

## **Precise thin metal cutting using the Laser MicroJet**

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### **Summary**

*This paper presents an overview of thin metal cutting applications performed using the water jet-guided laser technology. The applications include stencil cutting, OLED screen cutting, fuel injection nozzle drilling, watch hand cutting, and stents cutting.*

**Key words:** thin metal, laser, Laser MicroJet, cutting, drilling, micromachining

### **1 Introduction**

The water jet-guided laser technology, first presented in 1993 [1,2], has found a broad range of applications in the precision micromachining field. The water jet-guided laser (also called Laser MicroJet® or LMJ®) is used today in a wide range of industrial fields, such as semiconductor, solar, electronics, medical, tooling [3], high-brightness LED [4], watch and automotive industries.

The LMJ principle is to couple a high power, pulsed laser beam into a hair-thin, low-pressure water jet. A schematic of the principle is shown in Figure 1. The beam of a high power laser is transmitted by fibre optic cable to an optical head. There the laser beam is focused through a transparent window into a nozzle placed at the bottom of a thin water-filled chamber. Pure de-ionized, degassed and filtered water is introduced into the water-filled chamber. The water pressure ranges from 50 to 600bar, depending on the nozzle diameter. Larger nozzle

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diameters require a smaller water pressure. Typical nozzle diameters range from  $20\mu\text{m}$  to  $150\mu\text{m}$ . The cylindrical water jet exiting the nozzle guides the laser beam by means of total internal reflection at the water/air interface, similarly to conventional glass fibers. When it reaches the work piece, the laser ablates the material by melting and vaporization.

The capabilities and performances of this process are different from those of conventional dry lasers. First, because the water jet is cylindrical and the guided laser beam parallel, kerf walls are highly parallel. The working distance – corresponding to the stable length of the jet – can be several centimeters long, depending on the jet diameter. Working distances in excess of 15 cm are possible with the largest nozzle diameters. Given the long working distance, there is no need for expensive focus control optics. Second, the water jet-guided laser prevents heat damage to the material by cooling the cutting edges in between the laser pulses. Third, contamination is greatly reduced, as the water jet develops a high kinetic energy that efficiently removes the molten material generated by the laser ablation. Contamination by particle deposition is avoided thanks to a thin water film that covers the wafer surface during the cutting process. The particles, already cooled down by the water jet, do not adhere to the wafer surface. The mechanical force of the water jet onto the wafer is negligible ( $<0.1\text{N}$ ) due to the small jet diameter and the low water pressure. This leaves the material unscathed when exposed to the bare jet. The process does not generate chipping or micro-cracks. As a comparison, the assist gas jet used in conventional laser cutting applies a force of around  $1\text{N}$ , ten times higher than the water jet-guided laser. Water consumption is very low, averaging about  $1.5\text{l/hour}$ .

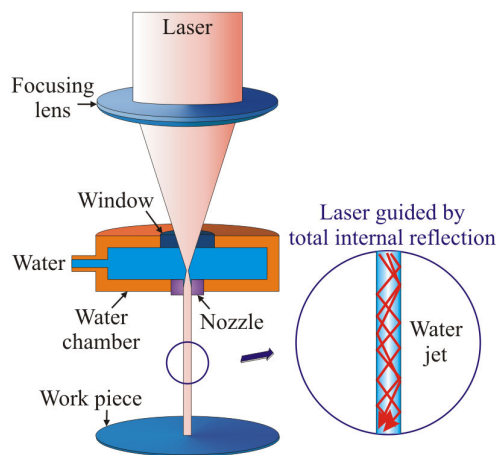


Figure 1: Principle of the Laser MicroJet

Different Nd:YAG laser sources with wavelength of  $1064\text{ nm}$  working in pulsed or Q-switch regimes have been used with the water jet-guided laser technology. Flash-lamp-pumped and diode-pumped infrared lasers were implemented. In recent years, new laser technologies such as disc and fiber lasers have been deployed with success in a wide range of demanding applications, where the LMJ

system operates in 24/7 production environments. IR lasers operating around 1064nm are the preferred laser sources for the micromachining of thin metal layers as they cause less heat affected zone.

