Laser Micromachining-A Review

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Abstract : In the current manufacturing scenario, micromachining is state-of-the-art technology for precision manufacturing. Laser micromachining (LMM) utilizes a laser beam for producing complex shapes and miniature devices on any known material. This process eliminates the use of a physical tool, thereby reducing the problems of tool wear and minimizing the cutting forces on the work material. In LMM, material removal occurs by the localized heating, melting, and subsequent vaporization. Several process parameters govern the process and have a major influence on the machining quality. Therefore, investigating the optimal parameters for achieving the best machining quality is required. In this paper, an attempt is made to review the literature on Laser micromachining process optimization and the most focused process parameters and performance measures have been identified. Furthermore, an attempt is also made to recognize the most used on which LMM has been performed. Finally, this work tries to point out the process parameters, performance measures, materials, and machining operations which have future scope for research in Laser micromachining.

***IndexTerms* - Laser Micromachining, Heat affected zone (HAZ), Pulsed lasers, Pulse frequency**

I. INTRODUCTION:

The current inclination of the manufacturing scenario towards precision manufacturing calls for a drastic improvement in the materials and the processes employed for production. Also, the increasing demand for reduction of thermal stresses, fabrication of intricate surfaces, reduced size of the components, stringent design and fabrication requirements, increased use of advanced materials call for the development of novel machining techniques [1]. Laser beam micromachining (LBMM) finds applications in micro-milling, micro-cutting, precision manufacturing, micro-drilling, micro structuring fabrication of periodic structures in the range of micro and sub-micrometer, and microfabrication and offers many advantages over other unconventional manufacturing processes. Materials with thickness up to 10 mm can be cut with relatively less power using laser cutting [2]. The process can be completely automated to increase productivity [2, 3]. Laser machining is environmentally friendly as it confines the fumes emitted within a precise interaction zone and can be a good choice for dismantling nuclear sites [4]. The components manufactured also show a reduced tendency for crack formation. The elimination of the need for finishing operations also promotes the use of lasers for machining. The advances in precision position control systems and the availability of industrial lasers are one reason for the increased deployment of the ultra short pulsed lasers in the continuous production lines [5]. For a given application, the productivity achieved by a process is the deciding aspect for the selection of the process [6]. The processing speed and the productivity of industrial lasers can be increased by scaling up the average laser power [7].

II. LASER BEAM MACHINING PROCESS :

LASER is the acronym for Light amplification by Stimulated Emission of Radiation is a high-energy electromagnetic radiation beam and differs from other light because of its unique properties like directionality, brightness, monochromaticity, and coherence [8]. It is a steady-state thermal energy-based unconventional process. In laser machining, the material is removed by localized melting and evaporation of the workpiece material [9]. In this process, a focused light beam is used for removing material by localized heating, melting, and vaporization. Laser Micromachining can be performed in both continuous and pulsed mode with pulse durations ranging even up to femtoseconds. The components of a laser machining system include optics, a lasing medium, a deflection system, a beam delivery unit, a gas jet to provide assist gas, and the workpiece. The schematic of the laser cutting system is shown in Fig. 1.

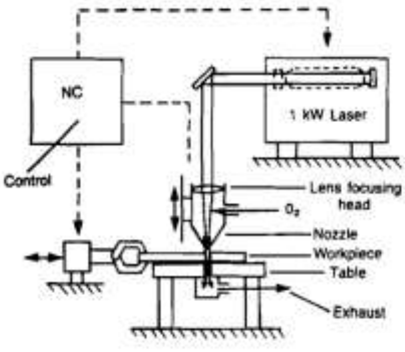

Fig.1 Layout of LASER cutting system [1]

