Optical 3D measurement of cooling holes in gas turbine and aircraft engines

K. Zangl, R. Danzl, D. Urlep, F. Helmli
Bruker Alicona, Austria

Abstract

The quality control of cooling holes is an important topic for increasing the efficiency and ensuring the safety in high-performance systems. Even if heat-resistant materials are used (Inconel steels), the surface must be cooled because the surrounding gases are in the range of the melting point. This is done with compressed air from the inside of the blade. The position, orientation and shape of the holes thus play a major role in the safety of the turbine. These turbine blades are used in aircraft turbines and gas turbines.
Currently, the geometry is measured using computer tomography or fiber probes. The proposed method (vertical focus probing) offers advantages in terms of measurement time, resolution, non-contact measurement and the possibility to measure deep into the hole. We demonstrate the strength of vertical focus probing for cooling hole measurement by several results of highly accurate 3D measurements of differently shaped holes as well as their geometric inspection.

1 Introduction

Cooling holes have an important functionality to avoid the overheating of turbine blades. By blowing cooling air through these holes, a thin insulating layer is generated between the combustion gases and the blade. In addition to other measurement tasks as e.g. the break edge measurement, the geometric verification of cooling holes is a challenging task in 3D metrology on aerospace parts. The difficulty in the 3D measurement of these holes is based on several aspects. On the one hand, one turbine blade may consist of many differently shaped cooling holes with different sizes, angles, and positions which must fulfil their nominal values in tight tolerances. On the other hand, the measurement of such cooling holes is complicated by their difficult accessibility for measurement (see Figure 1 left for a typical blade including measurement directions for some holes).

There are some approaches to automatically measure micro holes in general and cooling holes in particular including computer tomography, using fiber probes or fringe protection [3, 4, 6]. These methods are either limited by their resolution, their ability to measure deep into the hole, long measurement time or their contact-based measurement where accessibility is based on the probe size and the blade can be damaged.
In this paper, the automatic, repeatable and traceable 3D measurement of different kinds of cooling holes by vertical focus probing (VFP) is presented, which is an extension of focus variation (FV), but enabling the measurement of vertical structure with slope angles ≥ 90°.

2 Measurement and results

2.1 Measurement principle

For the application, vertical focus probing was used [5]. VFP is an optical measurement principle which measures vertical walls and holes with a slope angle ≥90° by focus variation (see also [1, 2]). Typically, FV uses the small depth of focus of an optical system to provide topographical information. Thereby, exactly one z value is measured for each x, y position by vertical scanning and analysis of the focus information along the vertical axis, whereas the measurement of vertical 90° structures is not possible at all. VFP extends this principle by measuring many z values for each position through which vertical structures as holes can be measured. VFP exploits the reflective properties of the surfaces where depending on the type and position of the illumination, the geometry of the sample and the roughness properties of the surfaces always a part of light is reflected to the objective (see Figure 1 right).

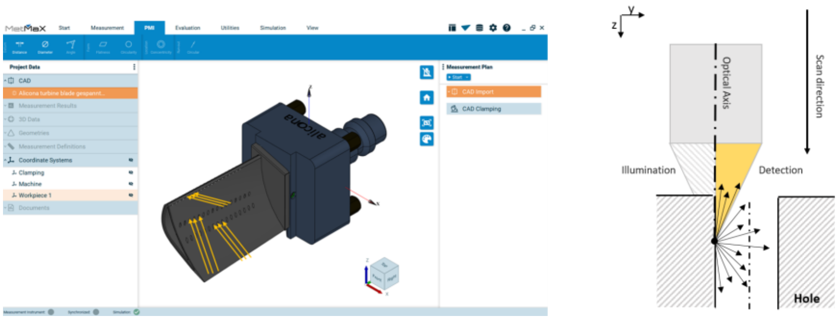

Figure 1: Left: Turbine blade with different kinds of holes. Yellow arrows show typical measurement directions which are parallel to the hole axis using VFP. Right: VFP measurement principle.

2.2 Experimental setup

In this paper, a Bruker Alicona µCMM was used for the measurements (see Figure 2a). The measuring instrument has an optical sensor based on focus variation and a measuring volume of 310x310x310 mm [7]. For this application the measuring instrument was equipped with an automatic tilt and rotation axis and a 5x magnification objective lens.

