Laser Machining of Polymer Matrix Composites: Scope, Limitation and Application

Pathik Patel[#1], Piyush Gohil[#1], Shilpesh Rajpurohit[#1]

[1] *Mechanical Engineering Department, CSPIT, CHARUSAT,*
Changa, Gujarat, India

***Abstract*—This paper presents an overview of laser beam machining and researches carried out so far in the area of laser cutting of polymer matrix composites. Composite materials are highly promising materials for applications in the aeronautic, aerospace, automotive and marine industry, but their properties like brittleness, anisotropy and non-homogeneity make it a difficult to machine material by conventional machining methods. In order to make parts of the required specifications from composites an appropriate machining method must be selected and laser machining offers an attractive alternative for machining the composites. Laser machining is thermal energy based non-contact type advance machining. Laser beam is focused on the material to remove material by melting and vaporizing. Laser cutting of composites find wide application in industry due to improved end product quality, low cost and short processing time. In recent years number of researches have explored laser beam machining of polymer matrix composites and the problem associated with that. This paper gives an overview of laser beam machining of polymer matrix composites, the effect of laser cutting parameters (laser power, cutting speed, gas pressure etc.) on the cut quality parameters (heat affected zone, surface roughness, kerfwidth, taper angle etc.) and at last the problems associated with cutting of composites are discussed as future work.**

***Keywords*- laser cutting, CO_2 laser, polymer matrix composites, kerfwidth**

Nomenclature

KW	Kerf width
SR	Surface Roughness
HAZ	Heat Affected Zone
a	Taper Angle
P	Laser Power
V	Cutting Speed
p	Gas Pressure
GFRP	Glass Fibre Reinforced Plastic
AFRP	Aramid Fibre Reinforced Plastic
CFRP	Carbon Fibre Reinforced Plastic
d	Material Thickness
PMC	Polymer Matrix Composites
µm	Micrometer
nm	Nanometer
W	Watt
J	Joule
µs	Microsecond
Hz	Hertz

I. Introduction

Composite materials are highly promising materials for applications in the aeronautic, aerospace, automotive and marine industry. These composites have advantages over other materials due to their superior strength to weight and stiffness to weight ratios and high service temperatures. Composite materials are made from two or more materials for producing properties that could not be obtained from any one material. One of those materials acts as the matrix and the others act as the reinforcement in the composite. The function of the matrix material is to protect the reinforcement material, to distribute the stress to the reinforcement material and to provide for the final shape of the composite part. The function of the reinforcement material is to provide the composite high mechanical properties and to reinforce the matrix in preferential directions. Polymer matrix composites, or PMC, are unique composite material consisting of reinforcing fibres embedded in an epoxy resin or polyester matrix. Their low density, good thermal stability and excellent mechanical properties at elevated temperatures make them an ideal material for aircraft and aerospace, automotive, constructions, corrosion resistant products, electrical components, marine and marine accessories. It can withstand high temperature without much deformation. Polymer matrix composites have densities in the range of 1.6–2.6 gm/cm³, much lower than those of metals and ceramics and hence make lower component weight an important consideration for aero-vehicles. However, they are anisotropic and non-homogeneous in nature, and their intrinsic brittleness and hardness make machining difficult, thus limiting their usefulness but where the weight is more important than the cost, the use of composite materials is advantageous.

II. Machining of Composites

Composite materials are brittle, anisotropy and non-homogeneous in nature which makes it difficult to machine by conventional machining methods. Some researchers have established the feasibility of applying conventional machining techniques to machine composites. According to their results, conventional methods damage the workpiece through chipping, cracking, delamination and high wear on the cutting tools. Therefore, other researchers have established that polymer matrix composites can be machined easily using non-traditional machining methods. In order to make parts of the required specifications an appropriate machining method must be selected. Among the various non-conventional machining methods available, Electro Discharge Machining can be used for electrical conductive materials, Abrasive Jet Machining and Water Jet Machining can be used for brittle materials and Ultrasonic Machining can be used for harder materials but Laser Machining offers an attractive alternative to all of above because it is a non-contact, abrasion less technique eliminates tool wear, machine-tool deflections, vibrations and cutting forces, moreover it can be used for almost all type of materials. Laser cutting of composites find wide application in industry due to improved end product quality, low cost and short processing time. The laser beams are widely used for cutting, drilling, marking, welding, sintering and heat treatment. Laser, known as Light Amplification by Stimulated Emission of Radiation is a high energy, directional coherent monochromatic beam. It is focused on a very small spot, usually 0.1-1.0 mm in diameter, and causes melting, vaporization, or chemical degradation throughout the depth of the material. A jet of gas removes fluids and degradation products, which is coaxial with the laser beam. For non-metallic materials, air is used as an assist gas since oxidation does not occurs, but other gasses have been used such as CO_2 for glass and helium for boron composites.

III. Types of Laser

There are two types of industrial lasers are used they are CO_2 lasers and Nd-YAG lasers.

