EFFECT OF ADDITIVE MANUFACTURING PROCESS PARAMETERS ON TURBINE COOLING

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ABSTRACT

Turbine cooling is a prime application for additive manufacturing because it enables quick development and implementation of innovative designs optimized for efficient heat removal, especially at the micro-scale. At the micro-scale, however, the surface finish plays a significant role in the heat transfer and pressure loss of any cooling design. Previous research on additively manufactured cooling channels has shown the surface roughness increases both heat transfer and pressure loss to similar levels as highly-engineered turbine cooling schemes. What has not been shown, however, is whether opportunities exist to tailor additively manufactured surfaces through control of the process parameters to further enhance the desired heat transfer and pressure loss characteristics.

The results presented in this paper uniquely show the potential of manipulating the parameters within the additive manufacturing process to control the surface morphology, directly influencing turbine cooling. To determine the effect of parameters on cooling performance, coupons were additively manufactured for common internal and external cooling methods using different laser powers, scan speeds, and scanning strategies. Internal and external cooling tests were performed at engine relevant conditions to measure appropriate metrics of performance. Results showed the process parameters have a significant impact on the surface morphology leading to differences in cooling performance. Specifically, internal and external cooling geometries react differently to changes in parameters, highlighting the opportunity to consider process parameters when implementing additive manufacturing for turbine cooling applications.

INTRODUCTION

Metal-based additive manufacturing (AM) has begun to see many uses in the gas turbine industry: from fundamental research to production airfoils, the benefits of AM are being leveraged in a number of ways. For engine development purposes, AM allows quick iteration of potential design concepts. Traditionally, development engines have used cast parts, which require significant lead times. By using AM, lead times for parts are reduced, allowing designers to test a handful of design concepts before moving to production [1,2]. For other purposes, the increased flexibility of AM is being used to create innovative components for production. AM can produce geometries not possible with traditional manufacturing methods like casting, thereby allowing complicated designs that can decrease weight, reduce part count, or improve component performance [3].

For any application of AM, it is critical to understand the consequences of this manufacturing method. One well-known consequence of the AM process is a high level of surface roughness. While surface finishing techniques are available to smooth exterior surfaces, smoothing small internal surfaces can be challenging depending on the geometry and scale of the features. The current authors’ previous work was some of the first to establish the effects of AM roughness on fluid flow and heat transfer in both internal and external turbine cooling configurations [4–6]. Results from this work showed that the measured pressure loss and heat transfer of the as-built AM micro-channels was similar to that of highly engineered cooling channels with ribs and trip strips.

Consequently, the AM surface roughness can be viewed as beneficial from a turbine cooling perspective. However, all AM surface roughness is not created equally: there are many variables in the AM process that can affect both the magnitude and morphology of the surface.

Many studies have evaluated different processing parameters to determine their effect on material properties and, in some cases, surface roughness. However, most of these studies used simplified geometries and did not evaluate changes to the performance of an entire part caused by changes to the process parameters. In other words, the link among the AM processing parameters, roughness, and the performance of the component is missing. This study uniquely shows the potential in changing the AM process parameters to tailor the cooling performance of additively manufactured turbine cooling schemes.

NOMENCLATURE

$A_c$ cross-sectional flow area
$A_s$ surface area
$Bi$ Biot number, $h\tau/c$
$BO$ laser beam offset
$D$ film hole metering section diameter
investigate the surface roughness on the top surface of small cubes. Their results showed that a 2-3x difference in arithmetic mean roughness ($R_a$) was possible just by changing the process parameters. Moreover, the researchers found that roughness first decreased with volume energy density, before increasing again, indicating there was an optimal energy density to minimize surface roughness. Similarly, Spierings et al. [8] found the existence of an optimum energy density which minimizes the surface roughness on the top layer of test specimens. However, this study also showed that this optimum energy density has a dependence on the powder size distribution.

Some studies have attempted to use statistical methods to determine the optimal combination of parameters to reduce surface roughness. One such study by Calignano et al. [9] utilized the Taguchi method to determine the influence of scanning speed, laser power, and hatch distance on surface roughness of upward facing surfaces. However, there was significant interplay between the parameters in their results, highlighting the need to consider a lumped parameter such as energy density.

Other studies have looked at multiple surfaces of test coupons using the variation of a single process parameter. Mumtaz and Hopkinson [10] built single-pass thin wall parts with Inconel 625 using a pulsed laser. As the energy input was increased, an inverse relationship between roughness of top and side surfaces was observed. Roughness on the top surface decreased while roughness on the side surface increased, illustrating the need for different parameters in different regions of the component.

Exploring more realistic part geometries, studies by Wang et al. [11,12] investigated the response of curved and flat overhanging surfaces to various process parameters. In the study with the curved overhanging surfaces [11], the roughness increased as the curved surface approached the horizontal plane. This effect was studied more systematically [12], where test samples having flat overhanging surfaces from 25°-50° were built with a range of scanning speeds and constant laser power. The results showed that the energy input must be decreased as the overhanging angle is decreased to obtain a smooth and repeatable surface.

In a comprehensive study conducted by Tian et al [13], the authors built parts with surfaces at different angles to explore the effect of processing parameters on surface roughness. Their results showed that roughness was more dependent on the angle of the surface on downward facing surfaces (downskins) than for upward facing surfaces (upskins). Moreover, their results showed that the minimum roughness for both types of surfaces was achieved using the lowest heat input. Although this result was counter to that of Mumtaz [10], the findings of Wang et al. [7] show that these studies may still be in agreement. The energy densities tested by Mumtaz were lower than optimal, while those tested by Tian et al. were higher than optimal, leading to the different trends with energy density.

