

# Laser MicroJet<sup>®</sup> for High Precision Drilling of Mechanical Devices such as Fuel Injection Nozzles

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Manufacturing of injection nozzles necessitates a drilling precision of  $\pm 2 \mu\text{m}$ . Cut quality is also a critical requirement. Presently, the main process used is EDM, a method known for its cut quality, but implying a long processing time. Water jet-guided laser has proven to be even more suited to the micromachining of these parts. Due to the cooling effect provided by the water jet between laser pulses, the cut edges are immediately cooled and the material does not suffer from thermal effects nor mechanical damage. Tool replacements and post-processing are also avoided.

**Keywords:** laser microjet, water jet laser, micro cutting, precision drilling, fuel injection nozzle

## 1. Introduction

The water jet-guided laser technology - also known as Laser MicroJet<sup>®</sup> or LMJ - was developed in 1993 as a solution to avoid cracks, chipping and deposits of silicon slag in wafer dicing [1,2]. It is now used in a variety of applications like solar cells, integrated circuits, stencils, OLED masks, etc [3-5]. More recently, research was carried out to develop this technology for high precision machining for automobile industry applications, and as a result, very competitive cutting speed and unequalled quality were achieved.

In this article, a brief introduction to the Laser MicroJet<sup>®</sup> technology is given, then the technique for cutting fuel injection nozzle is presented, and finally a comparison to the common techniques is discussed.

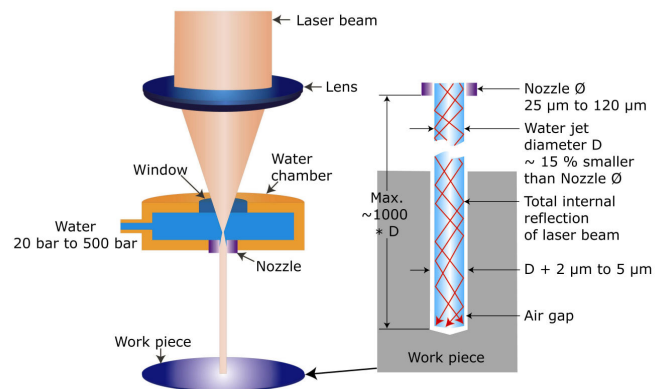
## 2. The water jet-guided laser principle

The Laser MicroJet<sup>®</sup> is a unique process based on the combination of a laser beam and a water jet. The concept is to focus a laser beam into a nozzle while passing through a pressurized water chamber; a schematic of the principle is shown in Figure 1. The low-pressure water jet emitted from the diamond nozzle guides the laser beam by means of total internal reflection at the water/air interface, in a manner similar to conventional glass fibers.

The water jet acts thus as a fluid optical wave-guide of variable length that remains stable while penetrating into the material, which means that the beam size impacting the material is always constant. Only the laser is used for ablation; the main function of the water jet is to guide the laser beam onto the work piece. It ensures the consistency of the spot diameter and consequently enables a single, centimeters-long focus. The water jet has other beneficial effects that prove extremely interesting for precision cutting: maintaining kerfs absolutely clean, simultaneously cooling the edges between the laser pulses and thus preventing heat

damage within the material. Hence the water jet-guided laser can be called a "cold laser".

The laser beam is coupled to the water jet in the nozzle, which shape contracts the water jet. The diameter of the water jet is about 83% of the nozzle diameter. A 300-500  $\mu\text{m}$  water chamber is formed between a quartz window and the nozzle, with up to 500 bars of water pressure.



**Fig. 1** Schematic of the Laser MicroJet<sup>®</sup> working principle.

## 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

$\mu\text{m}$  diameter and 120-220  $\mu\text{m}$  thickness, with a tolerance of  $\pm 2 \mu\text{m}$ , 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 (typical composition in %: 16-18 Cr : 0.95-1.20 C : 1.0 Mn : 1.0 Si : 0.040 P : 0.030 S : 0.75 Mo : balance Fe).

The results presented in this article are based on a series of tests, summarized in table 1, consisting in drilling holes of different diameters in samples made out of different materials. The tolerance on the hole diameter is of  $\pm 2 \mu\text{m}$ .