The CO_2 laser system consists of three gases; carbon dioxide, nitrogen and helium are mixed and fed into one end of a discharge tube at a pressure of a few torr. The gas flows down the end of the tube in about one second and is pumped out the far end with a mechanical forepump. An electrical discharge is maintained between the metallic end flanges of the tube. The ballast resistance is required because of the negative dynamic resistance of the discharge. With a fully reflecting mirror on the left and a partially transmitting mirror on the right, the device becomes a laser, which radiates in the far infrared at 10μm. They are mostly uses for cutting sheet metals at high speed.

Nd:YAG (neodymium-doped yttrium aluminum garnet; Nd:Y3Al5O12) is a crystal that is used as a lasing medium for solid-state lasers. It is the neodymium ion, which proves the lasing activity in the crystal, in the same fashion as red chromium ion in ruby lasers. Nd:YAG lasers are optically pumped using a flashtube or laser diodes. Nd:YAG lasers operate in both pulsed and continuous mode. Pulsed Nd:YAG lasers are typically operated in the so called Q-switching mode: An optical switch is inserted in the laser cavity waiting for a maximum population inversion in the neodymium ions before it opens. Then the light wave can run through the cavity, depopulating the excited laser medium at maximum population inversion. The high-intensity pulses may be efficiently frequency doubled to generate laser light at 532 nm, or higher harmonics at 355 and 266 nm. These are one of the most common types of laser, and are used for many different applications, especially thicker materials.

IV. Laser Principle

Atoms at their resting energy state, or ground state (E^0), can be excited to a higher energy state (E^*) when they absorb electrical, optical, or thermal energy by pumping. At the E^* level, atoms are unstable and spontaneously return to their E^0 ground state, this liberates the absorbed energy as light or photons. This process referred as spontaneous emission of radiation. If, on their brief descent from E^* to E^0, the excited atoms or molecules at E^* are further bombarded with the same energy that caused the initial transition from E^0 to E^* or a proportional amount, the net result is the liberation of an amount of energy twice the original. Thus, if a photon strikes an atom at E^0, causing it to go to its E^* level, and if a second photon strikes the atom as it returns to E^0, the atom emits two photons of the same frequency. This emission occurs in phase (coherence) with and in the same direction as the first bombarding photon. This process is called stimulated emission. The two emitted photons may then each strike other excited atoms, further stimulating emission of photons with the same phase and frequency. As more atoms are excited to the upper energy level E^* to the extent that the number of atoms in the active medium at E^* is greater than those at E^0, a population inversion occurs in the system. This chain reaction rapidly produces a powerful eruption of a coherent beam of radiation, which called as laser.

V. Laser Components

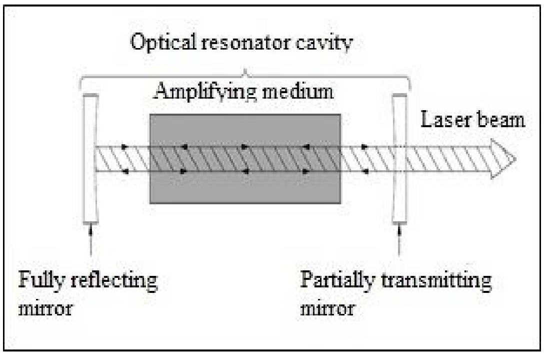

Fig. 1 Schematic diagram of laser system [3]

A laser consists of three parts: a resonant optical cavity called the optical resonator, a laser gain medium (also called active laser medium) and a pump source to excite the particles in the gain medium.

Optical resonator: The optical resonator consists of at least two mirrors between which the light bounces up and down resonantly. In most cases, one or more mirrors are curved, so that a resonant optical mode forms. Modern dielectric mirrors used in lasers typically have a reflectivity of up to 99.9%. However, one of the end mirrors is usually only partially reflective, so that a portion of the light is transmitted. The transmitted part forms the laser output. In order to operate, the laser requires a gain medium in the resonator, which amplifies light and thus compensates for the loss through the output coupler. The type of gain medium they employ (gas laser, solid-state laser, dye laser, semiconductor laser, etc) typically classifies lasers. The stimulated emission process takes place in the gain medium.

Laser gain medium: The gain medium amplifies light of any direction. However, only the light that bounces up and down between the resonator mirrors is amplified many times and therefore reaches a high intensity. In a continuous wave (CW) laser, the gain in the laser gain medium and the loss from the output coupler plus other losses are in equilibrium. The fact that the photon energy has to match a given energy transition makes the laser monochromatic. Since the amplification process maintains the phase and direction of the light, the laser output is directional and coherent.

Pump source: The active particles in the laser gain medium need to be in a state of inversion for the laser to operate. To reach this state requires some pumping process, which lifts them into the required energy state. Typical pumping processes are electrical current in a gas or semiconductor laser or optical pumping in a solid-state or dye laser. Optical pumping can achieved either by flash lamps or by another laser.

VI. PROPERTIES OF LASER BEAM

Monochromaticity: The light emitted from a laser is monochromatic, that is, it is of one wavelength (color). A laser can be constructed to operate in only one longitudinal mode to give better monochromaticity.

