Raydiance Application Spotlight

A Primer on Femtosecond Laser Ablation

Precision Machining Without Heat

Abstract

Ultrafast light comprises extremely short pulses of light. The brevity of the pulses—generally in the several hundred femtosecond regime—causes the light to interact with matter in a way that is fundamentally different from other forms of energy. This unique interaction enables athermal ablation—the ability to machine micron resolution features in virtually any material without introducing heat to the target. It is a capability that is transforming advanced materials applications.

Background

This century is seeing an explosion of materials applications that represent multi-billion dollar opportunities. At the same time, the machining challenges that come with these opportunities are significant. The materials themselves—bioabsorbable polymers, shape-memory metals, hardened materials, laminates or multi-layer composites—are often difficult to machine with traditional methods. And the feature size requirements continue to get smaller and smaller, with there being little tolerance for any collateral heat damage, a common byproduct of traditional laser and mechanical machining methods. Post processing to remove thermal damage is expensive and difficult to do.

Increasingly, light, and more specifically femtosecond light, is providing the machining solution to these challenges. The reason is that femtosecond light enables true athermal ablation—the ability to machine precise features without introducing heat to the target.

Material Ablation – Thermal versus Athermal

Traditional laser ablation is fundamentally a thermodynamic event. A continuous wave (CW) laser, for example, emits a steady stream of photons that are linearly absorbed by the target. In other words, the energy and its associated electric field create oscillations in the lattice electrons, but it is not intense enough to actually break the atomic bonds and liberate the electrons from the target atoms. The oscillations ultimately impart heat to the target, which, in turn, leads to classic thermodynamic phase changes: solid to liquid to gas. In some situations, the material simply combusts. While the target atoms and/or molecules might be ablated, considerable heat transfers to the material surrounding the target causing unwanted collateral damage (*Figure 1*).

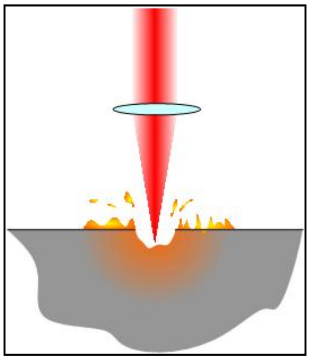

Figure 1: Ablation with a CW laser or even a long pulse laser (nanosecond or several picosecond pulse duration) causes heating of the areas peripheral to the target and subsequent thermal damage.

In stark contrast to CW lasers, femtosecond lasers ablate by a nonlinear process called optical breakdown. This is fundamentally an electronic event rather than a thermodynamic one.

A femtosecond laser emits pulses of light less than a picosecond long, generally in the few hundred femtosecond range. The brevity of the pulses creates a very intense electric field capable of stripping the target atoms of their electrons and creating a transient cloud of charged particles. Subsequent electrostatic forces cause the target ions to be ejected. This ablation process happens much faster than thermal diffusion. The result is that precise features can be machined without ever introducing heat to the sample (*Figure 2*).