The Tian et al. [13] study also evaluated the effect of using a contour scan, or single laser pass around the edge of each layer, on the surface roughness. In their tests, the addition of a contour scan always decreased the roughness regardless of the layer thickness or laser parameters used for fabrication.

Fox et al. [14] varied the contour parameters in an attempt to determine the effect on the roughness. However, they struggled...
to find correlation with $R_s$; the roughness data did not show significant changes and thus no conclusions could be drawn.

Other researchers have begun to investigate AM for turbine cooling applications. Work by the current authors initially investigated the use of AM to create micro cooling channels for airfoils and other turbine components [4,5,15]. Results from these studies showed that the measured pressure loss and heat transfer of the as-built AM micro-channels was similar to that of highly engineered cooling channels with ribs and trip strips, illustrating the ability to use AM surface roughness for heat transfer augmentation.

In addition to internal cooling, film cooling holes produced with AM have also begun to be studied in literature. Studies by Schulz and Behrendt [16] and Vinton et al. [17] utilized AM to study different diffusion cooling designs, while studies by the current authors investigated the impact of AM roughness on the performance of a single row of shaped film cooling holes [6,18]. While there have been some studies showing the effect of in-hole roughness on film effectiveness [19], the extent to which the AM parameters can affect the performance of an AM hole has yet to be explored.

Therefore, there is an opportunity to leverage the flexibility of the AM process to control surface roughness for turbine cooling applications. This study serves as a unique proof of concept showing that the performance of a given internal or film cooling design can be controlled by adjusting the AM process parameters used for manufacturing.

**PROCESS PARAMETER BACKGROUND**

Although there are hundreds of variables to consider when constructing an AM part [20], the process parameters that were chosen in the current study are those that are highly influential on surface roughness for laser powder bed fusion (L-PBF) processes. These variables include the laser power (P), laser speed (V), and hatch distance (HD). The laser power and laser scan speed determine how much energy is input to the laser spot and how fast the laser spot is traversed across the powder bed, while hatch distance defines the spacing between laser passes.

To solidify the metal powder adequately, an appropriate amount of energy must be input by the laser. However, the effects of laser power, speed, and hatch distance (spacing between laser passes) on energy input are all interdependent, making comparisons of different cases difficult. Therefore, defining scaling parameters can help account for this interdependence. For single laser passes, the linear heat input (LHI = P/V), accounts for the opposing trends of power and speed to energy input. For hatching regions, the LHI can be divided by the hatch distance to define an energy flux (E = P/V HD) which accounts for the overlap of hatching passes. Another parameter commonly found in literature is the energy density, which is the simply the energy flux divided by the layer thickness. Since all cases in this study used the same layer thickness, energy flux is used to compare cases. However, the scaling would be the same as energy density.

When defining the parameters used for a given part, the different thermal boundary conditions within a layer must be considered. These boundary conditions affect the heat conduction away from the melt pool, resulting in changes to its size and stability. To account for these different boundary conditions, most L-PBF machines split each layer into three different 2D regions so that laser parameters specific to each region can be applied. These regions are shown in Figure 1.

The first region is classified as “core” material as shown in Figure 1. This region is typically at the center of the part with no exposed surface, where each new layer is built upon previously solidified material. The second and third regions are known as “skin” material, located near the edges of the part. The edge of these regions forms the final exterior surface of the part. These skin regions are then further classified by whether new material is built upon solid material or powder. Upskin, or upward facing surfaces, are those built upon solid material, while downskin, or downward facing surfaces, are surfaces built upon powder.

Defining the parameters in each of these regions allows the energy input to be adjusted to complement the different boundary conditions present in these regions. For example, downskin surfaces overhang unmelted powder, which has a much lower thermal conductivity than the solid material. Therefore, the energy input required to fully melt the material in the in downskin regions is lower than the core or upskin regions of the layer.

The need to adjust the parameters to the local boundary conditions has been highlighted by some studies in literature [11–13,21], as well as in some of the L-PBF machine manufacturer’s recommended parameter sets. However, the proper methodology for defining the parameters in these skin regions is still an open area of research.

In addition to hatching, single laser passes called contours are used for the edges of a particular layer, as depicted in Figure 1. Contours also follow the upskin/downskin classification, each having their own unique laser power and speed. Contours must also have a beam offset (BO) defined, which prescribes the offset from the CAD outline for the single laser pass. Contours have typically been implemented to reduce surface roughness by remelting some of the surface. As such, contours can be defined with various levels of energy input, tuned to remelt roughness features on the edges of each layer [13].

**INITIAL PARAMETER STUDY**

Before manufacturing turbine cooling geometries, numerous test elements were built to evaluate the effect of AM process parameters on surface roughness. The geometry of the test elements is shown in Figure 2.

![Figure 1. Schematic illustrating different exposure regions and geometric variables for creating an L-PBF part](image-url)
The test elements were designed to emulate a section of the internal cooling geometry provided similar thermal boundary conditions during the build, allowing the roughness measurements from the test elements to be representative of the internal surfaces in the coupons used for cooling tests.

Five different parameter sets were used to manufacture the initial test elements on a state-of-the-art L-PBF machine with a powder feedstock with the same composition as the Hastelloy-X alloy [22]. The parameter settings used for the build are defined in Table 1. These combinations of parameters for the upskins, downskins, and contours ultimately defined the properties of the final solidified part, including its surface roughness.

The roughness coupons were stress relieved before being removed from the build plate using wire electro-discharge machining (EDM). Finally, the parts were cut open to allow optical access to the channels for surface characterization.

