Effects of Coolant Build Direction on Additively Manufactured Fan-shaped Cooling Holes

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Abstract

For a combustor liner, the cooling holes design plays a significant role in combustor aerodynamic designs, in this case, the high- temperatures- rise combustor can benefit from improved designs based on Additively Manufactured. In this study, five test coupons were made from high-temperature nickel alloy using a laser powder bed fusion process. The effects of the different build direction are studied via these coupons containing three rows of fan-shaped cooling holes. The research shows the different feed directions affect the surface roughness quality of the cooling holes channel which influences the discharge coefficient and cooling performance. The effectiveness measurements showed that the fan-shaped hole cooling performance is better when the fan-shaped side is built first compared to the circular side is built first.

Keywords: combustor Additively Manufactured cooling performance

1. INTRODUCTION

With the development of Additively Manufactured (AM), it is possible to create aero-engine combustor components using high temperature nickel alloys to build the promising designs which were difficult to implemented. Compared with the conventional manufacturing approaches, AM technology has great advantages in fabricating components with complex geometries and is now an important strategical direction for the manufacturing industries. AM as a cutting-edge smart manufacturing technology, will lead to profound changes for the production processes. Furthermore, AM is quite attractive for aerospace industries for airframe and engines components.

A large number of components in the aerospace engines could be integrated into one component fabricated by AM, which could certainly make these engine parts lighter and more reliable. Furthermore, the complex-shaped components, which are difficult for conventional manufacturing approaches, could be easily fabricated by AM. This could significantly reduce the design concept validation and the turn-around time, and further shorten the airworthiness certification cycle. For the fabrication of the combustion chamber flame tube, the conventional manufacturing and assembling approach normally contains: 1. laser cut cooling holes in the forged component; 2. weld the individual component into flame tube. This assembling process could be time-consuming and expensive, which makes the design and fabrication of cooling structures with higher efficiency for the flame tube walls extremely difficult and costly via the conventional approaches.

In this study, laser powder bed fusion (L-PBF) process, one of the most commonly used AM techniques, is used to fabricate the flame tube. The effects of shaped hole, which could be easily fabricated by using L-PBF, on the cooling efficiencies were investigated. This paper studies a fan-shaped cooling hole. Compared with the film cooling hole and tiles cooling structures that commonly used on flame tubes, the fan-shaped hole cooling structure does not require film grooves or tongues and it can be made of sheet metal. Thus, the flame tube has a simpler structure, lighter weight, fewer cooling holes and a shorter processing cycle. Compared with divergent cooling structure, fan-shaped cooling structure has less cooling holes and better cooling efficiency.

The direction of placement of AM parts is the first step for successful printing, however, there is no relevant research on the hole type and the surface roughness of the hole formed by this kind of cooling hole under different placement directions of the flame tube. The aim of this paper is to study the influence of different printing growth directions on the cooling efficiency of the cooling holes on the wall of the 3D printing flame tube.

2. LITERATURE REVIEW

Numerous researches have been carried out for the comparison of lateral expansion holes and cylindrical holes. The exit velocity of the traditional cylindrical hole is high, when the cooling airflow enters the mainstream flow and encounters the front flow, it becomes a structure similar to a bluff body. A large horseshoe vortex will be generated at the upstream of the hole outlet. Passing through the hole outlet, the cooling airflow could be divided into two branches and flow from both sides to the downstream, forming a reverse kidney-shaped vortex downstream. The kidney-shaped vortex will induce the mainstream to flow to the wall surface while separating the cooling air from the wall surface. Furthermore, the kidney-shaped vortex could accelerate the blending of the cooling air, increase the temperature of the cooling air, and reduce its adherence, thereby reducing the effectiveness and the lateral expansion. The hole can greatly reduce the jet outlet velocity, thereby significantly reducing the horseshoe vortex and the kidney-shaped vortex downstream of the hole outlet. The cooling air flow is flat and covers the wall surface. With the increase of the blowing ratio, the advantage of the lateral expansion holes becomes more obvious [1][2]. Behrendt [3] study the cooling characteristics of small holes in the condition close to the real one. It was found that the blowing ratio of the primary and secondary flows is about 5.2, which is considered as the high blowing ratio, with the pressure loss of the combustion chamber 3%. Thus, it can make full use of lateral expansion holes under this aerodynamic condition.

