Avoiding Material Damage with Cold Laser Cutting

A new technology that uses a water jet to guide a laser enables precision micromachining without causing damage to delicate metal materials.

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The medical device industry's use of sensitive metal materials has created an important demand for precision micromachining. The technologies chosen to work with such materials must be selected based on precise criteria. When working with the materials, it is critical that heat effects, mechanical damage, particle deposition, and other potential fabrication distortions are avoided. High precision is also generally required for machining delicate metals.

Stent manufacturing is a good example of a demanding application. The delicate operation requires cutting sheets or tubes of metal to make mesh tubes with an intricate structure. A water-jet-guided laser, or laser microjet, technology provides an efficient way to cut stents. The material sustains neither heat nor mechanical damage while being cut, and the microjet prevents any temperature increase in the stent, which is essential. A hair-thin water jet provides a cooling effect as it guides the laser beam. After cutting, even stents made from shape-memory materials retain clean structures to a degree difficult to achieve with conventional lasers. Shape-memory materials tend to melt more than other materials (such as stainless steel), and more burrs are produced during cutting. Moreover, laser microjets significantly reduce the need for postprocessing steps because they generate no burrs or dross on the material surface. Moreover, particle contamination is reduced.

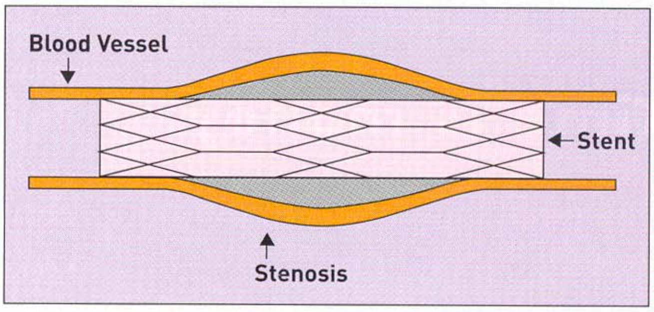

Figure 1. A stent serves as a sort of scaffold in a blood vessel.

Demanding Application

Stents are mesh tubes that improve and ensure blood flow in blood vessels narrowed as a result of atherosclerosis or other vascular conditions. After being tightened over a balloon catheter, the stent is moved into the blocked vessel. When the balloon is inflated, the stent expands into the vessel. There, it forms a scaffold that holds the vessel open (see Figure 1). Stents are designed to remain in the artery permanently.

Various materials can be used in making stents. Stainless steel and nitinol are the most common materials. But other shape-memory alloys and polymers are also viable options. The stent tube is typically about 2 mm in diameter and has a wall thickness between 100 and 200 μm.

Stent cutting is a demanding procedure. Because the stents will be placed inside the human body, certain requirements must be met. First, there can be no cracks. Second, the edges must be clean, without dross or burrs

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attached. Also, precision and consistency are critical because the cut curvature is fine and highly complicated. Finally, thermal damage must be minimal. Some materials, like the shape-memory metal alloy nitinol, are heat sensitive; thermal loading could damage their shape-memory ability. Stainless steel expands by 16 µm per meter of length per degree Celsius as the material is heated. For example, a variation of 15°C of a 2-cm-long stainless steel stent will imply a variation of about 5 µm in length. Biocompatibility is also essential because of the risk of rejection. A good surface finish is required when applying an additional coating that contains antirejection drugs.

Certain mechanical and chemical methods may remove dross and moderate heat-affected zones after cutting. However, it is more productive to obtain the requisite quality and geometry—or as close to such as possible—during the initial cutting step. Obtaining the necessary quality early in the process helps prevent the need for sandblasting at a later stage. It also minimizes the need for electropolishing to round off the edges and achieve a smooth surface finish.

Water-Jet-Guided Laser

The laser-microjet principle couples a high-powered, pulsed laser beam with a hair-thin water jet. A fiber carries the laser beam to the center of the system. There, it passes through a transparent window and enters a water-filled chamber. Once past the window, the laser beam is focused into a nozzle where it is coupled with the water jet exiting the chamber. From this point, the laser beam is guided along the cylindrical jet by total reflection at the interface between air and water. The reflection is the result of the difference between the refractive indexes. When the beam reaches the workpiece, the laser cuts the material by heating.