To examine the surface morphology of the test elements qualitatively, scanning electron microscopy was used to image the as-built surfaces. Images from the upskin and downskin surfaces of the channels are shown in Figure 3 for each of the four test cases at the same level of magnification. Only one of the channels within the test elements was imaged, but the entire channel was viewed to ensure the images in Figure 3 were representative of the entire surface.

Also shown in Figure 3 are the values of surface arithmetic mean roughness ($R_a$) for each of the surfaces calculated from optical profilometry scans. The optical scans produced a two-dimensional surface representation with lateral (x, y) resolution of 1.6µm, and normal (z) resolution of $\ll 1$µm. To calculate $R_a$, a mean surface was fit to the data and the normal ($z$) heights of all of the discrete surface points were then averaged. This process was repeated for five discrete surface patches to obtain an average $R_a$ value. A 95% confidence interval is reported along with the average roughness value.

Figure 3a and 3f shows the results for the first parameter set, P1, which was a baseline case. Note that Figure 3a is the upskin (US) and Figure 3f is the downskin (DS) for the same parameter test case. For P1, one set of parameters was used for the entire part with no contours employed. The laser power and speed for this parameter set were chosen to ensure a fully dense part. These settings resulted in relatively large surface roughness with many cavities and partially melted particles, as seen in Figure 3a and 3f.

In an attempt to tailor the laser parameters to the local boundary conditions, the P2 parameter set used different parameters for the upskin and downskin regions. The results of this change are shown in Figure 3b and 3g. For the downskin, the applied energy flux applied was reduced by 55% to account for the higher conduction resistance encountered by building over powder. As was shown by Tian et al. [13], a reduction in energy input reduces the penetration depth of the melt pool, resulting in a smoother downskin surface. This result was achieved in the current study by reducing the downskin energy flux by 55% from the P1 settings. Figure 3g shows fewer drastic peaks and valleys on the surface than Figure 3f, corresponding to a reduction in roughness magnitude ($R_a$ value) by 31%.

On the other hand, the energy flux of the upskin surface was increased by 5% in the P2 parameter set. By increasing the energy flux, and decreasing the hatch spacing, a more consistent melting of the upskin surface was achieved, as seen in Figure 3b. In addition to changing the morphology, this increase in energy flux also reduced the roughness magnitude by 22%.

Given the roughness was reduced with increasing energy flux, the findings of Wang et al. [7] suggest that the upskin roughness may actually decrease further if a higher energy flux is used. Therefore, the optimal settings may not have been reached with these P2 upskin parameters. Nonetheless, the reduction in roughness of 22% was significant.

The P3 parameter set introduced contour passes to both the upskin and downskin surfaces. Results for this change are shown in Figures 3c and 3h. Since the edges of each layer are comprised of the ends of the hatch vectors, as shown in Figure 1, contours mitigate surface roughness by remelting these ends of hatch vectors into one horizontal weld. To achieve this outcome, the upskin contour was defined with an LHI 29% higher than the upskin hatching vectors. Comparing the upskins shown in Figure 3b and Figure 3c reveals that the intended result was achieved, with the P3 surface having horizontal weld lines and a roughness magnitude 37% percent lower than the P2 case. This result is consistent with the findings of Tian et al. [13], where the addition of a contour showed significant reductions in roughness.

Given the larger roughness magnitude on the downskin compared to the upskin in the P2 case, the downskin contour LHI was increased by a larger amount for the downskin, 67% over the P2 downskin hatching LHI, to melt the large roughness features together. While the resultant change in downskin roughness morphology, shown in Figure 3g to Figure 3h, was less severe than the upskin, adjusting the downskin parameters in the P3 case successfully decreased the roughness magnitude by 22%.

Since the reduction in roughness magnitude was lower for the downskin than the upskin in the P3 case, it is possible that the LHI of the downskin contour was too high for the downskin surface. Alternatively, this discrepancy could also be attributed to the non-uniform thermal conductivity present under the downskin. The conductivity of the powder is strongly dependent on the packing density and coordination number [23], which can vary considerably in the region of the rough downskin surface. Therefore, achieving an optimum set of parameters for downskin contours is difficult. Similarly, the melt pool is more unstable...
under these circumstances, making the surface roughness on the
downskin more difficult to control.

For the P4 parameter set, a second contour was added to the
both the upskin and downskin surface, with the results shown in
Figure 3d and 3i. Results indicate that a second contour did not
have a noticeable effect on the morphology or magnitude of the
roughness. This asymptote in roughness reduction can be
partially attributed to the powder particles present on the surface.
As the roughness of the underlying surface is reduced, the powder
particles themselves represent an increasing portion of the
roughness magnitude.

To understand the contribution of the powder particles to
the roughness magnitude, an analysis was carried out to
determine the $R_a$ value of a theoretical plane with a varying
number of spherical particles attached to the surface. The $R_a$ was
calculated in a similar manner to an actual measurement, whereby
all roughness heights are defined relative to a mean plane which
accounts for presence of the particles. All of the particles were
assumed to have a 35 micron diameter and the theoretical plane
dimensions were chosen to match the size of the surfaces shown
in the SEM images.

The analysis showed that to achieve the same roughness
magnitude as Figure 3c, 15% of a theoretical flat plane would
need to be covered by 35 micron spheres. Approximating the
coverage of particles on the actual surface shown in Figure 3c
using an image processing technique [24] revealed about 10%
particle coverage. Therefore, the upskin surface roughness has
reduced to a level where the powder particles are now playing a
major role in the roughness magnitude. To reduce the roughness
substantially from the levels achieved with the P3 parameter set,
the partially melted particles must be eliminated. The level of
partially melted particles is difficult to control, as evidenced by
similar amounts of particles in all of the images. For the upskin,
these particles are deposited by the complex flow field of the inert
gas flow mixing with the weld vapor plume [25,26], which is a
function of a number of variables.