Meanwhile, Bai-Tao An [4][5] studied the adiabatic cooling efficiency of rectangular expansion holes and fusiform expansion holes in a numerically approach, and found that the cooling efficiency of such fusiform expansion holes raised on the upper wall is higher than that of rectangular expansion holes under the high blowing ratio. It is more obvious when the cross-sectional width is small. W. Colban [6] measured the heat transfer coefficients and adiabatic cooling effectiveness of the fan-shaped hole under low-speed conditions. The result shows that the heat transfer coefficient at the edge of the blade reaches a peak value, and reduced to a constant at the pressure surface. The cooling efficiency of the fan-shaped hole on the blade is higher than that of the traditional cylindrical cooling hole. Sun-min Kim [7] studied the adiabatic cooling efficiency of four shaped holes (louver hole [8], dumbbell hole [9], fan hole, crescent hole [10]) in a numerical approach. The calculation results in this study show that the shutter hole has the worst cooling efficiency, while the dumbbell hole has the best cooling efficiency among these four shaped cooling holes.

Until now, the researches on the cooling efficiency of the lateral expansion holes and cylindrical holes on the curved surface are mostly focused on the geometric characteristics and working environment of the turbine blade. The turbine blade profile includes the convex suction side and the concave pressure side. It is found in the published researches that the cooling efficiency of the pressure side is lower than that of the suction side in the same cooling method due to the characteristics of external airflow of the turbine blade [11]. Based on the suction side of the low-speed cascade with an enlarged size, Davidson [12] studies the effects of the curvature on the profile on the film cooling performance of the cooling hole. The experiment found that the curvature of the cascade has a greater impact on the cooling efficiency of the cylindrical hole and a smaller impact on the cooling efficiency of the lateral expansion hole, Moreover, the lateral expansion hole at different curvatures is superior to the cylindrical hole, and the advantage is proportional to the blowing ratio.

The flow characteristics of the airflow are different from those of the turbine blades at the position of the small curved pipe of the recirculation combustion chamber, the convex side of the turbine blade is affected by the pressure gradient, the pressure of the mainstream flow help the cooling airflow adhere to the wall. The small bend of the return combustion chamber is also convex, but its curvature is large, and it is necessary to guide the mainstream flow to produce a 180-degree rotation. The cooling airflow is greatly affected by the centrifugal force, and it is extremely easy to produce separation, so it needs to be studied in detail.

3. LITERATURE REVIEW

3.1 Description of testing samples

Four flat-plate cooling efficiency testing samples fabricated by the L-PBF process from Hastelloy-

X ,which commonly used for combustor components, was used and labelled as: A, B, C, D. Each testing sample contains 90 holes, which were aligned in 3 rows with 30 holes in each row. The schematic diagram of shaped hole structure is shown in Figure 1.

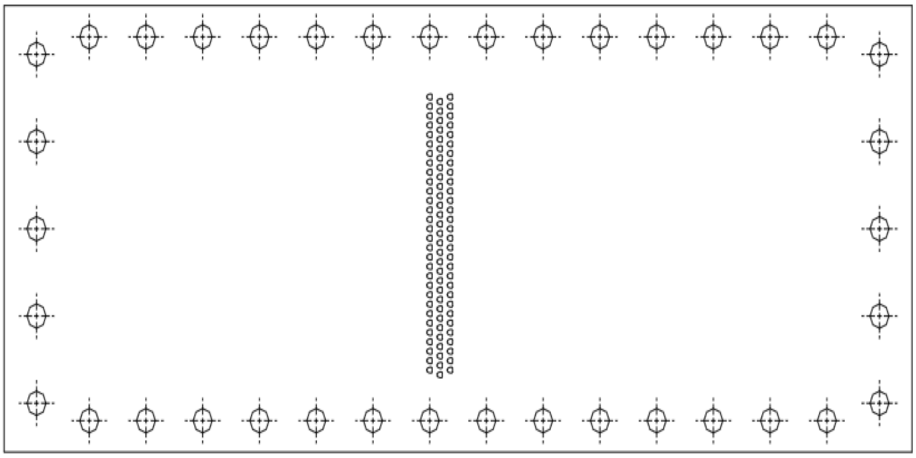


Figure 1 –The layout of LPBF fabricated sheet with fan-shaped cooling hole

The cooling air gradually expands along the flow to the outlet channel, and the cooling gas flow rate gradually decreases. This could help the cooling gas film attaching with wall and expanding in the circumferential direction. A cooling air coverage area at the outlet that is wider than traditional cooling coverage could be formed. Furthermore, this could guide the cooling air, which is blown into the flame tube, flow in the designed direction, as shown in Figure 2.