**Table 1** Material, thickness and target hole diameter for the samples used in the present study.

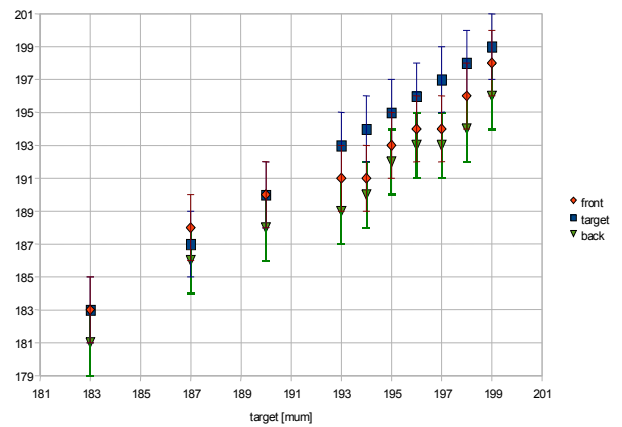
sample	Material	Thickness	targeted diameter
		$\mu\text{m}$	$\mu\text{m}$
S1	AISI 440C	220	255
S2	AISI 440C	220	255
S3	AISI 440C	160	180
S4a	AISI 440C	160	183-193
S4b	AISI 440C	160	194-199
S5	AISI 440C	127	260
S6	steel	200	260
S7	stainless steel	140	160

### 3.1 Cutting Parameters

For these tests, a long pulsed diode pumped (Nd:YAG) infrared (1064 nm) laser has been selected, as it causes less HAZ (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  $\mu\text{m}$  diameter and a water pressure of 350 to 450 bar were used, producing a water jet of  $\sim 26 \mu\text{m}$  diameter, with a water pressure also optimized for obtaining the best cutting quality.

## 4. Results

Figure 2 show the measured frontside and backside hole diameters for AISI 440C samples of 160  $\mu\text{m}$  thickness. For all samples, the front and back side hole diameter was measured to be within the targeted diameter tolerances.



**Fig. 2** Measured frontside and backside hole diameter vs target.

Excellent results were also obtained with samples S1, S2, S5 and S6, which targeted diameter was of 255-260  $\mu\text{m}$ . The front and back side hole diameter was measured to be within the tolerance of the targeted diameter.

### 4.1 Processing Time

In the case of sample S6, the total processing time per injection nozzle with 4 holes was of 20 s, including the water jet setup ( $\sim 6$  to 10 s). More generally, on an industrial time scale, 500 injection nozzles were produced in a total of 2h, taking into account the laser alignment procedure. The processing time can be made significantly shortened as the cutting quality surpassed the target: a faster cutting speed would allow the drilling of holes with reasonable cutting quality. Batch processing by stacking several injection nozzles on the 300 x 300 mm working surface of the Synova LCS 300 machine, or even bigger for the LSS 800, greatly improves the processing time, as water jet setup is done only once per cycle.

### 4.2 Quality

After the cutting, the quality of the samples is evaluated by observing the cutting edges with a microscope with three points of view:

1. front side, where the Laser MicroJet<sup>®</sup> is incident;
2. back side, where the Laser MicroJet<sup>®</sup> comes out after the cut;
3. cross-section.

The illumination is done in two modes: backfield illumination, for which the light is incident on the sample, and dark field illumination, for which indirect light enhances the details of a sample.

Photos shown in figures 3-6 were taken with a yardstick of 200 to 500  $\mu\text{m}$  precision, showing in most cases edges linearity down to 10  $\mu\text{m}$  ( $\sim 6\%$  of the thinnest sample) on all three points of view. The edges are sharp and perfectly clean, and there is no recast, nor thermal effect. This dem-

onstrates the potential of the Laser MicroJet<sup>®</sup> technology for achieving very high cutting quality.

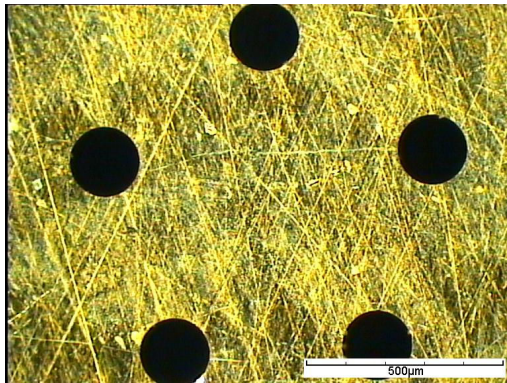


Fig. 3 Sample S4a front side (dark field illumination)

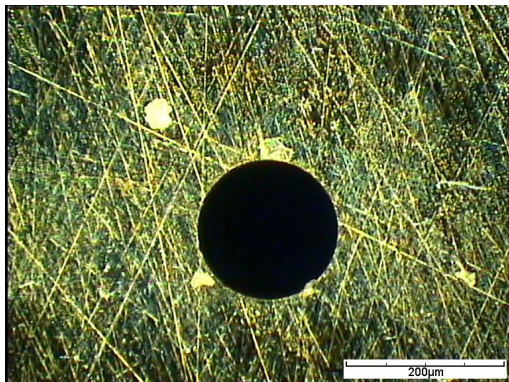


Fig. 4 Sample S4a front side (dark field illumination)

