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# New approach to the inspection of cooling holes in aero-engines

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ABSTRACT

This paper explores a new design for inspecting turbine blade cooling holes. Cooling holes have been incorporated in the design of turbine blades to combat and avert blade failure caused by excessive operating temperatures. In the paper, we examine the inspection techniques currently in use and present a novel optical technique as an alternative. Our design consists of two stages of inspection, each optically based. In the first stage, a sample is mounted on an XY micro-positioning stage, a vision system captures an image of the sample and displays the size and shape of each entrance hole. To measure the presence of a bottom, a second XYZ inspection stage is used. Using a small collimating tube, a micro-beam illuminates a drilled hole in a pre-programmed fashion. Depending on the level of reflected intensity and where it occurs, the presence of a hole's bottom is determined. The optical inspection system consists of a laser, motorized micro-positioning stages, collimating tubes, vision system, data acquisition software and a customized fixture for manipulating the samples.



## 1. Introduction

The research on higher engine efficiency of aero-engines has led to changes in the design of gas turbines. One area of focus has been the area of combustor design, especially involving higher combustor inlet and exit temperatures. With higher combustor exit temperatures, improved efficiency and reduced fuel consumption can be achieved. Modern turbine stage inlet temperatures now exceed the melting point of turbine blade materials. To combat and avert blade failure caused by excessive operating temperatures, film cooling has been incorporated into blade design. Much research in recent years has been focused on improving the manufacturing cost and quality of laser-drilled turbine blade cooling holes [1,2].

The aerospace industry has used laser drilling in components such as turbine blades, vanes, outer air-seals and combustors. Laser drilling is a thermal, contact-free process that utilizes a focused laser beam to remove material by either vaporization and/or melt ejection. The most popular choice for laser drilling is the solid-state Nd:YAG laser. Laser percussion drilling is widely used in the aerospace industry, and a variety of theoretical models have been developed to predict the outcome of the drilling process. Percussion laser drilling consists of firing a sequential set of focused optical pulses on a target material. The minimum spot size or focal point is typically set at or near the surface of the whole entrance. The diameter of the focused spot coincides roughly with the diameter of the hole produced.

During each optical pulse, the drilling process follows a sequence of events. First, within the area of the spot size, a small depth of the target material's surface becomes heated to a liquid state. Next, the upper portion of the liquefied volume reaches the vaporization temperature of the metal. At this point, the expanding gas produces a recoil pressure that pushes down on the liquid portion of the metal. Liquid metal flows outward and as the hole forms, moves up the sidewall and out in a conical fashion. The material removal process continues for the duration of the incident pulse. When the optical pulse ends, the liquid metal cools and re-solidifies within the hole. As successive pulse arrives, melting, vaporization and expulsion of liquid metal take place. With each pulse, the hole gets deeper until the desired depth is reached or the beam punches through the backside of the target material. Valuable contributions in modeling of laser percussion drilling, laser drilling of multilayer aerospace materials and hole taper characterization and control are presented in Refs. [3–5].

The laser drilling of metals involves four stages: (1) surface heating, (2) surface melting, (3) vaporization and (4) melt ejection. The intensity of laser radiation and the thermal losses [6] at the drilling zone influence the drilling time and melt ejection at the drilling zone [7]. Typical defects associated with the drilling process are tapering, barreling, micro-cracking and the presence of recast layers [8]. An area of focus in recent years has been improving the geometry and quality of laser-drilled holes by optimizing the parameters of the process. A key factor in laser drilling is maximizing the laser drilling speed and material removal rate, while maintaining predictable beam breakthroughs

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[9]. The operating parameters are initially set to ensure beam break-through by slightly over-pulsing. This procedure, without proper feedback, results in sub-optimal drilling speed [10], wastage of beam energy and a risk of back wall damage to the interior of the turbine blade. In the case of laser drilling of blind holes, the estimation of depth depends primarily on laser power, pulse width and the number of pulses [11].

The critical components fabricated by the laser drilling process are normally inspected for defects such as taper, barreling, recast layers and micro-cracks [12]. During the drilling process, any variation of critical parameters, material quality and changes in assist gas flow cause changes in the process outcomes including blind hole depth [13].

The quality of percussion and single-pulse-drilled holes in terms of diametric reproducibility and roundness is comparatively poor. Laser trepanning uses a laser beam that is smaller than the hole and cuts out the hole by moving the laser beam or the work piece in a circular motion. Trepanning pierces the material with the laser beam and then cuts out the hole using one circular cut.

One common inspection process involves manual inspection of the cooling holes. An operator manually passes a piano wire through each cooling hole to determine, if there is any obstruction. Although this process is near error free, it is very labor intensive.

Optical inspection systems have a long and successful track record in the area of manufacturing metrology. In this paper, we present a new optics-based design procedure for inspecting first stage turbine blade cooling holes. The results could be used for in-process estimation of drilling hole depth and speed.

