ADVANCED MANUFACTURING BY ULTRASHORT PULSE LASERS

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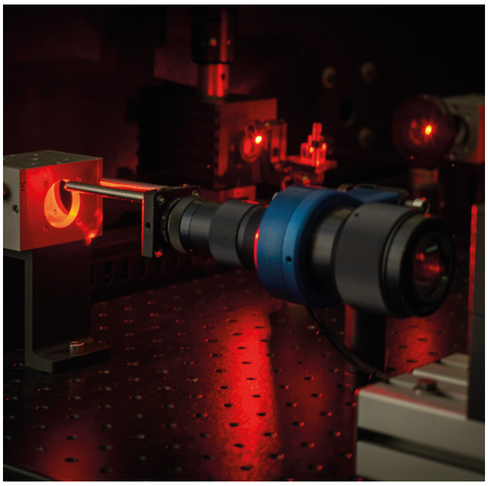

By achieving extremely high peak power with remarkably low energy, ultrashort pulse (USP) lasers have unlocked innovative and original approaches for material structuring and micromachining. After explaining the fundamental principles of how these ultrashort pulses interact with matter, this discussion will present their primary applications and the associated challenges.

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Lasers have long been used in manufacturing for cutting, drilling, welding, and thermal annealing of a wide range of materials, from polymers to metals. However, with Continuous Wave (CW) and nanosecond pulse lasers, the absorption rate is highly material-dependent. Additionally, a thermally affected zone inevitably forms around the processed area. Ultrashort pulse lasers where pulse durations range from 10 femtoseconds (10^{-15} s) to 100 picoseconds (100^{-12} s) exhibit fundamentally different behavior. Due to non-linear absorption mechanisms (such as multiphoton absorption, avalanche ionization, or tunneling), the laser pulse can be absorbed by virtually any material once a specific fluence threshold is reached. This versatility makes USP lasers "universal tools."

Another key advantage is that USP laser processing is often considered non-thermal. While it is commonly stated that the ablation process is "faster" than thermal processes, this is not entirely accurate. To understand why, it is essential to recognize that the material's response primarily depends on the peak power density (W/cm^2). With USP lasers, exceptionally high peak power Ppeak (W) can be achieved with relatively low pulse energy (E [J]) due to the ultrashort pulse duration (Δτ): $P_{peak} = E/\Delta\tau$ (see Figure 1). For example, 1 joule is the energy emitted by a basic LED in less than a second, an almost negligible amount. When this 1 joule is concentrated into 1 picosecond (10^{-12} s), it results in a peak power of 10^{12} W, or 1 terawatt (TW). This immense peak power is further spatially concentrated using an f-theta lens or microscope objective, focusing it onto an area of just a few square micrometers. This enables the achievement of extraordinarily high peak power densities (W/m^2). In the example above, concentrating the energy onto a 10 µm^2 surface yields a peak power density of 10^{18} W/cm^2 (10,000 petawatts/cm^2). In practice, with a pulse duration of 300 femtoseconds, only a few microjoules from a 1030 nm Ytterbium laser are sufficient to ablate metals or transparent glass. Since each pulse involves only a few microjoules, the thermally affected volume remains minimal. The extraordinarily high peak power density allows for the modification, fusion, or ablation of any material, but only within a highly confined volume due to the low energy involved.

THERMAL EFFECTS AND MATERIAL PROCESSING WITH USP LASERS

In reality, the extent of the thermal effect depends on both the repetition rate (the number of pulses per second) and the thermal response of the material. The local temperature increase after a single pulse is minimal. If the interval between two consecutive pulses exceeds the material's thermal diffusion time, the thermal effect is negligible. However, at high repetition rates—where the time between successive pulses is shorter than the thermal diffusion time—thermal accumulation occurs (see figure 2). USP lasers can thus be considered remarkable tools for controlling temperature fields with exceptional spatial and temporal precision, even at microscopic scales.