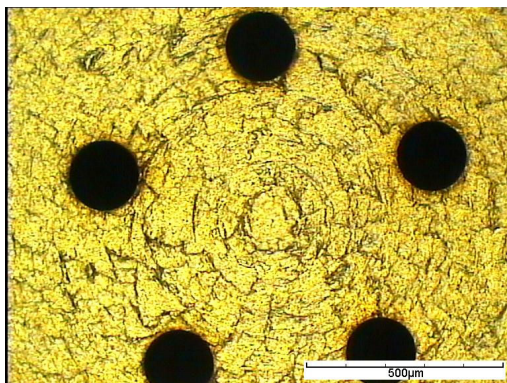


Fig. 5 Sample S4a back side (dark field illumination)

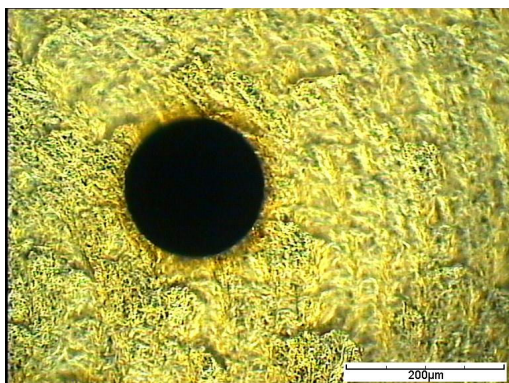


Fig. 6 Sample S4a back side (dark field illumination)

### 4.3 Technical improvements

Figure 7 shows the great improvement in the cutting quality between samples S1 and S2; this is due to the fact that sample S1 was not properly secured during the drilling. This issue was solved for the remaining of the tests.



Fig. 7 Sample S1 (top) and S2 (bottom) front side (dark field illumination)

In the case of sample S7, shown in figure 8, the holes were drilled with a 11° angle. The targeted hole diameter of the backside was of 160 µm with 2 µm tolerance, and was measured to be of 162 µm; the frontside hole diameter was measured to be 164 µm. Therefore the Laser MicroJet<sup>®</sup> technology is appropriate for drilling injection nozzle holes with an angle, with a cutting speed and cutting quality similar to the drilling of straight holes discussed above.

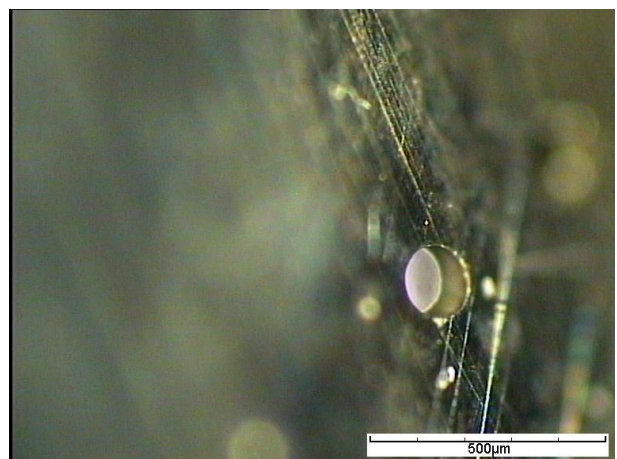


Fig. 8 Sample S7 cross-section (dark field illumination)

## 5. Comparison with other techniques

The Laser MicroJet<sup>®</sup> performance is compared to the most common techniques used in the automobile industry for drilling fuel injection nozzles: conventional laser, punching and EDM (electro-discharge machining).

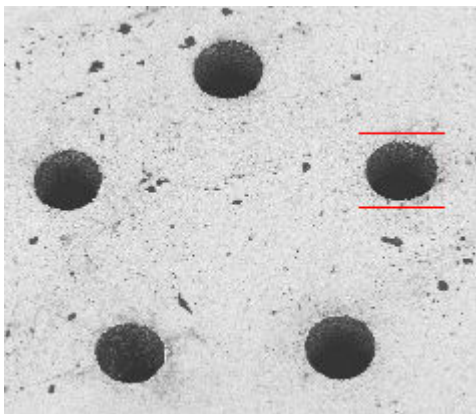
The major advantage of conventional lasers is their processing speed. But the thermal damage caused during the drilling leaves depositions and burrs on the workpiece, which makes this technique unfit for the drilling of high aspect ratio holes with precise diameter and smooth surface.

