Damage-free micro machining using the water-jet-guided laser technology

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Abstract

The principle of the water-jet-guided laser is to focus a laser beam passing through a pressurized water chamber at a small nozzle entrance; the low-pressure water jet emitted from the nozzle guides the laser beam by means of total internal reflection at the water/air interface, in a manner similar to conventional glass fibers. For applications requiring high precision, the water-jet-guided laser obtains excellent results in terms of speed and quality at low maintenance cost, since it does not present any tool wear. The latest results in major applications will be presented. 1) Clean cutting of inserts in hard materials such as PCD and CBN for the tooling industry. 2) Precision cutting of metal parts such as hands for watches (steel and brass). 3) Damage-free cutting of solder masks for the PCB (printed circuit board) industry – 40-micron holes can be drilled through 40-micron thick stainless steel at a rate of 40,000 apertures per hour.

Introduction

The water jet is historically the first optical fiber. In the middle of the 19th century, Daniel Colladon, a 38-year old professor at the university of Geneva (Switzerland), conducted light for the first time in free water jets to demonstrate their break-up ability. 150 years later – more exactly in 1993 – scientists of the Institute of Applied Optics from the Swiss Federal Institute of Technology in Lausanne (EPFL), succeeded in guiding a powerful laser beam in a thin water jet, sufficient to ablate metals. Originally, the technology was developed to decrease the heat damages during laser dentistry. In fact, it revealed that the use of a water jet instead of an assist gas stream had many other advantages besides the cooling effect. Therefore, after the first prototype, the technology was adapted to a large field of applications and markets in industrial laser machining.

1. Laser MicroJet technology

1.1 Basic principle

The basic idea is simply to couple a laser beam into a water jet (see Figure 1). However, the realization is not as simple – if not, there would not have been 30 years between the invention of the laser and the realization of a water-jet-guided laser.

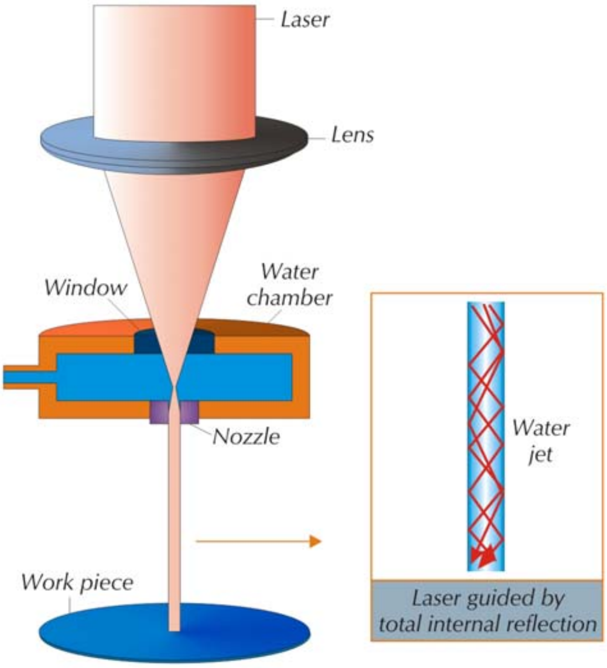

Figure 1 – Basic principle of coupling a laser beam into a water jet

The main difficulty consisted in combining two contrary elements – light and water – that are not compatible at first sight. At the position where the light passes, the water is heated; this temperature change induces a negative refractive index change (so-called thermal lensing) resulting in an expansion of the laser beam strong enough to render the coupling completely inefficient. Understanding this nonlinear optical phenomenon and inhibiting it by an adapted construction of the coupling unit was the key for success. This was realized using a highly dynamic flow in the coupling unit, still generating a stable water jet due to the rotational symmetric water inflow. This trick allowed the coupling of high laser powers in a hair-thin water jet, which can be used for material processing. From its creation more than ten years ago, the Laser MicroJet process was improved in many ways, but the basic principle remained the same.

The water-jet-guided laser can be used for almost any kind of material ablation. Limits are set by insufficient absorption of the laser light by the material of the work piece (glass, wood, tissues) or by high reflectivity (copper). In addition, some applications cannot be performed, such as deep hole drilling at beam size where the water cannot be evacuated. However, holes with aspect ratio (thickness / diameter) of less than 3 can be realized. The use of water (pure H_2O) does not represent a problem. Besides these exceptions, the water-jet-guided laser process has nearly no limits.

