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LASER BEAM MICROMACHINING– A REVIEW

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Abstract- Laser essentially is a coherent, monochromatic beam of electromagnetic radiation that can propagate in a straight line with negligible divergence and occur in a wide range of wavelength (ranging from ultra-violet to infrared). Lasers are widely used in manufacturing, communication, measurement and medical. Energy density of the laser beam can be altered by varying the wavelength. This property has made the lasers proficient for removing extremely small amount of material and has led to the use of lasers to manufacture very small features in work piece materials. The production of miniature features (dimensions from 1 µm to 999 µm) in sheet materials using laser machining is termed as laser micro-machining.In the present study, the fundamental understanding of short and ultra-short laser ablation process has been explained. The critical analysis of various theoretical and experimental studies is used to describe the performance of laser beam micromachining (LBMM) on some of the advanced engineering materials.

Keywords: Laser beam micromachining, Short and Ultrashort laser, Laser ablation, Advanced engineering materials

I. INTRODUCTION

Laser, an acronym for light amplification by stimulated emission of radiation, is surely one of the greatest and considerable innovations of 20th century. Its continued advancement has been an exciting chapter in the history of science, engineering and technology. Emergence of advanced engineering materials, intricate shape and unusual size of work piece restrict the use of conventional machining methods .Laser beam machining is one of the most widely used thermal energy based non-contact type advance machining process which can be used for almost all range of materials. The foundation of laser was laid by Einstein in 1917 when he first introduced the concept of photon emission, where a photon interacts with an excited molecule or atom and causes the emission of a second photon having the same frequency, phase and direction [1].

The laser beam is generated by providing energy to lasing medium from an external source. The electrons at ground state of lasing medium gets excited, which causes electron to move from a lower energy level to a higher energy level and due to very high instability at higher energy level it comes back to its ground state within a very small time by emitting a photon. The frequency of this emission is then amplified by using two mirrors one with 100% reflective surface and the other with partially reflective one. Laser beam machining isused to perform various operations such as drilling, cutting, turning, milling etc. [2].

Although material removal by pulsed light sources has been studied since the invention of the laser [3, 4], reports in 1982 of polymers etched by excimer lasers stimulated widespread investigations aimed at using the process for micromachining. In the interceding years scientific and industrial researches in this field has proliferated to a staggering extent, probably aroused by the remarkably small features that can be etched with little damage to surrounding region of material [5, 6].

In recent years, manufacturing industry has observed a rapid increase in demand for micro-products and micro-components in many industrial sectors including the electronics, optics, medical, biotechnology and automotive sectors. These micro-system-based products are an important contributor to a sustainable economy. The laser pulses used in micromachining processes are divided in two groups, one is short (nanosecond) laser pulse and other is ultra-short (picoseconds, femtosecond) laser pulse. Due to the short pulse duration, peak powers of more than 15GW can be reached, which gives access to further ablation mechanisms, like multi-photon ionisation. Due to the short interaction time, only the electrons within the material are heated during the pulse duration and heat affected zones are negligible [7].

Laser micromachining or ablation phenomenon can occur during laser–polymer interaction in two distinct mechanisms: one of them is photo thermal and the other one is photochemical ablation. Since polymers exhibit strong absorption in ultraviolet and deep infrared wavelengths, but weak absorption at visible and near-infrared spectra, thus the ablation mechanism is a combination of photochemical and photo thermal processes. The chemical bonds of the polymer material decompose by the photon energy of the laser light, whereas in photo thermal mechanism, polymer ablation takes place by rapid melting and vaporizing. For photochemical ablation to occur, energy of the photons at that wavelength should exceed the intermolecular bond energies of the polymer [8]. The photon energy decreases as the wavelength increases. Thus, the high energy of the UV photon breaks the molecular bonds and results in direct photochemical ablation.

The excimer laser has wavelengths available at 308 and 248 nm when using gas mixes of XeCl and KrF respectively. The frequency converted Nd:YAG lasers with a fundamental wavelength of 1,064 nm have wavelengths of 355 nm and 266 nm for the third and fourth harmonics, respectively.Pulsed Nd: YAG laser beam was used by Lau et al. [9] for experimentation to see the effect of HAZ on 2.5 mm thick carbon fibre composite plate with some parameters. They found that HAZ increases with increase in pulse width, pulse frequency, pulse energy and decreasing with the feed rate. They also observed that heat affected zone will be more when compressed air used as assist gas while argon used as assist gas have smoother cut surface and less HAZ.

