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Laser Micromachining a short Review

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ABSTRACT:

Laser micromachining is a non-contact material removal technology that can produce micro-scale components up to 500 μm in size. This technique has received substantial interest across a wide range of industrial industries, owing to the growing demand for high-precision material processing at the micro and atomic sizes while being cost efficient. Using laser ablation, the technique focusses on small constituent regions to produce maximum energy absorption and effective material removal. This study examines current research breakthroughs in laser micromachining, focussing on its many applications and technical innovations. Particular emphasis is devoted to the use of ultra-short and femtosecond pulsed lasers, which enable outstanding accuracy and considerably reduce heat damage. Transparent materials, such as glass and sapphire, are particularly well-suited to femtosecond laser micromachining. Laser micromachining has various benefits over traditional contact-based machining technologies, including automation, increased precision, and shorter processing times. With continuing advances, this technology plays a crucial role in microfabrication, notably in the electronics, healthcare, and aerospace sectors.

Keywords: Laser, micromachining, automation, microfabrication.

Main text

For many decades, traditional machining has been the foundation of industrial manufacture, relying on the physical interaction of a cutting tool and a workpiece to remove material in the form of chips. However, the growth of high-performance materials, increased environmental concern, and the requirement for miniaturised components have highlighted some limits in traditional machining processes. In response to these problems, several strategies have been developed to improve precision and efficiency. Laser micromachining has evolved as a very effective option for manufacturing delicate features with minimum material loss. Laser micromachining uses concentrated laser beams to treat materials on a microscale, making it perfect for creating intricate and delicate structures. A significant advantage of this technology is its versatility, which allows for a wide variety of wavelengths, pulse durations ranging from femtoseconds to microseconds, and repetition rates ranging from single pulses to megahertz frequencies. This approach, which typically uses power levels of less than 1 kilowatt, guarantees precision material removal while minimising thermal damage and heat-affected zones. Furthermore, its adaptability enables effective processing of a wide range of materials, facilitating both quick and scalable manufacturing across many sectors.

Several specialised laser micromachining techniques have been improved to fulfil application-specific requirements. Metal micromachining is a popular method, which is commonly used for operations such as micro-drilling and micro-milling. This is especially useful in areas that demand precise metal structure, such as electronics, aircraft, and biomedical engineering. Another prominent approach is the use of ultra-short laser pulses, which are extremely successful when working with transparent materials like glass or building silicon-based photonic structures like waveguides. These ultra-short pulses provide exceptionally high peak intensities with no thermal effects, resulting in excellent accuracy. Femtosecond laser micromachining is a significant achievement in this sector. Its ultra-short pulse durations enable the processing of problematic materials such as Shape Memory Alloys (SMAs) and polyurea aerogels, which are difficult to machine using traditional techniques due to their porous and sensitive nature. This approach allows for precise structuring without compromising the material's integrity, making it a vital tool in the manufacture of specialised components such optical resonators, beam splitters, and micro-scale waveguides.

Beyond metal and optical device applications, laser micromachining is essential for making components for Micro Electro-Mechanical Systems (MEMS), precision glass cutting, micro-hole drilling in printed circuit boards (PCBs), and polymer cutting, such as polyimides. These examples demonstrate the method's versatility in enabling high-accuracy manufacturing requirements. The overall performance and quality of laser micromachining are influenced by several key Process parameters. Pulse duration influences thermal impact and machining precision, with shorter pulses often producing cleaner results. The strength of the laser beam determines how deeply and rapidly material is removed, whereas the relative movement of the laser and substrate effects machining consistency [29-30]. Additionally, the number of pulses used has a direct influence on surface smoothness and structural integrity. As the demand for ultra-precise and economical production increases, laser micromachining emerges as a transformational technology. Its ability to handle a wide range of materials with unrivalled precision and minimum thermal side effects places it at the forefront of current microfabrication. With continued research and technical breakthroughs, laser micromachining is set to widen its field of applications, playing a critical role in the future of sophisticated, sustainable, and cost-effective manufacturing, as demonstrated in Figure 1.

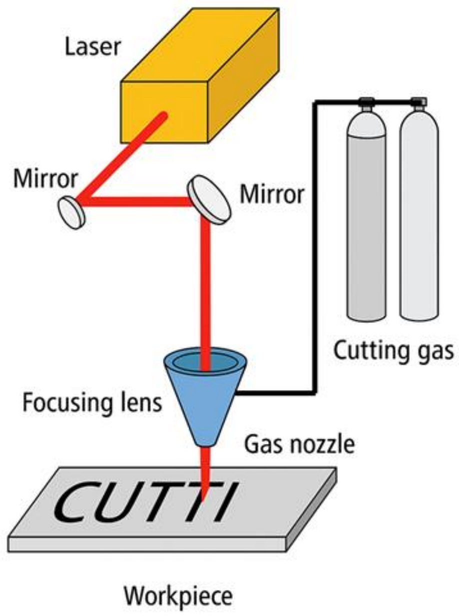

Fig. 1 - Laser machining layout.

