

GT2017-64903

EFFECTIVENESS MEASUREMENTS OF ADDITIVELY MANUFACTURED FILM COOLING HOLES

Curtis K. Stimpson, Jacob C. Snyder, Karen A. Thole
Department of Mechanical and Nuclear Engineering
The Pennsylvania State University
University Park, PA, USA

Dominic Mongillo
Pratt & Whitney
East Hartford, CT, USA

As additive manufacturing (AM) technologies utilizing metal powders continue to mature, the usage of AM parts in gas turbine engines will increase. Current metal AM technologies produce parts with substantial surface roughness that can only be removed from external surfaces and internal surfaces that are accessible for smoothing. Difficulties arise in making smooth the surfaces of small internal channels, which means the augmentation of pressure loss and heat transfer due to roughness must be accounted for in the design. As gas turbine manufacturers have only recently adopted metal AM technologies, much remains to be examined before the full impacts of applying AM to turbine parts are understood. Although discrete film cooling holes have been extensively studied for decades, this objective of this study was to understand how the roughness of film cooling holes made using AM can affect the overall cooling effectiveness. Coupons made from a high temperature nickel alloy with engine-scale film holes were tested in a rig designed to simulate engine relevant conditions. Two different hole sizes and two different build directions were examined at various blowing ratios. Results showed that the effectiveness is dependent on the build direction and the relative size of the hole. It was also discovered that commercially available AM processes could not reliably produce small holes with predictable behavior.

INTRODUCTION

Additive manufacturing (AM) is receiving increasing recognition as a valuable method for producing some gas turbine components. AM provides increased design flexibility, short turnaround time for single component production, and possible economic advantages. As gas turbine designers find innovative and creative ways to design parts with the AM process in mind,

AM may become the preferred manufacturing method for many gas turbine components.

For the benefits of the AM technology to be properly leveraged by the gas turbine industry that already has extensive experience in conventional manufacturing methods, creative exploration within the design space offered by AM must be fostered. However, designers must also understand the design constraints and functional implications of AM processes to generate useful designs. The current body of literature has a dearth of information necessary for designers to understand what implications their design and use of AM will have on the performance of a gas turbine component. The motivation of this study is to aid designers in understanding the implications of and constraints when using AM.

Previous research done by the current authors has aided in identifying constraints and implications related to the surface roughness on parts made with laser powder bed fusion (L-PBF), a common type of metal AM [1]. It has been shown that the roughness on L-PBF parts is significantly larger than with conventional manufacturing methods. The same causes of roughness also lead to challenges maintaining tolerances for geometries where negative features (e.g. flow channels) are not much larger than the roughness features themselves [1]. Additionally, orientation of the part relative to the build direction was seen to have direct impacts on the tolerances and roughness levels.

The authors have also previously investigated flow through small internal channels that might be used for internal cooling of turbine hardware [2–4]. As many components employ film cooling in addition to internal cooling to manage temperatures, the next step in trying to understand impacts of AM on turbine cooling designs is assessing the impact AM has on film cooling performance. Film cooling provides essential cooling to high heat load parts in the turbine engine; it is expected that AM will

impact the performance of film cooling due to changes in feature tolerances and surface roughness. The uniqueness of this study was to examine the effects roughness and building tolerances have on the performance of film cooling holes built with L-PBF.

NOMENCLATURE

A_c	cross-sectional flow area
A_{min}	minimum cross-sectional area of cooling hole meter
A_s	surface area
Bi	Biot number, $h_\infty t / \kappa$
c_p	specific heat capacity
D	film hole metering section diameter
D_h	hydraulic diameter, $4A_c / p$
DR	density ratio, ρ_c / ρ_∞
FP	mass flow parameter, $\dot{m} (RT_c)^{0.5} / P_c A_c$
h	convective heat transfer coefficient
H	mainstream channel height
HLP	heat load parameter, $\dot{m} c_{p,c} / (A_s h_\infty)$
ℓ	length coordinate along axis of film cooling hole
L	hole length
$\dot{m}$	mass flow rate
M	blowing ratio, $(\dot{m} / A_{min}) / (\rho_\infty U_\infty)$
Ma	Mach number
Nu	Nusselt number, $h D_h / k_{air}$
p	wetted perimeter
P	pressure
PR	pressure ratio
Pr	Prandtl number
R	gas constant
R_a	arithmetic mean roughness
Re	Reynolds number, VD_h / ν
S	lateral distance between holes, pitch
t	coupon wall thickness
T	temperature
U	maximum/centerline velocity
V	mass average velocity
x	streamwise distance

Greek

η_{th}	internal effectiveness
κ	thermal conductivity of coupon
κ_{air}	thermal conductivity of air
ν	kinematic viscosity
ρ	fluid density
ϕ	overall effectiveness, $(T_\infty - T_s) / (T_\infty - T_c)$
$\bar{\phi}$	area averaged overall effectiveness

