Technology

by Henry Kobsa

Micromachining with Lasers

In many high-tech fields today, smaller is better. There is an accelerating trend toward miniaturization, and the machining business contributes to this trend through micromachining. The field of micromachining presents industrial physicists with a challenge—performing more delicate operations on ever smaller parts. One of the most common problems faced in micromachining is cutting minute holes in metals and ceramics. I participated in the R&D on a new laser system that can cut holes as small as 20 μm in diameter.

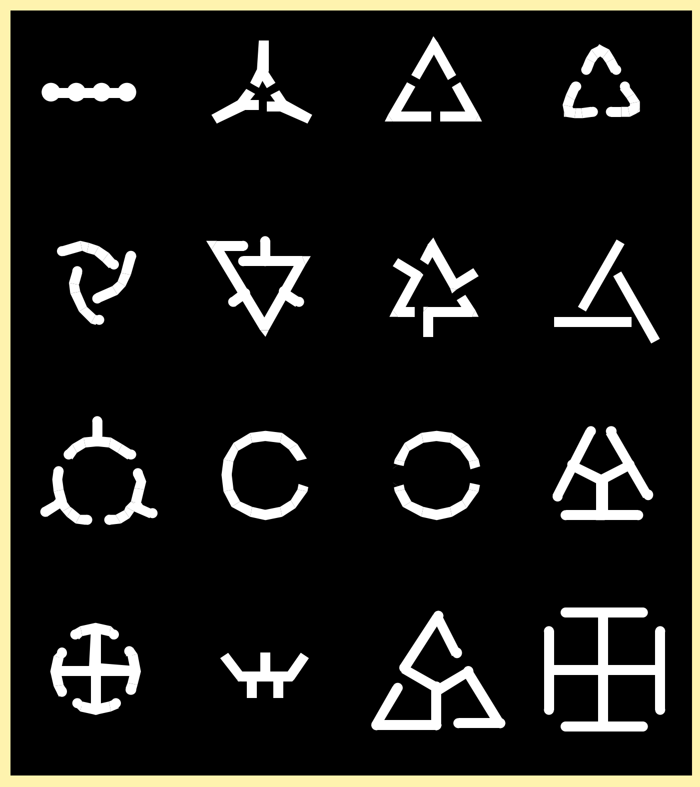

Figure 1. Cross sections of extrusion nozzles micromachined with lasers for synthetic fibers.

Minute holes must be made in equipment and products in many industries. For example, about one-third of all clothing consists of synthetic fibers, which are produced by extruding polymers through tiny nozzles (Figure 1). Some of these nozzles are simple round holes, 100–200 μm in diameter and 300–900 μm long; others are complicated systems of slots that are typically 60–80 μm wide. Automotive fuel injectors also include many tiny holes, typically 100–200 μm across and 1,000 μm long. The fabric and fuel-injector industries around the world cut a combined total of at least 200 million tiny holes each year. Many other applications also require similar tiny holes.

Prior to 1990, three technologies could be used to make such holes—drilling, punching, and electric-discharge machining. Round holes could be drilled, but drilling is poorly suited for ceramics, and drilling holes smaller than about 50 μm in diameter is difficult even in metal. Punching works well in certain alloys, but is limited to making holes whose length is about twice their width, and punching becomes impractical for holes less than 50 μm across. The third option—electric-discharge machining—is slow, expensive, limited to metals, and usually will not work for holes that are much less than 50 μm in diameter.

Limitations on lasers

Theoretically, lasers should be free of the limitations that affect the three standard technologies. An ideal laser would produce an intense, almost perfectly collimated beam of light that could be focused to a tiny spot—say, about 10 μm in diameter. Outside the focused spot, there would be very little energy; inside it, the laser's intensity would be high enough to melt or evaporate any known material. That tiny, intense spot of light could be used like a surgeon's scalpel to precisely and reproducibly cut any shape hole in any material.

Unfortunately, such a well-focused, high-intensity laser was hard to come by prior to 1990, and those that existed were impractical for cutting holes. The problems can be explained through the following equation:

$$D_F = M^2 (4/\pi) \lambda (f/D_L)$$

where D_F is the diameter of the light beam in the focal plane of the focusing lens; M^2, the beam-quality factor, describes how much worse the real laser beam is than the diffraction-limited beam would be; λ is the wavelength of the laser light; f is the focal length of the focusing lens; and D_L is the diameter of the collimated laser beam on the focusing lens. At first glance, this equation suggests that it would be easy to make a fine scalpel. To make D_F small, simply make f small and D_L large.

However, the problem gets more difficult, because one must also consider the laser's Rayleigh length (R_L):

$$R_L = D_F (f/D_L)$$

By definition, the Rayleigh length is the distance above and below the focal plane where the beam's diameter has increased by √2 and the beam intensity has dropped by a factor of 2. In practice, one can only get very good cuts in materials that are slightly thicker than two Rayleigh lengths, but no more.