The optic system includes mirrors, lenses, prism plates, wave plates, optical filters, mode cleaners, etc. which can help in transporting and manipulating the laser beam [10]. Optics system can be used to manipulate the beam by focusing, shaping, pulsing by normal pulsing, Q-switching, mode-locking, polarization, splitting, spinning. Generally, for industrial lasers, the beam delivery unit transmits the laser beam to the workpiece by using optical fibers. For CO2 laser, owing to their long wavelengths, metallic mirrors are used in series to achieved the transmission. But using optical fibers for transmission offers increased freedom and flexibility for usage in manufacturing environments [8]. The laser beam is coaxially assembled with delivery optics, gas delivery nozzle, and focusing lens which together comprise the cutting head. This is so positioned that the workpiece surface is normal to the laser beam. The relative motion between the workpiece and the laser system is achieved by the precise control of the movement of either the workpiece or cutting head or both. The laser's spatial intensity profile can be controlled by beam steering using galvanometric or fixed scanning mirrors, using homogenizers for beam shaping, spatial light modulators, tunable acoustic gradient index lenses, deformable mirrors, etc. [11].

The lasing medium acts as the source of the optical gain. Based on the type of lasing medium used, there are many industrial lasers commercially available like gas lasers, Solid State lasers, liquid lasers, fiber lasers, semiconductor lasers, and excimer lasers. Today, Nd: YAG lasers are much preferred for machining applications due to their high absorption efficiency, transportability, focusing properties, the better cut quality offered, and increased flexibility. Nd: YAG solid-state laser even though they have low beam power, the high values of peak power achieved during the pulsed mode of machining make them a good choice for cutting even thicker materials [12]. The usage of CO2 lasers has been predominantly for the machining of materials like polymers, rubber, and organic materials like wood. CO2 lasers are found to be a good choice for applications like microfluidic device fabrication in which material removal occurs by photothermal ablation [13].

III. MECHANISM OF MATERIAL REMOVAL THROUGH LASER MACHINING

Laser machining can process any material, ranging from metals, insulators, semiconductors to dielectrics and ceramics [14]. The f-number of the lens used, the beam quality factor (M2) (M2~1), power density, and the wavelength of the laser beam control the feature size [12]. The thermal and the photonic effect related to the laser beam interaction with the materials are utilized for material removal. Laser interaction with the material can be classified as a photolytic and pyrolytic process. The photolytic process, also known as photochemical process and cold cutting, where a short wavelength, short-pulsed laser beam irradiates the material, thereby breaking the chemical bonds of a thin layer of material. This phenomenon is generally observed for organic materials [15]. In the photothermal or the pyrolytic process, a portion of the incident energy is absorbed by the surface and some portion is reflected, the values being dependent on factors like surface finish of the workpiece, wavelength of the beam, etc [16]. This absorbed energy is transformed into thermal energy. This conversion can result in the localized increase of temperature of the work surface and subsequently, in either vaporization or ablation of the material.

Material removal occurs by one of the four modes: vaporization, fusion, ablation, and fracture. Laser vaporization creates a keyhole that behaves as a black body. This causes an abrupt spike in the absorptivity due to which the depth of the hole increases. An assist gas jet can be utilized to eject the vapor out of the cut portion, thereby avoiding further precipitation of the hot gases. This method is more common for the processing of materials like carbon, polymers, wood, etc. which do not melt [3,17]. For polymer materials, the material removal by laser interaction occurs by decomposition of bonds in the material by the high energy density of the lasers [18]. Laser fusion is the method where material removal occurs by pressurized assist gas jet before the material around the affected zone reaches the vaporization state. In this method, the material is removed with relatively less laser power [4]. For certain cases, the assist gas interacts with the workpiece material and the exothermic energy is released during this interaction which acts as additional energy for material removal. This mode is known as reactive laser fusion cutting [19]. In laser fracture, the absorbed power initiates cracks within the material. The compressive stresses created in the material due to high temperatures relax with the passage of the laser beam and this induces local residual tensile stresses [20]. These residual stresses aid in the crack propagation along the laser spot direction, resulting in the kerf formation [21, 22]. In laser ablation, an intense laser beam ablates a target material resulting in the separation of the constituents, forming nanostructures [14]. The laser ablation takes place only if the fluence exceeds a certain threshold value dependent on surface morphology, material properties, defects present in the material, absorption mechanism, laser wavelength, pulse duration, etc.

IV. PROPERTIES INFLUENCING CUTTING QUALITY

Many factors like the thermal and optical properties of the workpiece material greatly influence the quality of the machined component [23]. The performance of the laser machining is evaluated using surface finish, productivity, heat affected zone, kerf quality, etc. In this paper, an attempt is made to present the influence of some process parameters on the cut quality during laser micromachining.