Subscripts

avg	averaged
c	coolant
cl	centerline of film hole
f	film cooling flow
h	region on surface adjacent to film hole breakout
i	coupon internal channel
s	coupon surface
∞	mainstream

REVIEW OF LITERATURE

Because the use of AM is still emerging in the gas turbine industry, relatively few publications have addressed applications of AM to gas turbines. Within that limited body of literature, most papers focus on characterizing the manufacturing process and the resulting material properties; only a few focus on the effects AM has on heat transfer performance of gas turbine parts. However, patents describing inventions with AM film cooling [5–8] and a paper written by Schurb et al. [9] clearly show that gas turbine engine manufacturers are exploring the use of AM for actively cooled turbine hardware.

Within the open literature, two papers were identified that present the thermal performance of film cooling holes made with metal AM. Vinton et al. [10] studied the film effectiveness of an array of cylindrical holes made at engine scale with L-PBF. They observed decreased effectiveness for the entire array with AM holes compared to an array of smooth holes. They attributed the reduction to the roughness inside the holes but did not characterize the geometry of the holes or the roughness to compare it to their results. Jackowski et al. [11] performed similar experiments on an array of film cooling holes made with L-PBF. They studied six different hole geometries at engine relevant scales taking advantage of the additional design freedom AM allows to produce hole geometries that cannot be easily made with other manufacturing methods.

Several researchers have exploited the cost, manufacturing time, and design flexibility benefits of AM to perform experiments that likely could not have been realized with traditional manufacturing methods. Aghasi et al. [12] evaluated the use of fused deposition modeling, stereolithography (SLA), and photopolymer material jetting to quickly evaluate adiabatic effectiveness of novel film cooling hole designs. Kirollos and Povey [13] validated the use of L-PBF to produce prototypes of turbine vanes for thermal performance evaluation. This approach to product development allows for several iterations in the same amount of time it takes to produce a single prototype with conventional casting methods. Krawciw et al. [14] used L-PBF to create a panel with arrays of various shaped film cooling holes. They measured adiabatic effectiveness to evaluate performance of the array of film cooling holes. Although they used L-PBF, the film cooling holes were significantly larger than holes one might find in real engine hardware suggesting that the roughness is not as influential on their results as one might observe in an engine component made with AM.

A few investigators have examined the impact of in-hole roughness on film cooling effectiveness. Schroeder and Thole [15] performed detailed experiments with artificially roughened, shaped film holes and reported flow field, thermal field, and adiabatic effectiveness results. They showed that roughness has a significant impact on the thermal performance of film cooling holes. In particular, they found that the film cooling effectiveness was lower for holes with large relative roughness ($R_a/D \approx 0.018$). Schroeder [16] looked at the effect of spiraled grooves in a film cooling hole on its thermal performance. They found enhanced performance because of the spiral grooves as compared to axial or compound angled cylindrical holes. This was attributed to the

secondary flows generated by the swirling, which altered the typical flow patterns exhibited within and near the exit of cylindrical holes.

As the roughness of AM is random in nature and its size relative to the film cooling hole diameter is very large, none of the work currently found in public literature is directly useful for predicting the thermal performance of an individual row of shaped, AM film cooling holes. This study uniquely evaluated the thermal performance of a single row of shaped film cooling holes made with AM. As this information has not been published before, this paper generates initial design guidelines that will aid gas turbine designers as they utilize the emerging and constantly evolving technologies of AM.

STUDY APPROACH

To achieve the objective of this study, several test coupons were made with L-PBF using an alloy commonly used in high temperature turbine components. In order to capture the effects that the internal roughness might have on the film cooling performance, it was essential to produce coupons with film cooling holes comparable in size to those found in operational turbine components. An experimental rig was built to hold these coupons and provide both internal and external crossflows. The approach described by Albert et al. [17] was taken in this study whereby the dimensionless parameters of Biot number, Bi , and external to internal heat transfer coefficient ratio, h_o/h_i , were matched to those found in engines which implies that the results of this study can be directly applied to engines. Average Bi and h_o/h_i for a modern engine were calculated using values reported by Bunker [18]. This section describes the test coupons, the experimental setup, and the data analysis methods.