![Figure 3. SEM images of upskin (US) and downskin (DS) surfaces from internal channels of test elements. Arithmetic mean roughness value and confidence interval from optical profilometer corresponding to each surface is overlaid. Width of images = 1.5mm.](image)

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**Table 1. Details of process parameters used for each of the four test cases**

<table>
<thead>
<tr>
<th>Parameter Set</th>
<th>Exposure Region</th>
<th>Hatching</th>
<th>Contour 1</th>
<th>Contour 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V (mm/s)</td>
<td>P (W)</td>
<td>HD (mm)</td>
<td>LHI (J/mm)</td>
</tr>
<tr>
<td>P1 Core</td>
<td>960</td>
<td>285</td>
<td>0.11</td>
<td>0.297</td>
</tr>
<tr>
<td>P1 Downskin</td>
<td>960</td>
<td>285</td>
<td>0.11</td>
<td>0.297</td>
</tr>
<tr>
<td>P1 Upskin</td>
<td>960</td>
<td>285</td>
<td>0.11</td>
<td>0.297</td>
</tr>
<tr>
<td>P2 Core</td>
<td>960</td>
<td>285</td>
<td>0.11</td>
<td>0.297</td>
</tr>
<tr>
<td>P2 Downskin</td>
<td>2400</td>
<td>145</td>
<td>0.05</td>
<td>0.060</td>
</tr>
<tr>
<td>P2 Upskin</td>
<td>600</td>
<td>153</td>
<td>0.09</td>
<td>0.255</td>
</tr>
<tr>
<td>P3 Core</td>
<td>960</td>
<td>285</td>
<td>0.11</td>
<td>0.297</td>
</tr>
<tr>
<td>P3 Downskin</td>
<td>2400</td>
<td>145</td>
<td>0.05</td>
<td>0.060</td>
</tr>
<tr>
<td>P3 Upskin</td>
<td>600</td>
<td>153</td>
<td>0.09</td>
<td>0.255</td>
</tr>
<tr>
<td>P4 Core</td>
<td>960</td>
<td>285</td>
<td>0.11</td>
<td>0.297</td>
</tr>
<tr>
<td>P4 Downskin</td>
<td>2400</td>
<td>145</td>
<td>0.05</td>
<td>0.060</td>
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<tr>
<td>P4 Upskin</td>
<td>600</td>
<td>153</td>
<td>0.09</td>
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<td>P5 Core</td>
<td>960</td>
<td>285</td>
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<tr>
<td>P5 Downskin</td>
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</tr>
<tr>
<td>P5 Upskin</td>
<td>960</td>
<td>285</td>
<td>0.11</td>
<td>0.297</td>
</tr>
</tbody>
</table>
Switching focus to the downskin, as shown in Figures 3h and 3j, the plateau of the downskin roughness magnitude between P3 and P4 was higher than the theoretical particle limit. The exact cause of the downskin limit is unclear; however, the 20\(\mu\)m magnitude is consistent with the minimum roughness achieved for a 45° downskin surface by Tian et al. [13]. As discussed previously, the downskin parameters are difficult to tune due to the irregularity of the boundary conditions. Therefore, it is likely that smoother downskin surfaces could be achieved with further parameter development.

Given the success of a single contour in reducing the magnitude of the upskin roughness, the P5 parameter set featured a single upskin contour added to the baseline parameters. Results of this change are shown in Figure 3a and 3j. The intent was to smooth the upskin to see if the effects of the upskin could be isolated. Unfortunately, this setting actually caused the roughness to increase slightly from the P1 levels.

The increase in roughness relative to the baseline from the contour could be attributed to two factors. For one, it is likely the energy input was not high enough to remelt the large roughness features shown in Figure 3a. The location of the contour was also likely defined without enough overlap. Since the beam offset was set to zero, the contour pass may have been too far away from the base of the roughness features preventing the contour pass from reducing the roughness. Instead, the contour added to the roughness features, slightly enlarging them. This result illustrates the need to properly tune the contour parameters for the level of roughness.

Ultimately, exposures P4 and P5 were selected to manufacture the turbine cooling geometries, serving as smoothest and roughest cases, respectively. Despite the similarities in surface roughness and magnitude between P3 and P4, the P4 parameter set was ultimately chosen for its lower confidence interval in roughness magnitude. With less spread in the roughness, the P4 surface had a tighter roughness height distribution and more uniform surface morphology than P3.

**TURBINE COOLING TEST COUPONS**

To evaluate the effect of the process parameters on cooling performance, internal and external cooling coupons were manufactured using the parameters described previously. This section presents details of the cooling coupons and their manufacture, as well as the characterization of the as-built geometry and roughness.

**Coupon Geometry and Manufacturing**

The first type of coupon was designed to study internal cooling as shown in Figure 4. The overall architecture of these coupons were first introduced in previous studies by the current author [4,5], and have been utilized in numerous other studies [15,27–31] from the same research group. In this geometry, rectangular cooling channels pass through a 25x25x3mm block of material, with flanges on the ends that mate with the test rig. The internal cooling coupons were all built at a 45° orientation, shown in Figure 4. This orientation allowed reliable manufacturing, and represented a realistic situation where a combination of upskin and downskin surfaces make up the internal channels.