Collimation: Collimation of the laser radiation is related to the directional nature of the beam. Highly directional beams are said be highly collimated beams, which can be focused on a very small area even at longer distances. Hence, energy can be efficiently collected on a small area without much loss in the beam intensity.

Beam Coherence: The light from a laser is said to be coherent, which means the wavelengths of the laser light are in phase in space and time. Coherence properties can be improved by operating the laser in a single longitudinal and transverse mode.

Brightness or radiance: Brightness or radiance is defined as the amount of power emitted per unit area per unit solid angle. Laser beams are emitted into very small divergence angles; hence it can be focused on a very small area ensuring the correspondingly high brightness of laser beams.

VII. LASER MATERIALS INTERACTIONS

For understanding the capabilities and limitations of laser-machining requires the knowledge of physical processes occurring during the laser beam interactions with materials. When the electromagnetic radiation is incident on the surface of a material, various phenomena that occur include reflection, refraction, absorption, scattering, and transmission. One of the most desirable and important phenomena in the laser processing of materials is the absorption of the radiation. Absorption of radiation in the materials results in various effects such as heating, melting, vaporization, plasma formation, etc., which forms the basis of several laser materials-processing techniques. The laser parameters include intensity, wavelength, spatial and temporal coherence, angle of incidence, polarization, illumination time, etc., whereas the materials parameters include absorptivity, thermal conductivity, specific heat, density, latent heats, etc. The interaction of laser with material is a complex interdisciplinary subject and requires knowledge from several branches of physics.

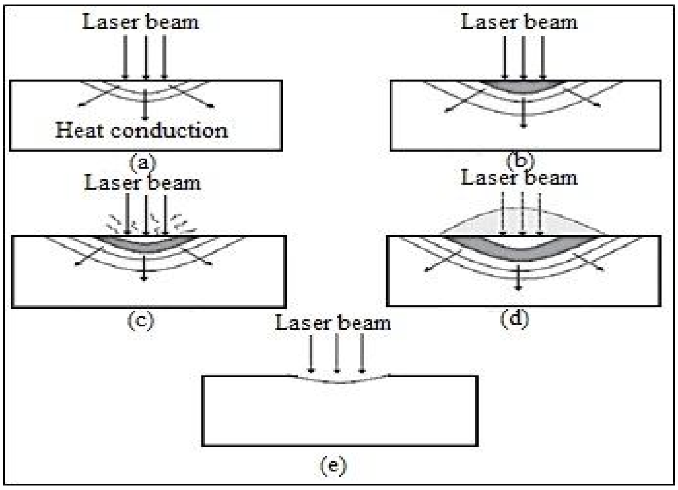

Fig. 2 Various effects of laser–material interaction: (a) heating, (b) surface melting, (c) surface vaporization, (d) plasma formation, (e) ablation [5]

Absorption of Laser Radiation: Absorption of light can be explained as the interaction of the electromagnetic radiation with the electrons (either free or bound) of the material. The absorption process is sometimes referred to as the secondary "source" of energy inside the material and is used to determine the extent of various effects on the material during laser–material interactions.

Thermal Effects: When a laser beam of intensity I_0 is irradiated on the surface of material, it results in the excitation of free electrons (in metals), vibrations (in insulators), or both (in semiconductors). This excitation energy is rapidly converted into heat. This is followed by various heat transfer processes such as conduction into the materials, and convection and radiation from the surface.

Heating: The important characteristics of the temperature changes in a material during laser irradiation can be listed as (Wilson and Hawkes 1987):

1. At the surface ($z = 0$), the temperature increases with increasing irradiation time, reaches maximum corresponding to pulse time t_p, and then rapidly decreases. Thus, the heating and the cooling parts of the curve are clearly separated at a time corresponding to pulse time.
2. At certain depths below the surface ($z > 0$), the temperature increases with increasing irradiation time, reaches maximum, and then decreases. However, the

maximum temperature does not reach exactly at the pulse time tp, but at the longer time ($t > t_p$). The time ($t > t_p$) to reach the maximum temperature increases as we go further into the depth below the surface of the material.

Melting: In the preceding discussion, it was considered that the incident laser power density was sufficient to heat the material without any phase transformations. However, the surface temperature may reach the melting point or the boiling point at sufficiently higher laser power densities ($I_0 > 10^5$ W/cm^2). The corresponding laser power densities are often referred to as the melting and boiling thresholds.

Vaporization: Once the surface temperature reaches the boiling point, further increase in the laser power density or the pulse time cause the evaporative material removal from the surface without further increase in the depth of melting. Surface vaporization is initiated when the laser intensity becomes sufficiently high ($I_0 > 10^5$- 10^8 W/cm^2).

Plasma Formation: When the material is irradiated with sufficiently larger laser intensity (I_v), significant surface evaporation takes place as explained in the previous sections. Once the vaporization is initiated, the interactions between the resulting vapor and the incident laser beam become important in determining the overall effect of the laser irradiation on the material. One of the most important interactions is the ionization of vapor. The highly ionized vapor is termed as plasma.