In contrast to the UV laser, a CO_2 laser emits infrared radiation at a wavelength of 10.6 μm which means that the laser beam always ablates the underlying material photo thermally. The area on which focused laser beam meets the work piece surface, temperature of the irradiated spot rises so rapidly that the material first melts and then decomposes, leaving a void in the work piece. Laser power, pulse length, cutting speed was used as main parameters by Olsen et al. [10] for cutting mild steel cutting using pulsed Nd: YAG and CO_2 laser to perform experiments. It was observed by their study that the CO_2 laser can cut faster than Nd: YAG but Nd: YAG laser serves better surface roughness. It has also been observed that the two parameters i.e. pulse length and cutting speed also affects the surface roughness.

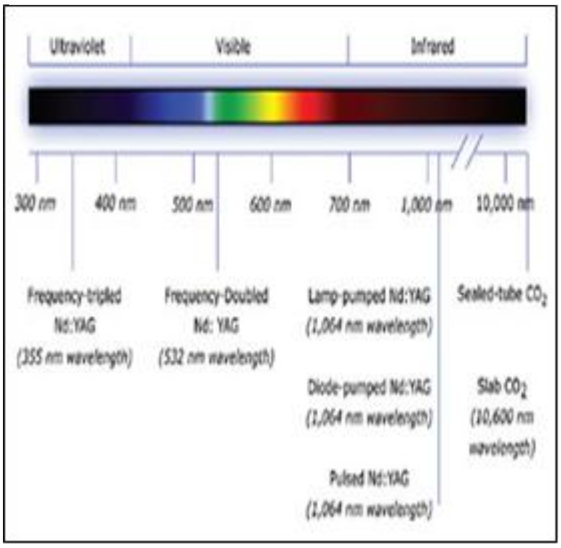
In the present study, the fundamental understanding of short and ultra-short laser ablation process has been explained. The critical analysis of various theoretical and experimental studies is used to describe the performance of laser beam micromachining (LBMM) on some of the advanced engineering materials.

II. LASER BEAM MICROMACHINING (LBMM)

A. Types of lasers used in LBMM

There is range of industrial lasers available in a present scenario for micromachining applications (Figure 1). Generally two types of laser are used for micromachining metals—**short pulse laser** which emits short pulses of light, of the order of picoseconds to nanoseconds and **ultrashort pulse laser** which emits ultrashort pulses of light, of the order of femtosecond to ten picoseconds [11]. These lasers are named based on the duration of their beam pulses. For example, the pulse emitted by a femtosecond laser only lasts femtosecond (a femtosecond is one millionth of a nanosecond or 10-15 of a second). Similarly each pulse emitted by a picoseconds laser lasts picoseconds and each pulse emitted by nanosecond laser lasts nanoseconds. The short pulse means the energy is localized at small depth.

Fig. 1. Types of laser [12]



B. Interaction of short and ultrashort-lasers with different materials

The laser beam can be modelled as a radiant energy source with an arbitrary spatial and temporal intensity distribution. The fraction of total beam energy absorbed at the erosion front depends on the radiation properties of the work piece and the geometry of erosion front. The intensity of the incident beam is expressed by I_o. The decrement in the laser intensity with the depth is given by (1)

$I_x = I_o\, e^{-\alpha x}$(1)

Whereα is optical absorptivity of the material and x is depth into the material. The optical absorptivity (α) of the material accounts for the decay of laser intensity with depth inside the material. The absorption coefficient depends on the temperature and wavelength but at constant α, decay of laser intensity with depth is given by Beer–Lambert Law as (2)

$I(z)=I_o e^{\alpha z}$(2)

Where I_o is the intensity just inside the surface after considering reflection losses. **Lambert's law** states that absorption of a particular material sample is directly proportional to its thickness (path length).The depth at which the intensity of the laser drops to 1/e value of its initial value at the interface is its optical penetration or absorption depth (δ) given by $\delta = 1/\alpha$ [13].