Frequency-doubled Q-switched DPSS and disc lasers operating at 532nm and 515nm have become the standard laser sources for all other LMJ applications due to their excellent compatibility with water absorption spectrum. The only constraint on the laser wavelength is that it must be compatible with the water transmission spectrum, which has a minimum in the green region of the optical spectrum. The absorption coefficient  $\alpha$  in the water jet is the lowest ( $\alpha = 4E-4 \text{ cm}^{-1}$ ) at wavelengths around 532nm. The absorption coefficient is about 500 times higher around 1064nm ( $\alpha = 0.2 \text{ cm}^{-1}$ ). The light transmission over a 2.5cm water jet is as high as 99.9% at 532nm, and 60% at 1064nm. This means that the light absorption at 532nm can be neglected. At 1064nm the absorption in water is not an issue as long as the average power remains below about 200W.

## **2 Thin metal cutting applications**

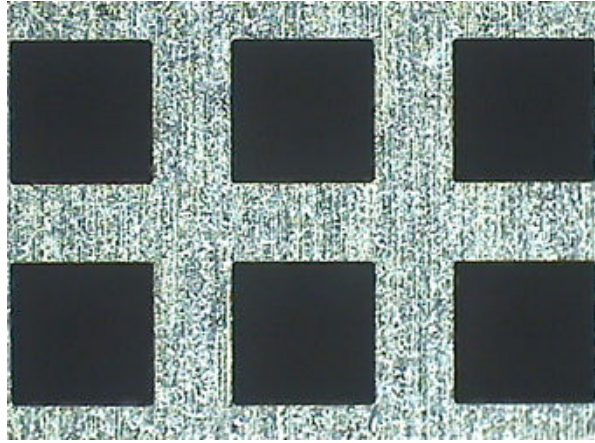
### **2.1 Stencil cutting for Surface Mount Technology**

Stencil cutting imposes rigorous requirements: precision, quality and speed are paramount. When the number of apertures increases, achieving high speed is very important. The tapered angle of the apertures must be controlled, since it is necessary to ensure that the solder paste detaches easily from the stencil. It is also essential to avoid burrs and particle deposition and ensure high cutting precision so that the volume of solder paste in each solder bump is precise and consistent. Last, applied forces and heat affected zone (HAZ) should be reduced to the extent possible when cutting thin metal foils. Stainless steel expands by 16 to 18  $\mu\text{m}$  per meter length per  $^{\circ}\text{C}$  as the material is heated. Consequently, stencils measuring 500x500 mm must be cut with an average temperature as stable as  $\pm 0.6 \text{ }^{\circ}\text{C}$  to achieve a  $\pm 5 \mu\text{m}$  tolerance.

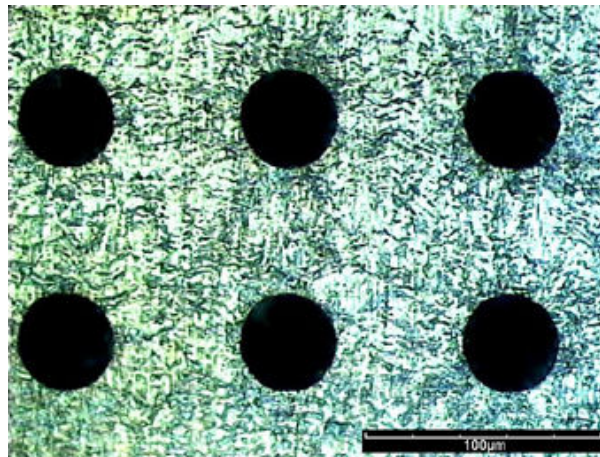
The water jet guided laser is well suited for stencil cutting as the process is fast, accurate and clean. A high cut quality can be achieved using an infrared pulsed laser. In percussion drilling, the LMJ can make very small round holes at high speed – up to 50'000 apertures per hour in 50 $\mu\text{m}$  thick steel. However, as the roundness is not perfect in percussion drilling, the water jet guided laser is usually used in trepanation drilling (e.g. the axes are moved in a circular motion), which produces high quality apertures.