The focal position of the beam is an important factor in deciding laser energy received by the workpiece. A fully focused beam has the focal point located on the workpiece. Benton et.al showed that the spot size can be varied by changing the distance between the lens and the workpiece. This eliminates the need for the adjustment of the lens for changing the spot size. When the beam is less focussed, the energy is dissipated over a large area, reducing the beam intensity. This affects the dimensions of the fabricated channel where the channel width is increased and depth is decreased [24].

The spot size can be related to the distance between the component and the focal position as

$$d = \frac{\pi\omega_0^2}{\lambda}\sqrt{\left(\frac{\omega}{\omega_0}\right)^2 - 1} \qquad (1)$$

Where

ω_0 = Size of the spot at the focal plane
ω = Spot size
d = Distance between focal plane and the component

The focal position is said to be positive when the focal position is located above the workpiece. A positive focal position results in lesser energy being received by the workpiece since the laser energy density will be highest at the focal plane, compared to any other plane [25]. During the study of laser cutting of stainless steel and mild steel sheets of different thicknesses, it was observed that the focal position for mild steel is positive, while for stainless steel, the focal point is negative. In some cases, the distance between the workpiece and the nozzle tip is considered as the Standoff distance, by changing which the focal position can be changed. Similar studies for trepanning on Inconel show that a higher positive SOD combined with higher pulse frequency results in reduced hole taper [26]. Standoff distance is also shown to have a major influence on Dimensional error, contributing to nearly 53.34% as reported in [27].

Laser power is another factor that influences the machining quality. Investigations performed on a Copper substrate with and without the presence of water medium shows that the with same value of flux, deeper cavities can be obtained in Liquid

Assisted-LBMM compared to that in LBMM due to the presence of the delivered heat for a long time in the liquid medium [28]. Similar results were observed for Alumina, where the increased power resulted in the increased cavity depth. Increasing the laser power also have shown to increase the surface roughness which might be caused due to the re-deposition of the debris on the cavities [29]. For low values of power and unfocused spots, the power is insufficient to ablate the material from the workpiece. Also, when the interaction effect of power and line distance is considered for the assessment of surface roughness, for an increase in power and line distance, a slow rise in the surface roughness is observed as ablation capacity is not too high. A study on understanding the interaction effects of scanning speed and frequency shows that low values of frequency and scanning speed can result in smaller dimensional deviations.

The scanning speed decides the exposure time of the workpiece to the laser, thereby impacting the amount of heat added, depth of cut and other features of the channels fabricated [30]. The intensity of power delivered to the channel decreases as the scan velocity increases resulting in a lower depth of cuts [24, 29]. Local warming of the workpiece is also impacted by the scanning speed, a higher scanning speed results in reduced local heating. The pulse distance also reduces when the scanning speed is increased keeping the pulse repetition frequency constant, as scanning speed (S_S), Pulse repetition rate (PRF), and pulse distance (P_d) are related as

$$S_S = P_d \times \text{PRF} \qquad (2)$$

But a decrease in Pulse distance tends to increase the pulse overlap, thereby resulting in worsened surface roughness [29]. During the investigation of the effect of scanning speed during laser processing on CRFP materials, it is observed that with increased scanning speed, a decrease in HAZ and taper of the drilled holes was observed [31]. A critical scanning speed is suggested by Bauer et.al below which the ablated surface has been bumpy and dark [32].

For a material with low values of thermal conductivity, the penetration of the delivered heat is difficult through the depth of the material due to the localization of heat to a confined area during laser ablation. Therefore, for materials with low thermal conductivity, lower depths of cut are observed for the same amount of laser power. The cross-section of the channel is regulated by the thermal diffusivity of the material. Depth of cut increases with increased coefficient of thermal conductivity as it results in removal of the higher amount of heat by convective heat transfer [24]. Also due to low values of thermal conductivity, the recast layer formation is restricted since the molten metal remains molten for a longer time and can be ejected completely [26].

