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Laser Micro-Drilling Applications

Jo Ann Clarke ■ *Metalase Technologies*
Joseph Profeta III ■ *Aerotech*

Abstract

Metalase Technologies and Aerotech are currently developing advanced techniques for laser micro-drilling materials with a thickness of 1mm or greater. There are two key enabling technologies: (i) a laser with short pulse duration, high peak power, and small wavelength, and (ii) a multi-axis motion system capable of high precision, high speed, and advanced blended motion paths. Metalase is working with Aerotech as the supplier of the high precision multi-axis motion system. This paper will describe a system designed for drilling precision apertures in thicker materials and discuss an application example for direct-injection diesel fuel injector nozzles.

Introduction

Laser micro-drilling is widely used for a number of applications involving materials such as metals and ceramics. The majority of these applications comprise thin materials, less than 1 mm thickness. Metalase Technologies and Aerotech are currently developing advanced techniques for laser micro-drilling materials with a thickness of 1 mm or greater. Of particular interest is the laser drilling of direct-injection diesel fuel injector nozzles. There are two key enabling technologies to achieve this goal: (i) a laser with short pulse duration, high peak power, and short wavelength, and (ii) a five-axis motion system capable of high precision, high speed, and advanced blended motion paths. These enabling technologies will be presented and discussed in this paper.

Background

In a direct-injection diesel engine, fuel is directly delivered into the combustion chamber by the fuel injector nozzle. An example of this type of fuel injector nozzle is shown in Figure 1. The nozzle delivers a high energy, diffuse spray of atomized fuel into the combustion chamber near the end of the compression stroke, as depicted in Figure 2. The fuel mixes with the air and ignites spontaneously as the mixture temperature reaches the fuel ignition point [1,2].


FIG. 1 : DIESEL FUEL INJECTOR NOZZLE

The tip of the fuel injector nozzle is drilled with a series of small apertures, as shown in Figure 3. A high-pressure pump is used to deliver fuel to the injector nozzle. The small apertures promote fuel atomization into a spray of fine droplets as the fuel travels through the nozzle [2].

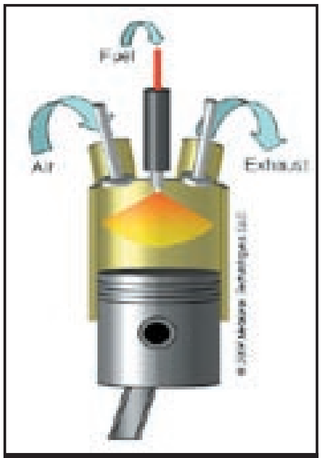

FIG. 2 :: FUEL ENTERING COMBUSTION CHAMBER

Due to the high pressures involved, these fuel injector nozzles have a thickness of 1 mm or more (even up to 2 mm) at the spray aperture location. Currently, the apertures in most direct-injection diesel fuel injector nozzles are drilled with EDM (electrical discharge machining) [3,4], in which a hollow, cylindrical electrode is maintained at a controlled distance from the work surface. The electrode is continuously rotated as sparks jump across the gap, eroding a hole in the work piece. The EDM process has several disadvantages [4]: (i) the sacrificial electrode is consumed at a rate equal to or exceeding the injector material removal rate; (ii) the work piece must be submerged in a dielectric fluid that acts to insulate the electrode and work surface; (iii) the dielectric fluid is also used to flush away the minute chips as they are eroded, and thus must be either filtered or discarded; and (iv) production cycle time for EDM micro-drilling of fuel injector nozzles is approximately 24 seconds per hole for a typical 200 μm diameter aperture.

Regulations in both North America [5] and Europe [6] for lower diesel engine emissions are imminent. Presently, apertures are typically around 200 μm in diameter. Smaller diameter apertures, however, will increase the velocity of the flow and thus promote more complete atomization of the fuel as it exits the nozzle and enters the combustion chamber. The resulting spray will be composed of finer droplets that will mix more effectively with the air. This produces more complete combustion, thereby reducing emissions and increasing fuel economy.