C. Mechanism of laser ablation

Laser ablation is the process of removal of material from a solid surface by irradiating it with a laser beam. At very low energy density, there is no material removal until a point is reached where material removal starts to occur; this is called the **ablation threshold**[15]. A significant removal of materials occurs above a certain threshold power density, and the ejected material forms a luminous ablation plume. This threshold power density required to form plasma depends on the absorption properties of the given material, the wavelength of laser employed, and pulse duration [16]. The removed material is directed towards a substrate where it re-condense to form a film. The total mass ablated from the target material per laser pulse is called as ablation rate.

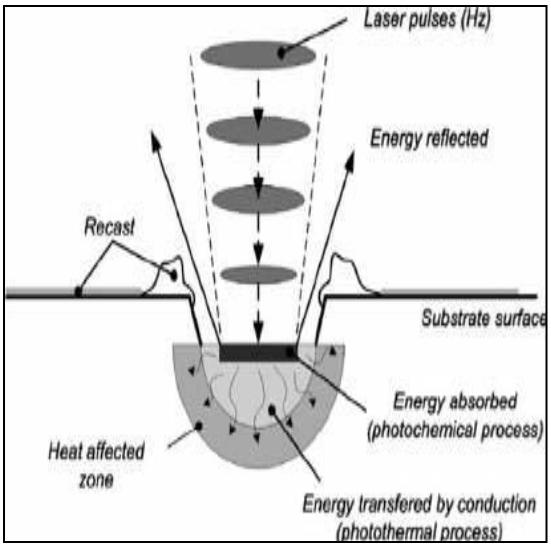


Fig. 2. Laser interaction with metal [14]

To enhance the reactivity of the background gas with the ablated species, either a RF-plasma source or a gas pulse configuration are used [17].

D. Generation of short laser pulses

Short or ultrashort optical pulses can be generated with the help of continuous light source and fast modulator, which lets the light pass only for a short period of time. However, this method is not competent, as most of the light gets lost at the modulator, and also the duration of pulse is limited by the speed (bandwidth) of the modulator [18]. The most commonly used methods are:

1. *Q-Switching*- Photons that evolve as a result of spontaneous emission in directions other than that of the laser axis are amplified. These photons, however, are not reflected back into the cavity and are lost to the environment. The total loss of photons because of travelling off-axis is called as amplified spontaneous emission (ASE). “Q-Switching” is a pulse energy enhancement technique and is used in many solid state lasers to minimize the negative effects of ASE [19].

2. *Gain-Switching*– This is usually the most direct method to generate laser pulses. Gain switching is a technique in optics in which a lasers are made to produce pulses of light of extremely short duration, of the order of picoseconds. This technique is named as “Gain-Switching” because of the fact that the optical gain is negative when

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carrier density or pump intensity in the active region of the device is below threshold, and it switches to a positive value when carrier density or the pump intensity exceeds the lasing threshold [20].

3. *Mode locking* – It is used in active or passive form for generating ultrashort pulses, in the range of megahertz or gigahertz pulse and moderate pulse energies (typically Pico joules to Nano joules). Combination of higher pulse energies along with lower repetition rates can be generated with cavity-dumped mode-locked lasers and with regenerative amplifiers, particularly with chirped-pulse amplification or divided-pulse amplification [21]. It is also possible to reduce the repetition rate with a pulse picker. It can be called as an optical switch which transmits only every N^{th} pulse, before amplifying these pulses, e.g. in a fibre amplifier.

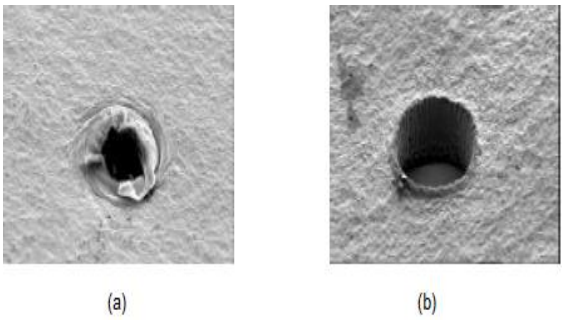
III. APPLICATIONS OF LBMM

The pulsed lasers are being used for micro processing materials in several manufacturing industries. Microvia, ink jet printer head and biomedical catheter hole drilling, thin-film scribing and micro electro-mechanical system (MEMS) are some of the important applications of LASER micromachining.