Since turbine blades including computer-aided design (CAD) data are confidential in most cases, a cooling hole artefact (see Figure 2b and c) was constructed and manufactured. The artefact is a metal plate which consists of differently shaped cooling holes with diameters from 350 µm to 1.6 mm.

For the measurement, the artefact is clamped into a rotation unit to ensure different measurement directions dependent on the hole geometry, position, and orientation. To measure all holes on a turbine blade different measurement directions are needed, as the optical axis of the system is aligned parallel to the hole axis during a vertical focus probing measurement (see Figure 1). For the geometric verification only relevant measuring positions are measured, and those measurements are precisely set in relation to each other. The relevant measurement position can be easily defined by the instrument's software which allows to define them directly on the CAD data, and the software automatically determines the measurement principle, either FV or VFP, as well as the needed measurement directions. A prerequisite for such an automatic measurement is, that the virtual and the real instrument is exactly aligned. Additionally, a rotation- and tilt unit calibration was performed to adjust the unit exactly with respect to the measurement system.

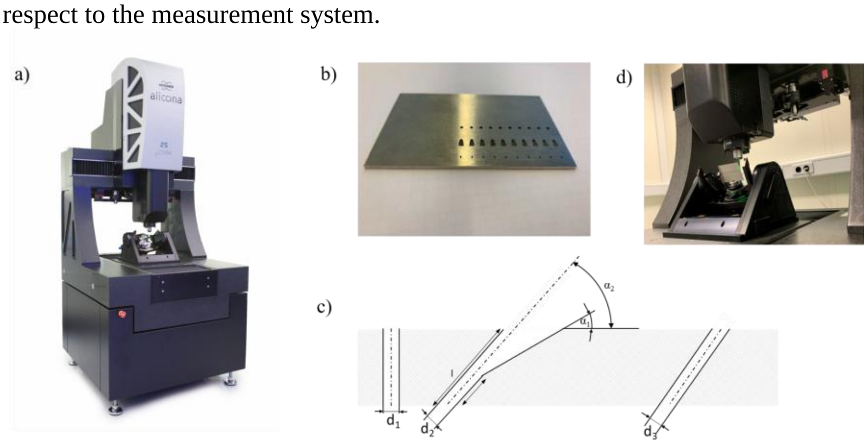

Figure 2: a) Bruker Alicona µCMM. b) Measurement artefact. c) Schematic cross section of the plate. d) Experimental setup.

2.3 Measurement results

Several measurements were performed on the measurement artefact. In Figure 3a, a 3D measurement of a fan-shaped hole is shown. The 3D dataset consists of a FV measurement of the top surface including colour information and a VFP measurement of the cooling hole without colour information which where fused together to one 3D dataset. The hole was measured into a depth of around 3 mm and minimum diameter of 360 µm at the bottom. As these results demonstrate, holes with a diameter:depth ratio up to 1:10 depending on the used objective lens, the lighting conditions, and the hole geometry can be measured. In Figure 4a, a 3D dataset of a multi-measurement is shown. In each line of the measurement artefact four holes were measured and the single measurements were fused together to one dataset. Thus, each hole geometry (see Figure 2c) was measured four times. Again, each hole measurement of this dataset consists of a top surface measurement using FV, and a VFP measurement of the hole. It can clearly be seen that the orientations and shapes of the holes differ significantly. In Figure 4b, an exemplary geometric verification of a cooling hole is shown. In addition to the orientation, the diameter was verified at three different positions along the hole.

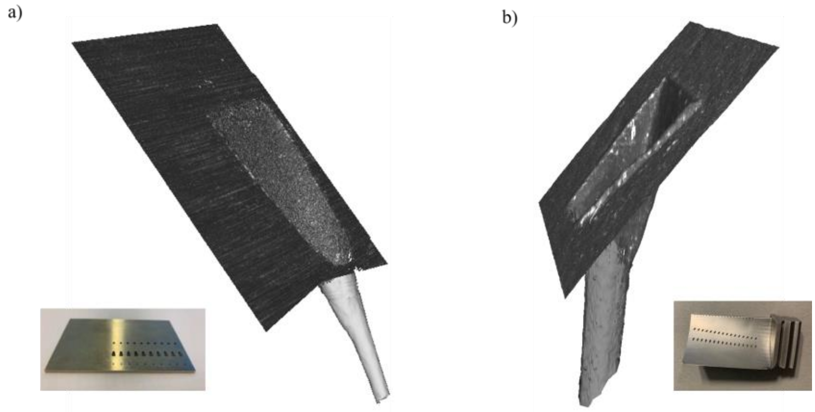

Figure 3: 3D measurements of cooling holes by FV and VFP. The FV measurement of the top surface is fused with the VFP measurement of the hole. a) Cooling hole of the measurement artefact. b) Cooling hole of a turbine blade.