Line distance is defined as the spacing between the two scanned lines. Surface roughness and depth of the machined cavities are increased as the line distance decreases due to the increase in the number of scanned lines, which requires a smaller number of ablation pulses. The temperature of the ablated pockets is found to increase with the decrease in pulse distance.

Laser machining can be done both in pulsed mode and continuous mode, the former being more suitable for micromachining applications. In pulsed mode, the energy supplied depends on the pulse frequency or the pulse repetition frequency defined as the number of pulses delivered in unit time. Increasing the pulse frequency has been shown to decrease the pulse energy. Different parameter search matrices were built considering different ranges of frequency and available power percentages on the Y and X-axis respectively to investigate the suitable values for structuring the material, keeping the pulse distance, line distance, and the number of repetitions constant [29]. The combination of frequency at 261.55 kHz and available power percentage 60-80% of the maximum power was found more suitable for most industrial applications. Studies also show that frequency has a major influence on the straightness, cylindricity, taper angle of the holes drilled on CFRP material [31] Investigations for the influence on frequency on hole circularity keeping trepanning speed, laser current, gas pressure constant show that increasing frequency decreases the hole circularity. This can be attributed to the laser energy being delivered repeatedly at a higher frequency, resulting in insufficient time for the ejection of molten material to complete, thereby resulting in poor circularity [26]. Higher values of pulse frequency affect the volume error while low values of pulse frequency may not have a major influence on volume error[33]. Chen et.al showed that even though a higher pulse repetition frequency can result in reduced cut roughness, a too high frequency might result in the pulsed mode approaching the continuous wave mode which may reduce the versatility of the process [34]. Hu et.al [35] studied the laser percussion drilling of copper in multi burst mode and the results show a decrease in surface roughness and increase in MRR when the laser in burst mode.

The assist gas performs two main functions: ejection of molten metal from the machined area and aiding in the cooling of the surface of the workpiece. Generally, the assist gas is supplied coaxially to the laser beam. Oxygen, nitrogen, and inert gases like argon, helium are preferred choices for assist gases. The cooling action and the rate of ejection are controlled by the pressure of the assist gas used. The right amount of gas pressure can result in the proper ejection of the molten metal but gas pressures with values more than the required levels can rapidly cool the molten metal due to increased forced convection [36]. The nature of the assist gas used also plays a deciding factor for the surface finish. Nitrogen when used as an assist gas has given better results for stainless steel whereas for mild steel Oxygen was employed. Studies show that cutting with nitrogen gives a better surface finish compared to oxygen as performing with oxygen resulted in reactive fusion cutting [37]. An increase in the gas pressure increases the circularity of the hole up to 8Bar and after that, a reduction in the hole taper is observed. The increased forced convection with increased pressure also results in increasing the mean diameter at the entrance and decreasing the mean diameter at the exit, hence increasing hole taper [26]. During the ANOVA study of laser processing on Al7075-TiB2 In situ composite, it was observed that the influence of gas pressure on volumetric material removal rate is more significant (42.32%), compared to that of cutting speed and standoff distance [27].

Lamp current is another important parameter in deciding the kerf quality. The peak power (P) increases as the square root of the lamp current and is shown as

$$P = \eta k_0 I^{(1/2)} \qquad (3)$$

Where η = Conversion efficiency
k0 = Constant for a given flash lamp
I = Lamp current

During the production of microchannels using Laser, a high laser current at low cutting speed tends to produce wider and deeper channels [38].

Cutting speed is the relative speed between the workpiece and the laser delivery nozzle. This factor decides the interaction time of the laser with the material. As cutting speed increases, the time of interaction decreases, which results in less amount of energy being transferred to the material. Studies on the processing of Al7075-TiB2 In situ composite show that cutting speed strongly influences the surface roughness having 56% contribution followed by standoff distance 41.03% and gas pressure 2.58% [27].