Figure 2 shows square apertures (600 $\mu\text{m}$  x 600 $\mu\text{m}$ ) made in a 50 $\mu\text{m}$  thick stainless steel sheet. The resulting speed was 5'000 holes per hour. The edge is clean and the material has no visible heat effect. Figure 3 shows a round aperture (diameter 40 $\mu\text{m}$ ) made in a 40 $\mu\text{m}$  thick stainless steel sheet. The

resulting speed was 40'000 holes per hour. The infrared fiber laser was used with this stencil (average power 30 W), coupled with a thin water jet (diameter 23 $\mu$ m).



*Figure 2: square apertures, 600 $\mu$ m x 600 $\mu$ m, in 50 $\mu$ m thick stainless steel*



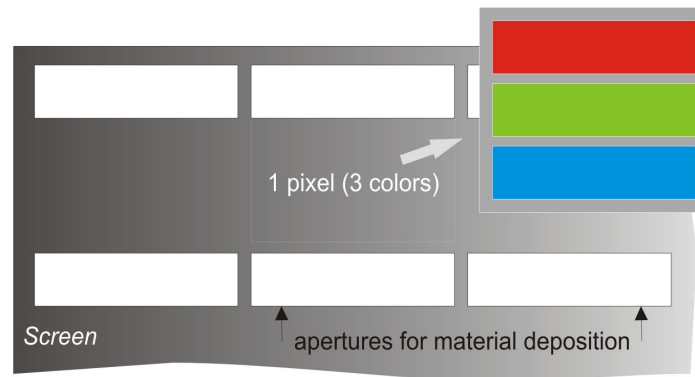
*Figure 3: round apertures, diameter 40 $\mu$ m, in 40 $\mu$ m thick stainless steel*

## 2.2 OLED mask cutting

Metal screens are used during manufacturing of OLED displays to deposit the emitting layers onto the substrate of the panel. An OLED cell – corresponding to one pixel – contains all three colors (RGB). Therefore, the mask openings have to be rectangular (see Fig. 4), so at the end of the process a square containing the three colors is obtained. An example of mask configuration can be seen in Figure 5 (succession of 100 $\mu$ m x 300 $\mu$ m openings).

The usual materials for these masks are stainless steel and nickel/steel alloys, and the thickness of the sheets typically ranges from 30 to 50  $\mu$ m. A single mask can be used for parallel fabrication of several small screens. For example, as one

cell-phone screen has more than 30'000 pixels, the total number of openings in the mask can reach 3 millions. The cut quality is paramount – very precise and constant shapes are required. In addition, due to the production requirements, screens must be manufactured at high speed.



*Figure 4: example of an OLED mask design*

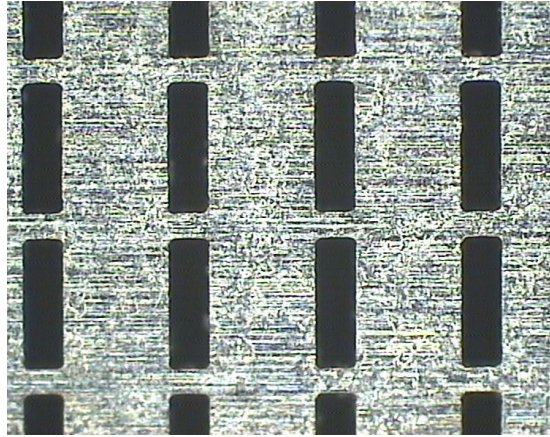
Etching is currently the most widely used method for producing these screens. It is however an expensive process and accuracy-related problems can arise as screens become larger. Lasers present several advantages compared to etching as they combine high flexibility and relatively low running costs. Dry laser cutting is however limited due to the presence of heat affected zones, making its use for fine-pitch structures unsuitable, as heating generates inaccuracies and bending. In addition, small particles and burrs remain, imposing post-processing steps. The water jet guided laser is a cutting technology that provides excellent quality in a single step process, permitting lower costs when compared to the other available processes for higher production rates.