The second type of test coupon was designed to evaluate film cooling performance as shown in Figure 5. These coupons featured a row of five film cooling holes fed by an internal cooling channel. The 7-7-7 hole, a laidback fan-shaped hole developed by Schroeder and Thole [32], was selected as the hole geometry for this study. This hole has been characterized extensively in the open literature by the inventors and other researchers, and was the design used in the authors’ previous paper investigating additively manufactured cooling holes [6]. This hole features an inclination angle of 30°, with forward and lateral expansion angles of 7°. The nominal hole diameter used in this study was 0.762mm. Further details on the cooling holes and the coupon geometry can be found in [6].

Unlike the internal cooling coupons, two different build orientations were used for the film cooling coupons, as shown in the inset of Figure 5. The intent was to evaluate both a favorable (hole axis aligned vertically) and unfavorable (hole axis angled at 21° above horizontal) build condition in an attempt to bound the multitude of build orientations that may exist when manufacturing a turbine component.

Both types of cooling coupons were built on a state-of-the-art L-PBF machine using the same Hastelloy-X powder as the test elements. The coupons then underwent a stress-relief heat treatment, before being removed from the build plate using wire EDM. Manual finishing for the cooling coupons involved support removal and abrasive smoothing of critical surfaces. For both the internal and external cooling coupons, the flanges were smoothed to ensure a proper seal with the test rig. For the external cooling coupons, the mainstream surface was also smoothed to a...
flat machined finish ($R_s < 1\mu m$). A smooth mainstream surface allowed for a predictable external boundary layer, a necessary condition to estimate the external heat transfer coefficient using correlations.

**Roughness Characterization**

The roughness characterization of the cooling coupons was limited to non-destructive methods to preserve the coupons. As such, there were no direct measurements of the cooling coupon roughness magnitude. However, since the test elements were simply a sector of the internal cooling coupon geometry, the roughness data from the initial parameter study can be assumed to represent the internal cooling coupons. Therefore, the P5 internal cooling coupon was expected to be approximately 50% rougher than the P4 coupon, as shown in Figure 3(d,e,i,j).

Optical access was available to the cooling holes in the film cooling coupons. The orientation of the surfaces in the holes did not allow for quantitative measurements; however, SEM images were taken to allow qualitative characterization of the in-hole roughness.

Figure 6 shows SEM images looking down the film hole axis for each build orientation of the P5 and P4 coupons. Coupons built in the angled orientation showed the largest change in morphology between the two parameter sets. This result is not surprising given the presence of an overhanging surface in the corner of the hole. As described previously, the heat input of the P5 parameter set was too high for the downskin regions, generating large roughness features. For the film holes in the angled orientation, Figure 6 shows these large roughness features in the corner of the hole.

When built with P4, however, the corner of the hole was produced closer to the intended geometry, and the entire hole shows lower levels of roughness. The metering section does appear skewed, however.

For the holes built in the vertical direction, the SEM images do not show much difference in surface roughness between P5 and P4, due to the lack of upskin or downskin surfaces. Therefore, certain geometric features are more resilient to non-optimal parameters than others, depending on their build orientation. This result illustrates the importance of including a relevant build orientation and part geometry when attempting to optimize AM process parameters.

**Geometry Characterization**

In addition to surface roughness, the as-built dimensions of the coupons were determined using x-ray computed tomography (CT). Scans were taken of both the internal and external cooling coupons, having resolutions of 30 and 70μm respectively. Using a software algorithm, the true surface of these scans was determined to within ±3μm and ±7μm, respectively. With the surface determined, the scans were then sliced in the direction of the flow: down the channel length for the internal cooling coupons, and along the axis of the film cooling hole for the external cooling coupons. From these slices, area, perimeter, and hydraulic diameter were calculated.

For the internal cooling coupons, the geometric parameter of interest was the hydraulic diameter, $D_h$, since this length scale was used to reduce Reynolds number, friction factor, and Nusselt number. The average hydraulic diameter for each coupon is plotted in Figure 7a normalized by the design intent hydraulic diameter. The data show that the P5 coupon was almost 20% undersized, while the P4 coupon was only slightly larger than the design intent. This reduction in hydraulic diameter of the P5 coupon was not surprising given the large roughness features seen in Figure 3. With micro-sized cooling channels, these large roughness features have a significant effect on the dimensional accuracy.

For the film cooling holes, the minimum cross-sectional area was the most relevant geometric parameter, given its use in calculating the blowing ratio and metering the coolant in an engine application. For each coupon, an average minimum area across all five holes is presented in Figure 7b. Data is presented for the coupons built in both the angled and vertical orientations. When built with P5, the data show that coupons in both build orientations resulted in metering areas smaller than the design intent. The vertical orientation, although optimal from a build orientation perspective, still resulted in a reduction of over 10%. The less optimal, angled, orientation resulted in a large reduction in metering area of nearly 40%. When built with P4, however, both build orientations were able to achieve the metering area much more accurately – to within ±10% of the design intent.

These results are promising, proving it is possible to create film cooling holes accurately at engine scale with AM. However, this study also illustrates the importance of developing process parameters that are optimized for a given geometry and

**Figure 7.** SEM images of film cooling holes built in the vertical and angled orientations using P5 and P4. Width of images = 2mm.

**Figure 6.** CT scan measured (a) hydraulic diameter of internal cooling channels and (b) minimum cross sectional area of film cooling hole metering section, normalized by CAD value.
orientation; the accuracy of the process is determined by the combination of the process parameters and the local part geometry.

EXPERIMENTAL SETUP AND METHODOLOGY

The methods used to evaluate the cooling performance of the previously described coupons are described in the following section. Details of the test rig and data reduction methods are presented for both the internal and external cooling tests.