1.2 Technical parameters

The laser beam completely fills the water jet (spatially) and is guided by total internal reflection at the water-air interface. The only losses are caused by the absorption in the liquid, depending on the applied wavelength, and Raman-scattering at high peak powers. The water jet diameter is about 83% of the nozzle diameter because of the usage of sharp-edged nozzles and the consequential jet retraction effect (vena contracta). The generated kerf width is in average 10% larger than the water jet diameter. For example, a 30-µm nozzle generates a 25-µm water jet and a 27-µm wide cut. The jet length that can be used for guiding light is roughly 1000 times the nozzle diameter. For example, a 50-µm water jet will be stable on 5 cm at optimum pressure (around 300 bars).

The laser source is typically a pulsed solid-state laser at the fundamental wavelength of 1064 nm (infrared), or a frequency doubled (green, wavelength: 532nm) or tripled (UV, wavelength: 355nm) laser. The choice of the laser parameters depends on the material to process. Intermitted irradiation is used in order to make sure that the water jet cools the work piece during the time between two laser pulses. The average laser power ranges from 50 to 200 W, the pulse length ranges from the nano- to the microsecond, and the pulse repetition rates range, depending on the pulse duration, from 500 Hz to 50 kHz. All lasers are used with fiber delivery, using a step index fiber of 100 to 200 micron core diameter. The optics, that images the end of the delivery fiber onto the water jet nozzle, allows imaging factors ranging from 4:1 to 8:1. The resulting image size or laser spot diameter on the nozzle is thus 50 to 12.5 micron. It is possible to use conventional lamp pumped or diode pumped lasers, or fiber lasers.

A pressure intensifier pump especially developed for this purpose delivers the water, allowing for a constant water flow with pressures ranging from 2 to 50 MPa (500 bars). The water is de-ionized (inverse osmosis and ion exchanger), filtered (1 micron), and de-gassed (vacuum membrane). Water consumption is low, as flow rates are typically only 5 to 75 ml/min. The water jet nozzles (diamond or sapphire) have diameters between 25 and 150 microns. The lifetime of the nozzles can be several months if the video-assisted alignment between nozzle and laser spot is carefully done and regularly controlled.

1.3 Advantages

The first advantage of this technology compared to conventional dry laser cutting is intrinsic cooling. The water jet removes the heat introduced by the laser into the material immediately after the end of each laser pulse. In consequence, the cut edges remain cool and material changes caused by heating, such as recrystallization, oxidation and micro cracks, are avoided. Additionally, the material is not distorting or warping. The tolerances of the final products are very small.

The second significant advantage over dry lasers is cleanness. The water jet removes the molten material from the cut, thanks to a much higher kinetic energy than any assist gas flow; however, the pressure is too low to ablate sold material. A thin water film maintained on the work-piece surface during processing prevents contamination. The remaining particles, already cooled down by the water jet, cannot adhere to the material surface. The ablation products are bound to the water and no hazardous materials are released to the atmosphere. They can simply be filtered out of the wastewater.

The efficient melt expulsion and the immediate cooling enable the process to generate kerfs with very smooth walls, free of deposition. Trenches with a depth precision of only 3 µm can be manufactured. Peak-to-valley wall roughness of less than 1 µm upon cutting can be realized.

Finally, due to the light guidance, no focus-control system is necessary, as the distance between work piece and nozzle is arbitrary within the working distance of the jet. The cut quality does not vary with the distance. As the water jet guides the laser down to the bottom of the cut, very high aspect ratios can be achieved during cutting. Cut edges are parallel. The diameter of the laser beam is determined by the diameter of the water jet, which is constant. These stable conditions allow a cutting precision of down to 1 micron.

Compared to mechanical cutting methods, such as abrasive sawing, the Laser MicroJet offer important benefits for micro machining, the most important being the absence of mechanical damage to the work piece. Indeed, the constant force applied by the water jet is negligible (< 0.1 N). Cutting speeds on thin materials are also higher (up to 300 mm/s on 50-µm thick silicon). Running costs are lower, mainly because there is no tool wear; water consumption is also very low.

2. Applications

Nearly all usual laser applications (except deep hole drilling and cutting of thick metal sheets) can be performed with the water-jet-guided laser. In addition, the Laser MicroJet proved efficient for delicate applications that are beyond dry lasers, such as semiconductor wafer dicing.