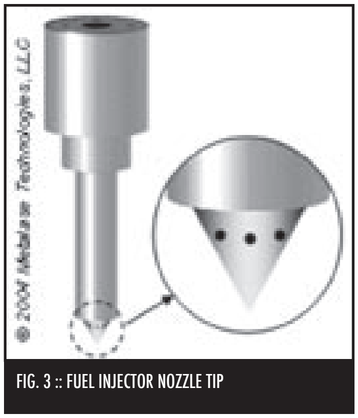

FIG. 3 :: FUEL INJECTOR NOZZLE TIP

Simply reducing the aperture diameter alone will not necessarily lead to optimum atomization of fuel in the combus-

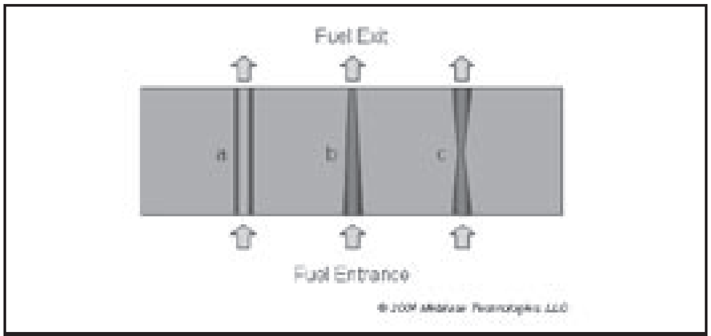

FIG. 4 : EXAMPLES OF ENGINEERED APERTURE CONFIGURATIONS: A) STRAIGHT HOLE, B) REVERSE TAPER, C) VENTURI

tion chamber. As the fuel travels through the aperture at the nozzle tip, it undergoes a pressure drop. For the large 200 µm diameter apertures, this pressure drop occurs at or near the exit of the hole: the fuel maintains a high energy level. As the aperture becomes more constricted, however, the pressure drop occurs earlier and will therefore not atomize with the same energy. Thus the advantages achieved by the smaller diameter are diminished.

However, fuel atomization can also be enhanced by using apertures that have an “engineered” configuration rather than a simple, straight-walled, cylindrical shape [7]. A reverse tapered hole, for example, may help delay the pressure drop so that the fuel maintains a high energy level and atomizes more effectively. Other aperture configurations may also help promote more complete atomization. Examples are shown in Figure 4.

However, EDM micro-drilling technology is not suitable for very small diameters, nor engineered configurations. Small-hole capability of EDM is limited by the electrode diameter. For 1 mm material thickness, this limit is approximately 120 µm in production. Moreover, a reverse tapered or venture-shaped hole would be impossible to achieve with the cylindrical EDM electrode.

Thus, a new type of system capable of drilling small diameter apertures in 1 mm thick steel is required. However, in addition to drilling high-aspect-ratio straight holes, the system must be further capable of micro-drilling engineered aperture configurations such as reverse taper and venturi. To achieve these objectives, Metalase Technologies and Aerotech worked together to design the sophisticated laser-based system described in this paper.