As demonstrated, high-power USP lasers can modify any material—whether on the surface or within the volume (if transparent)—at the micrometer scale while precisely managing thermal effects. This technology enables applications as diverse as engraving your name on ultra-hard materials like diamonds or performing delicate procedures such as correcting corneal curvature in LASIK eye surgery. USP lasers are therefore invaluable tools for advanced manufacturing.

INDUSTRIAL ROBUSTNESS AND LASER TECHNOLOGIES

USP lasers have been robustly integrated into industrial applications for years, including glass cutting and drilling for smartphone screen manufacturing. The two most widely used high-power USP laser technologies are:

- **Ti-Sapphire (Ti:Al$_2$O$_3$) lasers** (λ = 800 nm): These lasers achieve higher peak power with shorter pulses (>10 fs) but operate at lower repetition rates (kHz range).
- **Ytterbium fiber lasers** (λ = 1030 nm): These lasers offer higher repetition rates (up to 10 MHz or more) with pulse durations exceeding 100 fs. Their fiber-based design enhances robustness, making them ideal for industrial use.

For example, commercial 300 W (average optical power) femtosecond Ytterbium lasers can generate 1 million pulses per second, each delivering 300 µJ of energy in 300 fs. The first kilowatt-level average-power USP lasers are now also available. Other high-power USP laser technologies have emerged at different wavelengths, such as Erbium-doped fiber lasers (1550 nm), Holmium femtosecond lasers (2100 nm), etc.

Most of these lasers can be frequency-doubled or -tripled using nonlinear crystals to produce wavelengths like 515 nm or 343 nm, though this process reduces the output power.

Unlike conventional lasers, the advantage of exploring new wavelengths with USP lasers is not to enhance absorption but to exploit the material's transparency windows. This enables volumetric processing rather than surface-only modification. For instance, glass is transparent at 1030 nm, while silicon wafers are transparent at 1550 nm.

SURFACE FUNCTIONALIZATION

One of the most studied applications of USP lasers is **surface functionalization**—the modification of a material's physical properties through micro-structuring. Micrometer-scale structuring can be achieved by etching the material •••

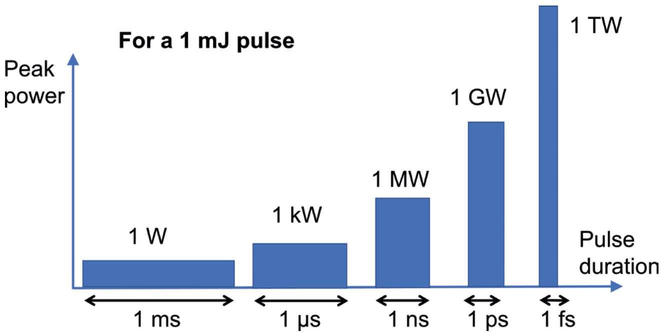

Figure 1. Peak power of a 1 mJ pulse depending on its duration, or how high peak power can be reached with low energy.

with a focused USP laser. A galvanometric scanner is typically used to scan the surface and create specific patterns. Alternatively, **Laser-Induced Periodic Surface Structures (LIPSS)** can be formed when the material's surface is melted, leading to self-organized structures smaller than the laser spot (see figure 3). The quasi-periodic structures that form are oriented based on the incident polarization, with periods comparable to or smaller than the laser wavelength.

Surface texturing alters a range of physical properties, including:

- **Wettability:** (Super-)hydrophobic or (super-)hydrophilic surfaces can be created using the lotus effect. Wettability gradients can even be used to manipulate the movement of micro-droplets.
- **Color:** Grating effects produce iridescence, similar to the colors seen on butterfly wings.
- **Non-adhesion properties:** These improve the lifespan of industrial molds.
- **Drag reduction:** Riblet structures on surfaces reduce drag for objects moving through fluids, such as aircraft, boats, submarines, or rockets, enhancing energy efficiency.
- **Biocompatibility:** Certain textures exhibit antibacterial properties, while others promote cell growth.
- **Absorption and emissivity:** Specific textures can trap light, creating ultra-dark surfaces with high thermal emissivity.