Ablation: The term ablation is generally used for material removal processes by photo-thermal or photo-chemical interactions. In photo-thermal process, the absorbed laser energy gets converted into thermal energy in the material. The subsequent temperature rise at the surface may facilitate the material removal due to generation of thermal stresses.

VIII. ADVANTAGES OF LASER CUTTING

Noncontact process: The workpiece need not to be clamped or centered on the precise fixtures as in conventional machining. Accurate positioning of the workpiece on the X–Y table with defined direction of cut can be easily obtained during laser cutting thus facilitating the machining of flimsy and flexible materials.

Ease of automation: Most of the laser-cutting processes are CNC-controlled giving accurate control over the dimensions of cut and faster cutting speeds.

High cutting speeds: Laser cutting is a fast process. The typical cutting speed for 4 mm carbon steels with a 1250 W CO_2 lasers is 3 m/min [5].

Fine and precise cut dimensions*:* Laser cutting can be carried out with a very narrow kerf width (~0.1 mm) such that the process can be used for fine and profile cutting.

Better quality of cuts*:* Laser heats and melts the material in a localized fashion. This in combination with the melt expulsions during cutting minimizes the heat affected zones and the thermal stresses

Flexible process: Laser cutting can be used for a variety of materials ranging from ferrous and nonferrous to non-metallic materials.

IX. PARAMETERS OF LASER

The tables shown below gives the lists of parameters with their units, which can be vary for laser machining. first table is for continuous mode and second table is for pulse mode.

TABLE 1 PARAMETERS FOR CONTINUOUS MODE OPERATION

Processing parameters	**Unit**
Laser Power	W
Cutting Speed	mm/min, m/min
Type of Assist Gas	Oxygen, Nitrogen, Argon
Gas Pressure	Bar
Focal Length of lens	mm
Focal Diameter	mm
Focus Position	Surface of work material
Nozzle Tip Distance	mm
Nozzle Diameter	mm
Material Thickness	mm

TABLE 2 PARAMETERS FOR PULSE MODE OPERATION

Processing parameters	Unit
Laser Power	W
Cutting Speed	mm/min, m/min
Type of Assist Gas	Oxygen, Nitrogen, Argon
Gas Pressure	Bar
Focal Length of lens	mm
Focal Diameter	mm
Focus Position	Surface of work material
Nozzle Tip Distance	mm
Nozzle Diameter	mm
Wave Length	nm
Pulse Energy	J
Pulse Frequency	Hz
Pulse Duration	µs
Material Thickness	mm

X. CUT QUALITY PARAMETERS

Surface roughness: Surface roughness is an effective parameter representing the quality of machined surface. It can be measure using a surface roughness tester. Minimal roughness and the visual appearance of the cut edge are key quality requirements in laser cutting. In laser- cutting optimal cutting parameters are decided for minimum surface roughness. Experimentally it is found that laser power and cutting speed are the most affecting parameters for surface roughness.

Kerfwidth and Taper angle: The main important parameters which decide the quality of the laser machining are the kerfwidth and taper angle. The laser beam is in the form of converging-diverging shape, so taper is always exists, but it can be minimize by selecting appropriate parameters. The kerfwidth and taper angle can be measure using scanning electron microscope, optical microscope or by image analysis software after taking the images of the straight cuts. Experimentally it is found that the laser power, cutting speed, gas pressure and duty cycle are the most affecting parameters for kerfwidth, while laser power, cutting speed, gas pressure, duty cycle and pulse frequency are the most affecting parameters for taper angle.

Heat affected zone: The metallurgical characteristics of laser machine is governed by heat affected zone (HAZ). It is one type of edge damage occurs due to heat. It can be measure using optical microscope, Scanning electron microscope or photomicrograph. Experimentally it is found that laser power, cutting speed, gas pressure, repetition rate (RR) and pulse duration are the main affecting parameters for HAZ.

XI. Review of previous work

Here it is shown the experimental researches, which have been done on, laser cutting of polymer matrix composites. More over the effect of process parameters (laser power, cutting speed, type of gas and its pressure, material thickness) on the cut quality of the workpiece (surface roughness, heat affected zone, kerfwidth, taper angle) are discussed in detail.

Caprino et. al. (1995) has studied cutting glass fibre reinforced plastic (GFRP) composites using a CO_2 laser with Multimodal-Gaussian power distribution. They have proposed an analytical model which allows the depth of the kerf to be predicted as a function of the direction of beam travel in relation to the material. They have taken polymethylmetacrylate (PMMA) of 100 mm square and 3 mm thick as a sample material. The test results are used to calculate the depth of the kerf obtained in different working conditions on two types of GFRP with differing amount of fibre, V_f = 0.265 and V_f = 0.408. Their experimental data show substantial agreement with the theoretical predictions given by the model. The cutting system used for the experimental tests consisting of a CO_2 laser source with a nominal power of 2500 W and a lens of 7.5” focal length. The working of system gave multimodal Gaussian power intensity. They have used a jet of inert gas at right angle to limit the matrix combustion and to protect the focus lens from contamination by vapors. The proposed analytical model can be usefully employed to predict the depth of the kerf width and maximum cutting speed as a function of the travel direction of the beam.