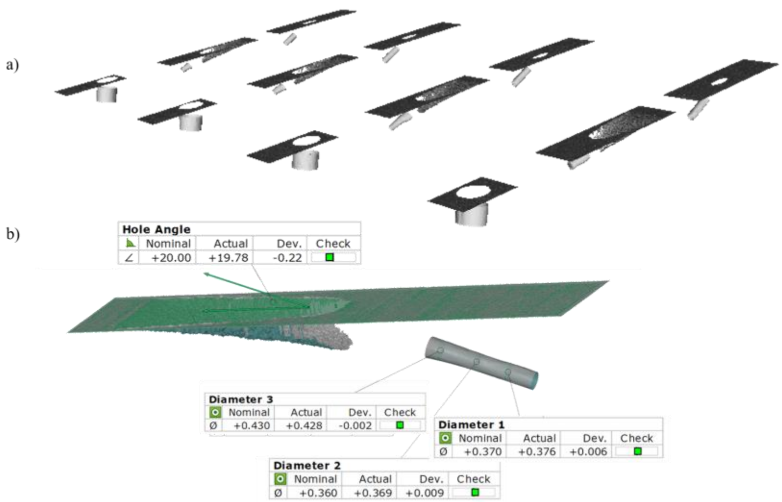

Figure 4: a) Multi-measurement on the plate. b) Geometric verification exemplarily for a fan-shaped cooling hole.

3 Conclusion and discussion

The results show the strength and the high potential of vertical focus probing for high-precision 3D measurements of cooling holes on turbine blades. The main benefits of the proposed measurement principle are the optical and non-destructive data acquisition of holes with a high diameter:depth ratio in combination with a highly accurate multi-measurement procedure which allows the measurement of cooling holes on turbine blades in an automatic, traceable and repeatable manner. Influence factors that need to be considered for VFP are the illumination conditions, the geometry of the measured hole as well as the surface texture properties, as these factors determine how much light is reflected to the lens. A quantification of the VFP performance can be found in [5], whereas the quantification on cooling hole is ongoing work. Current activities include the further evaluation of the measurement principle on different kinds of real turbine blades (see Figure 1 left and Figure 3b for a first measurement). Further research will focus on the further development of vertical focus probing with respect to measurable geometries, so that VFP can be used in a fast and robust manner for different types of cooling holes including those that do not always have a circular geometry inside the hole.

References

[1] R. Danzl F. Helmli, S. Scherer, *Focus variation—a robust technology for high resolution optical 3D surface metrology*, 2011, J. Mech. Eng.

[2] F. Helmli, *Focus variation instruments* in Optical Measurement of Surface topography edited by R. K. Leach, 2011, Springer, Berlin

[3] C. Munkelt, P.Kühmstedt, L. Aschermann, F. Seidel, *Automatic complete high-precision optical 3D measurement of air cooling-holes of gas turbine vanes for repair*, 2015, Proc. of SPIE Vol. 9525

[4] B. Muralikrishnan, J.A. Stone, J.R. Stoup, *Fiber deflection probe for small hole metrology*, 2006, Precision Engineering

[5] C. Repitsch, K. Zangl, F. Helmli, R. Danzl, *Focus variation* in Advances in Optical Surface Texture Metrology edited by R. K. Leach, 2020, IOP Publishing, Bristol UK

[6] G. Robinson, *Measurement of Cooling Holes in Gas Turbine Blades using Computer Tomography*, Survice Engineering Company, online: https://www.cmsc.org/stuff/contentmgr/files/0/2bdcf766d9d5daf6e892c46153c591d3/misc/cmsc2011_wed_gh_0800_survice.pdf

[7] K. Zangl, R. Danzl, F. Helmli, M. Prantl, *Highly accurate optical μCMM for measurement of micro holes*, 2018, Proc. CIRP