Because of its original features, the water jet-guided laser is well suited for screen cutting. It is three to five times faster than conventional laser in same conditions, and less expensive than etching. For an optimal quality-to-speed ratio, the Laser Microjet is used in trepanation-drilling mode: the axes are moved on a controlled path (e.g. circle or rectangle) to produce precise openings.

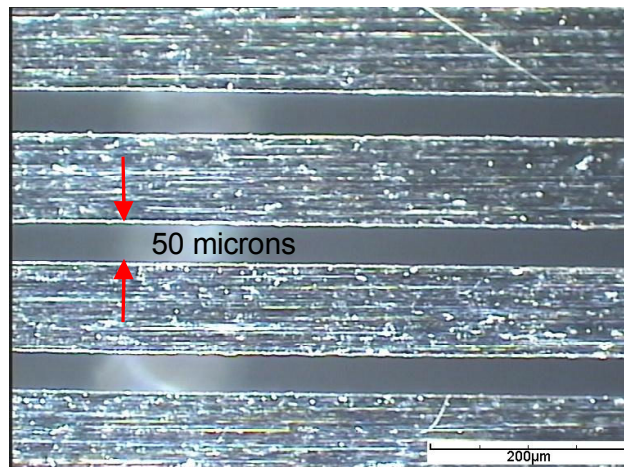
The cutting width depends on the nozzle diameter, ranging from 20 to 150 $\mu\text{m}$ . Very small openings are therefore possible. The cutting speed depends on the thickness and the material of the screen; the thinner the pieces, the higher the speed.

In the case presented above, where rectangular openings need to be drilled (dimensions: 100 $\mu\text{m}$  x 300 $\mu\text{m}$ ) in 50 $\mu\text{m}$  stainless steel, the water jet guided laser achieves a drilling rate of 20'000 openings per hour. In these dimensions, a 40 $\mu\text{m}$  nozzle is usually used. An infrared fiber laser was selected for this application. Openings are very constant and clean; processed screens show no

burrs and very few non-adhering particles, which are easy to remove with a standard ultrasonic cleaning process. The material has no visible heat affection.



*Figure 5: rectangular openings, 100 x 300 $\mu$ m wide, in 50 $\mu$ m stainless steel*



*Figure 6: narrow slots in 30 $\mu$ m thick Invar*

The microscope picture shown in Fig. 6 illustrates the high cutting quality results obtained using the Laser MicroJet® technology for the manufacture of very long narrow slots (aspect ratio of 1/1000) in 30 $\mu$ m thick Invar material. Due to the efficient cooling effect of the water jet, neither heat nor warping effects exist.

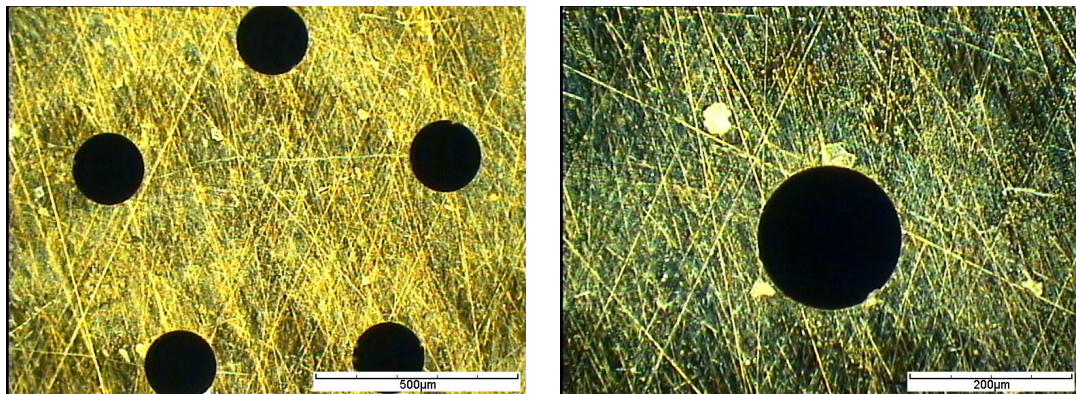
Besides of this high requirement on through-cut quality, a symmetrical and controlled wall taper of the cut is essential for the optimal deposition of electroluminescent materials. In one experiment, the taper angle was varied from 52° to 60° by changing the laser current. Because of a high speed of 200mm/s, a mask sample with 60 cells and 14,520 total lines was cut in only 110 minutes.

