Enabling More Efficient, Cleaner Turbine Engines

The ongoing quest by design engineers for reduced fuel consumption, lower emissions, and longer life of aircraft turbine engines has led to implementation of new capabilities for laser processing systems. The goal is to achieve more consistent cooling holes in laser-drilled components. This article describes a number of new capabilities now employed in aircraft and land-based turbine engine component manufacturing which have been validated by industrial experience to produce more consistent cooling holes.

In today's complex engine designs, producing components that deliver the right amount of cooling air in the correct locations is a huge challenge.

To decrease fuel consumption and reduce emissions, designers strive to maximize the gas temperature from combustion. This leads to operating temperatures at or above 1600°C, which are higher than the melting point of the nickel-based alloys used within the turbine engine. Film cooling has been used for many years to keep surfaces within the hot section of the engine from melting. Using more air than necessary reduces engine efficiency, while using too little can reduce the life of the engine.

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components. Therefore, the goal of the manufacturing process is to produce components that deliver "just the right amount" of cooling air in the correct locations.

Using new processing techniques and features of modern laser processing system design, manufacturers have demonstrated the ability to produce more consistent laser-drilled holes. The more-robust manufacturing process resulting from these developments is also paying dividends in reduced scrap and rework. Design engineers are increasingly looking to modern laser processing techniques to support cooling schemes that were not possible several years ago.

While the use of laser hole drilling in manufacturing is an accepted process with recognized standards for rotating and nonrotating hot-section engine components, there has been a perception that tolerances in hole size and limits of metallurgy must be relatively wide in order to use laser processing in production. A brief look at why this is the case is warranted.

Laser drilling is a thermal process in which the intense energy of the laser beam is focused onto the workpiece surface to produce a combination of vaporization and melt expulsion. The sparks that are so often seen in hole-drilling pictures are in fact molten material being forced from the laser-drilled hole by vapor pressure. In addition to laser-process variables that affect the material removal rate (volume removed per laser pulse), there are other sources of variation in airflow of laser-drilled holes that must be accounted for: material thickness, coating type and thickness, assist gas flow in the vicinity of the hole, and hole angle to the surface.

Laser manufacturers and system builders have studied this process and have developed ways to maximize productivity while adding control to hole size, hole shape, and metallurgical results.

Producing a laser beam with the optimum beam quality and simultaneously controlling the focused beam size is critical to accomplishing these goals. Note that the "best" beam is not always the most effective given the diameter and depth of holes and material removal rates required to make the process economical.

Following is a review of the tools for increasing the consistency of laser-drilled holes that are now part of a modern laser drilling system.
Tools for More Consistent Airflow

Historically, the laser process has been developed around the smallest diameter hole within a part. The focusing lens and laser beam diameter at the focusing lens are selected to produce this hole size. Larger diameter holes are then produced by defocusing the laser beam. Adjustments in hole size require a “guess” or estimate of how much to change the amount of defocus. As can be observed from Figure 1a, drilling with the workpiece at the ‘focal point’ or, more precisely, at the center of the focal range, provides for a more-robust process than when drilling out of focus, that is, by defocusing.

The focused laser beam has a depth of focus which is on the order of a few millimeters depending upon the focal length of the focusing lens and diameter of the beam incident on the lens. Drilling away from the focal point in order to increase the hole diameter involves a great deal of skill in setup and execution of the process, even with methods of automatically maintaining (within a tolerance) the relative position of the focal point to the workpiece.

Optical Focus Control Replaces More Traditional Methods

A fast and accurate way to locate the surface and place the ‘focal point’ at the workpiece surface is required for manufacturing. Given that the angles of laser-drilled holes are often less than 30° from the surface and can be as low as 10° from the surface, an optical means of focus control is most often required to ensure the most precise detection of the surface at the location of the hole to be drilled. The traditional method of focus control, capacitance sensing between the workpiece and a metallic (usually copper) gas-assist delivery nozzle, is increasingly not useful because the long taper of the nozzle or large distance between the end of the nozzle and workpiece results in large sensing areas and imprecise location of the focal point. New designs of sheetmetal combustors and cast parts require cooling hole placement in locations very difficult to reach. While design engineers are aware of the limitations of the cone angle (line of sight) for laser processing, the placement of cooling holes cannot be compromised by older sensing technology.

The increased use of non-electrically conductive thermal barrier coatings (TBC) to help improve temperature resistance of materials also adds the necessity for an optical means of focus control (OFC). OFC uses a visible (689 nm) laser aligned coaxial with the drilling laser beam and coincident to the processing beam. This beam, which senses continuously, allows the focal point of the processing beam to be positioned to a greater accuracy because of its higher (4×) sensing rate. There

The consistency of airflow through laser-drilled cooling holes has been increased to ±3% on TBC sheetmetal components.
is also no side sensing as with capacitance sensing. OFC allows more aggressive design of nozzles that place the nozzle at the correct distance from the hole entrance. The same sensing features for capacitance sensing have been made available using OFC. These features include the ability to detect manually or from within a part program the location of reference features on a workpiece, to automatically determine the orientation of a surface, and to reduce setup time by detecting the location of one or more tooling balls on the workpiece fixture.