A. *Hole drilling*

The ability of drilling smaller holes up to 1µm diameter is a key enabling technology to manufacture high-tech products. Laser micromachining provides solutions to vital problems in manufacturing integrated circuits, hard disks

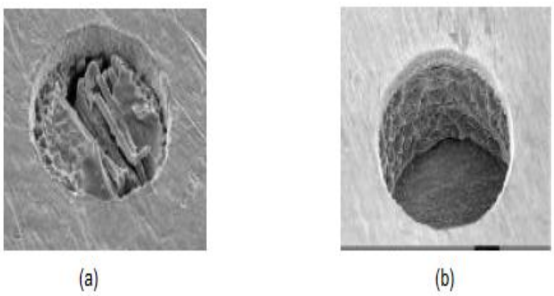
Fig. 3. 100mm holes drilled in 75mm high-density polyethylene with (a) a twist drill bit (b) an Excimer laser [22]



,displays, interconnects, computer peripherals and telecommunication devices. The requirement for material processing with micron or submicron resolution at high-speed and low-unit cost can be fulfilled by this technology. The combination for high-resolution, accuracy, speed and flexibility is allowing laser. The combination of high-resolution, accuracy, speed and flexibility provided laser micromachining to gain acceptance in many industries [22].

1. *Microvia hole drilling in circuit inter connection*- Microvia drilling in printed circuit boards and flexible circuits is a huge business with hundreds of lasers (mostly in Asia) drilling billions of microvias annually. A microvia is a small hole drilled for electrical conductivity in printed circuit boards. As diameter decrease (below 100µm) lasers are preferred over mechanical drills. Since copper is highly reflective thus, Q-switched Nd: YAG lasers (fundamental or 3rd-harmonic) are used to drill the metal, while CO_2 lasers are used to drill the dielectric material.Drilling microvias by ablation was first investigated in the early 1980's using pulsed Nd:YAG and CO_2 lasers [23, 24].Excimer lasers led the way in applying it to volume production when the Nixdorf computer plant introduced polyimide ablative drilling of 80µm diameter vias in MCM's - as used to connect silicon chips together in high-speed computers [25].Other mainframe computer manufacturers such as IBM rapidly followed suite and installed their very own production lines for this application

Fig. 4. 100µm diameter blind microvia drilled in a PCB.
(a) Step 1. Nd laser trepanned hole in top copper conductive layer.
(b) Step 2. CO_2 laser drilling of fibre reinforced composite [22]



[26, 27]. With fewer process steps than other methods, laser-drilling is regarded as the most versatile, robust, reliable and high-yield technology for creating microvias in thin film packages.

2. *Inkjet printers nozzle drilling*- It comprises of a row of small tapered holes by which ink droplets are squirted onto paper. By simultaneously

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reducing the nozzle diameter and by decreasing the hole pitch and lengthening the head, increased printer quality can be achieved. Modern printers like HP's Desk Jet 800C and 1600C have nozzle of input diameter equals to 28μm giving a resolution of 600 dots-per-inch (dpi). At average yields of more than 99%, excimer laser mask projection is now routinely used for drilling arrays of nozzles each having identical size and wall angle [28]. Most of the ink jet printer heads currently sold in Asia and US are excimer laser drilled.

3. *Biomedical device* - Lasers play an enormous role in the manufacturing of disposable medical devices and the market is huge. Micro drilling by excimer lasers is used for making delicate probes for analyzing arterial blood gases (ABG's) [29].These consist of a spiral rectangular holes of 50×15μm machined in a 100μm diameter acrylic (PMMA) optical fiber by a laser. Clean cutting capability of the laser provides the necessary strength that prevents kinking and blockage when inserted into the artery. In intensive care units, decisions on patient's ventilator conditions and the administration of different drugs are made on the basis of ABG results.
4. *Hole Drilling in Aircraft Engine Components*- Modern jet engines have up to hundreds of thousands of holes drilled into various components such as turbine blades, nozzle guide vanes, combustion chambers, and afterburners. These holes are less than 1 mm in diameter, some are through-holes and some are shaped holes. Near-IR lasers (high pulse energy Nd: YAG or fiber lasers) are typically used in either a percussion or trepanning mode [30]. These holes allow a film of cooling air to blanket the components; this extends life, reduces maintenance, and achieves superior performance characteristics.

