Femtosecond Laser Machining of Nitinol – What you need to know!

Dr. Andrew Pequegnat & Michael Byrne
Memry Corporation, 3 Berkshire Blvd., Bethel, CT 06801, USA
www.memry.com

Nitinol's unique super-elastic and shape memory properties have made it an essential material in the medical device engineer's toolbox. Nitinol has become a staple in the cardiovascular, neurovascular, endovascular, peripheralvascular, orthopedic, spinal, urology and dental arenas with applications ranging from neurovascular stents and heart valve frames to orthopedic anchors and orthodontic archwires.

Over the last two decades countless advancements in medical device technologies have been made possible not only due to the application of Nitinol but also advancements in the state-of-the-art manufacturing technologies required to produce such devices. Laser manufacturing technologies have been at the forefront of these innovations. The non-contact, precision and low thermal input characteristics of laser processes have made lasers the technology of choice for welding, cutting/ablation and marking. More specifically, the extreme thermal-sensitivity of Nitinol's microstructure and thermomechanical performance makes low heat input secondary processes a necessity. In this article the state-of-the-art femtosecond laser machining processes will be presented with a specific focus on manufacturing Nitinol medical devices.

The Femtosecond Laser

The femtosecond laser is an ultra-short pulsed laser capable of producing pulses with a temporal magnitude in the $x10^{-15}$ second range (e.g. 1 fs = 1x10^{-15}s). For context, light travels about ¾ of the way to the moon in one second whereas light only travels 0.3 µm (or 0.00012") in one femtosecond. Using chirped pulse amplification (CPA), which essentially stretches, amplifies and compresses laser pulses produced by a laser oscillator, extremely high peak power pulses with ultra-short temporal profiles can be generated (Figure 1)[1]. These high power, ultra-short pulses can be used to cause direct solid to plasma ablation of most materials including metals, ceramics and polymers[2]. Since the laser-material interaction time is so short, heat is not conducted into the bulk material. This is the reasoning behind many medical device manufacturers using the term "athermal" (i.e. no heat) when promoting their femtosecond laser machining processes.

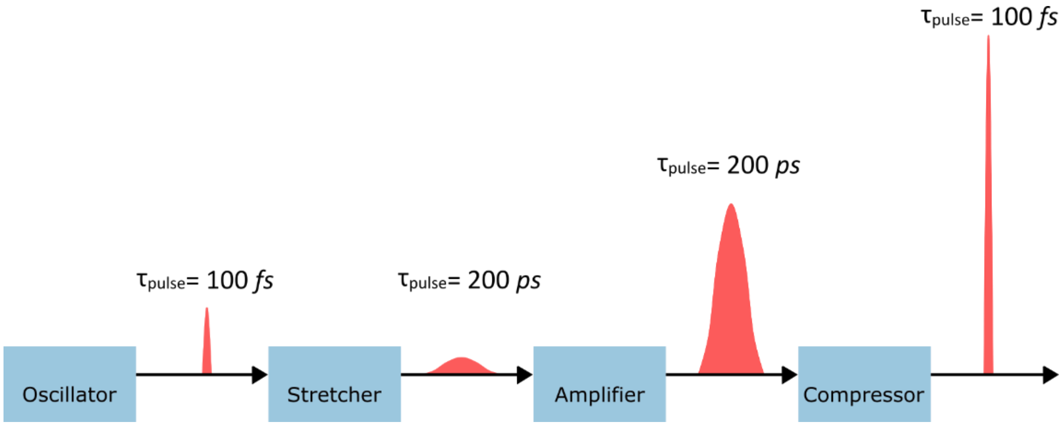

Figure 1: Chirped pulse amplification (CPA); how to build an ultra-short laser pulse.

As with most new technologies, the first femtosecond lasers were expensive and often unreliable. However with constant improvements in the technology and as more laser companies enter the femtosecond laser market, the initial capital investment has drastically decreased and the reliability and customer support now parallels more established laser technologies. In the late 1990’s researchers were beginning to apply femtosecond laser technologies to cut cardiovascular stents[1]. Now many Nitinol medical device manufacturers are integrating femtosecond laser sources into their laser cutting systems in an effort to reap the benefits of the ultra-short laser pulse.