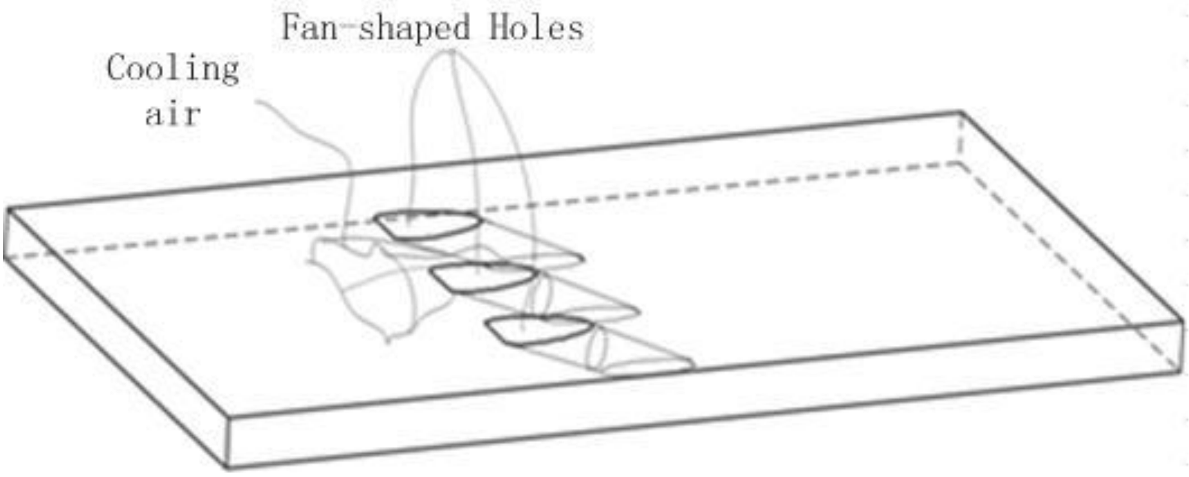


Figure 2 –The cold air flow out of fan-shaped cooling holes

In order to study the cooling efficiency of the shaped holes in different directions, the test samples were fabricated by LPBF (Figure 3) from Hastelloy-X. Three different growth direction are defined in this study, which are different in the angles between the plate and the vertical directions: SAMPLE A (+45°), SAMPLE B (0°), SAMPLE C (-45°). Figure 3 shows the outlets of the shaped hole expanded sections in these three printed sheets all face down.