2.1 Dicing of semiconductor wafers

Wafers are thin plates of semiconductor materials like silicon (Si), gallium arsenide (GaAs), indium phosphide (InP), gallium nitride (GaN), silicon carbide (SiC), low-k wafers, etc. Once that circuits have been generated on the wafer, it has to be diced into individual chips. Because a majority of these materials are brittle, damage-free dicing is difficult; this problem is aggravated by the present trends aiming at reducing the wafer thickness (minimum: 50 µm) and using fragile top layers.

The established method for wafer dicing is abrasive sawing with a diamond blade. Conventional laser cutting was not able to penetrate this market because of important quality problems. In the past few years, the water-jet-guided laser proved its capabilities to enter this market, thanks to very low surface contamination, absence of heat damage and increased cutting speeds.

Figure 2 shows a 100-µm thick GaAs wafer. Using a 25-µm nozzle, a kerf of 23 µm was produced. The chosen laser was an infrared fiber laser (wavelength 1064 nm). Considering the brittleness of this material, a high cutting speed was achieved (40 mm/s). Circuits are not damaged by the dicing step (no cracks, no chipping). Kerfs are constant and no contamination is visible.

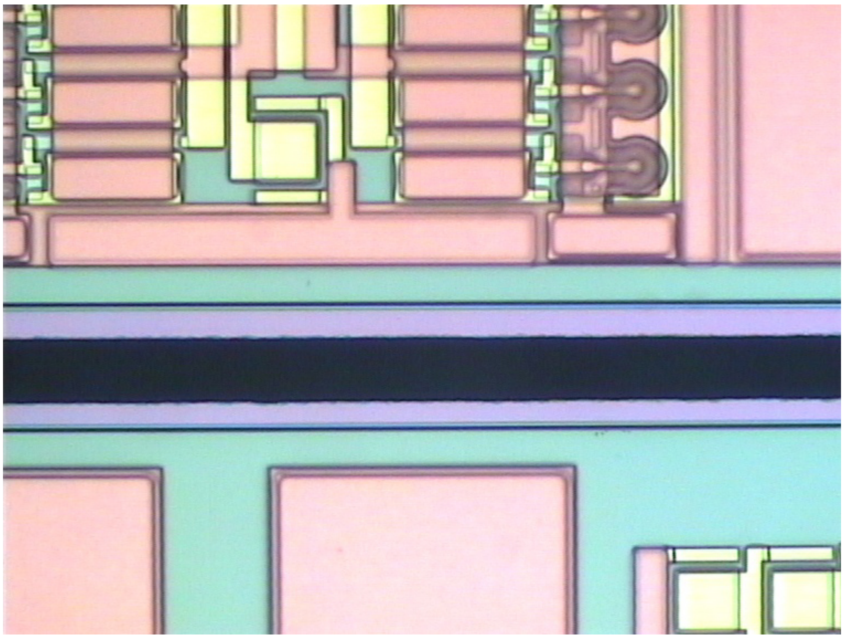

Figure 2 – Dicing of a thin GaAs wafer at a speed of 40 mm/s

2.2 Stencil drilling

Stencils are metal masks, employed for example during the production of printed circuit boards to apply solder paste, or for the manufacturing of flat panel displays. Standard methods for stencil production are conventional laser cutting and for thin precision stencils, etching. The trend towards smaller apertures, increasing aperture number, thinner stencils and lower tolerance requirements make the water-jet-laser cutting very attractive. Thin bridges between holes do not bend, nor does the stencil warp. The small beam radius of 14 microns allows for sharp edges. No oxidation occurs, nor contamination, and practically no burrs remain to remove. The wall angle is programmable in order to assure easy solder paste release. Thanks to an adapted image processing system, repair of only partially cut apertures is also possible.

Figure 3 shows square openings (600 µm x 600 µm) made in a 150-µm stainless steel sheet. The resulting speed was 5,000 holes per hour. Edges are very clean and the material is not affected by the heat.