Femtosecond Machining of Nitinol Tube

As one can imagine, there is a learning curve associated with working with more complex theories such as laser absorption by free electrons due to the inverse Bremsstrahlung effect. Simply heating the Nitinol to the melting point and blowing it through the tube wall using high pressure gas (i.e. conventional fiber or Nd:YAG laser cutting) is no longer relevant. There is also engineering-know-how that must be obtained in cleaning and final processing of such femtosecond machined Nitinol components.

When looking to use a femtosecond laser cutting process whether or not the final device will really benefit from such a process must be considered. As a general guide, tubes with a thin wall (<125 µm) and designs with thin struts or small geometrically critical features (i.e. <100µm) will benefit from such a process. Conduction of heat away from the cut is less efficient in geometries with small cross-sectional area; ultimately leading to heat affected regions even in the most carefully optimized thermal cutting processes. Utilizing a femtosecond laser, finer more precise geometries are possible due to low thermal distortion during cutting and kerf widths (i.e. cut width) as small as 5 µm resulting from a high quality laser beam (Figure 2). Moreover, in many cases using a femtosecond laser process is advised not because of component size or precision requirements but simply to minimize or even eliminate time consuming downstream post processes. For example, tubes with small inner diameter and fine, complex features are near impossible to hone and consistent chemical etching and electro-polishing is challenging. Minimizing heat input and eliminating re-cast and slag through a femtosecond laser processes mitigates these common challenges.

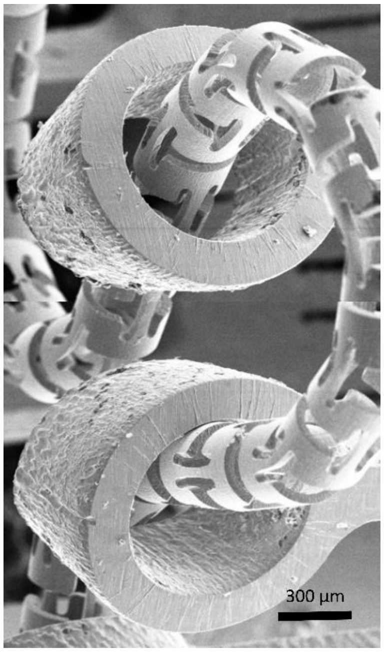

Figure 2: Laser cutting process extremes. Fiber cut tube (5 mm OD x 0.56 mm wall) vs. Femto cut tube (0.343 mm OD x 0.044 mm wall). Stents shown are in as-cut condition where a typical re-cast surface structure is observed on the component cut using the thermal based fiber laser cutting process.

To better understand the Nitinol femtosecond laser cutting process we need to re-visit whether or not the process truly is athermal and also consider cutting efficiency. Laser fluence (F) is the energy delivered per unit area which is most commonly expressed in J/cm^2. With a laser fluence just above the ablation threshold of Nitinol and a low pulse frequency (e.g. <1 kHz) the femtosecond laser can ablate Nitinol with little to no heat transmitted to the bulk material. However, a multiple pass cutting strategy with painfully slow speeds would be required. This doesn't make economic sense. In order to speed up the process the laser fluence must be increased along with repetition rates (i.e. to 100-200 kHz) and single pass cutting strategies with specific beam polarization must be explored. This however leads to process challenges with respect to cut quality and keeping the heat input as low as possible. A non-optimized femtosecond cutting process can lead to thermal damage such as re-deposited debris, re-cast layer on the cut wall and heat affected layer; similar to that observed from a traditional thermal laser cutting process. An example of cutting with optimized versus non-optimized femtosecond laser parameters if provided in Figure 3.