Typical dimensions are as follows: 55 mm line length, 95 $\mu$ m cut width on the front side, 50 $\mu$ m cut width on the backside and 140 $\mu$ m pitch between lines. Due to the acceleration or deceleration of the x or y movement at the start and end of the line, a widening at the slot ends could occur. To overcome this, a synchronous function was introduced. When using this synchronous function, the laser is switched on and off while the axis is moving. All accelerations and decelerations are outside the slot and hence have no influence on the cutting results.

### 2.3 Fuel injection nozzles

Fuel injection devices are designed for directing and optimizing the fuel flow into the combustion chamber. The fuel is forced through the injection nozzles under high pressure, which atomizes the fuel into a spray. When the fuel spray is mixed with the proper ratio of intake air, the combustion process is almost complete, yielding high engine fuel efficiency. The diameter and depth of the fuel injection nozzles are adjusted to the desired flow rate, speed and pressure. Their dimensions of typically 180-260 $\mu$ m diameter and 120-220 $\mu$ m thickness, with a tolerance of  $\pm 2\mu$ m, require very high precision machining. The operating conditions require the use of hard materials, extremely resistant to wear and corrosion, such as stainless-steel and AISI 440C, a high-grade Chromium martensitic stainless steel.

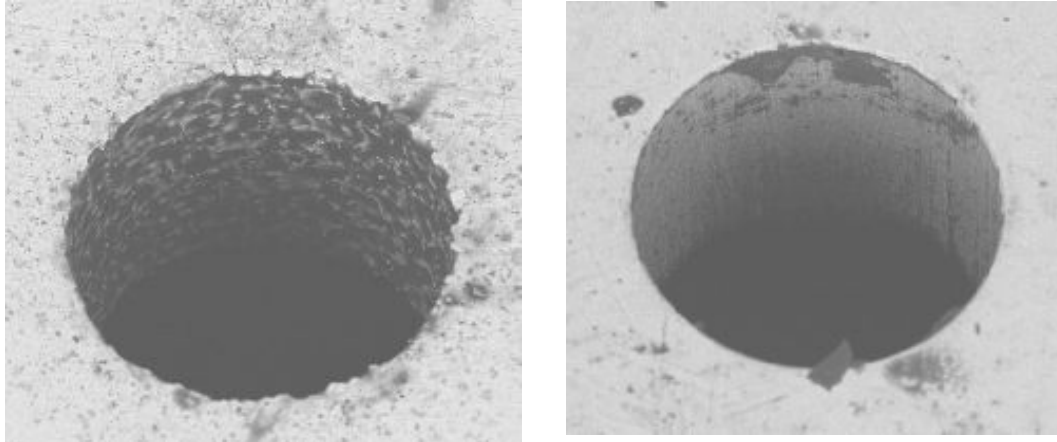
The results presented in this section are based on a series of tests consisting in drilling holes of different diameters in samples made out of different materials. The tolerance on the hole diameter is of  $\pm 2\mu$ m.