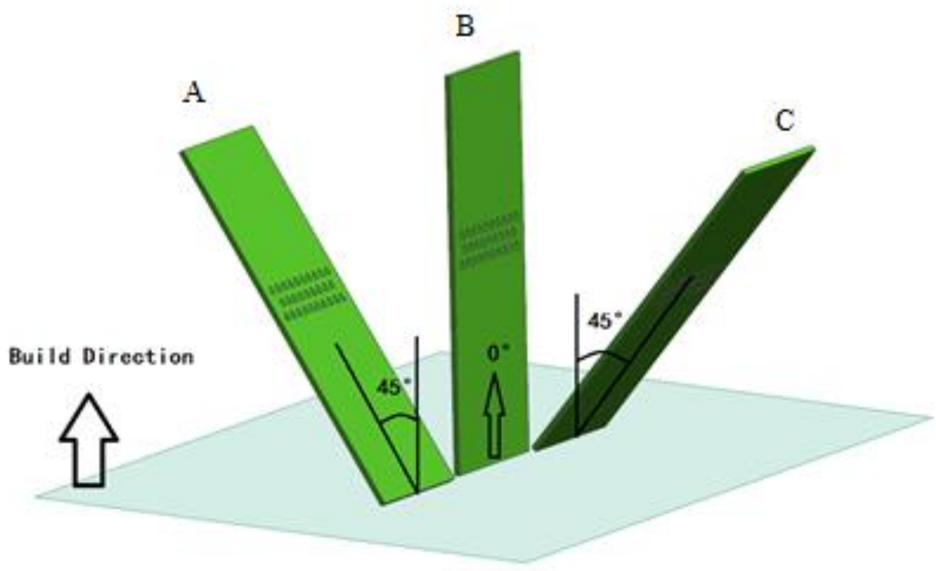


Figure 3 –The growth directions of hole plate

SAMPLE B has the shaped hole with the angle of 0°, which is widely used in engineering. Another AM testing sample with the expansion section outlet facing up are added to compare the cooling efficiency under these build directions with their schematic drawings shown in Figure 4.

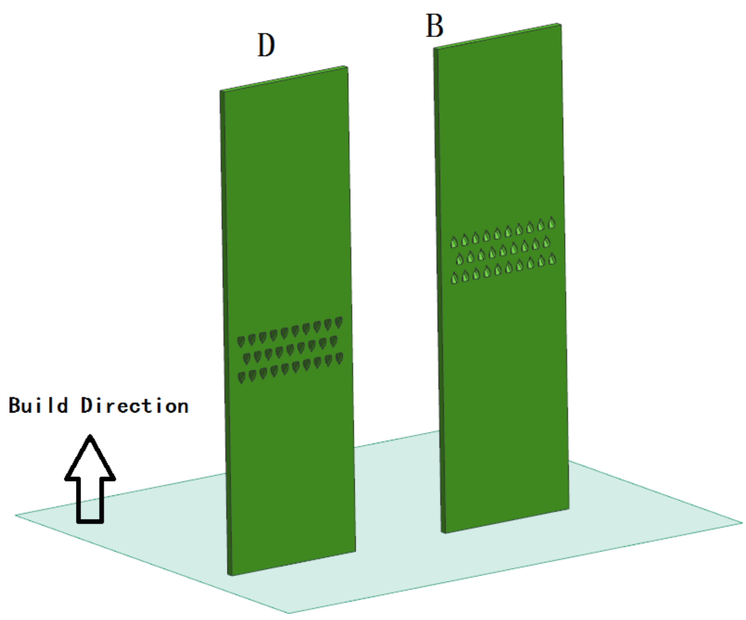


Figure 4 –The opposite build directions of hole plate

Table 1 Structural parameters of flat test pieces

Testing Samples	Direction (angle with the axial surface)	Directions
A	45°	Down
B	0°	Down
C	-45°	Down
D	0°	Up

3.2 Experimental Device Set-up

The cooling efficiency experiment setup is composed of the main pipeline system, monitoring system, testing system, cooling system, electric heating system, electric control system and flat cooling efficiency test section. The main pipeline system supplies air, while the valve controls the primary and secondary mass flow distributions. The mainstream flow enters the hot side channel of the testing section after the electric heater, and the secondary cooling gas passes into the cold side channel of the test section. The plate cooling efficiency test device was consisted of cold and hot sides, the air flow channel, the cooling efficiency test piece, the temperature and pressure probe, with the schematic diagram and the real parts shown in Figures 5. The flow rate of the cold air inlet was modified based on the different flow rate (cold air per unit area), while all of the gas in the cooling channel was used for flat panel cooling. During the test, K-type thermocouples were used to measure the wall temperature at different positions of the lateral expansion hole outlet.