These functionalizations can be applied to a wide range of materials, from metals and polymers to ceramics and glasses.

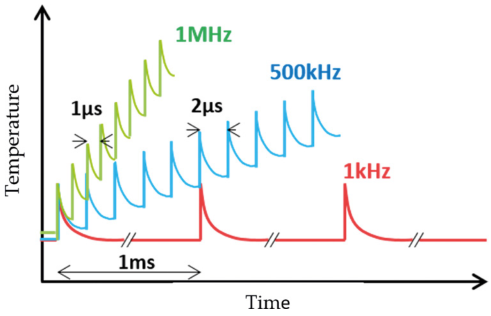

Figure 2. Illustration of thermal accumulation depending on the USP laser repetition rate.

3D MANUFACTURING OF DIELECTRIC MATERIALS

In transparent materials, structuring is not limited to the surface but extends into the volume. Glasses can be etched through **direct ablation** or **laser-induced etching**. In the latter case, wet etching—using hydrofluoric acid, for example—is employed. The wet etching rate is several orders of magnitude higher in regions irradiated by the laser. This enables the fabrication of highly complex shapes through **subtractive manufacturing**, following three-dimensional laser scanning of the material to be removed.

A notable application involves **Through-Glass Vias (TGV)**, which are micrometer-scale holes drilled through glass plates to separate and connect multiple electronic circuits *via* conductive material filling. TGVs can be created through **direct laser ablation** or, more efficiently, *via* **laser-induced etching**. Non-diverging Bessel-like beams allow for the production of long TGVs with high precision.

USP lasers also enable **glass welding**. By focusing the laser beam on the interface between two materials, **multiphoton absorption** occurs, locally melting the glass. This technique can join different types of glass—even those with varying thermal and mechanical properties (e.g., thermal expansion)—as well as glass with metals, semiconductors, and ceramics. Applications include optoelectronic **component packaging, microfluidic systems**, and other scenarios where adhesives are unsuitable due to high temperatures or degassing concerns. While fused silica may develop micro-voids that scatter light, most other glasses achieve excellent transparency after welding.

USP lasers are also used for **precision glass cutting**. The focused beam creates micro-cracks within the material, guiding controlled fracture propagation. Another key application is the **inscription of waveguides** in the volume of the glass by modifying the refractive index. This technique can also produce **Bragg gratings** and other complex optical filters.

FUTURE CHALLENGES

One of the primary challenges is **increasing throughput** to process large mechanical components efficiently (see figure 4). High-power laser sources are already available, and **process parallelization** can be achieved using **multibeam arrays**. As example, it is a requirement for lithium-batterie electrode texturing. These arrays can be generated using static diffractive optical elements, multi-plane light conversion beam shapers or dynamic spatial light modulators (*e.g.*, liquid crystal-based).

High-speed scanning can be accomplished with polygonal mirrors, reaching speeds of up to km/s, while **real-time pulse energy control** is enabled by high-speed triggers. With repetition rates now exceeding **10 MHz** and commercially available **burst modes up to GHz**, process optimization

Figure 3. (left) color effect by surface texturing achieved by (right) Laser Induced Periodic Structures (LIPS) at smaller scale (zoom).

Figure 4. 3D glass manufacturing and micro-drilling in stainless steel plate by IREPA LASER using USP laser.

is within reach. The initial pulses in a burst can preheat the material, enhancing absorption and ablation rates. Methods to monitor the process in real time are also a requirement.

Two additional challenges include: (1) **the developing USP lasers at new wavelengths** to access transparency windows in novel materials and (2) **achieving finer-scale material machining**, such as for **metamaterial fabrication**.

Laser sources that were once unimaginable a few decades ago are now commercially available. They enable **advanced manufacturing** across a spectrum of materials—from the softest to the hardest—and scales—from the smallest features to large surfaces. Their applications span **biotechnology, aerospace, information technology, quantum optics**, and beyond. We are only at the dawn of their potential. These lasers will serve as a **pen to write the future**. ●

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