Literature

Traditional machining processes have played an important role in manufacturing for decades; nevertheless, they confront difficulties when dealing with high-strength materials, maintaining environmental regulations, and enabling the manufacture of microscale components. To address these restrictions, alternative machining methods, notably laser micromachining, have gained popularity. This approach allows for the precise fabrication of complex microstructures by laser ablation, a non-contact method in which material is eliminated using focused laser light. Numerous research initiatives have studied the adaptability and accuracy of laser micromachining, emphasising its efficacy across a wide variety of industrial applications.

1.1. Laser Ablation and Surface Formation

Swaraj et al. [1] studied the possibility of laser ablation in creating accurate and complicated surface shapes. Their research focused on two main strategies: the beam path and profiled route procedures. The beam path approach generally uses short-wavelength laser pulses (about 250 nm) that are tuned to the unique characteristics of the work material. In contrast, the profiled path approach employs a sequence of successive pulses, which may occasionally result in uneven material removal depths without significantly reducing the intensity of the laser profile.

1.2. Industrial Effectiveness of Short Pulse Lasers

Klotzbach et al. [2] investigated the industrial usefulness of short pulse lasers, notably for detailed machining processes such as drilling and cutting metals and ceramics. Their results showed great accuracy levels, making such systems suitable for manufacturing operations requiring precise tolerances. Knowles et al. [3] further on the ablation process, describing it as a combination of melt ejection and evaporation under controlled laser exposure, resulting in effective micro-drilling and high-quality cuts. By focussing energy with short pulse lasers, materials attain critical conditions that increase machining performance.

1.3. Applications in Microfluidics and Alloy Machining

Brettschneider et al. [4] investigated the use of laser micromachining to implant metal foils into polymer layers during the manufacture of microfluidic devices. Laser integration benefits these systems, which are crucial in current technology, by ensuring strong adherence without the need of chemical adhesives. Patel and Patel [5] investigated laser cutting of aluminum-based alloys, emphasising the method's benefits over traditional cutting techniques and outlining potential implications for attaining high-precision material removal.

1.4. Use in MEMS and Advanced Materials

Rejab et al. [6] performed Finite Element Modelling (FEM) simulations to optimise laser micromachining procedures for Micro Electro-Mechanical Systems (MEMS), presenting parameters that potentially replace traditional machining techniques. Parashar et al. [7] investigated the use of numerous types of short pulse lasers in micro-component manufacture, demonstrating their extensive application. Manjaiah et al. [8] studied femtosecond laser machining of titanium-based Shape Memory Alloys (SMAs), highlighting the method's capacity to produce high material removal rates, outstanding surface quality, and dimensional precision.

1.5. Miniaturization and Specialty Material Processing

Agrawal [9] emphasised the importance of laser micromachining in miniaturisation, describing techniques like as mask projection, direct writing, and interference-based structure. The use of ultrafast laser pulses in these approaches reduces material damage while increasing structural strength. Bian et al. [10] concentrated on machining polyurea aerogels, which are recognised for their durability and resilience to heat. Traditional cutting procedures frequently destroy these materials, but femtosecond lasers give a non-contact option that maintains the material's integrity.

1.6. Integration with Electrochemical Machining

Yu Hong Long et al. [11] described a hybrid approach to stainless steel etching that combines laser and electrochemical techniques. The Laser-Induced Electrochemical Micromachining (LIECM) approach used a 248 nm excimer laser in a NaCl solution to produce precision etching with minimum heat effects. Similarly, Syed Nadeem Akhtar et al. [12] presented excimer laser micromachining as a dry and efficient option for prototyping in microwave systems and integrated circuits, allowing for component miniaturisation and increased system performance.

1.7. Medical and Industrial Usage

A. Sen et al. [13] investigated fibre laser ablation for machining Ti-6Al-4V, a titanium alloy used in medical devices due to its biocompatibility. Their research centred on how scanning speed, pulse frequency, and laser power influence micro-groove features and surface texture. N.S.M. Shalahim et al. [14] discussed the growing need for MEMS production, illustrating how laser micromachining offers flexible design, complicated geometries, and quick prototyping. Their FEM-based simulations of acrylic micromachining helped optimise heat distribution, ensuring defect-free output.

1.8. Precision in Waveguide Fabrication

C.K. Walker et al. [15, 21] described a novel laser micromachining approach for generating cost-effective and precise waveguides capable of handling frequencies of up to 10 THz. Their experimental results demonstrated machining precision of 1 μm, corroborated by beam pattern evaluations. L. Slătineanu et al. [16] investigated the basic removal mechanisms in laser machining, such as micro-cracking and micro-cutting, that contribute to the precise removal of tiny material volumes.