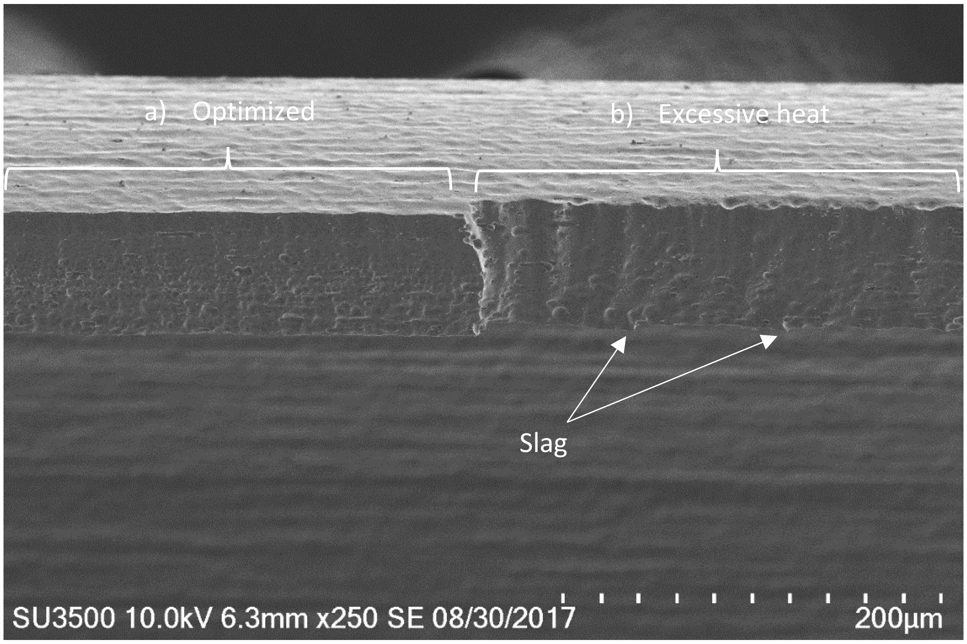

Figure 3: a) Optimized femtosecond laser cut versus b) laser cut with excessive heat input (i.e. increased fluence and pulse frequency). Sample was cleaned/deoxidized to remove debris from femtosecond process before imaging. Note that laser kerf increases greatly with more heat input. Excessive heat also lead to rounding of cut edges, poor cut wall quality and slag at the bottom edge.

So where does the heat come from? The heat generated during femtosecond laser ablation primarily results from two mechanisms; i) A portion of the Gaussian beam that has a fluence below the ablation threshold (F_{th}) of Nitinol, and ii) Interaction of the beam with the vaporized material created from previous pulses. A portion of the tails of the Gaussian beam will always have a fluence below the ablation threshold but the diffraction and scattering of the beam caused by interaction with the debris/plasma will also reduce fluence across the beam's spatial profile (Figure 4). Optimizing cut speed, pulse frequency and laser focus as well as using an assist gas or even processing underwater can reduce these effects[3, 4]. Understanding these mechanisms and managing these effects allows for high quality cuts with minimal thermal damage. As for cutting efficiency, the ablation process is not necessarily asymmetric in all travel directions due to laser absorption varying with the direction of beam polarization[5]. Beam polarization is critical in considering cutting efficiency in different directions and in particular when the cut has a large aspect ratio (i.e. *kerf width : material thickness*)[6].

