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Laser Micromachining: Technology and Applications

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ABSTRACT

Miniaturization is an important trend in many modern technologies. In view of this increasing trend toward miniaturization, micromachining becomes an important activity in the fabrication of microparts. Laser micromachining is controllable, highly accurate non contact machining and offers better flexibility in dimensional design of microproducts as it reduces deposition of recast layer and gives higher yield [1, 2]. Here, science behind the laser micromachining is explained and fabrication of optical vibration sensor with ultra short laser micromachining is also described.

Keywords: Laser micromachining, Laser ablation, Optical vibration sensor, ultra fast pulse laser

I. INTRODUCTION

Miniaturization is an important trend in many modern technologies. The requirement for material processing with micron or submicron resolution at high speed and low unit cost is an underpinning technology in nearly all industries manufacturing high-tech microproducts for biotechnological, microelectronics, telecommunication, MEMS, and medical applications. In view of this increasing trend toward miniaturization, micromachining becomes an important activity in the fabrication of microparts [1]. Various technologies such as mechanical micromachining (microdrilling and micromilling), focused ion beam micromachining, laser micromachining are being used in microfabrication. Ultra short pulses produce very high peak intensity (> 10^{15} W/cm^2) and deliver energy before thermal diffusion occurs, thus giving high efficiency and precision to the process without significant thermal degradation (melting, spatter, recrystallization, recasting of layer etc.) to the surrounding region. Ultra short laser can machine the transparent material like glass and can be used to fabricate a single mode waveguide in silicon.

II. LASER ABLATION

The ablation during laser processing refers to the material removal due to thermal and/or photochemical (nonthermal) interactions. In nonthermal ablation, the energy of the incident photon causes the direct bond breaking of the molecular chains in the organic materials resulting in material removal by molecular fragmentation without significant thermal damage. So the photon energy must be greater than the bond energy. However, ablation also takes place when the photon energy is less than the dissociation energy of the molecular bond as in the case of far ultraviolet radiation with longer wavelengths (correspondingly smaller photon energies), due to multiphoton absorption. In multiphoton mechanism, even though the energy associated with each photon is less than the dissociation energy of bond, the bond breaking is achieved by simultaneous absorption of two or more photons [1] [2].

During thermal ablation, the excitation energy is rapidly converted into heat, resulting in temperature rise. This temperature rise can cause the ablation of material by surface vaporization or spallation (due to thermal stresses). Thermal ablation mechanisms dominate the material removal during micromachining of metal and ceramics. One of the important considerations during the laser–material interaction during ablation is the thermal relaxation time (τ), which is related with the dissipation of heat during laser pulse irradiation and is expressed as [1]

$$\tau = d^2/4k \qquad (1)$$

Where, d is absorption depth and k is thermal diffusivity. Thus, the two important parameters that determine the ease with which the ablation can be initiated are absorption coefficient (a) and thermal diffusivity (k). The large value of absorption coefficient and small value of thermal diffusivity generally provide the high ablation efficiency of a material. The ablation of material by confinement of laser energy in thin layer can also be facilitated by using short pulses (pulse time shorter than thermal relaxation time). For longer pulses (pulse time longer than thermal relaxation time), the absorbed energy will be dissipated in the surrounding material by thermal processes. Thus, efficient ablation of the material during laser material interactions necessitates the lasers operating with short pulses. The ablation process is characterized by the ablation threshold, which corresponds to the laser fluence at which ablation starts. Different materials have different ablation thresholds primarily due to differences in the optical and thermal properties. The ablation rates during laser micromachining depend primarily on the laser parameters like wavelength, fluence, number of pulses and the materials properties.

III. LASER MICROMACHINING TECHNIQUES

The primary mechanisms of material removal during precision micromachining of materials are ablation and etching. The material removal by these mechanisms can be performed in various ways. The three important techniques of micromachining are described below:

a) Direct Writing Technique: The laser beam is focused on substrate surface. The micromachining of desired pattern is carried out either by translating the substrate with respect to the fixed laser beam or by scanning the laser beam. The important parameters during direct writing technique are size of the focus, the working distance, and the depth of focus. The minimum spot size is limited by the diffraction phenomenon.

b) Mask Projection Technique: A mask consisting of the shape of pattern to be produced on the substrate is illuminated with the laser light. The resolution of the features in the micromachined structures are determined by the mask and projection systems. Excimer lasers are extensively used for micromachining using the mask projection technique. In addition to the high resolution, better reproducibility and fine depth control are the main advantages of mask projection techniques. It allows the micromachining of large substrate areas.

c) Interference Technique: Laser interference technique involves splitting of a laser beam using a beam splitter followed by superposition of the beams to generate interference patterns. The interference pattern thus produced shows unique intensity variation which can be used for periodic micromachining of the substrates. The geometry of the interference patterns formed by the superposition of two or more coherent and linearly polarized beams depends on the wavelength and the angle between the beams. The intensity distribution resulting from the superposition of two linearly polarized beams with their [1] E vectors in the x-direction can be expressed as:

$$I(x) = 2\, I_0\, [\cos(2\pi x/l) + 1] \qquad (2)$$

$$l = \lambda/2\sin(\Theta/2) \qquad (3)$$

Where, I_0 is intensity of a laser beam, λ is wavelength, Θ is angle between the beams, and l is periodicity of the two beam interference pattern.