V. MATERIAL DEPENDENCE ON LASER CUTTING:

Even though the laser machining processes are suitable for almost every known material, certain parameters must be tailored as per the challenges posed by the materials. For materials that do not melt like wood, polymers, carbon, material removal occurs by breaking the chemical bonds. Poor thermal and physical properties like low glassy transition, variable crystallinity, and melting temperatures make polymers, especially thermoplastics difficult to machine [38- 40]. For materials such as the PMMA (Poly methyl methacrylate), the initial processing method is also found to influence the machined quality features like surface roughness and bulge formation. It was observed that using extruded PMMA for microfluidic channel fabrication resulted in reduced surface roughness and increased bulge formation while using cast PMMA, the effect was the opposite [41]. Also due to the low conductance and low heat capacity of PMMA, it is observed that the material increases local temperature rapidly instead of forming thermal cracks. But the burr formation, formation of HAZ, removal of decomposed material become limitations for micro-processing owing to the high thermal energy content of PMMA [38]. For bioabsorbable materials like PLLA with low melting temperatures, athermal lasers are preferred for improving the cut quality and reducing the heat-affected zone [42].

Cutting of composites is difficult due to heterogeneity and anisotropy and for such materials, Laser Beam Cutting is a promising technique since it generates a localized heat cone. Organic matrix-based composite polymers are characterized by their high strength of the fibers, high compositional heterogeneity, anisotropy, the sensitivity of matrix at high temperatures, low thermal conductivity, abrasive nature of the reinforcements, thereby negatively influencing the machinability of these fibers [43-47].

Laser Beam machining being a contactless machining process has become a promising technique for the processing of hard-to-machine materials. For laser cutting on alloys like carbon-manganese steel, oxygen is generally used as an assist gas as it provides better cutting speed [3]. material like galvanized iron and aluminum-coated steel sheets require high cutting speeds during LBC. Stainless Steels are machined by using an inert gas fusion cutting. Aluminum, copper, and alloys are hard to machine due to their high reflectivity and high thermal conductivity [3, 23]. Titanium and nickel-based superalloys are machined by high-pressure inert gas cutting. Superalloys like Inconel due to their high toughness and improved mechanical properties have been shown to create high-temperature zones, thereby increasing brittleness and thermal stresses in both the workpiece and the tool materials [48].

Certain material properties like low density, high hardness, wear resistance, compressive strength, brittle nature, low electrical and thermal conductivity, and high chemical stability of the ceramics make them hard to machine materials calling for techniques promising high productivity and improved material removal rates [49]. Silicon nitride is considered high-performing ceramics due to its high hardness, wear, thermal and chemical resistance [50]. The higher machining forces and increased crack sensitivity during machining are induced in the Silicon nitride due to its high hardness [51, 52]. Similar studies have been reported in laser processing of Alumina and Tungsten Carbide [49, 53]. The properties of the ceramic material also influence the surface quality and material integrity of the workpiece during laser ablation. Studies show that materials like zirconia, Alumina show more structural damage during laser ablation due to their higher chemical stability [54]. The study of laser interaction with transparent ceramics like Spinel (MgAl2O4) reveals that focusing ultrashort pulsed lasers can result in processing due to nonlinear absorption for high peak intensities [55].

5. DEFECTS PRODUCED IN LASER MACHINING

Laser machining is a thermal process and some defects are inherent to this process. This section outlines some of the defects observed for laser micro-machined components. A high thermal load is induced at the cut surface by the pulsed nanosecond lasers used for micromachining which favor the tendency of crack formation and propagation. This resulting in unfavorable cutting conditions [53]. This thermal load may also result in the formation of new phases of the material as observed in the laser ablation of uncoated carbide inserts [56]. Stria formation is one of the defects observed during machining when the cutting speed is less than the moving molten layers speed caused by oxidation and sideways burning [57-59]. Heat accumulation is one major problem since laser ablation is not a cold process and a part of laser power absorbed by the material is delivered as heat [60]. The thermal damage is reported in USP laser ablation on the Spinel when spatial pulse overlap is increased and pulse repetition frequency is increased due to increased heat accumulation in the material [55]. However, the width of the heat-affected zone can be minimized by using short-pulsed lasers instead of long-pulsed lasers as shown in Fig. 2.

Some limitations like surface roughness, irregular surface profiles, and bulge formation of the microfluidic channels are found during laser fabrication, for whatever is substrate material used [61].