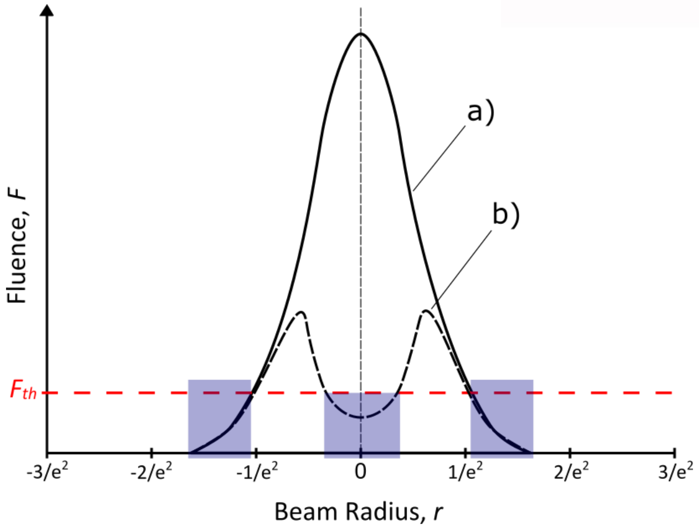

Figure 4: Laser fluence of a Gaussian laser beam expressed in 2D. F_{th} represents the threshold fluence for the ablation of Nitinol. Below this threshold the laser energy will be transmitted into the bulk material through thermal conduction. Curve a) illustrates typical undistorted beam having fluence below F_{th} only at tails. Curve b) illustrates a distorted beam profile where the fluence drops below F_{th} at the center.

Partial Penetration Ablation

One of the most commonly overlooked benefits to femtosecond laser machining is the ability to perform partial penetration ablation. Since there is no need for high pressure gas to expel molten material or prevent excessive oxidation, material can be ablated up to a specific depth with careful parameter optimization. This technique is demonstrated in Figure 5 where the Memry logo has been cut into the surface of a Nitinol hypo needle. This ablation process was performed using a femtosecond laser systems equipped with galvanometric scanner optics. Surface ablation of Nitinol can be used for surface texturing, creating unique geometries out of monolithic components, and even textured surfaces for drug delivery or echogenic applications.

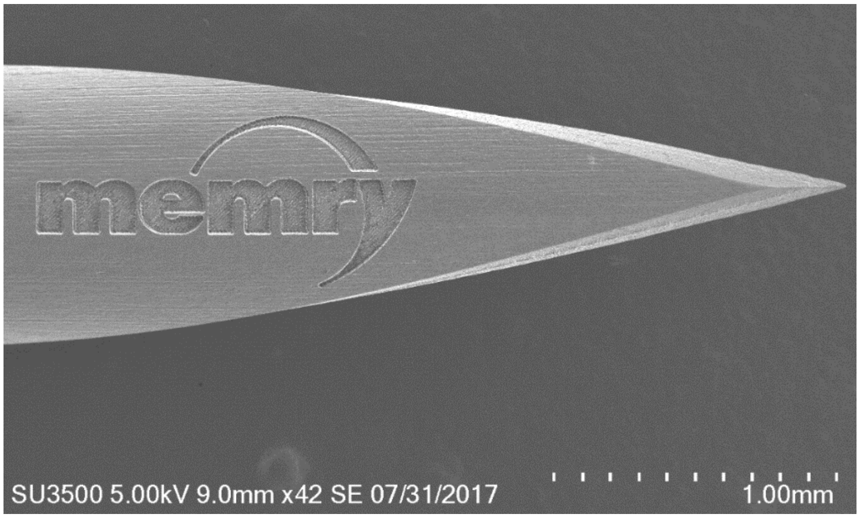

Figure 5: Partial penetration ablation of Memry logo using femtosecond laser equipped with galvanometric scanner. Low thermal input allows for maintaining a hard and sharp needle edge which was cut using a multi-pass off-axis cutting strategy.

About Memry Corporation

Memry is a vertically integrated world leader in medical and industrial applications requiring Nitinol alloys and complex manufacturing processes. Our production capabilities consist of a wide variety of fabrication, finishing, testing and quality processes, which together deliver the highest quality Nitinol components. Laser cutting, shape setting, laser welding, wire EDM, electropolishing and surface treatments are just a few of our core capabilities. Our engineers bring decades of Nitinol experience to every project, providing valuable insight on how the material reacts in real-world conditions. These initial discussions will translate into time savings and cost effectiveness for your component project. Let the Memry experts assist you in selecting the right path to your precision component, manufactured from raw Nitinol wire, tube, strip or sheet.

References

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