Another common technique for the drilling of fuel injection nozzles is the punching, which consists of the forging of deep bores by backward extrusion using a punch. The major drawback of this technique is the heavy wear of the punch outer edge during the forging due to friction. The quality of the holes is also not satisfactory.

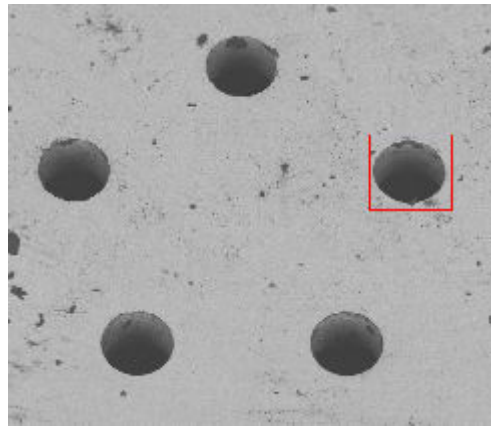
### 5.1 EDM

Results obtained with EDM were of reasonable quality when compared to conventional lasers and punching. The main issue is that EDM can be applied to electrically-conductive materials only. The process is also rather slow, a major disadvantage for using this technique in industrial applications.

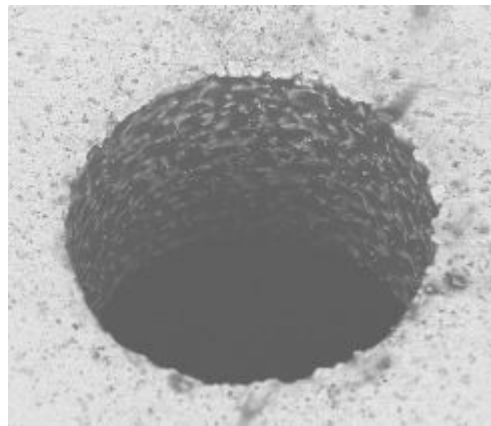
The same material as for samples S4a and S4b was used for testing the drilling of fuel injection nozzles using EDM. The results shown in figures 9-12 demonstrate the indisputable cutting quality obtained with the laser MicroJet<sup>®</sup> technique.



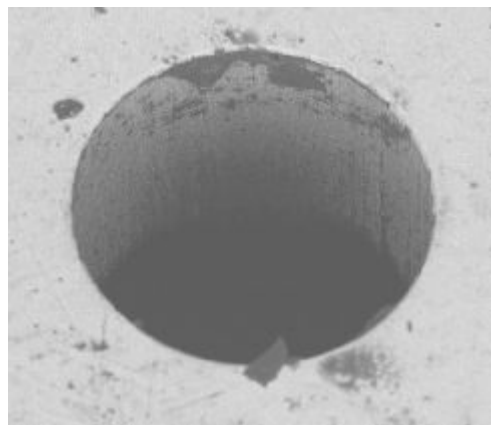
**Fig. 9:** sample S4a/b drilled with EDM. The red viewfinder has a width of 200  $\mu\text{m}$ .



**Fig. 10:** sample S4a/b drilled with Synova Laser MicroJet<sup>®</sup>. The red viewfinder has a width of 200  $\mu\text{m}$ .



**Fig. 11:** sample S4a/b drilled with EDM. The hole diameter is of 190  $\mu\text{m}$ .



**Fig. 12:** sample S4a/b drilled with the Synova laser MicroJet<sup>®</sup>. The hole diameter is of 190  $\mu\text{m}$ .

## **6. Conclusion**

The Laser MicroJet<sup>®</sup> technique gathers all the features necessary for the drilling of high quality fuel injection nozzles:

- Good cutting speed: similar to conventional laser, 2 to 4 times faster than EDM
- Edge quality even higher than EDM, 10 times higher than conventional laser
- No need for electrical conductivity
- No need for polishing or brazing

The same quality was obtained for holes drilled with an angle.

The results presented in this article demonstrate the potential of the Laser MicroJet<sup>®</sup> technology for the machining of fuel injection nozzles. An increasing number of manufacturers are adopting the process, as it presents major advantages over other techniques: higher throughput than EDM, superior quality to conventional lasers, punching and EDM, no burring, and low operating costs. The overall processing

time makes the Laser MicroJet<sup>®</sup> appropriate for industrial applications.

The Laser MicroJet<sup>®</sup> allows the machining of a wide range of materials with a good cutting speed and high reproducible quality, without burrs and HAZ, and is demonstrated to be one of the best techniques for the drilling of fuel injection nozzles.

## **References**

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