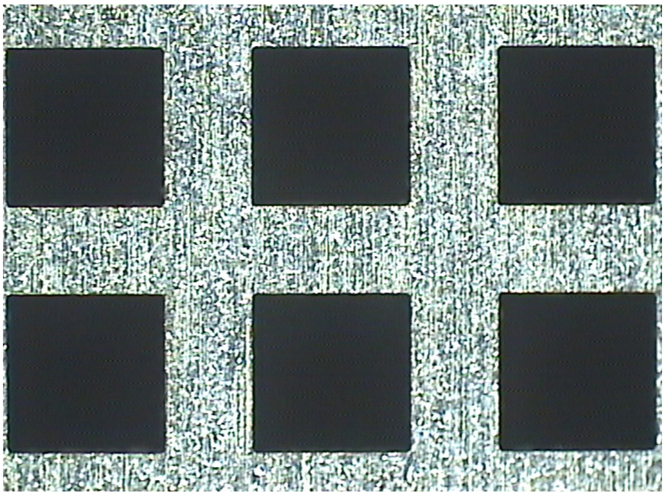

Figure 3 – Square openings, 600 µm x 600 µm, in 150-µm thick stainless steel; rate: 5,000/hour

2.3 Medical devices: stents

Stents are used in medicine to open up congested blood vessels. They support and dilate the tissue and thus allow a normal blood flow. Stents are usually made in stainless steel or shape-memory alloys such as Nitinol. The contours, which have to be cut in these thin tubes, are very small and complicated. Up to now, the main manufacturing methods have been conventional laser cutting and chemical etching. Dry laser cutting, however, requires important post treatment by mechanical and chemical cleaning and polishing steps, in order to reach the final required quality. Because the water-jet-guided laser is a gentle process (no mechanical or thermal damage), no material changes occur when cutting – an important property for this application as product failure is fatal. The quality after Laser MicroJet processing is much higher than with dry laser cutting, resulting in reduced post-treatment steps. The small radius of only 14 microns enables fine contours. Cutting speeds of more than 12 mm/s allow high throughput.

Figure 4 shows the typical quality obtained after Laser MicroJet cutting of a Nitinol stent, as no chemical post treatment was applied. Only a soft rinsing in de-ionized water has been applied. There is no visible heat-affected zone, no oxidation, no thermal deformation, no change in elastic properties and no cracks. For this stent, a pulsed infrared laser (wavelength: 1064 nm, average power: 23 W) and a 30-µm nozzle were chosen as the most suitable configuration. The stent is fixed on a rotary axis with a tubular plastic fixation during cutting and water flows inside the stent to prevent damaging the inner wall.

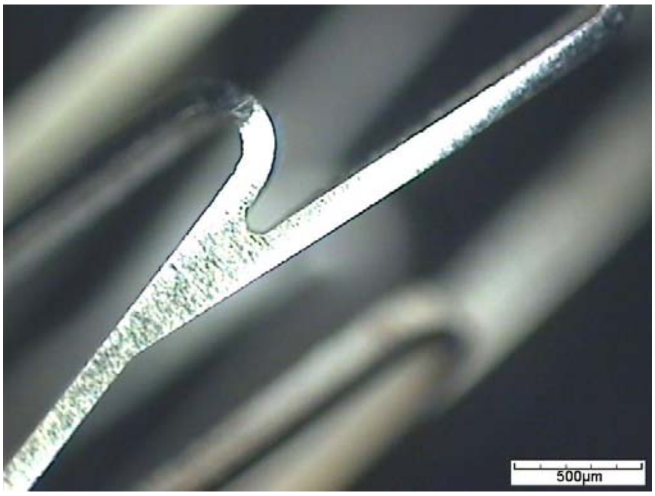

Figure 4 – Detail of a stent in shape-memory metal alloy Nitinol directly after cutting with the Laser MicroJet (thickness: 200 µm)

2.4 Cutting of hard materials (CBN, PCD)

Hard materials like cubic boron nitride (CBN) and polycrystalline diamond (PCD) are mostly used as inserts for abrasive tools. The “active material” is often bonded to a substrate, usually tungsten carbide (WC). During insert production, both layers need to be completely cut. The cutting quality obtained by Laser MicroJet cutting is high enough to use the inserts without additional post-processing. The cutting speed is high, considering the hardness of these materials and the thickness of the inserts.

Figure 5 shows a triangle insert with PCD on the front side and WC on the backside (total thickness: 1.6 mm). A green Q-switched laser (wavelength: 532 nm, average power: 150 W) was coupled into a 72-µm water jet. The WC layer was cut first and is referred to as “front side”. For through cut, a total processing speed of 12.8 mm/min was reached in 70 passes.