Description of Test Coupons

A set of test coupons was designed to simulate hardware one might find in a gas turbine engine. An image of one of the coupons is shown in Figure 1. The coupons have an internal channel of height H that allows coolant to flow in a co-flow configuration with that of the mainstream. Halfway along the channel, a row of film cooling holes eject coolant from the coupon through laidback fan-shaped cooling holes spaced at a specified pitch, S . The cooling hole shape selected for this study was a baseline shape proposed by Schroeder and Thole [19], which had expansion angles of 7 degrees in both the forward and lateral directions and was inclined relative to the surface by 30 degrees. The holes in these test coupons have the same relative

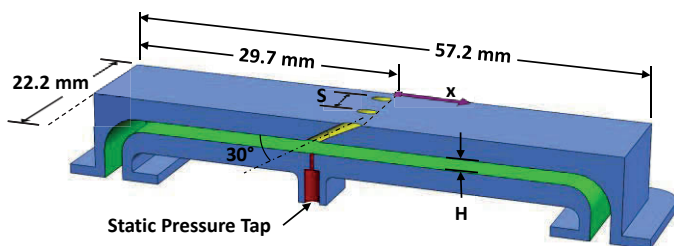


Figure 1. Test coupon features and dimensions.

dimensions for the metering length and diffuser length as did those defined in [19]. This meant that the wall thickness, t , of each coupon was dictated by the hole diameter D , meter length, and diffuser length specifications. Two different hole diameters were investigated in this study: 1x holes comparable in size to the smallest holes used in turbine components, and 2x holes that were twice that scale. The overall coupon dimensions stayed the same, but the wall t , S , and H were adjusted to maintain the correct non-dimensional parameters, hole shape, and H/D ratio. The coupons also have three static pressure ports just below the row of film holes; these were built into the coupons during the L-PBF process. The pressure taps enabled an accurate measurement of the pressure drop across the film holes.

All coupons were fabricated on a L-PBF machine during a single build using a nickel-chromium-iron-molybdenum based powdered alloy [20] with a composition matching that of Hastelloy® X. Material specific machine parameters recommended by the L-PBF machine manufacturer were used to build the coupons [21]. Some coupon geometries were duplicated and built in a different orientation relative to the build direction. The first orientation was selected to align the axis of the film hole metering section parallel with the build direction (i.e. vertical) as illustrated in Figure 2. Previous work by the authors suggested that this would give the least amount of in-hole roughness [2]. The other selected build direction aligned the top surface of the coupon at a 45° angle from the build direction (i.e. angled) as shown in Figure 2. The resulting hole was built at a 69° angle from the build direction (i.e. 21° above horizontal).

Cooling holes are rarely all aligned in the same direction on gas turbine airfoils. This means fabricating turbine components with L-PBF will result in holes with varying build orientations. The build direction will have a significant impact on the net hole shape and the in-hole roughness. This is the reason for investigating cooling performance at two different build direction. Because there are infinite build direction possibilities, ease and reliability of coupon fabrication was a key factor in selecting the orientation of the angled coupon. This build direction simplified support structure design, removal from the

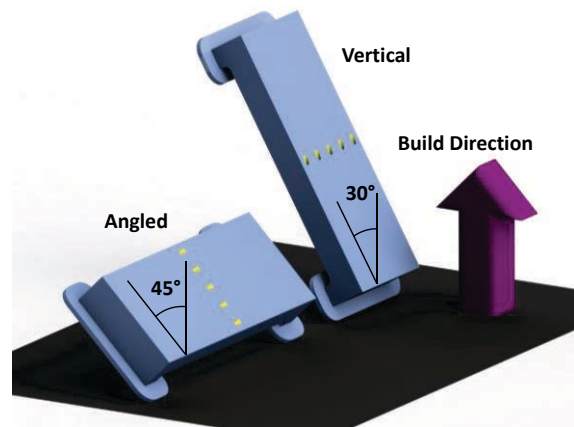


Figure 2. Coupon orientation during build showing vertical build direction and angled build direction.

build plate, and support removal. Previous work by the authors suggests that this orientation would result in greater surface roughness and poorer dimensional tolerance than the vertical build orientation [2].

After fabrication, excess powder was removed, and the parts were stress relieved before removal from the plate to minimize warping. Supports were removed, and the external surfaces were ground flat and smooth. All internal surfaces of the coupon were left unaltered. External roughness features are relatively simple to remove with conventional methods, but roughness features on small internal channels, like the ones in these coupons, cannot be removed with commercial processes currently available [3]. Installing pressure tubes, painting the surface with black paint, and sanding the paint smooth were the final steps in preparing the coupon for testing. Paint was not applied in the hole to avoid reducing the hole size or roughness magnitude; the absence of paint in the holes was confirmed by inspection with a light microscope.

