of the groove. It was shown that complex shapes can be machined even with sharp corners due to the small radius of the focused spot. It was concluded that further investigations should be performed on forming cavities in different plastic materials which have different responses to CO_2 radiation. The laser cutting of perspex (PMMA) has also been studied by Black [52]. He reported that samples of PMMA up to 12.5 mm thick could be cut fairly easily with relatively low-power lasers (around 400 W) and cutting speeds of 1500 mm/min. It was found that the pressure of the shielding gas (normally air) must be kept above 0.1 bar, to prevent vapour ignition. This is achieved by creating as air stream of sufficiently high velocity to ensure that the vapour forming from the plastic flows to the bottom of the kerf. He suggested an inert gas for the assistant gas for a better quality of cut and to avoid frosting of the top edge of the cut as the pressure increases. However, the gas cost would be substantially greater than if compressed gas is used. Di Illio et al. [53] have studied the laser cutting of aramid fibre-reinforced plastics. They discussed the effect of process parameters on the quality of the laser cut. They succeeded in presenting a new method of digital image processing for evaluating the cut quality. Zhou and Mahdavian [54] have discussed the capability of a low power CO_2 laser in cutting various non-metallic materials including plastics. They developed a theoretical model to estimate the depth of cut that can be achieved if the material properties and cutting speed are known. It was found that the theoretical model agrees with the experimental cutting results. It was mentioned that this development will assist those in manufacturing industries to choose a suitable laser system for cutting or marking non-metallic materials. Also, it was demonstrated that a 60 W laser power can be used for cutting non-metallic materials and is suitable for plastic board cutting. Finally, it was concluded that the deeper the cutting depth, the more energy is required. CO_2 laser cutting of reinforced plastic mould parts has been carried out and the cutting results have been compared with other cutting techniques, such as water jet cutting, milling punching, sawing, using a conventional knife, and using an ultrasonic excited knife. This work was carried out by Nuss [55]. It was shown that laser cutting is faster and cleaner and reduces the time spent on post-operation work. The laser cutting of composites of aramide, graphite and glass cloth-reinforced polyester have been studied by Tagliaferri et al. [56]. They examined the morphology of the cut surfaces by scanning electron microscopy. It was found that the thermal properties of the fibres and matrix are the principal factors which affect cutting performance. It was concluded that the quality of the cut surfaces depends on the type of composite being cut. Caprino and Tagliaferri [57] have proposed a simple analytical model to predict the kerf depth and optimal working conditions. It was confirmed that in the laser cutting of carbon reinforced plastic composite materials, the poor quality of the cut surface is due to the difference in the thermal properties of the carbon fibre and the resin matrix. In fact, they observed the best results when laser cutting of AFRP due to the polymeric nature of both of the fibre and matrix. It was reported that their experimental results are in excellent agreement with their theoretical predictions for GFRP, AFRP and GFRP- composites. It was proven that the depth of penetration is linearly correlated with the laser power. In addition, they formulated criteria for the classification of cut quality, based on kerf geometry and heat affected zone size to help in selecting the optimum cutting conditions. Caprino et al. [58] investigated the CO_2 laser cutting of GFRP composites. They introduced an analytical model which allows the depth of kerf to be predicted as a function of the direction of the beam in relation to the direction of travel of the material being worked. They reported