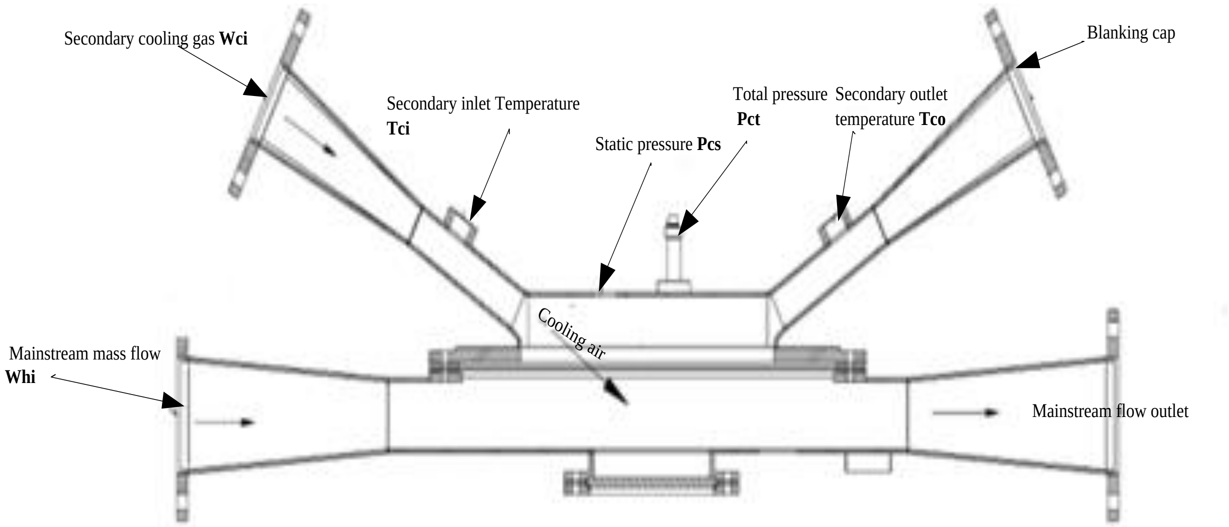


Figure 5 –The cooling efficiency rig test section

Some temperature and pressure measurement probes of the measurement device is shown in Figure 5. Table 2 shows the measured parameters and the accuracy in detail. The wall temperature with distance was measured by thermocouples in two rows of measurement points, as shown in Figure6. The measurement point rows were located 8 mm away from the plate centerline. The distances from the outlet of gas film are L=4mm、9mm、14mm、19mm、24mm、29mm totally of 6 points; the other row is located 6.5mm below the center line of the plate and the temperature measurement point of the flow direction is the same as above. A total of 12 thermocouple measurement points in the two rows.

Table 2 Measured parameters and their accuracy

	Symbol	Measured parameters	Devices	Accuracy
1	P_{CS}, P_{hsi}, P_{ct}, P_{hti}	Air pressure (Pa)	PSI9016 Pressure module and total and static pressure probes	±0.5%
2	P_H	Environmental pressure (kPa)	Barometer	±0.01%F·S
3	T_H	Main inlet temperature (℃)	K-type thermocouple	±1.5or ±0.4%t
4	T_{ci}	Secondary inlet temperature (℃)	K-type thermocouple	±1.5or ±0.4%t
5	Tco	Secondary outlet temperature (℃)	K-type thermocouple	±1.5or ±0.4%t
6	T_W	Wall temperature of test piece (℃)	K-type thermocouple	±1.5or ±0.4%t
7	T_H	Ambient temperature (℃)	K-type thermocouple	±0.5or ±0.4%t
8	W_{hi}	Mainstream mass flow (g/s)	Vortex Flowmeter	±2%
9	W_{ci}	Secondary flow mass flow (g/s)	Mass flowmeter	±0.5%

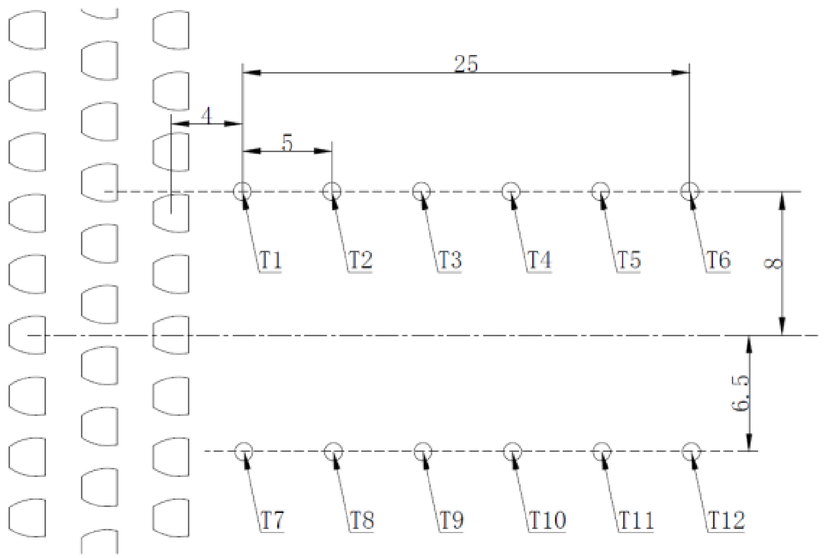


Figure 6 –Location of thermocouple measuring point of flat test piece

3.3 Data processing approaches

The data processing and performance parameters calculation were carried out by using the following equations, where Equation 1 was for blowing ratio and Equation 2 was for cooling efficiency.