*Figure 7: fuel injection nozzle with 30 $\mu$ m hole drilled*

For these tests, a long pulsed diode pumped (Nd:YAG) infrared (1064 nm) laser has been selected, as it causes less heat affected zone than shorter wavelength beam, and because the peck holes can be done in a single pass, improving the wall quality. The pulse frequency, pulse length and average power were optimized for obtaining the best cutting quality. A nozzle of 30 $\mu$ m diameter and a water pressure of 350 to 450bar were used, producing a water jet of about 26 $\mu$ m diameter, with a water pressure also optimized for obtaining the best

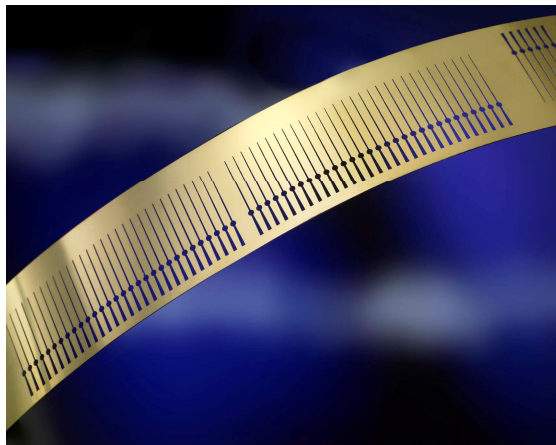
cutting quality. The cut quality can be assessed from the pictures on Figure 7. Injection nozzles were drilled using Electrical Discharge Machining (EDM) and water jet-guided laser technology. Figure 8 shows a comparison of the quality in both cases, with the LMJ clearly providing superior surface and wall quality.



*Figure 8: comparison of nozzle quality for a nozzle drilled with EDM (left) and LMJ (right).*

## 2.4 Watch applications

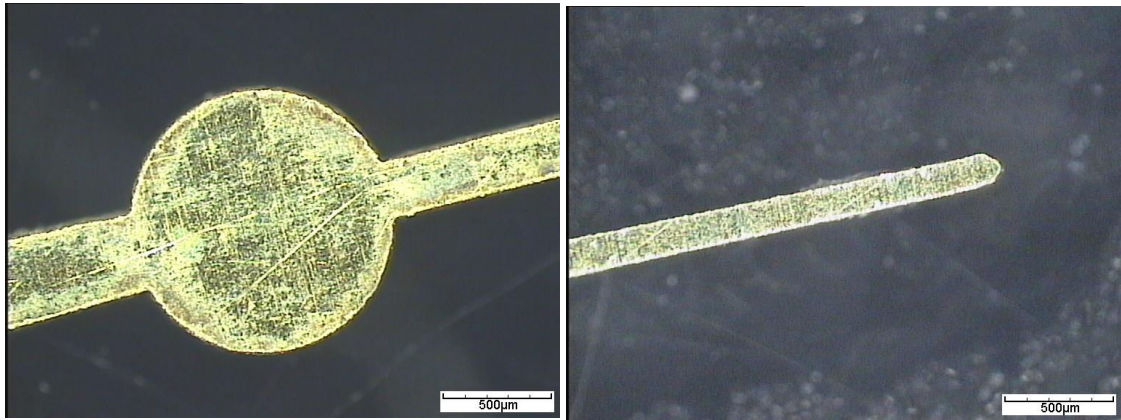
The hands on today's watch mechanisms, either pure mechanical or battery driven, place demanding requirements on the manufacturers, especially for items destined for the luxury market. Cutting such fine mechanical parts, which are normally made from brass or steel, with conventional dry lasers does not produce good results, due to the resulting heating effects, burrs and deposition of ablated material. These in turn require additional processing steps, before the part can finally be used.



*Figure 9: continuous cutting of watch hands*

Using the Laser MicroJet® as a cutting tool for watch hands from 200µm brass has been demonstrated, with excellent results. For the tests, a LSS800 stencil cutting machine was employed, using an Nd:YAG 532nm pulsed laser, operating at 15kHz and average power of 40W. The Laser MicroJet® was equipped with a 40µm nozzle, operating with a water pressure of 280bar.

One of the main goals was to demonstrate a high cutting speed and achieve a time of <8 seconds/hand in continuous operation. Figure 9 shows the results of a short sample test run. The following two images, Figure 10 shows magnified views of the front side and backside watch hand surfaces immediately after cutting.