Internal Cooling Tests

Internal cooling tests were run in a test rig designed to make bulk pressure loss and heat transfer measurements. This test rig, originally presented in [5], is shown in Figure 8. Air was fed to the inlet contraction at a constant pressure, while the flow rate was measured by a mass flow controller. Static pressure taps in the chambers upstream and downstream of the contraction and expansion were used to measure the pressure drop across the coupon. This measured pressure drop was then corrected for inlet and exit losses before being used in the friction factor calculation. Dimensions measured from the CT scans of each coupon were used to reduce the friction factor.

For heat transfer tests, a heater assembly was mounted to either side of the coupon to provide heat input to the system. Resistance heaters joined to copper blocks provided a constant temperature boundary condition on the exterior of the test coupon. To ensure proper thermal contact, a thin layer of thermal paste was applied between the coupon and copper block surfaces. Rigid foam surrounded the heater assemblies to minimize losses to the environment, while numerous thermocouples located throughout the rig were used to calculate conduction losses.

To calculate the heat transfer coefficient, the heat input to the system was first determined by calculating the electrical power dissipated in the heaters, less the calculated conduction losses. Then, the internal coupon surface temperature was determined through a 1-D conduction analysis. This temperature was then used with the fluid inlet and exit temperatures to calculate the log mean temperature difference. Finally, a bulk heat transfer coefficient was calculated using the heat input to the system, the log-mean temperature difference, and surface area of the channels.

Uncertainty was calculated for the friction factor and Nusselt number using the method described by Kline and McClintock [33]. Uncertainty in friction factor varied from 7-15%, depending on the Reynolds number and instrumentation used during the tests. However, the uncertainty was below 8% for all cases with Re>4000. Uncertainty in Nu was around 7% for all tests. Further details on the test rig and uncertainty can be found in [5].

Film Cooling Tests

Heat transfer testing on the film cooling coupons was performed in a rig first introduced by Stimpson et al. [6]. A schematic of this rig is shown in Figure 9. A cross-flow of room temperature air was imposed over the surface of the coupon, while coolant was fed to, and exhausted from, the channel within the coupon. Only a portion of the cooling flow exited through the row of cooling holes, imposing a co-flow internal cooling condition, similar to that found in many engine components.

The mainstream flow was supplied by compressed air at a nominal temperature and pressure of 20 °C and 4 bar. Alternatively, cooled carbon dioxide (CO₂) gas was used for the coolant in this study. The higher molecular weight of CO₂ allowed a density ratio DR = ρ₂/ρ₁ of around 1.7, without needing to reduce the temperature of the coolant to cryogenic levels. The flow rate of the coolant exiting the coupon was measured with a laminar flow element to calculate internal channel Reynolds number, Re. For all tests, Re, was held constant at 14,000 to maintain a similar coolant channel flow condition. The amount of flow exiting through the cooling holes was determined using a flow parameter versus pressure ratio curve generated in a separate experiment, as described in [6].

The non-dimensional parameters Bi and hᵢ/h₀ were not used to reduce any of the test data, but were necessary to ensure relevance to the cooling of engine components. These two parameters required values of the external (hₑ) and internal (hᵢ) heat transfer coefficients, which were determined using correlations. The value of hₑ was estimated using a formulation for developing flow between two parallel flat plates, with one side heated with a constant heat flux obtained from Kays et al. [34]. Details and justification of this formation can be found in the authors’ previous study [6]. Values for the internal heat transfer coefficient were estimated from a correlation for convective heat transfer in AM microchannels reported in Stimpson et al. [15]. A full list of non-dimensional parameters defining the experimental conditions is shown in Table 2.

Figure 8. Schematic of internal cooling test rig indicating measurement locations [5].

Figure 9. Cut-away schematic of the film cooling rig and test coupon showing testing configuration.
Table 2. Film cooling rig operating conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi</td>
<td>0.1</td>
</tr>
<tr>
<td>$h_w/\eta_i$</td>
<td>1.0</td>
</tr>
<tr>
<td>$M_{\infty}$</td>
<td>0.3</td>
</tr>
<tr>
<td>Re</td>
<td>14k</td>
</tr>
<tr>
<td>M</td>
<td>0 – 3.0</td>
</tr>
<tr>
<td>DR</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Surface temperatures of the coupon were measured using an infrared (IR) camera. Once steady state was reached for a given test condition, ten IR images were collected and averaged. These images were then converted to a wall temperature using a radiative heat transfer balance, as described in [6]. The surfaces of the coupons were painted with a flat black paint and smoothed to ensure a high and uniform emissivity.

From the IR data, overall cooling effectiveness was calculated using Equation (1), where $T_w$ is the wall temperature measured with the IR camera, $T_c$ is the mainstream static temperature, and $T_i$ is the coolant static temperature.

$$\phi = \frac{T_w - T_\infty}{T_c - T_\infty} = \frac{1 - \chi \eta}{1 + Bi + \frac{h_{\infty}}{h_i} + \chi \eta}$$

Also shown in Equation (1) is an alternate representation of overall cooling effectiveness, derived from a 1-D heat transfer analysis [35]. This form illustrates the dependence of overall effectiveness on the relevant non-dimensional parameters. In this study, Bi and $h_w/h_i$ were held constant at engine relevant values, allowing the effectiveness results to represent those seen in an engine under similar flow conditions.

