# Precision Spray Hole Drilling at High Speed with Femtosecond Lasers

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## Abstract

In a growing number of micro-manufacturing applications, commercial grade femtosecond lasers are providing the required precision and cost efficiency. With femtosecond laser microfabrication tools now accessible to industry, the relevance of femtosecond lasers to modern manufacturing has become clear based on compelling economics, unparalleled precision, and new flexibility with respect to materials and feature geometry.

Efficacy in producing the required precision and cost-efficiency is proven by recent experimental results of high precision, high speed fabrication of gas direct injection (GDI) fuel injector spray holes. Precise control of the GDI fuel spray pattern is a dominant factor in engine performance, and the spray pattern depends directly upon the geometry and surface quality of the machined spray nozzle holes. To maximize fuel economy and minimize emissions, the SAE gas fuel injector steering committee recommends very tight control over:

- Flow
- Spray angle
- Drop size distribution
- Fuel mass distribution
- Spray tip penetration

Control of these parameters in high volume production of GDI fuel injectors is made deterministic and cost-effective by the hole-drilling performance to be revealed in this presentation. Figure 1 shows a scanning electron microscope (SEM) image (300x magnification) of a 200 μm diameter hole drilled through 250 μm thick stainless steel (316L) using a Raydiance R-100 laser and a multi-axis galvo scanner for laser trepanning. The SEM image reveals pristine substrate material (no heat affected zone), negligible taper of the hole (nominally 0°), and excellent surface roughness figure ($R_a$ < 0.1 μm). It should be noted that no additional process steps beyond the laser drilling were executed to achieve this result. Laser process characteristics were: 45 μJ, 9 W (200 kHz) on target; helium purge gas (60 psi); and 1.3 s total drilling time.

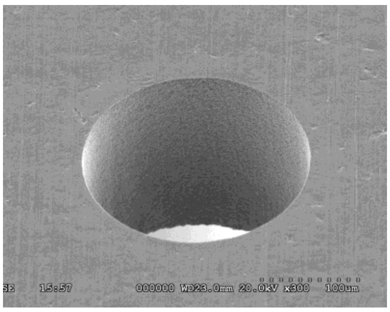


**Figure 1** 200 μm diameter fuel injector spray hole drilled in 250 μm thick stainless steel in 1.3 seconds using femtosecond laser trepanning.

We analyzed the repeatability of this hole drilling process by measuring the diameters of the hole entrance and exit faces for 99 consecutive iterations of the process. The standard deviations for the entrance and exit face diameters are, respectively, 0.488 μm and 0.233 μm. The maximum variations for the entrance and exit face diameters are, respectively, 1.37 μm and 0.88 μm. Furthermore, using the femtosecond laser trepanning process, a multitude of through-hole geometries can be created. This new flexibility is widening the design space for fuel injector spray hole geometry, and the new geometrical flexibility should enable greater control of spray patterns and improved engine combustion. In this presentation, we shall provide the salient experimental data regarding the hole drilling capability along with the connection between these figures of merit and spray characteristics.

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