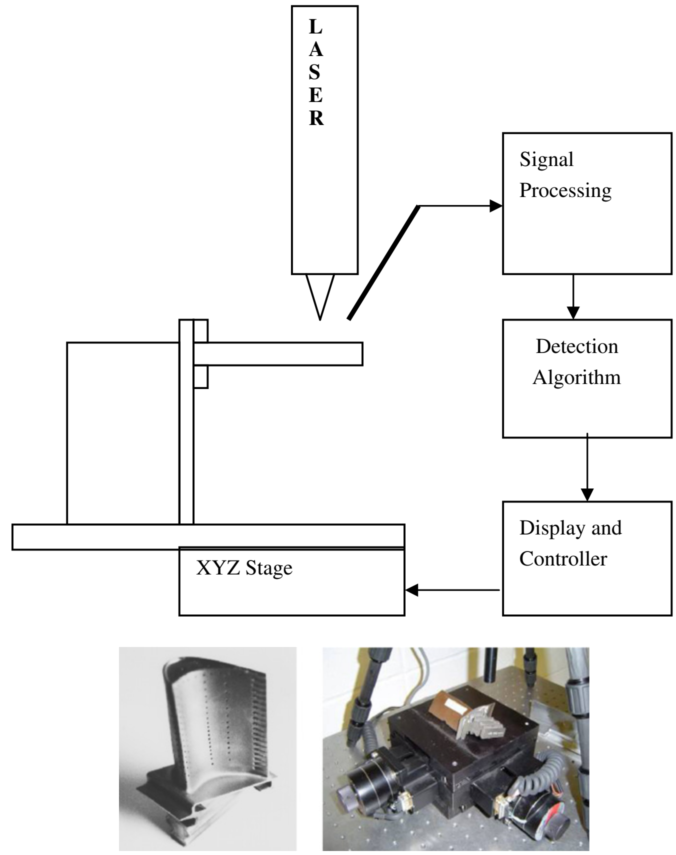


**Fig. 1.** Experimental setup.

## 2. Method of measurement

The design procedure consists of two stages of inspection, each optically based. The first stage uses a camera positioned axially in line with a laser beam. A sample is mounted on an XY micro-positioning stage, and a vision system captures an image of the sample and displays the size of the holes and distance between them.

To measure hole depth, a second XYZ inspection stage operation is employed. It contains a precision diffractive light tube that is used to capture the depth of the drilled hole. A laser beam is launched into the light tube and exits the tube as a micro-beam. The micro-beam scans the surface in a programmed fashion and depending on the point where it strikes the sample, the hole depth can be measured. This overall optical inspection system consists of a laser, motorized micro-positioning stages, light tube, a vision algorithm, data acquisition software and a customized fixture for mounting the sample. (Fig. 1).

## 3. Measurement concepts

For measuring the depth $H$ of micro-holes, where the diameter $D$ of holes may have values from 5 to 500 μm and the ratio of $H/D = K \gg 1$, two different methods of detection of hole depth are discussed. This is a useful approach for measuring the depth of blind holes with a large hole-to-diameter ratio.

### 3.1. Vertical displacement method to test flat specimens

In this method, we use a long and narrow collimator, where the incident laser beam may be considered as a parallel one and where the incident angle $\alpha$ of the beam on the sample's (flat) surface is almost perpendicular one, i.e. when $88^\circ \leqslant \alpha \leqslant 89^\circ$. For the collimator, a component made from soft graphite material having a large length-to-inner diameter ratio and narrow holes is selected (Fig. 2).

One hole in the graphite collimator is designed for the incident beam and a second one for the detected beam. The angle between these two holes is about 4°. The soft graphite component with two small diameter holes allows the generation of almost parallel incident and detected beams. If the incident angle of the rays $\alpha$ is less than the critical angle, $\theta_C$, then rays will be reflected from the graphite's surface (Fig. 3a), but if not, the rays will be absorbed by the graphite (Fig. 3b). Fig. 3 shows the behavior of the incident rays on the graphite collimator wall. One of the rays (Fig. 3a) has an incident angle $\alpha$ less than or equal to Fresnel's total external reflection angle. For the second one (Fig. 3b) $\alpha$ is larger than Fresnel's total external reflection angle.

This measurement technique is based on the following principle: for the given radius of the blind hole $D$ and the diameter $d$ of cylindrical collimator, the incident angle $\alpha$ of the laser beam is chosen in such a way that the minor diagonal $L$ of the rhombus formed by the incident and reflected beams (Fig. 4) is significantly less than the diameter of the hole, $D \gg L$.

In Fig. 4, $M$ is the distance from the bottom vertex of rhombus to the bottom of the hole. Based on the configuration shown in Fig. 5, one can obtain the formulae representing the dependencies of $D$, $L$, $d$ and $\alpha$.

One must consider those cases where the depth of the holes $H$ is several times greater than the diameter $D$, that is when in the relation $H = KD$, the coefficient $K \gg 1$. The dependencies between $D$, $L$, $d$ and $\alpha$ are given as: $d = L \sin\alpha$, and the minor diagonal length of the rhombus is

$$L = D(1 - 2K \cot \alpha), \quad d = D(\sin \alpha - 2K \cos \alpha). \tag{1}$$