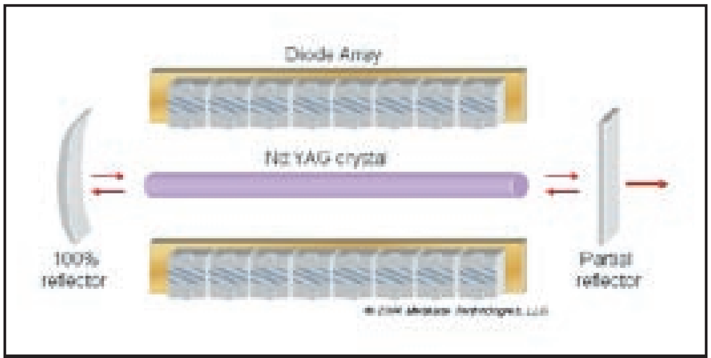

FIG. 5 : SCHEMATIC OF DIODE-PUMPED SOLID STATE ND:YAG LASER CAVITY

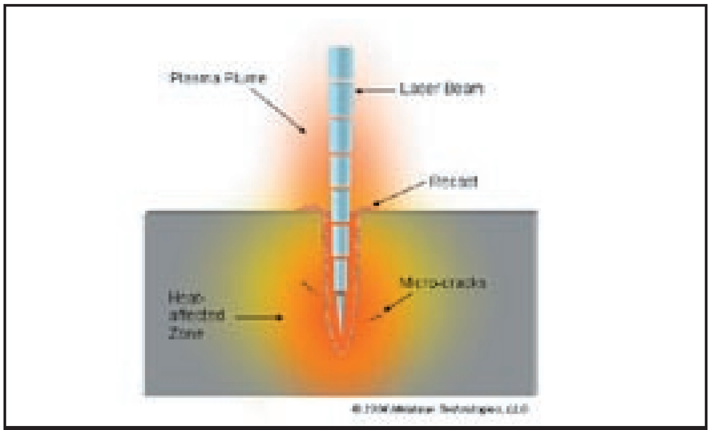

FIG. 6 : SCHEMATIC OF LONG-DURATION PULSED LASER PROCESSING

Requirements of the Laser

To successfully micro-drill high aspect ratio apertures in thicker materials, such as in direct-injection diesel fuel injector nozzles, the laser power source must meet three main requirements: (i) short pulse duration, (ii) high peak power, and (iii) short wavelength [8,9].

The most common laser for drilling is the solid state, diode-pumped, pulsed Nd:YAG laser. A schematic of the Nd:YAG laser is shown in Figure 5. The laser medium is neodymium (Nd) doped into an yttrium aluminum garnet (YAG) crystal contained in a cavity. This crystal is excited by diodes and emits light with a wavelength of 1064 nm. Mirrors at each end of the cavity reflect the waves back and forth until the build-up of photons is self-sustaining and the laser beam is well-collimated. This phenomenon is called “lasing”. One of the mirrors is partially reflective, allowing the laser beam to exit the cavity. Often, additional cavities are used to produce higher output power. For micro-drilling applications, the laser power is delivered in discrete, high-energy pulses [10,11].

Once the beam exits the laser, it is generally directed through a processing head containing optics that focus the beam onto the work piece. During processing with the high-energy density laser pulses, the energy concentration at the work piece is so intense that the material directly under the beam is vaporized or ablated with