The pure, deionized, filtered water is pressurized between 50 and 500 bar. However, its consumption remains low (about 1 L/hr) because of the jet's small diameter. The nozzles, which can be either sapphire or diamond, may be as small as 25 µm in diameter. The laser sources are diverse, but they are usually pulsed Nd:YAG lasers whose wavelength may be 1064 nm (infrared), 532 nm (green), or 355 nm (ultraviolet).

Because the water jet guides the laser, it ensures a consistent spot diameter, which enables a single, centimeters-long focus. The length for which the water jet is stable is about 1000 times the water-jet diameter. For example, a 50-µm jet will be stable for 5 cm. In addition to guiding the beam, the water jet has other functions. These functions prove significant for precision cutting, especially when requirements are as stringent as those associated with medical device manufacturing.

Minimal Heat-Affected Zone

Between laser pulses, the water jet cools the edges of the cut and its immediate surrounding area, preventing heat damage within the metal. It is efficient for avoiding heat load resulting from laser ablation on both sides of the processed pieces. Because of this cooling function, the water-jet-guided laser is referred to as a *cold laser*. No oxidation is visible.

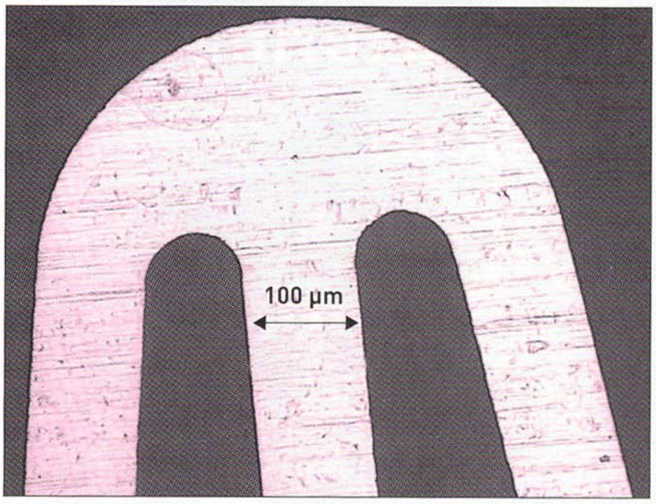

Figure 2. A water-jet-guided laser cuts stainless-steel edges cleanly.

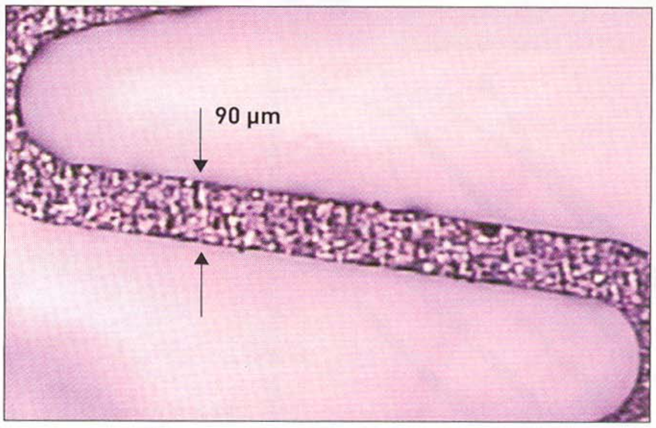

Figure 3. The laser enables consistent diameter, an important aspect of shape-memory nitinol used in stents.

Cleanliness

The microjet process produces no surface contamination caused by small-particle generation. The water jet instantly cools the removed material, which will not attach to the workpiece surface. The water jet is very thin—its diameter typically ranges from 30 to 50 µm for this application. However, it has a relatively high pressure—more than 300 bar in most cases—which is more than adequate for particle removal. A thin water film may be added to the workpiece for flat pieces; doing so prevents particles from attaching to the material's surface.

Negligible Mechanical Constraints

The force applied by the water jet onto the workpiece is very low because of the jet's small diameter and medium pressure. For example, a jet with a diameter of 35 µm and a pressure of 300 bar would create a force of 0.03 N, where force = pressure × surface area. The absence of mechanical constraints is good because the stent's thin, delicate structure requires minimal force for adhering to the workpiece to avoid vibrations and movements that reduce machining precision. A vibrating workpiece can cause surface defects in the stent structure.