1.9. Emerging Trends and Applications

Sanjay Mishra et al. [17] provided a detailed analysis of laser beam micromachining (LBMM), emphasising advances in femtosecond, picosecond, and nanosecond laser technologies. Their studies found crucial characteristics that influence machining outputs, as well as insights into each type's strengths and limits. In a similar work, N.S.M. Shalahim et al. [18] employed FEM simulations to optimise laser micromachining of acrylics, taking into account material thermal characteristics, mesh precision, and simulation circumstances. Klotzbach et al. [19] reviewed the applicability of short pulse lasers, complimenting their simple installation, acceptable cost, and performance in material joining applications such as bonding ceramics and polymers by localised melting. Gower et al. [20-23] investigated many industrial uses of pulsed lasers, such as drilling microvias, generating inkjet printer nozzles, and making holes in catheters, emphasising their excellent accuracy and dependability across multiple production domains.

Methodology

Laser micromachining is based on the ablation process, which removes material using either thermal or photochemical methods. In photochemical (non-thermal) ablation, the energy of incoming photons directly destroys molecular bonds in the target material, typically organic compounds, enabling the material to fragment and be removed without producing much heat. Thermal ablation, on the other hand, is the process of converting laser energy into heat, resulting in a rapid increase in temperature. This thermal energy causes the material to vaporise or shatter owing to thermal stress, making it ideal for treating metals and ceramics [24]. The ablation process's success is mostly determined by the material's thermal behaviour and absorption qualities. Materials with strong optical absorption and low thermal diffusivity ablate more efficiently because they retain more of the incoming laser energy on the surface. Laser pulse duration is also important shorter pulses localise energy inside the target material, enhancing precision, whereas longer pulses allow heat to diffuse, thereby reducing ablation accuracy.

The material-specific ablation threshold is an important aspect in effective micromachining, and it is influenced by laser parameters such as wavelength, fluence, pulse repetition rate, and workpiece qualities. Accurate management of these factors provides effective and regulated material removal while minimising peripheral damage. Excimer lasers and femtosecond lasers are the two most often utilised laser sources in micromachining [25–26]. Lasers, which operate in the ultraviolet range, are good in processing a variety of materials while producing minimal heat. Their photon energy is closely related to the bond energies in many polymers and some metals, making them ideal for micromachining operations requiring precise precision. However, at greater energy levels, the process can change to a combination of optical and thermal effects. In contrast, femtosecond lasers generate ultra-short pulses with high peak power, resulting in excellent precision in micromachining applications [27–28]. The incredibly short pulse length considerably reduces heat diffusion, resulting in very small heat-affected zones. This enables for the creation of extremely precise microstructures with exceptional dimensional precision and minimum heat damage, making femtosecond lasers ideal for applications requiring superior surface quality and exquisite detail.

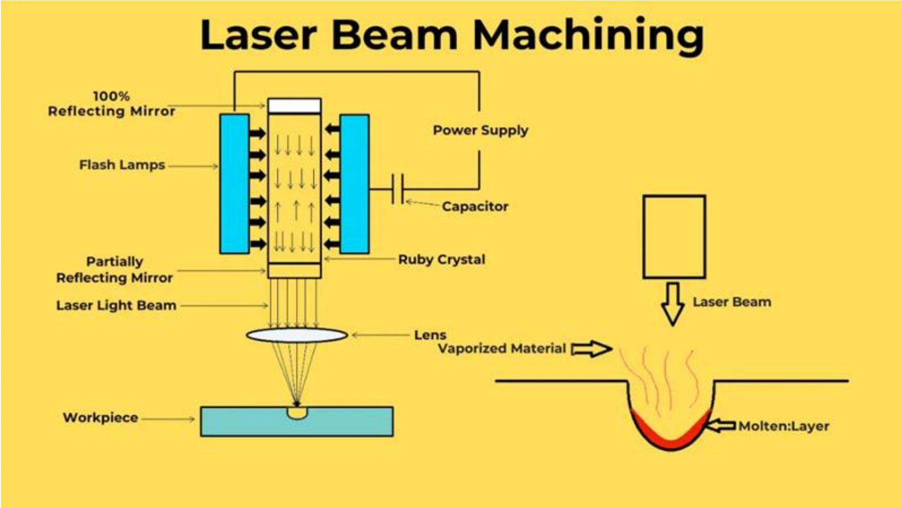

Fig. 2 - Laser Machining.