a substantial agreement between the experimental results and the theoretical predictions. They stressed the importance of the following when laser cutting of GFRP. This is to characterize the spatial distribution of power of the laser beam and to relate this to the distribution of the fibre in the matrix. The CO_2 laser cutting of glass fibre reinforced plastic (GFRP) composites has been investigated separately by Caprino et al. [59]. They again proposed an analytical model which allows the depth of the kerf to be predicted. It was found that the theoretical model is in substantial agreement with the experimental results. They developed an equation to determine the influence of the parameters of the material structure on the kerf depth. It was concluded that the optimal cutting conditions are strongly affected by any non-uniform distribution of the fibres across the thickness of the sample. Cenna and Mathew [60] have presented a theoretical model which considers the spatial distribution of the laser beam, the interaction time between the laser beam and the workpiece, the absorption coefficient and thermal properties of the material. They reported a good agreement between their results and the theoretical predictions. It was found that the theoretical model successfully predicts the cut quality parameters such as kerf width, the angle of the cut surfaces and the transmitted energy loss through the kerf. Moreover, it was suggested that a different material removal mechanism is involved in the laser cutting of GFRP. Finally, it was reported that as the cutting speed increases the kerf width and the kerf angle decrease. In 2010 Groke and Emmelmann [61] have investigated the influence of laser cutting parameters on the quality of carbon fibre reinforced plastic (CFRP) parts. Their challenge was to apply a CO_2 laser beam and a fibre laser to cut this material and achieve a small HAZ. A large HAZ is a result of the large difference between the decomposition temperatures of resin and fibre material (i.e. the decomposition temperature of carbon fibre is about 3000^0 K and that of epoxy resin is about 550^0 K). It was found that both the HAZ size and the kerf width decrease significantly with high cutting speeds and small energy inputs. Additionally, they demonstrated that both the CO_2 and the fibre laser beam sources are applicable for the LBC of CFRP forming high quality parts. However, it was found that when processing CFRP laminates with thickness between 1 and 7 mm the CO_2 laser has an advantage when compared to the fibre laser due to the higher absorption of the 10.6 μm wavelength, by the material. A study of the possibilities of using a high quality CO_2 laser to cut 3 mm thick samples of CFRP in plates form was presented by Riveiro et al. [62]. They investigated the influence of different processing parameters such as the pulse frequency, the pulse energy, the duty cycle, and type, and pressure of the assist gas on the cut quality. They evaluated the quality of the cuts in terms of kerf width, perpendicularity of cut kerf, delaminating degree, and extension of the heat affected zone. It was reported that an adequate selection of values for the processing parameters allowed good quality cuts to be obtained. The thermal damage caused during laser cutting of aramid fibre/epoxy laminates was investigated by Dillio et al [63]. They examined samples cut with a 500 W CO_2 CW laser using different parameters by both optical and scanning electron microscopy. It was reported that cracks were detected in plies with the fibre direction at 90° to the cutting direction. They developed a model to relate the material damage to the cutting parameters. Bamforth et al. [64] have investigated CO_2 laser cutting of nylon textiles with the aim of optimizing the edge quality. It was reported that nylon textiles can be cut using either a CW or a pulsed CO_2 laser. They optimized the process with the aid of a procedure referred to as 3D finite difference technique. It was mentioned that the edge quality can be significantly better when using the pulsed cutting mode.