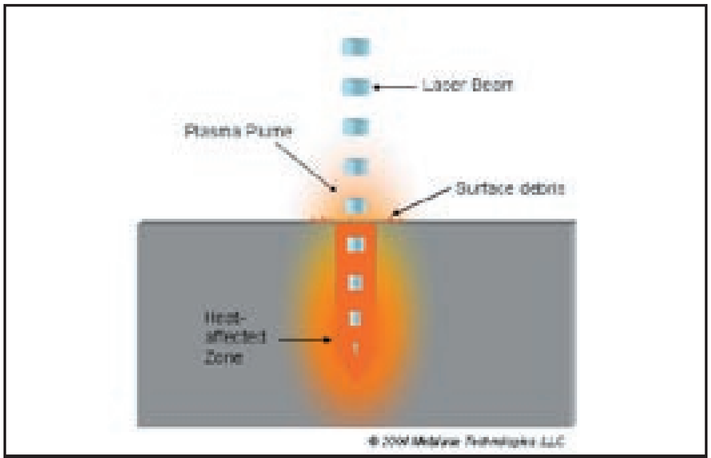

FIG. 7 : SCHEMATIC OF NANO-PULSED LASER PROCESSING

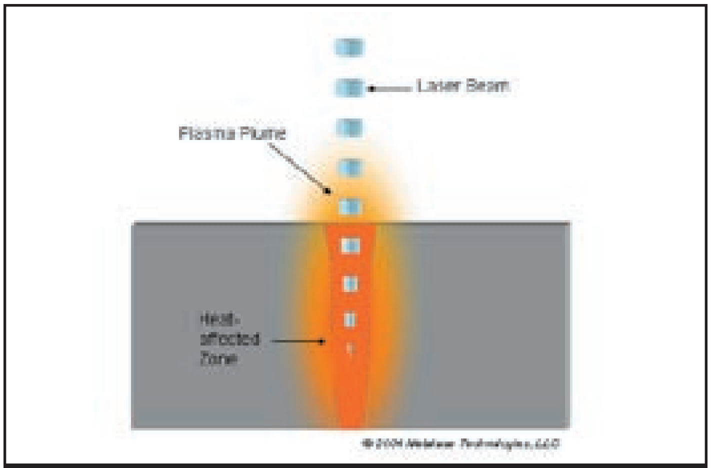

FIG. 8 : SCHEMATIC OF TAPERED LASER DRILLED HOLE

each pulse, producing a hole. This phenomenon is aptly called percussion drilling. An operating gas, such as nitrogen, is often used to enhance the drilling process. The interaction of the laser beam, vaporized material, and ionized gases produces a dense plume or plasma.

Many traditional pulsed lasers produce pulses that have a relatively long duration that increases heat input to the work piece. This excessive heat input during drilling produces a large heat-affected zone, recast layer, and even micro-cracking [8]. These occurrences are depicted schematically in Figure 6. In contrast, newer diode-pumped solid-state lasers, as shown in Figure 7, provide pulses with very short durations, in the nano-, pico-, or even femto-second range. These short duration pulses deliver higher peak power intensity, easily penetrating the plume, reducing the heat-affected zone, and virtually eliminating the recast layer and micro-cracking.

Some laser manufacturers employ additional crystals to produce the harmonics of the 1064nm Nd:YAG fundamental wavelength; for example, the second harmonic at 535 nm (“green”) wavelength and the third harmonic at 355 nm. These shorter wavelengths further enhance the coupling ability of the laser beam with the material being processed. In turn, this enables drilling of high-aspect-ratio apertures because the short-wavelength beam is able to penetrate the dense cloud of plasma and vapor that would attenuate a higher-wavelength beam [8,12].

In thicker (1mm and greater) materials, especially metals, the laser will produce a hole with a distinct forward taper. This phenomenon, shown schematically in Figure 8, is due to the concentration of heat energy at and near the entrance of the hole. This occurrence is likely, even using the most sophisticated of lasers.

Requirements and Design of the Motion System

Because most micro-drilling and micro-machining applications require more than simple percussion drilling of a single aperture, a motion system is often incorporated. These systems can be based either on:

1. Optics that manipulate the laser beam using optical wedges and lenses,
2. Part-positioning, in which the laser beam is fixed and the work piece is manipulated under it, or
3. A combination of 1 and 2.

These systems provide simple motions such as rapid scanning in the X-Y plane to produce micro-machined features and/or trepanning in a circular motion to produce apertures with diameters larger than the intrinsic laser spot size. Optical systems have the advantage of speed due to their low inertia. However, their work envelope (typically only 25 mm3) is severely limited compared to a part-positioning system that can have a work envelope up to 300 mm^3 or more.

Optical systems produce high-quality micro-features in thin components. However, for thicker components the concentration of heat near the surface of the work piece will produce a forward taper, as discussed earlier. Thus, a motion system is required that can compensate for this taper. Very few commercially available optical systems are able to compensate for this forward taper, or are very restricted in their angular scope.

The Metalase / Aerotech Solution

The production rate, feature characteristics, and feature tolerances drive the motion platform requirements. A primary feature of concern is the reverse taper hole in the fuel injector tip. A system has been designed to machine this feature at high production rates while maintaining tight tolerances.

The system is a five-axis platform. It consists of an X,Y pair of linear stages with two rotary axes (U for indexing and V for roll) mounted orthogonally to the X,Y pair, as depicted schematically in Figure 9. An independent Z-axis carries the optics and laser head. The optimal machine configuration must address the following system requirements:

1. Variety of injectors and features to be machined,
2. Tolerances on fixturing,
3. Practical mechanical tolerances of the platform,
4. Dynamic mechanical performance of the platform,
5. Minimized servo following error,