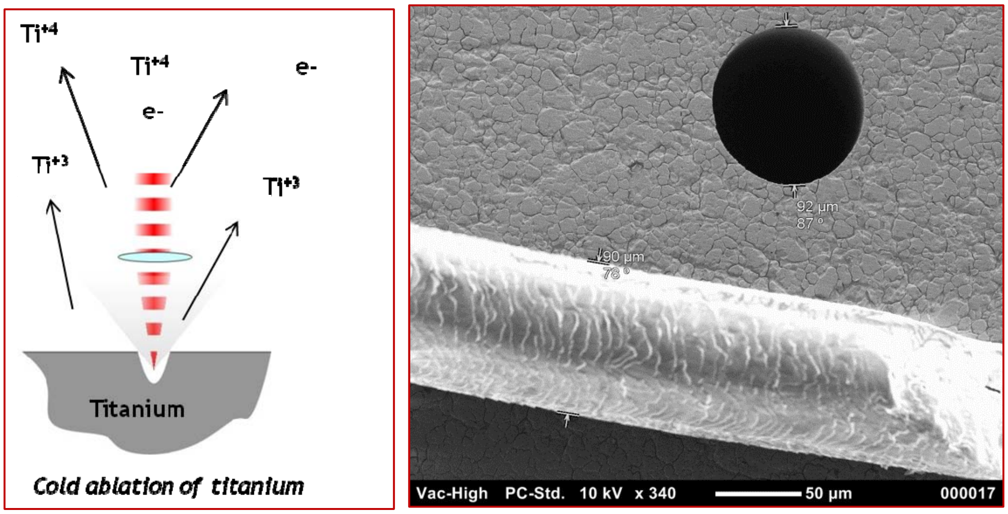

Figure 2: At left is an illustration of a femtosecond laser impinging on a titanium target. The ablation process occurs through optical breakdown. The time duration of the pulse is shorter than the thermal diffusion time, which means there is no thermal damage to the area surrounding the target. At right is an SEM image of a 92 µm hole machined with the Raydiance femtosecond laser platform through 830 µm thick stainless steel (400). A human hair is in the foreground to provide scale.

Of course there is a continuum of pulse widths between an femtosecond laser and a CW laser. In general, however, as the pulse width is lengthened into the picosecond and nanosecond regime, the intensity of the pulses decreases and there is an increasing thermal component to the ablation process. Further, the pulse duration for nanosecond and picosecond lasers exceeds typical thermal diffusion times. So while there is a certain degree of optical breakdown, there is also substantial heating of the sample (*Figure 3*).

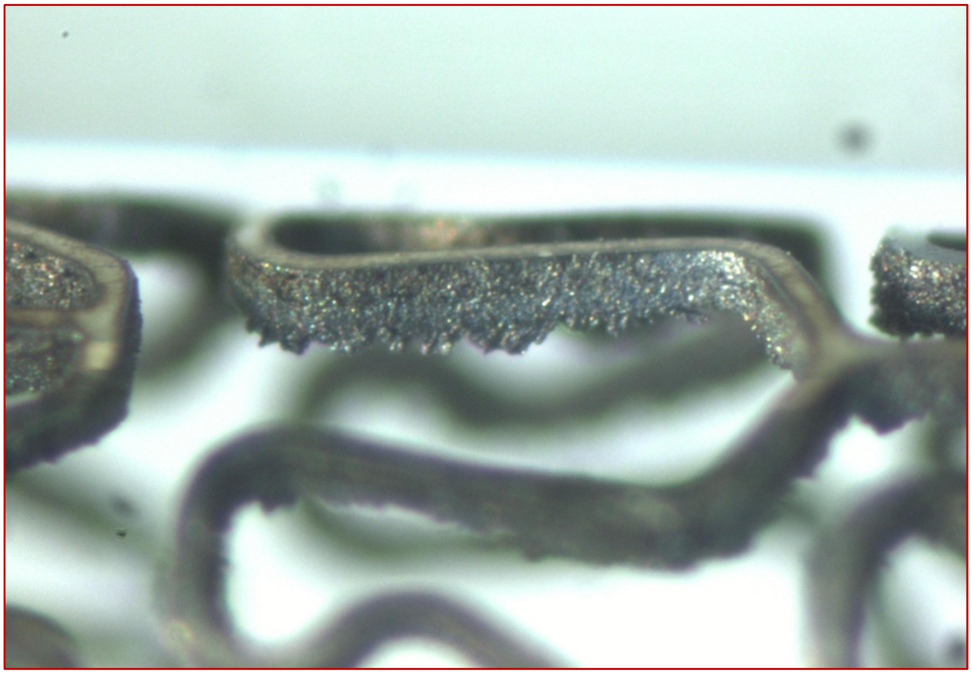

Figure 3: The vascular stent above was machined with a nanosecond laser. It exhibits thermal damage in the form of burrs and other heat affected zones (HAZ). A part like this would require several re-work steps, including manual honing and chemical etch steps to clean up the thermal damage.

Ultimately, the mechanism of ablation is a complex one. To achieve true athermal ablation, it is necessary that pulse durations be in the femtosecond regime. Longer pulses—from several picoseconds to nanoseconds—will ablate the target, but there will be thermal effects that compromise the part. It is also true, however, that femtosecond pulse duration is a necessary condition but not a sufficient one to achieve athermal ablation. Other factors, primarily the quality of the femtosecond pulses and beam, play a role in the nature of the ablation process.