IV. NUMERICAL ANALYSIS OF LASER MICRO DRILLING

Laser drilling is an extensively used process for fabrication of microvias and micro nozzlesas discussed above. After being exposed to short pulses, material is removed by ablation, leaving a crater. By this means, well-shaped micro-hole can be drilled into the material bulk. It is experimentally observed that time delay between pulses has great influence on the shape and machining quality [31]. There is a threshold time at which abrupt shape degradation occurs. To achieve good machining quality and desired shape, longer time delay is preferred. The effect of the time delay can be explained by coupling of residual heat between successive pulses. In this section, our focus will be on quantitative investigation of accumulation of residual heat.

1. The heat dissipation after laser irradiation will be described by a mathematical model.
2. FEM method will be used for the analysis of temperature at the bottom of the crater ablated by a train of pulses.

In FEM the whole problem domain is subdivided into simpler parts, called finite elements, and it minimizes an associated error function by using vibrational methods from the calculus of variations to solve the problem [32]. Unlike the idea that joining several small straight lines can approximate a larger circle, FEM includes methods for connecting several simple element equations over many small sub domains, named finite elements to approximate a more complex equation over a larger domain.

The threshold-like time delay has been observed for various lasers, including Nd-YAG laser and femtosecond laser. Through this research optical specification for lasers, especially ultrashort laser, used for micromachining can be found.

A. Laser direct writing

The versatility offered by laser-based direct-write methods is unique as it provides freedom to add, remove, and customize different types of materials without physical contact between a tool or nozzle and the material [33]. Laser pulses used to generate the patterns can be manipulated to control the composition, structure and properties of three-dimensional volumes of materials across length scales spanning six orders of magnitude, from nanometers to millimeters.

Laser direct writing is used to produce 2D and 3D structures with the help of two approaches. One of them is direct etching from PMMA sample and other one is replication from metal insert that has been carved by direct laser etching. The laser beam scans in XY plane through a two-axis galvanometer. A high speed precision translational stage is used to move the sample in Z-axis. The knowledge gained through studies on laser ablation will be used to attain high resolution and excellent quality of machining. The system will be used to manufacture fine parts used in aircrafts and miniaturized satellites.

Sub-micron/nano machining using ultrashort laser

The most recognizable characteristic of ultrashort laser micromachining is that the ablationthreshold is clearly defined [34]. Thus, feature size smaller than the laser spot-size can be achieved by controlling the fluency of the laser pulses. However, at the scale of few micron and sub-micron the quality of machining, throughput and reliability are not acceptable for industrial applications. In this research we aim at developing an ultrashort laser sub-micron machining, replacing the costly and complicated beam machining in some applications.

V. CONCLUSIONS

1. LBMM is a powerful machining method for cutting complex profiles and drilling holes at micro level in wide range of work piece materials. It uses short and ultra-short pulse lasers for processing of materials. Picoseconds lasers are preferred over nanosecond and femtosecond lasers.

2. Laser Micromachining enables us to machine advanced engineering materials using lasers of different wavelength. For short pulse beams the energy is localized at small depth. With ultrashort laser pulses the ablated spot size may be smaller than the laser focus spot size. Beam pulse duration and repetition rate are two factors that influence laser usefulness for industrial micromachining applications.

3. The most distinct characteristic of ultrashort laser micromachining is that the ablation threshold is clearly defined. Therefore, feature size smaller than the laser spot-size can be achieved by carefully control the fluency of the laser pulses.

4. The energy contained in the photons is imparted as heat into the material and it potentially changes the surface structure of the target material. The laser beam induces a non-equilibrium electronic distribution that thermalizes via electron–electron and electron–phonon interactions.

5. Laser-based direct-write methods is unique, given their ability to add, remove, and modify different types of materials without physical contact between a tool or nozzle and the material of interest. Thin films are preferably patterned by mask projection using flat top beams of excimer lasers.

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