*Figure 10: microscopic image of front side (left) and backside (right) of a brass watch hand.*

## 2.5 Stents

The Laser MicroJet has also proved itself in the manufacturing of medical devices, especially stents. These devices, which are essential for today's increasing use of non-invasive surgery practices, are used extensively for counteracting localised constrictions in bodily organs, such as arteries which have been cleared after angioplasty. The stent is installed on a balloon catheter in a collapsed state, moved to the affected area and then expanded by inflating the balloon, the stent then locks into place in the artery, forcing it to remain open.

Since the stent will remain inside the human body, and is crucial to the patient's long-term health, the finish is paramount, requiring a high level of quality control during fabrication, i.e., clean smooth surfaces with no attached dross or burrs.

The devices require the cutting out of intricate patterns in the metal sheet or tube to obtain struts, the shape of which together with the type of material employed, determine its expansion characteristics. The main materials used are flat or tubular stainless steel, titanium, or Nitinol (NiTi) of varying thickness or diameter. Of these three materials, 316L stainless steel, which is non-ferrous, is the most

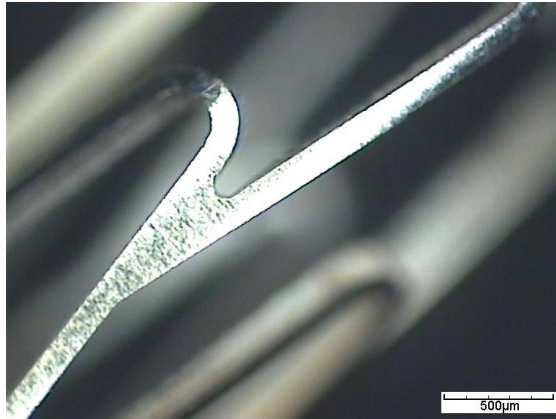
commonly used. For flat sheets, which are later bent to form a tube and welded; the material thickness can vary between 100 and 200 $\mu\text{m}$ . For tubular stents, the diameters typically vary from 1 to 5mm and the tube wall thickness from 30 to 600 $\mu\text{m}$ .

Conventional cutting using an Nd:YAG laser, characteristically leaves an oxide layer on the surface of the stent, and remelt on the sides of the struts due to diffusion of the laser beam as shown in Figure 11. These unwanted artefacts must then be removed, typically using a closely controlled micro blasting process, to avoid weakening the strut joints, which could subsequently lead to premature device failure. Besides these additional processing steps, other factors such as cutting speed and the degree of automation required, all contribute to a limited throughput in stent production.



*Figure 11: Microscopic image of a 316L stainless steel stent cut with dry laser, directly after cutting.*

In comparison, the LMJ provides excellent and fast cutting quality (parallelism and smoothness) and especially no thermal damage, as shown in Figure 12. Stent materials exhibit excellent absorption properties at infrared (IR) and so efficient machining with lasers operating at this wavelength is possible. Using a diode pumped pulse 1064nm IR laser operating at 1.5kHz, with 23W average power, and a cutting speed of 9mm/s. The nozzle diameter was 30 $\mu\text{m}$  and the water pressure 300bar. A clean, remelt-free cut was achieved and the continuous water jet immediately cools the material. The results are a very narrow burr-free cut, with parallel kerfs, little or no thermal penetration and no oxidation as shown in Figure 12. As no remelt is created during the cutting, micro blasting can be significantly reduced or even eliminated. The LMJ process increases the quality of the manufactured item and removes the danger of stent failure due to weakened struts, eliminating possible future legal liability issues.



*Figure 12: microscopic image of stent made from 200µm Nitinol directly after LMJ cutting*

### 3 Conclusion

The water jet-guided laser technology is ideal for micromachining applications of thin metal layers. The LMJ has already been deployed in a broad range of demanding industrial applications, such as stencil and OLED screen cutting, fuel injection nozzle drilling, watch hand and stents cutting, just to name a few.

The LMJ combines the advantages of a high energy pulsed infrared fiber laser with a hair-thin water jet. While the laser is used for material ablation, the water jet is used for guiding the laser light, cooling the edges and preventing the sample from particle contamination, advantages that are essential for cutting with high quality.

### 4 References

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