Augmented effectiveness, $\phi/\phi_0$, was also calculated in an attempt to isolate the impact of film cooling from that of internal cooling. The effectiveness of the coupon without film cooling, $\phi_0$, was used to normalize the effectiveness data. Evaluating this ratio using the definition given in Equation (1) shows that it scales with the product of adiabatic effectiveness, $\eta$, and coolant warming factor, $\chi$, as seen in Equation (2). Examining this ratio gives insight into the adiabatic film effectiveness without directly measuring it.

$$\phi = 1 + \chi \eta \left( Bi + \frac{h_{\infty}}{h_i} \right)$$

An uncertainty analysis was performed to determine the accuracy of the film cooling results using the same methods used for the internal cooling results. Uncertainty in overall effectiveness was calculated to be between $\Delta \phi = \pm 0.043$ and $\Delta \phi = \pm 0.050$, depending on the temperatures in a given operating condition. The uncertainty in blowing ratio was 11%. In additional to accuracy, the precision of the overall effectiveness measurements was established by repeating the experiments.

Repeatability in $\phi$ was within the uncertainty band for all tests, so the results from the different test cases can be compared with good confidence.

**PROCESS EFFECTS ON COOLING PERFORMANCE**

The ultimate goal of this study was to show the differences in cooling that can be achieved via manipulation of the AM process parameters. The following section presents these results for the aforementioned internal and film cooling geometries.

**Internal Cooling**

For internal cooling, the cooling performance of a given geometry is typically characterized by the tradeoff between pressure loss and heat transfer. Considering first the effect of the AM parameters on pressure loss, the data from the internal cooling coupons are presented as a friction factor and plotted versus Reynolds number in Figure 10.

From Figure 10, it is clear that the friction factor is lower for coupons built with P4 than those built with P5. In the fully turbulent regime, the friction factor of the P4 coupon is approximately 40% lower than P5. This result is consistent with the 40-50% reduction in roughness magnitudes for both the upskin and downskin surfaces shown previously in Figure 3. The lower roughness magnitude combined with the larger hydraulic diameter ultimately resulted in a lower relative roughness for the P4 coupon channels, leading to the reduced friction factor.

However, the effect of the parameters on the heat transfer performance was different than the pressure loss. Figure 11 shows the Nusselt number data for each coupon plotted versus Reynolds number. It is immediately clear that there is less separation between the P4 and P5 Nusselt numbers than was seen with the friction factor. Over the range of Reynolds numbers tested, the Nusselt number of the P4 coupon was only 5-10% lower than the P5 coupon.

The discrepancy between changes to friction factor and Nusselt number is likely due to differences in the effectiveness of the roughness features at transferring heat. As originally hypothesized by Stimpson et al. [5], the effectiveness of AM roughness for heat transfer is dependent upon the connectivity of the roughness element to the underlying surface. If a roughness element is not well connected to the base surface, the resultant increase in conduction resistance will decrease the element’s fin efficiency. Therefore, surfaces with these “inefficient” roughness

**Figure 10. Friction factor versus Reynolds number for internal cooling coupons showing differences between parameter sets P5 and P4. Smooth channel reference line calculated using Blasius correlation.**

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features are incurring unnecessary pressure loss, since the pressure loss is mainly related to the roughness size and not its surface connectivity.

Under this hypothesis, the images shown in Figure 3i and j indicate the roughness features of parameter set P4 were better suited for heat transfer than P5, particularly on the downskin surface. The P5 surface shows many undesirable cavities and lightly attached particles.

Consequently, the decrease in heat transfer that would be expected as a result of the decrease in relative roughness when moving from P5 to P4 was offset by an increase in the efficiency of the roughness elements. These counteracting effects resulted in the similar heat transfer performance shown in Figure 11.

Since turbine components typically operate under fixed pressure ratio, it is useful to also look at the friction factor data in this context. Using the fully turbulent friction factors and geometric values for the P4 and P5 coupons, an analysis was carried out to determine the change in mass flow rate under a fixed pressure ratio. When changing the parameters from P5 to P4, the coolant flow increases by 75%. This result is significant from a turbine design perspective, since the parameters used to manufacture a component can have a large impact on the amount of cooling flow that will be used by a cooling architecture. Alternatively, this result illustrates the ability to control the pressure loss of an internal cooling scheme simply by adjusting the AM process parameters.

Potential applications of this concept could be locally optimized pressure loss and heat transfer, or making a performance change to a component without requiring a redesign of the cooling architecture. However, further work in this area is needed to determine the degree to which the process parameters can be used to optimize for internal cooling performance.

Film Cooling

Since gas turbine cooling typically features both internal and external cooling, evaluating the effect of process parameters on film cooling performance was essential. Film cooling coupons built in two different orientations using parameter sets P5 and P4 were evaluated for overall cooling effectiveness in matched Biot number tests as described previously. Results are first presented as contours of overall effectiveness in Figure 12, at a constant blowing ratio and internal channel Reynolds number. The jagged edges of the contours in the upper row of images are an artifact of a different IR camera used for those measurements. However, the accuracy of the data was not affected by the change in camera.

Overall, the cooling effectiveness contours in Figure 12 show similar performance between coupons built in the angled orientation using parameter sets P5 and P4. There was a slight improvement in effectiveness immediately downstream of the holes with P4, but in general, the film appeared to be exiting the holes and covering the surface in a similar manner for the P5 and P4 coupons. On the other hand, the holes built in the vertical orientation showed much better cooling when built with P4 versus P5. This result is not immediately intuitive, given the angled coupon experienced larger changes in roughness and metering area when moving from P5 to P4, as shown in Figure 6 and Figure 7b respectively.