Microjets in Stent Cutting

The absence of mechanical or thermal damage ensures that neither cracks nor structural changes occur in the material. The accuracy of the axes and the vision control system of the cutting machine ensure precision and consistency. To avoid mechanical contact, the stent can be placed inside a tubular fixture in which it is supported by an air cushion.

The stent's edges can be cut cleanly because the water jet removes the molten material during cutting. Particle deposition, burrs, and dross are greatly reduced and, because of the water-jet cooling, no oxidation is visible. In addition, because stent manufacturers are looking for good surface quality, they perform cleaning operations after the cutting process. The water-jet-guided laser enables manufacturers to reduce these time-consuming steps, thus increasing productivity.

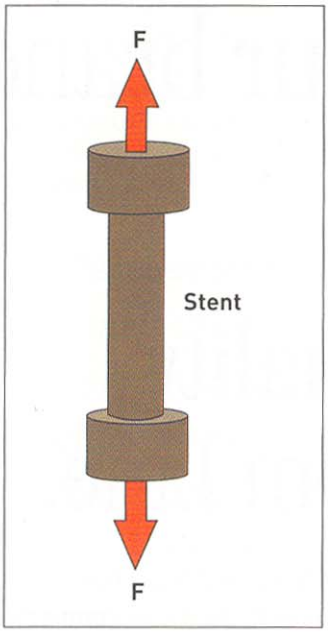

Figure 4. An elongation breaking test involves applying force to both ends of a stent to see where it will break.

Figures 2 and 3 show the quality obtained with a water-jet-guided laser for stainless steel and shape-memory nitinol, respectively. Both samples were cut using a long-pulse laser with an average power of 45 W and a 40-µm nozzle. The through cuts that formed the shapes were made in one pass at a speed of 4 mm/sec. Speed is limited for that application because of the structure's complexity and the high quality required. However, as a general rule, cutting speed increases as workpieces thin. In addition, these cuts achieved a particle level lower than 10 µm.

There is no visible heat effect on either side of the stent. The only residue is nonadhering dross. This dross along the edge on the back can be washed away with water.

Tube Processing

When the laser microjet was first used for stent cutting, only planar sheets were processed. Using planar sheets enabled the complex structure of stents to be tested. However, the objective was to process tubes directly. For that reason, a rotary axis was added to machines dedicated to stent cutting.

The challenge was to avoid damaging the internal backside of the cylinder while processing the external front side. With nothing to block it, the laser beam, still guided by the water jet, might have damaged the second wall of the tube after cutting the first. Several strands of copper placed inside the tube during the process solved this problem. The copper efficiently protects the inside of the tube, and the strands do not melt under the heat of the infrared laser because of copper's high reflection coefficient. The molten material generated by laser ablation and ejected during cutting is not problematic because the water jet cools the particles, avoiding damage inside the tube.

Material Strength: Comparison

Because stents are intended to remain inside blood vessels, it is important that they not break. Therefore, the cutting process should not weaken the stent's structure and should not damage its edge. Technologies that require demanding postprocessing steps tend to further weaken the stent's delicate structure.

In exploration of these considerations, one stent manufacturer recently performed elongation tests on shape-memory alloy stents cut with different cutting processes. The purpose of the tests was to find the method that produced the more resistant end product. The elongation test was quite simple. It involved applying a measured force at each tip of a stent part until it broke (see Figure 4). The force required to break the sample provided the sample strength. The strength necessary to break the stent relates to the damage generated by the cutting process. In this way, the test results enabled the manufacturer to rank the manufacturing methods in terms of machining-induced material damage.

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Etching, laser cutting, and microjet cutting were tested on shape-memory alloy stents. Conventional lasers had the poorest results because the process generated significant heat-affected zones. The two other technologies achieved equivalent strength.

Conclusion

Manufacturing medical stents, which involves cutting metal to obtain mesh tubes with intricate structures, is a highly demanding process. Lasers are commonly used for this application, but they can create burrs and produce substantial material damage as a result of heating. Postprocessing steps are time-consuming and can decrease yield. The water-jet-guided technology's advantages, which include low particle deposition, small heat-affected zones, and negligible mechanical constraints, can significantly reduce these additional steps. This tool, which combines the strengths of laser beam and water-jet processing, is well adapted to precision cutting of heat-sensitive metal materials. ■