Cenna et. al. (1997) presents an overview of the development in laser cutting of fibre-reinforced plastics materials. They have identified the important aspects of laser cutting process and discussed in detail. They have discussed types of lasers can be use, problems associated with machining, interaction mechanism of laser beam with fibre-reinforced plastics. They have found cut quality parameters in terms of cut surface morphology, kerfwidth, angle of the cut surfaces, length of protruding fibres, heat-affected zone and thermal stress. Moreover the effect of cutting parameters on cut quality i.e. effect of laser pulsing, material thickness, material properties fibre orientation and distribution are also discussed. They have found that in case of glass fibre and carbon fibres a negligible improvement in the cut quality with increased cutting velocity. Regarding to the kerf width they have found that the kerf width at the inlet (W_i) and at the exit (W_o) of the beam decreases as the cutting speed is increases. At highest velocity the kerf width at exit side tends to zero. The cut quality with respect to the angle between the surfaces has been studied, and suggested that the quality is affected by the cutting velocity. They have found that the length of protruding fibres from the matrix decreases with increasing cutting velocity. The HAZ in the material tends to reduce with increase in speed and increase in assist gas pressure but the HAZ increases with increasing in power.

Tuersley et. al. (1998) has studied laser machining of glass-matrix composite (GMC) comprising SiC fibres in a borosilicate glass matrix. To investigate the possibility of cutting and drilling GMC materials, laser machining and subsequent analysis were performed with a view to optimizing the laser pulse waveform parameters with respect to both material removal rate/efficiency and material damage. This paper has attempted to isolate the effects of individual laser parameters by the adoption of a systematic series of tests. The effect on depth of hole and induced damage of various pulse waveforms (in terms of pulse energy, duration and intensity) were investigated. They have taken plaques of GMC consisting of continuous silicon carbide fibres in a matrix of borosilicate glass as a sample material. All of the trial sets were performed with the Nd–YAG laser. They have used Ntrogen gas as inert gas in preference to oxygen and argon. The effects on material removal rate of varying the pulse energy, pulse duration and pulse intensity were investigated. The results shows that the rate of material removal is influenced primarily by the peak power of the laser, but the results suggest that the process has a greater dependence on the pulse energy than on the pulse duration at a given peak power. An optimum level of pulse intensity is inferred from the identification of a maximum in drilling penetration corresponding to a beam magnification setting of 1.7X. The degree of damage produced at the processed surface is assessed by electron microscope examination.

Tuersley et. al. (1998) has continues the study with the same material mention above but changes from drilling to cutting, and examines the influence of different process configurations. Trials are performed to optimize the type and pressure of the assist gas, the focal point of the beam with respect to the material surface and the variation of maximum cut speed with plaque thickness. In this part of the study, the trials are extended to cutting the materials, generating a larger and more exposed process surface that permits closer investigation of the surface quality in terms of surface roughness, nature and extent of any redeposit material and heat-affected zone (HAZ). They have found the effects of type of assist gas, gas pressure, focal position and maximum cutting speed. The gas assist trials show that the use of oxygen is to be avoided owing to oxidation of the molten matrix glass; this situation is greatly improved by the use of nitrogen, but a more cost-effective solution that produces similar cut quality is to use air under 2 bar pressure. Adjustment of the point of focus with respect to the surface of the plaque by varying the focal depth and beam expansion telescope setting shows that there is little influence on penetration with variations of up to ± 2 mm. A maximum cut speed of approximately 60 mm/min is identified for 7 mm thick material, rising to over 750 mm/min for 1.5 mm thick plaques.

Methew et. al. (1999) has developed a predictive model based on important process parameters, viz. cutting speed, pulse energy, pulse duration, pulse repetition rate and gas pressure. The responses considered are the heat-affected zone (HAZ) and the taper of the cut surface. The optimization of process parameters was done using response surface methodology (RSM). The effect of the process parameters on the output responses is also discussed. They have found influence of repetition rate and pulse duration on the HAZ, influence of cutting speed on the HAZ, influence of pulse energy on the HAZ, effect of parameters on kerf widths and taper. Moreover they found that the thermal properties of the constituent material and the volume fraction of the fibres are the principal factors that control the cutting performance. Workpiece material used by them was carbon fibre reinforced plastic (CFRP) composites of 2 mm thickness. For experimental work they have used a pulsed Nd:YAG laser cutting machine with a 300 W capacity (average power). The laser was operated in the TEM_{00} mode and the focused spot diameter was 0.1 mm. Argon gas was used as it was found to be more effective in obtaining a better quality cut. Samples obtained from each specimen were examined through photomicrographs. For influence of repetition rate and pulse duration on the HAZ, they found that the pulse repetition rate (RR) and the cutting speed are the two most important parameters affecting the HAZ, the latter being found to be directly proportional to the RR. According to them, higher pulse duration at lower RR gives a smaller HAZ. For influence of cutting speed on the HAZ they found, as cutting speed increases lesser the interaction time and lesser the HAZ. For influence of pulse energy on the HAZ they found, the HAZ is directly proportional to the pulse energy. For effect of parameters on kerf width and taper angle they found RR and pulse energy were the most influencing factors affecting the kerf widths. The top kerf width was found to decrease with an increase in RR, whereas the bottom kerfwidth shows a decreasing trend with an increase in RR. Increase in cutting speed decreases the kerf width. Too high a cutting speed may result in a no-cut situation. Also, increase in pulse energy leads to more material removal and increase in kerfwidth.