Laser Micromachining a advance process

With the microelectronics sector pushing the trend towards ever-smaller components, there is an increasing demand for production procedures capable of generating finer features and micro-holes while maintaining strict dimensional control. Laser micromachining has shown to be an effective option, offering high precision, consistent performance, quicker throughput, greater yield, and reduced production costs. Among the existing laser systems, those generating shorter wavelengths, notably in the ultraviolet (UV) spectrum, as shown in Fig. 3, are gaining popularity. These UV lasers have a low thermal influence on the surrounding material, making them excellent for precise applications that need minimal heat-affected zones.

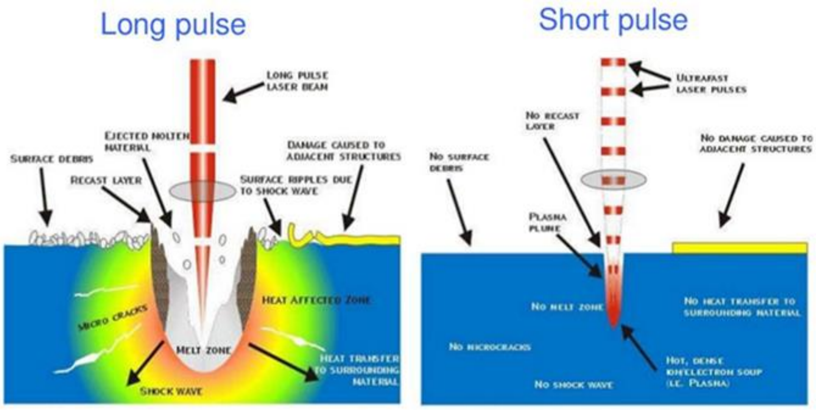

Fig. 3 - Short and large Pulse

To reduce heat damage during micromachining, pulsed laser systems, particularly nanosecond lasers, are widely used. These lasers provide high peak power while consuming very little energy on average, making them suitable for a wide range of applications. Despite these benefits, nanosecond lasers can still produce heat-affected zones (HAZ), which may restrict their applicability for applications that need ultra-precise temperature control.

To circumvent this issue, picosecond lasers have emerged as a more viable option. Their exceptionally short pulse lengths greatly decrease heat dispersion into adjacent regions, enabling for cleaner, more accurate machining with minimum thermal effect.

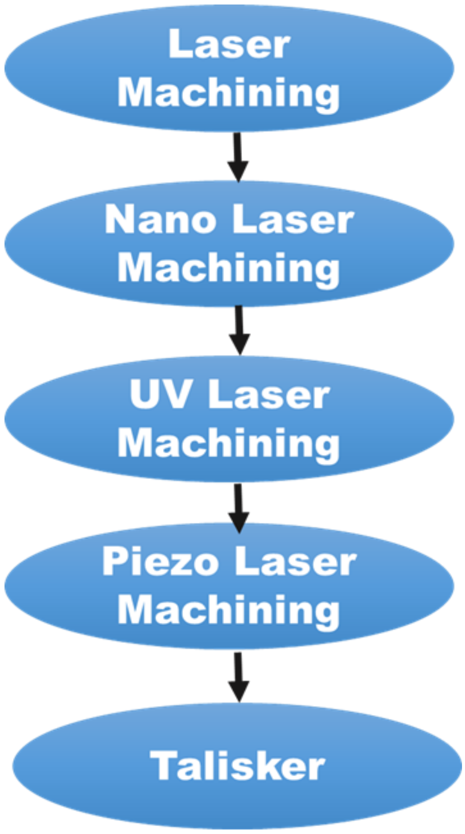

Fig. 4 - Advancements In Laser Micromachining

The Talisker laser system represents one of the most important developments in laser machining technology. This revolutionary system combines the advantages of fibre laser technology with a free-space amplifier, successfully resolving the limitations of previous laser models [31–32]. The Talisker laser is noted for its high precision, quick processing rates, and cost-efficiency, making it especially ideal for demanding applications in microelectronics and other sectors where excellent machining accuracy is required, as seen in Fig. 4.

Conclusion

Laser micromachining has shown to be a reliable and forward-thinking solution in the field of precision manufacturing, particularly in response to the rising need for miniaturised components. Its primary technique, laser ablation, enables highly localised material removal by energy absorption in specific locations. The success of this method is heavily influenced by important parameters such as pulse energy, laser wavelength, and beam profile. Advancements in laser systems, particularly femtosecond and ultrafast lasers, have considerably improved the precision, speed, and cleanliness of micromachining operations. These methods enable the creation of complex microstructures from a variety of materials, such as metals, ceramics, glass, and polymers. Laser micromachining has become a popular alternative in industries such as microelectronics and micromechanics due to its versatility and higher performance when compared to traditional methods. As research continues to optimise laser characteristics and system capabilities, laser micromachining is poised to play an even more critical role in the future of high-precision, sustainable manufacturing.

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