$$M = \frac{W_{film} A_{gas}}{W_g A_{film}} \tag{1}$$

Where, M is blow ratio, A_{film} is Air intake area of film cooling hole (m^2), A_{gas} is hot side channel area (m^2), W_g is hot gas inlet flow (g/s), W_{film} is cooling air flow through the gas film hole (g/s).

$$\eta_j = \frac{T_{tg} - T_{ti}}{T_{tg} - T_{tc}} \tag{2}$$

Where, $\boldsymbol{\eta_i}$ is the cooling efficiency at certain point ***j*** on the wall, $\boldsymbol{T_{ti}}$ is wall temperature at certain point ***i*** (K).

3.4 Test Parameters

The cooling efficiency testing was carried out on the flat-plate testing samples A, B, C, and D, with two sets of testing parameters used: mainstream (hot gas) inlet parameters and secondary flow (cold air) inlet parameters.

Mainstream inlet parameters are: inlet static pressure P_{CS} (set as room pressure), inlet temperature T_h =200°C and inlet flow W_{hi} =135g/s. Secondary flow inlet parameters are inlet temperature T_{ci}=25 °C, inlet flow W_{ci}=2.0, 4.0, 6.0 and 8.0 g/s, with the relevant blowing ratio M 1, 2, 3 and 4.

4. RESULTS AND DISCUSSION

4.1 Blow Ratio Change

With the different blowing ratios, the measured cooling efficiencies of the fan-shaped hole are shown in Figure 7. The test results show that the cooling efficiency of the fan-shaped holes increases with the increase of blow ratio M. Meanwhile, the cooling efficiency remained almost constant with M increased to 4.