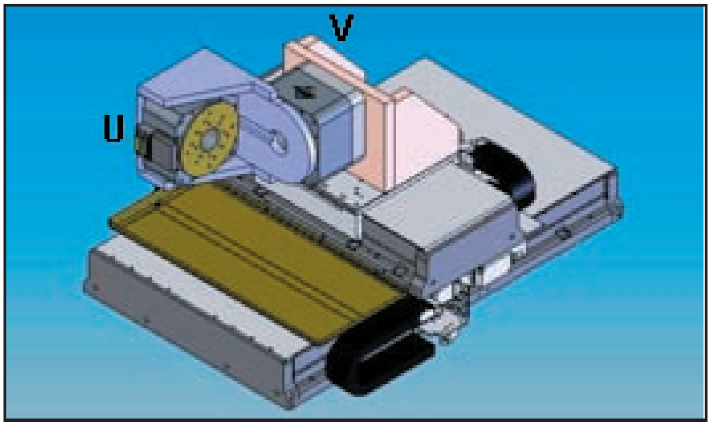

FIG. 9 : FOUR AXIS MOTION PLATFORM (INDEPENDENT Z AXIS NOT SHOWN)

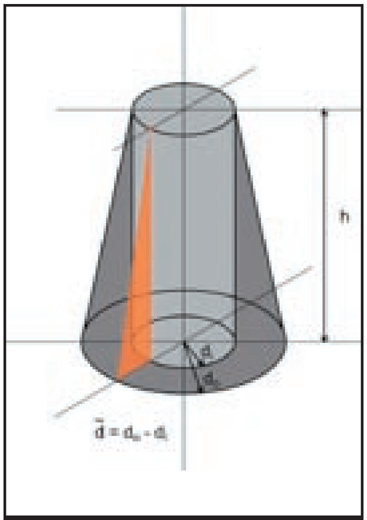

FIG. 10 : TYPICAL REVERSE TAPER HOLE

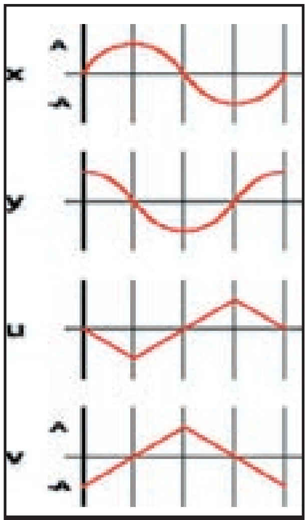

FIG. 11: X, Y, U, V AXIS TRAJECTORY FOR REVERSE TAPER HOLE DRILLING

6. Electronics error associated with the controller,
7. Motor sizing to achieve accelerations required, and
8. Coordinate transformation to accommodate offsets.

The following sections examine each of the design requirements.

Variety of Injectors and Features to be Machined

The injectors are 20 to 50 mm in length, 15 to 30 mm in diameter (at the base) and can have 4 to 20 apertures at a variety of angles with respect to the tip. Additionally, the plane of the holes may not be parallel with the base plane of the injector. The material thickness at the tip is 1mm. A typical reverse taper hole is depicted in Figure 10. Figure 11 shows the resulting trajectories that must be followed by the axes of the machine.

Practical Tolerances on Fixturing

The fixturing requires highly toleranced surfaces to maintain error motions of less than a few microns measured at the injector tip. The load / unload process must also be repeatable to within a few microns. Yet if the fixtured part can be located after loading then it is possible for the motion controller to adjust the trajectory to accommodate for the fixturing error, allowing greater tolerances on fixturing.

Mechanical Tolerances of the Platform

The straightness, flatness and roll of the X,Y stages affect the machining accuracy of the part. The impact of these errors must be evaluated at the work plane of the reverse taper feature. The orthogonality of the X,Y pair must also be considered. Each of these errors affects the quality of the circle to be machined. During the machining process multiple passes will be taken to drill the hole, which means the repeatability and Abbé error of the stages will directly affect the quality of the hole. Typically, the global accuracy of an X,Y pair at a work height (of, for instance, 150 mm) above the table will be unacceptable. To remedy this, the system is calibrated at the work height in two or three dimensions, as is necessary for the application. Applying this calibration table in real-time results in an acceptable global accuracy at the work height. In practice, error envelopes of +/- 2 μm (due to the X,Y pair only) can be achieved.