2.3 Laser cutting of wood and its composites

Some investigations have been done to determine interactive effects of laser parameters on the quality of the final parts made from different woods and wood- composites. Yet, laser cutting of wood and its composite materials has not been widely accepted by the wood industry. At present, most lasers for cutting wood are used to fabricate some items of furniture in mass production to reduce the cutting cost. In fact, cutting wood and wood-composites by means of a laser beam is a complicated process, as it involves an exothermic chemical reaction and it is influenced by several uncontrollable factors such as: composition, density, moisture, thermal conductivity and internal bond strength. In comparison with industrial reports, laser cutting of different wood based materials has received more attention in the academic literature; yet, in comparison with the cutting of metals and plastics few articles have been published on the laser cutting of woods and wood-composites. In the following section some articles related to the CO_2 laser cutting of woods and wood-composite materials will be summarized.

N. Yusoff et al. [65] have studied the CO_2 laser cutting of Malaysian light hardwood. They succeeded in developing a relationship between the processing parameters and the types of wood with different properties, specifying the optimum cutting conditions. Also, they have presented guidelines for cutting a wide range of Malaysian wood. It was reported that moisture content reduced the cutting efficiency due to the fact that water is readily absorbs the CO_2 laser radiation. It was also shown that the use of an inert gas such as nitrogen can be beneficial and results in a final product with better quality. However, they said that this hypothesis still needs to be proven and that the cost incurred still need to be identified before the approach can be justified. Hattri [66] has attempted to compare the different types of lasers in the processing of wood. He concluded that the CO_2 laser is the most suitable laser due to the fact that the CO_2 laser produces a higher energy density more easily than the YAG laser when interacting with wood. Barnekov et al. [67] have concluded that the factors affecting the ability of lasers to cut wood may be generally classified into three categories: the characteristics of the laser beam, the equipment and process variables and the properties of the workpiece. They have reported that most lasers for cutting wood have powers ranged from 200 to 800 W. They have stated that for maximum efficiency, the proper combination of cutting speed and laser power will depend on the workpiece thickness, density and the desired kerf width. Also, they have found that more power is required to cut wet wood than is required for dry wood if the cutting speed is held constant. Another study was carried out by Barnekov et al. [68] on the laser cutting of wood composites. They have found that the optimal focus position is at the surface, using laser power from 400 to 500 W and a cutting speed of 20 in/min. Moreover, they used compressed air with a nozzle diameter of 0.05 in. Finally, they reported that these preliminary results suggest that further research on the laser cutting of wood needs to be carried out. Both Khan et al. [69] and Mukherjee et al. [70] have carried out studies on the laser cutting of timber wood. Both addressed the significance of investigating the LBC parameters such as laser power, cutting speed, nozzle design and variation in shielding gas velocity and their effect on the quality of the cut sections. Lum et al. [71] have reported on the optimal cutting conditions for the CO_2 laser cutting of MDF. They found that the average kerf width reduces with increasing cutting speeds. It was presented that the composition of the MDF, including the additives such as the bindings, the bonding agent, the tar etc, is also likely to cause variations in cutting speed. In addition, they reported that no significant reduction in the kerf width was found when varying the shielding gas type or pressure. Furthermore, they mentioned that increasing the gas pressure did not improve Ra values. However, Ra values increase as the cutting speed increases. Finally, they pointed out that the maximum cutting speed for each thickness is independent of any increase in the gas pressure or type. Therefore it would be more economical to use compressed air rather than nitrogen to laser cut MDF. Ng et al. [72] have continued their investigation to estimate the variation in the power distribution with different cutting speeds, material thicknesses and pulse ratios. They succeeded in developing a test procedure to determine primary power losses when performing CW or pulsed mode laser cutting of MDF. Letellier and Ramos [73] have reported that when cutting MDF boards with thicknesses greater than 8 mm and keeping the focal position fixed at the surface, the result is that the kerfs have curved sides. This side curvature increases as the MDF board becomes thicker. Accordingly, they varied the focal position and beam velocity in order to investigate their effect on the shape of side kerfs. They suggested a focal position for each board thickness and process parameter combinations. Also, they succeeded in determining the optimal cutting conditions by combining the plot of the focal position against the board thickness for minimum side kerf with the plot of the cutting speed against the board thickness at a fixed laser power.

2.4 Laser cutting of ceramic and glass materials

Laser cutting of thick ceramic samples by carefully controlling the fracturing of an irradiated area has been studied by Tsai and Chen [74]. They focused the Nd-YAG laser to scribe a groove-crack on the surface of a substrate and then an unfocused CO_2 laser is used to induce thermal stress. They developed a model to predict the cut geometry and stress levels in the cut region. They succeeded in presenting the effect of the cutting parameters on the cut geometry.