Eight coupons were investigated in this study. Dimensions of each coupon are given in Table 1. The coupon name listed in the first column of Table 1 provides an abbreviated description of each coupon. The first two characters in the name describe the scale of the film holes: “1x” for the small holes, and “2x” for holes that are twice that scale. The next two characters describe the build direction: “A” for the coupons with the film hole built at an angle and “V” for the coupons with the film holes built in the vertical direction. The next two characters describe the channel height scale: “1H” for the low H/D ratio and “2H” for the H/D ratio twice that of the 1H. The final group of characters denote the manufacturing method used to produce the holes: “AM” for coupons with film cooling holes that were built in the L-PBF machine, “EDM” for cooling holes that were drilled with a plunge EDM into coupons built with L-PBF, and “BL” for baseline coupons that were also built with L-PBF and contained no film cooling holes. All coupons with film holes had a pitch to diameter ratio of $S/D = 6$. Only one coupon (1x-45-2H-EDM) had holes that were drilled with plunge EDM. Holes were drilled with EDM in one coupon for purposes of comparing a commonly used hole fabrication technique to film holes made with L-PBF. Although the holes were made using EDM, the coupon itself was made using AM such that the roughness elements from the AM build were present in the coolant supply channel.

Experimental Setup

The experimental rig, shown in Figure 3, was developed to facilitate cooling effectiveness measurements of the test coupons. It was designed to supply coolant to the coupon channel while simultaneously providing a crossflow over the external surface in the same direction as the coolant flow. The intention of using this configuration was to simulate components in turbines that are exposed to high heat loads and are actively cooled to reduce part temperature. Rig dimensions were chosen to represent engine conditions by matching parameters such as h_o/h_i and film hole blowing ratio, M , during experiments. Note that the coolant supply can be adjusted to be co-flowing or counter-flowing, but this particular study only used the co-flowing coolant configuration.

The external crossflow was supplied with dry, compressed air at a nominal temperature and pressure of 25°C and 4 bar. The flow rate of the air was measured with a turbine flow meter. A pressure regulator installed upstream of the rig and a throttling valve installed downstream of the test section allowed control of the supply pressure and mainstream flow rate. The mainstream air traveled through an aluminum rectangular channel that was nominally 25.4 mm in width and 9.5 mm in height. The bottom

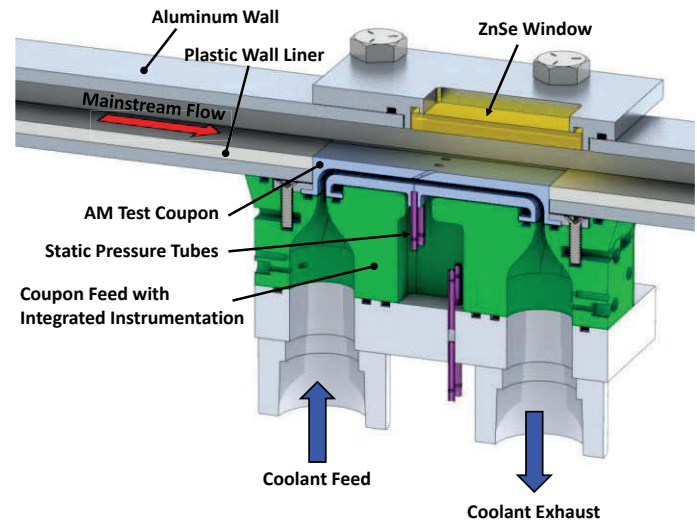


Figure 3. Test rig developed for this study.

Table 1. Test Coupon Dimension Specifications and Measurements

Coupon Name	Symbol	Design $D_{h,i}$ (mm)	Design t (mm)	Number of Holes	Design D (mm)	Design A_{min} (mm ²)	Build Direction	Measured $D_{h,i}$ (mm)	Measured t (mm)	Measured $A_{min,avg}$ (mm ²)
1x-A-2H-EDM	✕	2.45	1.14	9	0.381	0.114	Angled	1.78	1.18	0.107
1x-A-2H-AM	✱	2.45	1.14	9	0.381	0.114	Angled	1.76	1.20	0.0377
1x-V-1H-AM	○	1.26	1.14	9	0.381	0.114	Vertical	0.93	1.17	0.0760
1x-A-1H-AM	◇	1.26	1.14	9	0.381	0.114	Angled	0.72	1.20	0.0278
2x-V-1H-AM	●	2.45	2.29	5	0.762	0.456	Vertical	2.10	2.30	0.405
2x-A-1H-AM	◆	2.45	2.29	5	0.762	0.456	Angled	1.89	2.32	0.281
1x-V-1H-BL	○	1.26	1.14	-	-	-	Vertical	0.91	1.18	-
1x-A-2H-BL	✕	2.45	1.14	-	-	-	Angled	1.68	1.23	-
2x-V-1H-BL	●	2.45	2.29	-	-	-	Vertical	1.80	2.31	-
2x-A-1H-BL	◆	2.45	2.29	-	-	-	Angled	2.07	2.26	-

以上内容仅为本文档的试下载部分，为可阅读页数的一半内容。如要下载或阅读全文，请访问：<https://d.book118.com/195112000101011310>