The axial, radial and tilt error motions of the rotary stages also affect the quality of the hole. Errors in the V-axis cause the angle between the holes to vary slightly. While the radial error motion of the U-axis affects the position of the hole from the shoulder of the fuel injector. The tilt and axial error motions of the U axis influence the height of the injector with respect to the Z-axis. However, with high-precision stages, the Z error will not be large enough to move the part surface outside the focal point of the laser. In each case, the contribution of each individual error type is less than a micron error in the measurements of the hole. The orthogonality of the rotary axes affects the concentricity of the hole and will cause an elliptical tapered hole.

To machine the reverse taper holes, other configurations were considered but had certain drawbacks making them non-optimal. For instance, a curvilinear axis on a rotary stage could be used but, typically, the tilt specifications for these types of stages at the work height do not meet tolerance requirements. Another design could have an additional X-axis mounted on the U rotary axis to accommodate drilling holes in a plane that is not parallel to the injector base. However, with a transformation of the trajectory into a virtual pivot point space the design presented will permit the same hole pattern to be drilled in a less complex mechanical configuration.

Dynamic Mechanical Performance of the Platform

The motion platform must have a high servo bandwidth to meet through-put requirements. The dynamic performance of the system depends largely on the stiffness and the location of the center of gravity of the motion platform. The mechanics must be as stiff and lightweight as possible while still achieving low error motion. Optimized selection, location and integration of core elements, such as motors, encoders, and bearings yield a readily controllable system.

Minimized Servo Following Error

The servo control loop must be designed to minimize following error. The following error will be a function of the trajectory and the tuning. The X,Y pair motions are sinusoidal. If it takes 10 passes, for example, to drill a hole in 2 seconds then the bandwidth of the trajectory is 5 Hz. It is reasonable to reach a 10 Hz bandwidth on the X,Y pair in this system configuration and one should expect minimal servo following error. In steady state, the tracking error due to magnitude will be practically zero and the tracking error due to phase will be non-zero. However, if one compensates the X,Y stages to have identical closed loop transfer functions, then the phase error will not affect the quality of the circle as both axis will have the same tracking error. In practice, the transfer functions will be very similar but not identical, and therefore there will be some minimal affect on the quality of the circle made by the X,Y stages. There will be a transient following error that can be eliminated by starting the move and, after a short time, beginning the drilling process. The trajectory of the rotary axes is very close to a triangle wave and therefore has high harmonics that will fall outside the bandwidth of the rotary axes. However, the tolerance of the reverse taper angle is not overly stringent and the small following error is acceptable.

The bandwidth of the system will be limited by the first mechanical resonance of the platform. The control system structure consists of a current loop, rate loop, and position loop. Typically, the bandwidth of the current loop is set as low as possible while still meeting acceleration requirements and while supporting the rate-loop bandwidth requirements (somewhere between 1000 Hz and 2000 Hz). The rate-loop bandwidth is set at one fourth of the resonant frequency and the position-loop bandwidth is set at approximately one fourth of the rate-loop bandwidth. The control architecture also uses a feed-forward rate and acceleration command, as well as viscous friction compensation.

Electronics Error Associated with the Controller

Control electronics can cause following errors due to power transistors switching. Therefore, it is advisable to avoid using PWM amplifiers and instead use linear amplifiers. Other considerations include the encoder resolution, controller sample time, clock stability, and synchronicity. The resolution of the encoders is sufficient for the application to minimize servo dither and quantization error. It is advisable to have at least 10 times the resolution over the accuracy requirement. The resolution of the encoders selected is at least 50 times greater than the required tolerances. The axes are synchronized with a network system clock that drives each axis. Servo loop sample time is 8 kHz, which is sufficient for this application. For instance the digital trajectory generation error depends on the size of the hole, and number of points generated around the circle. At an 8 kHz sample time there will be 1,600 points. Therefore the error due to trajectory generation (e_N) will be less than 2.9×10^{-8} μm, as calculated by

$$e_N = r\left(1 - \cos\frac{\pi}{N}\right) \qquad (1)$$

where r is the radius of the top of the hole and N is the number of points around the hole.