**At Focus Drilling** for Robust Processes, Tighter Hole Size Control

With the At Focus Drilling method, the laser-beam focal point and therefore laser-drilled hole diameter is adjusted by varying the diameter of the laser beam incident on the focusing lens. Control of hole diameter follows a simple optics relationship whereby the focused laser beam is inversely proportional to the diameter of the beam incident on the focusing lens. It has also been noted through testing that all forms of metallurgy are improved when drilling with the beam at focus.

The diameter of the laser beam at the focusing lens is controlled by a precision, two-axis telescope built into the laser and controlled by the system CNC. The diameter is selected based on the optical equation shown in Figure 1b.

**Breakthrough Detection**

In order to balance hole size, metallurgical requirements, and shape control with drilling time (hole cost), the process often involves high pulse energy (tens of joules) and high peak power (tens of kilowatts). With tolerances on thickness and small variations in metal removal rate per pulse, the number of pulses required to produce a hole that penetrates the entire thickness of the material will vary. Using a fixed number of pulses, a number that represents the "worst case", results in wasted time for most of the holes and a wider variation in hole size and shape than if each hole is drilled with the optimum number of pulses.

Breakthrough detection uses feedback from the process to detect the pulse at which the hole has completely penetrated the material. The system is programmed to stop the process for this hole or to deliver a user-defined number of additional pulses. Breakthrough detection has been shown in tests and production experience to reduce variability of airflow by more than 5% compared to that when using a fixed number of pulses (Figure 2a).

**Reduced Debris/Dross**

Air flow is determined by a number of factors including hole size, shape, taper, surface finish within the hole, and dross at the entrance and exit of the hole. Drilling at focus combined with breakthrough detection result in a hole being drilled with reduced amounts of dross and dross. Modern lasers that allow for a variation of processing parameters from within the process also allow the engineer the opportunity to choose process parameters that can minimize debris from laser drilling. Older lasers used for hole drilling, while capable of high peak power and energy per pulse, have a limited range of operation and no chance for corrections within the process. These limits are set by their fundamental design.
“Tuned” resonators must always operate at a fixed average power. Variations in pulse length and pulse frequency must be used to maintain a fixed average power according to the following relationship.

\[ P_a = E_p \times f \]

where

- \( P_a \) = Average power, watts
- \( E_p \) = Energy per pulse, joules
- \( f \) = Pulse rate, Hz

Modern drilling laser design employs an optic internal to the laser cavity that provides controlled operation over a wide range of average power and, as a consequence, a greater degree of flexibility in choosing laser parameters. With this tool, the process engineer does not have to make compromises in laser parameters. Optimizing the peak power density for a given hole diameter, depth, and angle further minimizes debris and dross.

**Direct Control of Airflow**

The methods for airflow control described previously all rely on controlling the hole size, shape, and quality. For further improvement in airflow consistency, direct control of airflow is now being employed. This method uses the measurements from an airflow bench to dictate adjustments to laser-drilled hole diameter needed to control airflow. In its simplest form, feedback from the airflow bench is converted to an effective average hole diameter. The actual diameter is compared to the target diameter. Changes to the hole diameter, if warranted, are accomplished through changes in beam diameter at the focusing lens.

A complete implementation of automated flow compensation, called FlowComp, addresses the range of processes (percussion drilling, trepanning, drill-on-the-fly), part configurations, and airflow specifications. Software that supports this feature includes the ability to check completed parts and sections of completed parts and make corrections to sections of the component. It is now possible to divide the complete part into sectors and test and correct for airflow in these sectors. The processing engineer also has the ability to set upper and lower limits to airflow and make corrections based on trends. No longer is it required to have a “failed” part in order to make a correction.

In addition to the self-correcting nature of the process, it is possible to create records of in-process testing for each part that can become part of the permanent record for the serial number. Users now have an opportunity to examine the record for the individual serial number.

**Results**

One major aircraft engine manufacturer, using a portion of these techniques, has reported improvement in airflow consistency from a typical ±10% to ±3% on TBC-coated components and ±2% on sheetmetal components. In another case, a manufacturer of land-based turbine components reduced cycle time by 65%, with the use of only several of the advantages of modern laser processing. Modern laser hole drilling systems (supplied within the last five years) that employ the techniques described above will outperform older systems in terms of productivity and quality.