Yung et. al. (2002) has describes the characteristics of the heat-affected zone (HAZ) of a UV-YAG laser-drilled hole in glass fiber reinforced plastic (GFRP) printed circuit boards. The structures of the HAZ produced by different laser parameters were analyzed. They found that when hole is drill with lower power and repetition rate, a clear hole wall with very little black charred material was obtained. On the other hand, when the hole is drill with high power and repetition rate, matrix recession and fiber protrusion were observed, also a loose coating was found covering the protruded glass fibers. They have taken 1080 type GFRP PCB as a sample material. They were 1.6 mm thick laminated glass/epoxy composites clad on both sides with 18 mm copper foil. The specimens were cut into 25mm × 4mm rectangles. The laser light was generated by a pulsed and lamp-pumped Nd:YAG laser with third harmonics generation, and was operated at 355 nm. The output beam had a TEM_{00} (Gaussian) energy distribution and the focused spot was of 25 mm diameter. The maximum average power was 1.2 W. In the experiments, the pulse repetition rate varied from 0.5 to 20 KHz, and the laser power varied from 0.1 W to the maximum average power. Cross-sections of the drilled holes were examined by an optical microscope and scanning electronic microscope (SEM). The drilled holes were filled with epoxy resin to prevent the section edges from subsiding during polishing. Electronic dispersive X-ray was used for the analysis the components of the recast and charred layer. An image analyzer was used to measure the size of the HAZ. The experimental results indicate that the structure of the HAZ is influenced strongly by the laser parameters, such as the average laser power and the pulse repetition rate. They observed that the structure of the HAZ is influenced strongly by the average laser power and the pulse repetition rate. For a given pulse repetition rate, the equivalent width of the HAZ, increases as the average laser power. For a given average laser power, the equivalent width of HAZ increases with an increase in the repetition rate, with a further increase in pulse repetition rate, the equivalent width of HAZ starts to decrease.

Cenna et. al. (2002) has developed a theoretical model considering the spatial distribution of the laser beam, interaction time between the laser and the work material, absorption coefficient of the laser beam at the laser wavelength and the thermal properties of the material. The developed model predicts the various parameters in laser cutting of composite materials such as kerfwidth at the entry and at the exit, material removal rate and energy transmitted through the cut kerf. Experiments for different laser and material combinations were carried out to evaluate the effects of cutting parameters on the cut quality. In order to validate the model, they have taken 2 mm, 3 mm and 4 mm thick AFRP and GFRP material as samples. A 1.5 KW continuous wave CO_2 laser was used with powers varying from 600 W to 1000 W. The focused beam radius was 0.1 mm. Cutting speed was varied from 10 mm/s to 60 mm/s. The kerf widths were measured using an optical microscope and from the kerfwidths and the material thickness the average slope of the cut kerf was calculated. The model developed uses the energy balance equation to predict various parameters in laser cutting of composite materials. The developed model successfully predicts the cut quality parameters such as kerfwidth at the inlet and at the exit and angle of the cut surfaces. It also predicts the transmitted energy loss through the kerf. Overall the methodology used here is successful for analyzing laser cutting of composite materials.

Sulaiman et. al. (2006) presented study regarding to laser gas assisted cutting of the carbon–carbon structure composing of composite structure consisting of 64 layers of plain-weave carbon/carbon fibers with 0° orientation. The kerf size is predicted and the size of striation formation is formulated. An experiment is carried out to cut carbon–carbon workpiece. A CO_2 laser, power of 2 KW with 1500 Hz pulses is used. SEM and optical microscopy are carried out to investigate the end product quality. The workpieces used in the experiment are made of composite structure consisting of 64 layers of plain-weave carbon/carbon fibers. This carbon fiber-reinforced laminate (CFRL) has the layers placed at 0°. The matrix used is water based phenolic resin. SEM is used for micrographs of the cutting section while optical microscope is employed for kerf width size measurements. The kerf width size due to different laser irradiation power is predicted and compared with the experimentally obtained values. They found that the fiber orientation in the workpiece with reference to the workpiece motion during the cutting has significant effect on the kerf formation. In this case, fiber axis normal to the axis of workpiece motion results in relatively large kerf width size due to the influence of thermal conductivity. Striation width and depth vary slightly with increasing laser power.