Motor Sizing to Achieve Required Accelerations

The motors in each of the stages must generate the acceleration required by the trajectory within acceptable thermal boundaries. This requires of determining the load each axis will carry and calculating the required acceleration torques and forces. The peak acceleration of the linear stages is less than 1 m/sec^2. The peak acceleration of the rotaries is very high, requiring selection of a brushless motor with a high torque-to-inertia ratio. The motors are sized to produce more than twice the acceleration required by the trajectory thus minimizing thermal loading.

Coordinate Transformations to Accommodate Offsets

The surface of the injector tip where the aperture is to be drilled is not at the intersection of the rotary axes; therefore, it is necessary for the motion controller to perform certain transformations to drill the appropriate hole. This is done using the concept of a virtual pivot point that translates the axes appropriately. When an injector is mounted offset from the point of axis intersection, the transformation

$$\phi = \tan^{-1}\left(\frac{\tilde{d}}{l\tan\theta}\right) \qquad (2)$$

must be implemented, where l is the distance from the center of the sac to the intersection of the rotary axis, d is the difference between the top and bottom diameters, θ is the angle of the reverse taper, and ϕ is the angle of rotation the rotary stage should make. The Z-axis will also have to translate as required to keep the focal point at the cutting depth.

Summary

An integrated laser-motion system was designed such that a wide variety of features can be micro-drilled in thicker materials. The effect of the mechanical, electrical, and servo system errors on the motion was considered during the design process to ensure that the resulting features will meet the required tolerances and production rates.

The Metalase / Aerotech system compares well with traditional EDM technology for producing injector spray apertures of 200μm diameter and below. Advantages of the laser-based system are that the laser does not require consumable and can accomplish the drilling in a few seconds per aperture (depending on aperture diameter and wall thickness). In addition, the capital cost of a laser system is competitive with a fully automated EDM micro-drilling system.

Additionally, the Metalase / Aerotech laser system is inherently capable of drilling much smaller apertures in production than are possible using traditional EDM techniques. An example is given in Figure 12. The sophisticated micro-positioning system also en-

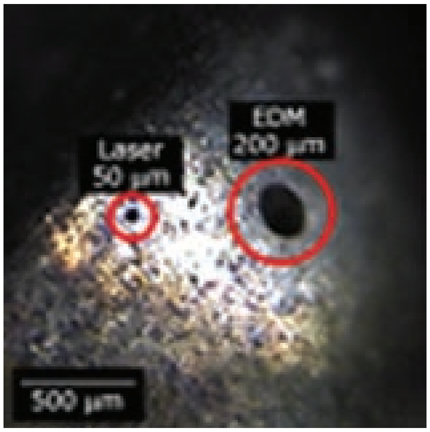

FIG. 12 : COMPARISON OF EDM AND LASER-DRILLED APERTURES IN A NOZZLE TIP

ables a variety of engineered configurations to be micro-drilled in thicker materials. Finally, the addition of the Z-axis to the laser head provides the additional flexibility of adjusting the focus spot location synchronous to laser drilling operation.

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BIOGRAPHIES

Dr. Jo Ann Clarke obtained her Bachelor's and Master's degrees in Mechanical Engineering from Carleton University, in Ottawa, Ontario and her PhD in Mechanical Engineering from the University of Waterloo in Waterloo, Ontario with a thesis specialization in welding of crack-sensitive aluminum alloys. After graduation, Dr. Clarke spent a year with Alcan's Kingston Research and Development Laboratory as a research scientist before transferring to Alcan Automotive Products in Farmington Hills, Michigan. She is currently a member of the American Welding Society and the Laser Institute of America. She serves on The Aluminum Association's Technical Committee on Welding and Joining and is a co-author of the textbook "Welding Aluminum: Theory & Practice."

Dr. Joseph Profeta has more than 15 years of experience in technology driven companies. At Aerotech he has P&L responsibility for the automotive, machine tool, assembly and packaging markets. In his past, Dr. Profeta has held CEO, CTO and COO positions at two software startup companies, and a global manufacture of train control systems as well as developed control systems for defense related systems. He has earned a BS, MS, Ph.D., and Executive MBA from the University of Pittsburgh. Additionally, he is a Senior Member of the IEEE; he has been awarded five patents and published forty-one papers.