IV. MACHINING WITH LONG PULSE LASERS

Heat deposited by the laser in the material, diffuses away during the pulse duration as laser pulse duration is greater than the diffusion time. This is desirable in laser welding but for micromachining heat diffusion into surrounding region is undesirable. The following are effects of heat diffusion:

- Heat diffusion decreases the efficiency of micromachining process as it takes away energy from work spot; it is more concerned in heat conductive material.
- It reduces the accuracy of micromachining operation due to heat diffusion away from the focal point, melts larger area, recasting of layers and collection of debris at surface.
- Area affected by heat diffusion results in micro/macro crack due to mechanical stress.
- It damages the nearby device structure or delaminate multilayer material.

V. ULTRA-FAST PULSE LASER MACHINING

The micromachining quality is a strong function of the amount of heat deposited in the work piece, or more exactly, a function of the amount of heat that is left behind in the material that can cause damage. Ultrafast pulses are extremely short (Femto second) and so short (<< heat diffusion time) that the energy they deposit in material does not diffuse away from the micromachining spot. So much energy (intensity ~ 100TW/cm^2) is deposited in the material so fast that the material is forced into a state of matter called plasma. This plasma then expands away from the material as a highly energetic gas, taking almost all the heat away with it. The material goes from a solid to a gas phase without going through a melt phase. Consequently, very little heat is left behind to damage the material; so efficiency is high and due to plume droplet does not condenses onto surrounding material. Thus machining quality is very good without melt zone, no cracks, no splattering of material etc. It is unique ability of ultrafast lasers to create this state (plasma) that is the reason why they produce results so different from those produced by traditional lasers as shown in Fig 1.

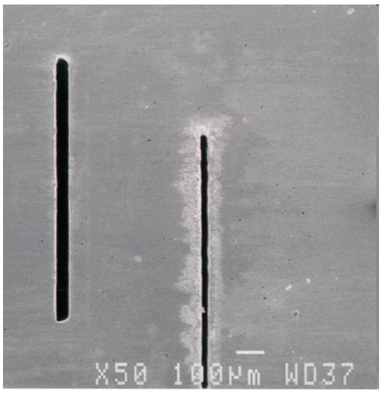

Fig 1: Sample machined with long pulse laser and ultra short pulse laser

VI. APPLICATIONS

Ultra short laser can be used for machining of hard material like diamond, tungsten and titanium with high aspect ratio (1:50). It can drill the hole at difficult angle (10deg). Excimer laser is used for drilling the nozzle hole- arrays for ink jet printer and μ-via/ via holes for high speed connection between surface mount components [5]. The laser micromachining is playing very critical role in biomedical like μ drills for analyzing arterial blood gases (ABG). Transparent material like glass does not absorb visible light - provided the intensity stays below the threshold for "multiphoton absorption" (via defect state or via inter-band absorption). Indeed, the multi-photon absorption process exhibits a highly non-linear dependence on the laser power density. When the intensity exceeds the threshold for plasma formation, much localized absorption does occur at the focal point spot. Once again, this plasma expands. But this time it is confined by the surrounding material. The effect of the expansion is to create a void within a very dense shell of material - a pit within the glass itself. This process is not limited to glass. Pits can be created in any material by focusing an ultrafast laser pulse inside the material, whether it is amorphous or crystalline.

VII. FABRICATION OF OPTICAL VIBRATION SENSOR

Single mode waveguide in glass materials can be fabricated with femtosecond lasers. At 775 nm, glass is transparent to incident light. Ultrafast laser pulses are used to locally melt the glass via confined multiphoton absorption and avalanche ionization inside the bulk material. The glass then resolidifies, changing its physical properties. The result is an index gradient that acts like a waveguide. A beam of light propagating along the same path in the glass will be guided in the same manner as an index-guided fiber guides light inside it. In [4], authors fabricated an optical vibration sensor using a high-repetition rate femtosecond laser oscillator. The sensor consists of a single straight waveguide written across a series of three pieces of glass. The central piece is mounted on a suspended beam to make it sensitive to mechanical vibration, acceleration, or external forces. Displacement of the central piece is detected by measuring the change in optical transmission through the waveguide. The resulting sensor is small, simple, and requires no alignment. The sensor has a linear response over the frequency range 20 Hz–2 kHz, can detect accelerations as small as 0.01 m/ s^2, and is nearly temperature independent is shown in Fig 2.

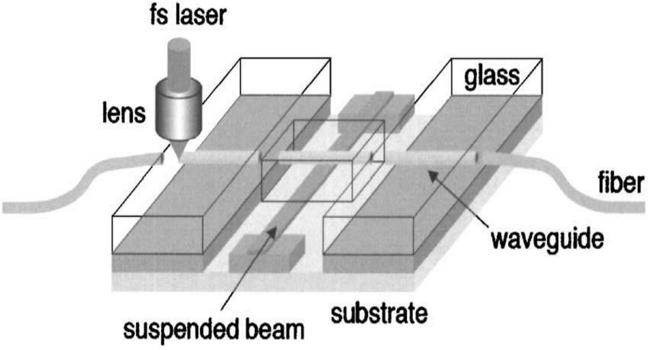

Fig 2: optical vibration sensor

VIII. CONCLUSION

Ultrafast laser pulses can machine materials (and/or locally change their chemical or physical properties) to produce no contamination to the surrounding material, no melt zone, no micro cracks, no shock wave, no delamination, no recast layer, and do damage to adjacent structures. It is highly reproducible, it can be used to create sub-micron features, and it can machine features inside transparent materials. Ultra fast lasers can micro machine virtually anything from metals to crystals to glass, ceramics and Teflon.

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