Davim et. al. (2008) has presented a preliminary study to evaluate the effect of the processing parameters (laser power and cutting velocity) under the quality of the cut for several polymeric materials. The objective was to evaluate the quality of the cut, presence of burr and dimension of heat affected zone (HAZ). The experiments were carried out with a laser system consisting of a 4.0 KW continuous CO_2 laser. They have taken PMMA and PC for experimental work. The laser power and the cutting velocity were varied from 280-900 W and 250-4000 mm/min, respectively. The thickness of the selected plates varied from 2-8mm according the commercial range. The range of pressure gas was 0.5-4 bar. The dimension of the burr and the heat affected zone (HAZ) was studied by shop microscopy, with 30X magnification and 1μm resolution. They have found that the HAZ increases with the laser power and decrease with the cutting velocity. The thermosets plastics (epoxy resin + GF and phenolic resin + algodon) present the cut surface deteriorated, burnout and high dimension of HAZ, with poor workability. The PC presents the dimension of burr between 0.06 and 0.15 mm and a HAZ between 0.10 mm and 0.20 mm. The PMMA present the dimension of HAZ between 0.06 mm and 0.13 mm without burr. They proposed the laser cutting workability of the polymers/composites is as follow: PMMA very high, PC high, PP high/medium and thermosets plastics reinforced lower.

Choughury et. al. (2010) has studied CO_2 laser cutting of three polymeric materials namely Polypropylene (PP), Polycarbonate (PC) and Polymethylmethacrylate (PMMA) is investigated with the aim of evaluating the effect of the main input laser cutting parameters (laser power, cutting speed and compressed air pressure) on laser cutting quality of the different polymers and developing model equations relating input process parameters with the output. The output quality characteristics examined were heat affected zone (HAZ), surface roughness and dimensional accuracy. From the analysis, it has been observed that PMMA has less HAZ, followed by PC and PP. For surface roughness, PMMA has better cut edge surface quality than PP and PC. A laser system consisting of a 500W continuous wave CO_2 laser was used for the cutting of the polymeric materials. Compressed air was used as shield gas. The experiments have been carried out according to the central composite first-order design based on response surface methodology. Response surface modeling was used to establish the mathematical relationship between the response Y (surface roughness and heat affected zone) and the input machining parameters (laser power, laser cutting speed and compressed air pressure). The dimension of the heat affected zone (HAZ) was studied under a microscope. They found Laser power is the most important variable affecting the HAZ. The greater is the cutting speed, lesser is the burning time and consequently lower is the HAZ. The arithmetic mean surface roughness was measured using a contact-type stylus. The measurements were taken three times and average value is reported for analysis. They found surface roughness appears to be inversely proportional to laser power, cutting speed and compressed air pressure. Surface roughness represents the quality of cut surface and its value decreases with increasing speed, power and compressed air pressure.

Riverio et. al. (2012) described a parametric study of the laser cutting of a CFRP composite in order to understand the influence of processing parameters, both in continuous wave and in pulsed mode, on the cut quality is presented and a relevant study on the influence of the assist gas injection system on the process was accomplished. A high-beam quality CO_2 laser has been used in order to ascertain the capabilities of CO_2 laser cutting machines. The base material used in this study was a CFRP composite sheet 3 mm thick. The fiber volume was 0.57 and the void volume 0.02. All experiments were performed by means of a CO_2 slab laser. The inspection of the specimens was performed by using an optical stereoscopic microscope with a photographic system in order to record and store the images. Moreover, both the cut edge and its cross-section were studied after the laser cutting process through scanning electron microscopy (SEM). In order to analyze the cutting process, quality characteristics evaluated in this work were the width of the cut slot (also called kerf width) in the entry (W_{entry}) and exit side (W_{exit}) of the cut, the slope (a) of the cut edge (also called taper angle) and the extension of the HAZ in terms of its width. They have proved that processing in Continuous Wave mode was seen to produce cuts with several imperfections. Protruding fibers are formed in the entry of the cut slot, due to the vaporization of the polymeric matrix. On the other hand, the penetration of the HAZ into the workpiece, measured in terms of its width, was assessed as a function of the laser power. They found that processing in Pulse Mode is good compare to continuous mode. They found experimentally that duty cycle is the most important parameter determining the kerf. Width while the pulse frequency slightly decreases the kerf width and the pulse energy slightly increases this parameter. The taper angle was seen to linearly depend on the pulse energy, pulse frequency and duty cycle. Whereas this parameter is linearly increased with the pulse energy or the duty cycle, the increment in the pulse frequency produces a linear decrease in the slope of the cut edge. Finally, the duty cycle was also revealed as the most influencing parameter on the extension of the HAZ. The increment of this parameter was seen to increase the HAZ up to a maximum value which corresponds to a duty cycle of 100%, i.e. with the processing in CW mode.

XII. Application of Laser Cutting

1. Cutting of die boards
2. Straight and profile cutting of metallic and nonmetallic sheets
3. Cutting of hard and brittle ceramics such as alumina, silicon nitride, etc.
4. Cutting of polymers and polymer matrix composites
5. Cutting of aerospace materials such as titanium- and aluminum-based alloys
6. Cutting of diamonds
7. Cloth and paper cutting
8. Cutting of decorative tiles
9. Cutting of wood
10. Cutting of polymers and polymer matrix composites

XIII. Future Work

There are many problem face out by the above authors during laser machining of polymer matrix composites they are listed as below:

A composite material is one which contains two or more chemically distinct phases that are not in thermodynamic equilibrium. The properties of the phases used in the material are usually significantly different, which makes the machining of them difficult.