Ji et al. [75] have presented a laser crack-free cutting method for Al_2O_3 ceramics by a single-pass process. They could produce both straight and curved profiles. It was found that to achieve crack-free cuts the process parameters must be as follows: the cutting speed must be between 0.23 and 0.42 mm/s, when the laser head moves with a speed of 3 mm/s, the piercing time must be between 0.1 and 0.5 s, the piercing pitch must be between 0.03 and 0.05 mm. The power must reach a peak of 3500 W and the cycle duty must be less than 30%. It was concluded that these results demonstrated that the laser crack-free cutting technique is a promising method to achieve complex profiles in ceramic materials. CO_2 laser cutting of thick ceramic tiles with thicknesses between 8.5 mm and 9.2 mm has been investigated by Black and Chua [76]. They used a combination of different cutting speeds to cut the tiles in order to determine the necessary cutting parameters for various tile geometries. They also looked into the effects on cutting of using various shield gases. Multipass cutting and underwater cutting were performed to examine their effects on the thermal load during the processing. It was demonstrated that the most critical factor arising from the use of the CO_2 laser to cut ceramic tiles is crack damage, which is caused by a high temperature gradient within the substrate. It was concluded that a reduction of process-induced crack formation is vital for the commercial use of lasers in cutting ceramic tiles. In another report Commercially-available ceramic tiles were cut using a CO_2 laser cutting machine, with the object of producing a laser beam machining (LBM) database that would contain the essential parameter information for successful processing. This was carried out by Black et al. [77]. They investigated various laser cutting parameters that would produce cuts in ceramic tiles, but which require minimal post-treatment. They also examined the effects of various shield gases, of multi-pass cutting and of underwater cutting. The effects of these parameters have been described above. Pulsed CO_2 laser cutting of Si_3N_4 engineering ceramics has been studied by Hong et al. [78]. They developed a model to investigate the effect of the cut front shape on the absorption of the laser beam. It was shown that "crack-free" cutting, the length of micro- cracks being limited to the grain size, could be obtained by using a high-speed and multi-pass feed cutting process. The effects of process parameters on the quality achieved during laser cutting of alumina were presented by Wee et al. [79]. The effects of the interaction time, irradiance and assist gas pressure on the quality output variables such as striation angle, striation wavelength and the distance of clearly defined striations were studied. It was observed that the inclination of the striation is most affected by the interaction time, with assist gas pressure having a secondary effect and irradiance playing a minor role. Also, it was reported that the striation wavelength and upper and lower striation lengths are most influenced by the interaction time and irradiance, both causing longer wavelengths. Grabowski et al. [80] have studied the laser cutting of a AlSi-alloy/SiCp composite by modelling the kerf geometry. They used a numerical model which describes the inhomogeneous optical and thermo physical properties of the AlSi-alloy/SiCp composite. It was found that increasing the laser beam scanning speed increases the slope of the cutting front. Hong and Li [81] have investigated the laser cutting of SiN4 ceramics. Their aim was to achieve crack-free cuts in this engineering ceramic with high efficiency by using a mechanical chopper Q-switched pulse CO_2 laser with optimised process parameters. It was found that the pulse duration should be short to reduce undesirable thermal effects during laser cutting. Moreover, they reported that those undesirable thermal effects can be reduced even more by using a high cutting speed and multiple passes. Boutinguiza et al. [82] have investigated the CO_2 laser cutting of slate. They studied the influence of some process parameters (average power and assist gas pressure) on the geometry and quality of the cut. It was shown that the CO_2 laser is a feasible tool for the successful cutting of slate. Also, it was confirmed that the mechanism of the CO_2 laser cutting of slate tiles is similar to that of metals. It was stated that the use of oxygen as an assist gas leads to a slight increase in cutting speed. Finally, it was found that tiles with a thickness of up to 13 mm can be cut with an acceptable cutting speed at a laser power of 1200 W. A dual-laser-beam method was proposed by Jiao and Wang [83] to cut glass substrates to improve the cutting quality. They used a focused CO_2-laser beam to scribe a straight line on the substrate and then an unfocused CO_2-laser beam was used to irradiate the scribing line to generate a tensile stress and separate the different parts of the substrate. They used finite-element-method (FEM) software ANSYS to calculate the temperature distribution and the resulting thermal stress field. It was concluded that a glass substrate can be divided along chosen path with this dual-laser beams system and the cutting quality is improved compared with cutting using an unfocused laser beam alone. A comparison of experimental results using high-power CO_2 and diode lasers under roughly equivalent experimental conditions has been presented by Crouse et al. [84]. It was found that the multimode diode laser produces a higher penetration rate when compared with the CO_2 laser under equivalent experimental conditions.

3. CONCLUSION

This paper presents an overview of recent experimental investigations in laser cutting of various engineering materials concerned with cut quality analysis. The objective was to identify the most common process parameters analyzed, cut quality characteristics and to investigate whether and which DOE design was adopted. Extensive research work is being done in laser cutting for improving the quality of cut. The review shows that quality of cut depends upon many control factors or parameters such as laser beam parameters (laser power, pulse width, pulse frequency, modes of operation, pulse energy, wavelength, and focal position); material parameters (type, optical and thermal properties, and thickness); assist gas parameters (type and pressure) and processing parameters (cutting speed). Many researchers have investigated the effect of these process parameters on different quality characteristics such as material removal rate (MRR), kerf quality characteristics (kerf width, kerf deviation and kerf taper), surface quality (cut edge surface roughness, surface morphology), metallurgical quality characteristics (recast layer, heat affected zone, oxide layer and dross inclusions) and mechanical properties (hardness, strength). To this aim, most of the experimental studies have been performed without using DOE approach. Surprisingly, only few researchers adopted Taguchi experimental design. In about half of the reviewed papers the optimal cutting parameter settings for cutting the given material was determined.

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