To further investigate this result, area-averaged augmented effectiveness, \( \frac{\phi}{\phi_0} \), was calculated for the region shown in the contour plots (S/D = ±9, X/D = 0-20). As detailed previously, the augmented overall effectiveness is the overall effectiveness normalized by the effectiveness of the same coupon without film. By holding the relevant non-dimensional parameters in Equation (2) constant, the augmented effectiveness provides an idea of the film effectiveness without directly measuring it [18].

Given the results from the internal cooling coupons, it is likely that the internal heat transfer coefficient of the film cooling coupons was affected by the change in processing parameters. Therefore, comparing augmented effectiveness isolates the differences in film effectiveness from any differences in the internal channel convection between coupons.

Area averaged augmented effectiveness is plotted vs. blowing ratio in Figure 13. Here the effect of the change in parameters is more visible than in the contours of effectiveness. With internal channel convection effects isolated, the effectiveness of the P4 coupons in both build orientations are now higher than those built using P5. While both orientations of P5 show similar results, the build orientation had a much stronger effect on the performance of the coupons built with P4. The vertically oriented P4 coupon showed a 20% higher augmented effectiveness than the angled P4 coupon. This result is likely because the vertical P4 film holes were the largest and smoothest hole tested, as evidenced by the SEM images in Figure 6, and the

Figure 11. Nusselt number versus Reynolds number of internal cooling coupons showing differences between parameter sets P5 and P4. Smooth channel reference line calculated using Gnelinks correlation.

Figure 12. Contours of overall cooling effectiveness at M=1.2, Re: 14,000. Top row are P5 coupons, bottom row are P4 coupons.
measured areas in Figure 7b. Therefore, these holes had the lowest relative roughness, minimizing the impact to the flow exiting the hole.

Interestingly, relative performance of the different test cases scales with the measured metering area of the holes: the angled P5 coupon had the smallest holes, followed by vertical P5, angled P4, and finally vertical P4. This trend seems to point to the importance of the roughness in the metering section to the performance of the film. Despite the fact that blowing ratio accounts for the difference in metering area among the holes, it does not account for the roughness magnitude. Also, because the two P5 coupons performed similarly over a range of blowing ratios (despite having different metering areas and roughness), the effect of the roughness appears to diminish with magnitude. In other words, once the roughness reaches a certain level in the film holes, the effectiveness ceases to decrease. Thus, film holes appear to be very sensitive to in-hole roughness.

Schroeder and Thole [19] investigated adiabatic effectiveness of roughened 777 holes and saw similar results. The “slightly rough” holes \((R_s/D = 0.006 – 0.009)\) in their study performed similarly to their smooth baseline holes, while the “rough” holes \((R_s/D = 0.017 – 0.020)\) showed a steep decline in adiabatic effectiveness with blowing ratio. Consequently there appears to be a narrow window of acceptable roughness magnitude for a film cooling hole.

Further work is needed to fully understand the sensitivity of film cooling holes to AM surface roughness. In the meantime, in order to maximize the performance of a traditional cooling hole made with AM, the process parameters should be tuned to minimize the in-hole roughness.

CONCLUSIONS
In this study, the parameters of the L-PBF process were altered to examine the effect on surface roughness, and ultimately, the performance of internal and external turbine cooling geometries. First, AM parameters were varied to observe the effect of laser power and contours on the surface roughness of small test elements coupons. From this initial testing, two different parameter sets were chosen to manufacture internal and external cooling geometries.

Results of the initial parameter exploration showed that decreasing the heat input of the upskin and downskin regions and adding contours resulted in smoother surfaces with more uniform roughness. Simply by manipulating process parameters, the roughness magnitude could be changed by 50% for both the upskin and downskin surfaces.

CT scans of internal cooling channels showed that applying different process parameters changed the dimensional accuracy of the process, with reductions in hydraulic diameter approaching 20%. Additionally, CT scans of the film holes showed large deviations from the designed metering area for certain parameter sets. However, adjusting the AM parameters ultimately allowed the film cooling holes to be printed within ±10% of the design intent.

Results from internal cooling tests showed that the reduction in roughness of the internal cooling channels caused a commensurate reduction in friction factor of 50%. However, the reduction in Nusselt number was negligible, indicating that the pressure loss is much more sensitive to changes in roughness than heat transfer. Furthermore, when considering a constant pressure ratio boundary condition, changing the parameters to achieve a smooth instead of rough surface can increase the coolant mass flow by 75%. Consequently, this result shows the ability to use the AM process parameters to control the flow and heat transfer through a turbine component.

For film cooling holes, results showed that the cooling effectiveness is very sensitive to surface roughness in the hole. A 30% reduction in cooling effectiveness was measured between the smoothest and roughest cooling holes generated with different parameter sets. Therefore, the goal for optimization of process parameters for traditional film cooling geometries should be to reduce the roughness as much as possible. Alternatively, new film cooling designs could be created that are less sensitive to surface roughness and take advantage of the capabilities of AM.

The sensitivity of film cooling holes to AM roughness has implications for both manufacturing as well as rapid prototyping. Considering manufacturing applications, roughness in the AM cooling holes may render laboratory tests of cooling with smooth geometries inaccurate. Similarly, if AM is used to prototype designs that are to be cast or drilled in production, the results from testing the AM prototype may not represent the performance of the actual production part. Therefore, it is important to understand how the AM process parameters affect these cooling geometries so that the AM process can be tailored to obtain the desired performance.

Ultimately, this study has demonstrated the ability to use the additive manufacturing process to control the performance of a given internal cooling or film cooling design. This result shows great potential in tailoring roughness morphology using AM process parameters. Further work is needed in this area to determine the limitations of this method and best practices. However, the work presented here is an essential first step to leveraging the AM process to improve turbine cooling performance.

REFERENCES