Processing of composites in continuous mode of laser is seen to produces cut with several imperfections. The protruding fibres are formed in the entry side of the cut slot due to the vaporization of the polymeric matrix.

Processing in Pulse Mode is a well-recognized approach to process heat sensitive material because of the high accurate supplying of energy into the workpiece but limitation is that full penetration cuts cannot be obtained because the energy supplied to the process is not high enough to completely cut the workpiece.

The energy require to melt the fibre or to vaporize them is higher to that require to melt or vaporize the polymeric matrix. Moreover the thermal conductivity of fibre is much higher than that of the polymeric matrix. For example in carbon fibre reinforced composites the resin is approximately decompose at 500 °C while the carbon fibres are vaporizes at 3300 °C [7]. In GFRP the resin is approximately decompose at 600 °C while the glass fibres are vaporize at 2000 °C.

A large amount of thermal energy is conducted into the matrix and a large heat affected zone (HAZ) is produced by the heat generated during the process. This ultimately causes matrix recession, matrix decomposition and/or delamination. Therefore the use of lasers for the processing of GFRP is regarded as critical due to the large material damage by the heat.

So one has to find the optimum parameters such that the above problems can be overcome.

References

[1] Available: http://www.worldoflasers.com/laserprinciples.htm

[2] Available:http://emedicine.medscape.com/article/838099-overview#aw2aab6b4

[3] William T. Silfvast, ‘Laser Fundamental,’ 2nd edtion, 2004.

[4] Marvin J. Weber. HANDBOOK OF LASERS. CRC Press LLC, 2001.

[5] Narendra B. Dahotre and Sandip P.Harimkar, Laser Fabrication and Machining of Materials. Springer Science + Business Media, 2008.

[6] G. Caprino, V. Tagliaferri and L. Covelli, “Cutting glass fibre reinforced composites using CO_2 laser with multimodal-gaussian distribution,” Int. J. Mach. Tools Manufact, vol. 35, pp. 831-840, 1995.

[7] A.A. Cenna and P. Mathew, “Evaluation of cut quality of fibre-reinforced plastics-a review,” Int. J. Mach. Tools Manufact, vol. 37, pp. 723-736, 1997.

[8] Ian P. Tuersley, Tony P. Hoult and Ian R. Pashby, “Nd–YAG laser machining of sic fibre/borosilicate glass composites. Part I. Optimisation of laser pulse parameters,” Composites Part A, vol. 29A, pp. 947–954, 1998.

[9] Ian P. Tuersley, Tony P. Hoult and Ian R. Pashby, “Nd–YAG laser machining of SiC fibre/borosilicate glass composites. Part II. The effect of process variables,” Composites Part A, vol. 29A, pp. 955–964, 1998.

[10] Jose Mathew, G.L. Goswami, N. Ramakrishnan, and N.K. Naik, “Parametric studies on pulsed Nd:YAG laser cutting of carbon-fibre reinforced plastic composites,” Journal of Materials Processing Technology, vol. 89–90, pp.198–203, 1999.

[11] K.C. Yung, S.M. Mei, and T.M. Yue, "A study of the heat-affected zone in the UV YAG laser drilling of GFRP materials," Journal of Materials Processing Technology, vol. 122, pp. 278–285, 2002.

[12] A.A. Cenna, and P. Mathew, "Analysis and prediction of laser cutting parameters of fibre reinforced plastics (FRP) composite materials," International Journal of Machine Tools & Manufacture, vol. 42, pp. 105–113, 2002.

[13] F.A. Al-Sulaiman, B.S. Yilbas and M. Ahsan, "CO_2 laser cutting of a carbon/carbon multi-lamelled plain-weave structure," Journal of Materials Processing Technology, vol. 173, pp. 345-351, 2006.

[14] J. Paulo Davim, Nuno Barricas, Marta Conceic and Carlos Oliveira, "Some experimental studies on CO_2 laser cutting quality of polymeric materials," Journal of materials processing technology, vol. 198, pp. 99-104, 2008.

[15] Avanish Kumar Dubey, and Vinod Yadava, "Multi-objective optimization of laser beam cutting process," Optics & Laser Technology, vol. 40, pp.562–570, 2008.

[16] I.A.Choudhury, and S. Shirley, "Laser cutting of polymeric materials: An experimental investigation," Optics & Laser Technology, vol. 42, pp. 503–508, 2010.

[17] A. Riveiro, F. Quintero, F. Lusquiños, J. del Val, R.Comesaña, and M.Boutinguiz. J. Pou, "Experimental study on the CO2 laser cutting of carbon fiber reinforced plastic composite," Composites: Part A, vol. 43, pp.1400–1409, 2012.