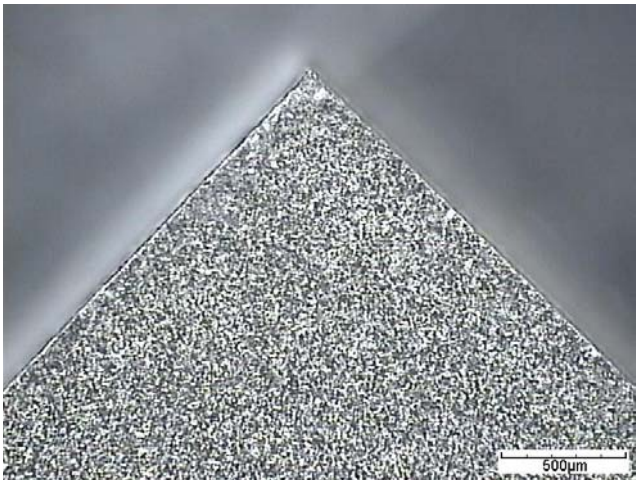

Figure 5 – Corner of a PCD / WC triangle insert (backside, PCD)

The water-jet-guided laser combines in one process the flexibility and speed of a laser with the precision and quality of the EDM process.

2.5 Silicon slotting for inkjet printers

In inkjet printer heads, a silicon chip is used as a barrier between the orifice plate, which contains hundreds of nozzles, and the ink reservoir. The slots are created by Laser MicroJet at high speed: 9 mm/s in 675-µm thick silicon, which corresponds to 3 seconds for a 12-mm long slot. With this process, the slot ends are always very steep and walls are parallel and smooth, free of chipping and burrs. In addition to through cutting, grooved slots can be created, at controlled depth, down to high-aspect ratio slots; the slot bottom remains flat (constant ablation depth per pass).

Figure 6 shows a slot start from the backside of a 650-µm thick silicon barrier. A green Q-switched laser (wavelength: 532 nm, average power: 33 W) was used with a 30-µm nozzle generating a 27-µm water jet. The cutting speed was limited to 5 mm/s because of the wafer thickness and to achieve the required cutting quality. A "race-track" method has been used, which allows higher speed and improved cutting quality. The water jet automatically removes the remaining inner part.

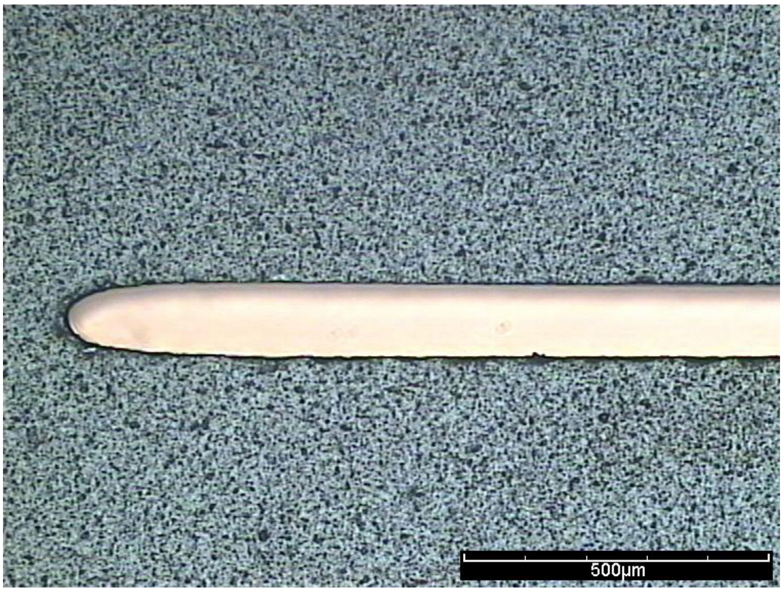

Figure 6 – Slot start in thick silicon (backside)

3. Conclusions

Fast, flexible, clean and damage-free, the water-jet-guided laser should not be confused with a conventional dry laser. Since its creation more than ten years ago, this innovative technology has proved its capabilities in many different fields, including the semiconductor, electronics, medical devices and tooling industries. Every year, new application fields open up to the Laser MicroJet. Thus, in 2005, the process has been adapted for three entirely new applications: silicon slotting for inkjet printer heads, cutting of substrates for hard-disk-drive heads and cutting of masks for OLED displays. The water-jet-guided laser is also constantly improved. For example, very small nozzles of down to 20-µm are currently being tested in the laboratory. New laser sources are also investigated.