Cutting through thicker material requires an adequately long Rayleigh length, which means that f/D_L must remain large. If f/D_L cannot be made very small, then only two parameters—the wavelength L and the beam-quality factor M^2—can be adjusted to reduce the spot diameter D_F.

Boosting beam quality

In the late 1980s, no available laser provided an adequate combination of wavelength and beam quality to cut small enough holes for micromachining. Nonetheless, the solid-state lasers, such as neodymium-doped yttrium aluminum garnet (Nd YAG), seemed

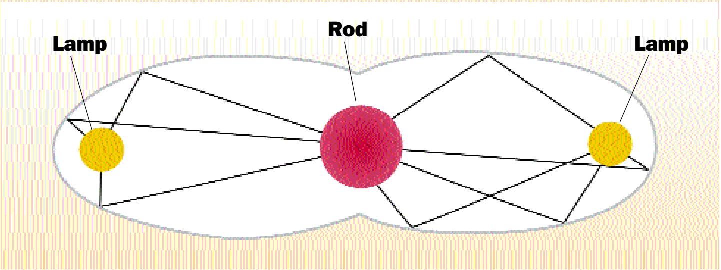

Figure 2. Typical dual flash lamp pumped laser.

promising. The Nd YAG laser was rugged, available at a reasonable price, and proven reliable in industrial applications. It lased at 1.064 μm, a short wavelength in comparison with other lasers, but its beam-quality factor exceeded 12, which was poor in comparison with some other lasers.

In mid-1987, the DuPont Company in Wilmington, Delaware, and the Institut fuer Lasertechnik of the Fraunhofergesellschaft in Aachen, Germany, started a collaboration aimed at reducing an Nd YAG laser's beam-quality factor to less than 4. If realized, a beam of that quality was expected to allow the cutting of slots 50 μm wide and 300–500 μm long in steel. Steady improvements by the research team, of which I was a member, brought that goal in sight by early 1989. So, we built a complete laser cutting workstation. With it, we could routinely make cuts that were 40 μm wide in material up to 1,000 μm thick. The best competing commercial equipment had trouble making cuts 60 μm wide even in very thin materials.

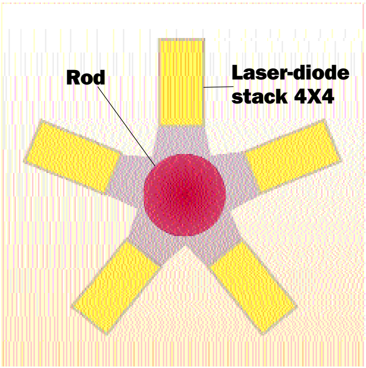

Figure 3. Diode-pumped laser.

Although we were already making the narrowest cuts, we wanted to make even finer cuts. Also, that first laser system would cut some ceramics without producing microcracks, but we wanted to be able to cut all types of ceramics. Finally, we wanted to increase the repetition rate of our pulsed laser from about 100 to at least 1,000 Hz.

Finer cuts

Building a more tightly focused solid-state laser depends on managing the waste heat. Our first cutting system used a laser pumped by flash lamps (Figure 2), which converted less than 5% of the electricity into laser light. In other words, for 1 W of laser power, the system needed to dissipate about 20 W of heat. Heat causes many problems, including an increase in the beam-quality factor, which increases the size of the laser's spot.

Some of the heating can be avoided by replacing the flash lamps with diode lasers. Conversion efficiencies from diode-laser light to Nd YAG light of more than 40% have been demonstrated. However, to achieve the best quality beam, only about 20% efficiency is obtainable. Such a system would produce only about 4–5 W of waste heat for 1 W of laser light.

In the laser that we built, five stacks of laser diode bars surround the Nd YAG rod (Figure 3). That provides uniform illumination of the laser rod, which leads to a beam that can be focused rather easily. Presently, the system pulses the diode bars at 1,000 Hz, and we expect even higher rates. In addition, the beam's quality ($M^2 = 1.2$) approaches the diffraction limit.

So far, our cutting system using this laser has established several micromachining records. It makes 20-μm-wide cuts in 300-μm-thick steel and 45-μm-wide cuts in 1,000-μm-thick steel. It cuts all types of metals, even the difficult ones, including refractory metals, copper, and aluminum. In addition, this system makes crack-free cuts in a wide range of ceramics, including single-crystal sapphire, polycrystalline alumina and hafnia, and silicon carbide.

All of the record-setting capabilities of our cutting system will push the machining industry deeper into miniaturization. With today's R&D advances, one can cut smaller and more precise holes in a wide variety of materials with this technology.

Henry Kobsa is a fellow at the DuPont Company in Wilmington, Delaware.