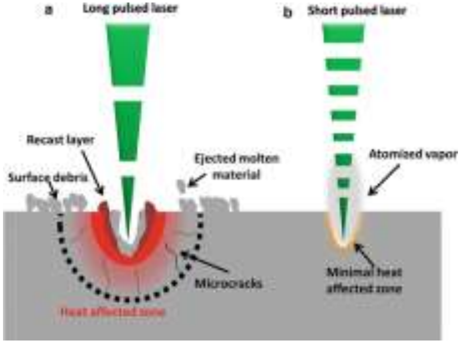

Fig. 2 Heat affected zone during long and short-pulsed laser machining [62]

Surface roughness is also found to increase with decreasing laser scanning speeds [34]. Kaur et.al observed that feed per tooth is one of the most influencing factors for surface roughness while investigating the optimum process parameters for micro-drilling of Alumina with Nd: YAG laser [63]. When performed in air, Heat affected zone becomes one of the major limitations of LBMM [64]. Tapered kerf formation, microcracks in the component, recast and solidification at the molten material around the affected zone, increased surface roughness are also some defects observed during the LBMM(laser beam micromachining) process [64, 65]. Even though performing LBMM in a Liquid medium instead of air has been shown to improve the effectiveness of the process, the increased volumetric material removal rates can result in shock waves and the cavitation effects due to the presence of a water medium. Therefore the exact dynamic interactions of the process with the water medium need further investigations [28]. The thermal damage happening during the laser interaction poses a great challenge in machining the fiber-reinforced composites due to the huge differences in the mechanical and thermal properties of the matrix and fibers [66]. The most common hindrances during the processing of carbon-reinforced composites for industrial applications are delamination of the fiber, carbonization of fibers, loss of resin material, HAZ [31]. Figure 3 shows some typical defects arising during laser machining of polymer matrix composites. Heat-affected matrix, matrix recession, and kerf width at entry and exit of the laser beam are indicated by numbers 1-6 respectively in Fig. 3.

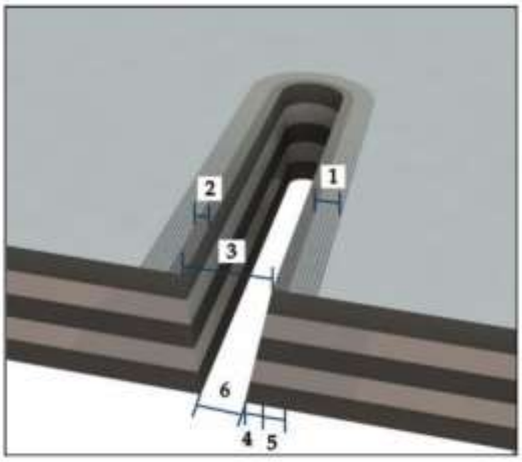

Fig. 3 Typical defects by laser at entry and exit on the surface of polymer matrix composites [31]

During the laser interaction with the material, mixed effects on the material properties were observed in different studies phase transformations or chemical reactions occur within the material, leading to the change in mechanical changes in the material[67- 69]. In investigations to understand the interaction of Spinel with Ultra-short lasers, electronic damage is reported when the spatial and temporal pulses are used in such a manner that the material is completely relaxed after each pulse.[55] With very high laser power density, the gas surrounding the focused region is transformed instantly into plasma, which might result in the formation of micro-cracks in the material.[34] Recast layer, spatter formation, lack in dimensional accuracy and heat-affected zones, micro crack formations have also been reported in the literature.

6.CONCLUSIONS

The following conclusions can be inferred literature review on the application of laser as an efficient tool for machining operations:

- The laser machining processes are being widely used for micro-drilling, micro-cutting of sheets, etc. to obtain intricate features and complex profiles.
- Although the process can be used for almost any material, further research can be carried out for making the process more effective for difficult to machine materials like Titanium-Nickel Superalloys, reflective materials like copper, aluminum, brass, bronze, etc., composites and polymers to meet their increasing demand for industrial applications.
- The process parameters like frequency, power intensity, cutting speed, assist gas parameters, etc. are the most influencing for deciding the quality of machined surface in laser micromachining.
- The optimization of the process is very important to minimize the defects and to maximize the surface quality during laser machining.

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