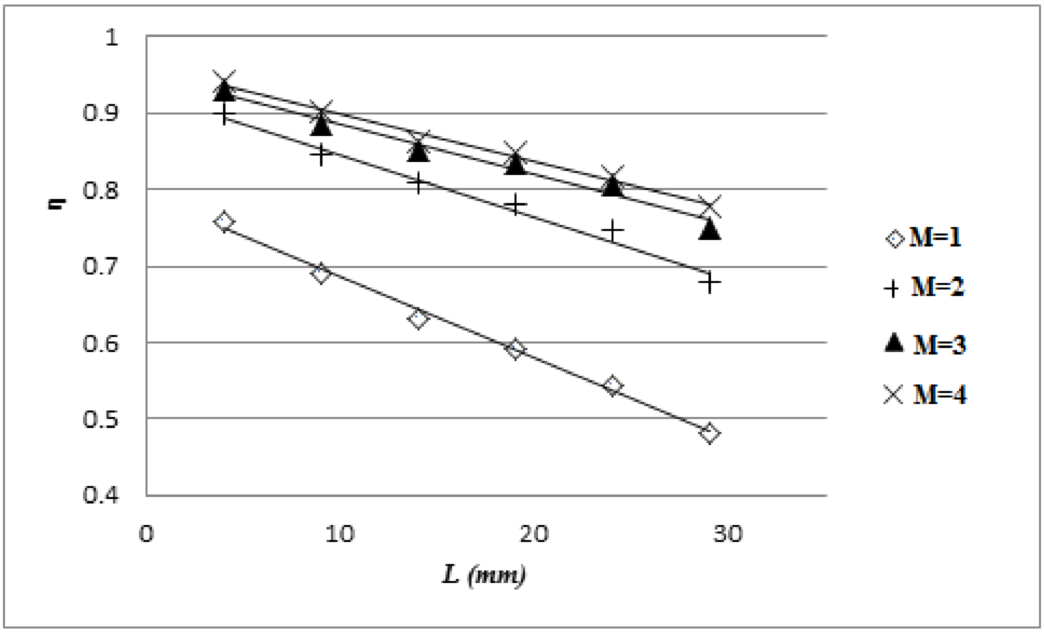


Figure 7 –Cooling efficiencies of shaped holes with different blowing ratios

When blowing ratio M=1 could lead to a smaller secondary cooling air flow and lower air flow speed, which lead to a smaller air covering. In the distance of 30 mm away from the cooling hole outlet, the cooling efficiency dropped to 50%. Meanwhile, with the increase of blowing ratio, the secondary cooling air flow and air flow speed increase, and the covering distance of the cooling air increases obviously, the cooling efficiency reaches 70% at 30mm of the outlet. When the blowing ratio increases to 3, 4, the cooling efficiency increases slightly and basically keeps the same level.

4.2 Changes in different growth directions

Three test samples with different growth directions of A, B, and C were subjected to a cooling efficiency test, and the measurement results are shown in Figure 8. The test results show that the fan-shaped holes of the same model in different growth directions have large differences in cooling efficiency. The fan-shaped holes of Sample A have the worst cooling efficiency, while the Sample B has a better cooling performance and Sample C has the highest cooling efficiency.

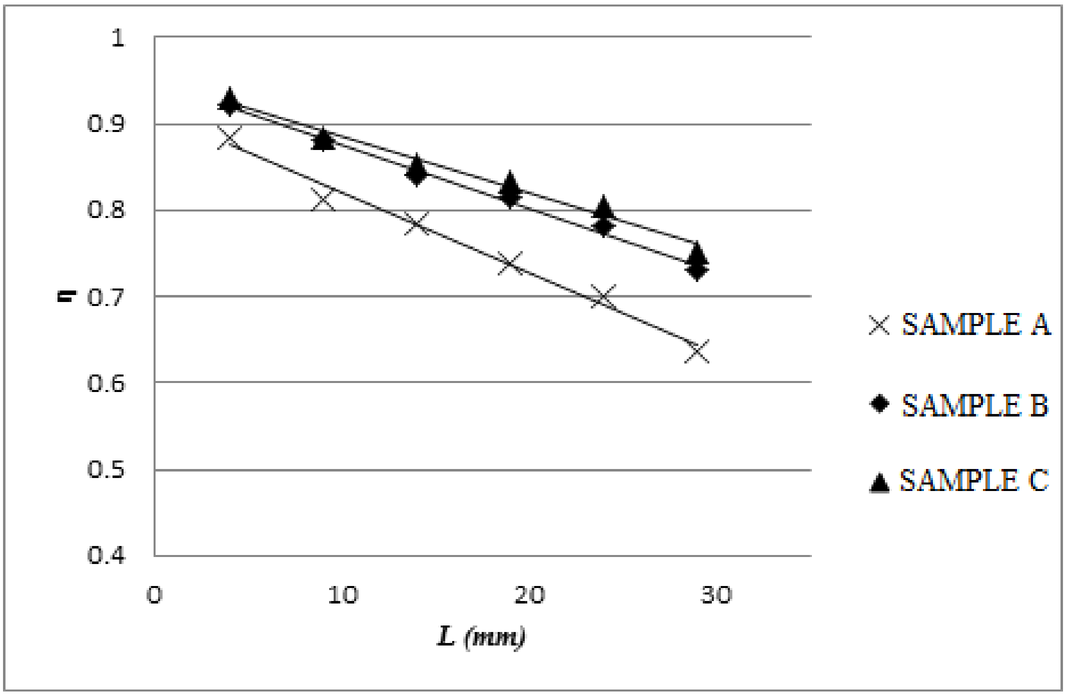


Figure 8 –Test results of cooling efficiency of samples

The angle between the centerline of the fan-shaped hole flow path of the test piece and the vertical growth surface is defined as β, shown in Figure 9. The β = 70 °, 25 °, -20 ° corresponds to the samples A, B, C. It can conclude from the test that the β between the centerline of the hole and the growth vertical plane affects the cooling efficiency of AM printed holes. The cooling efficiency of test piece A is the worst because the β of sample A is the largest while the angle of the other two samples is similar, the cooling efficiency is the same level.

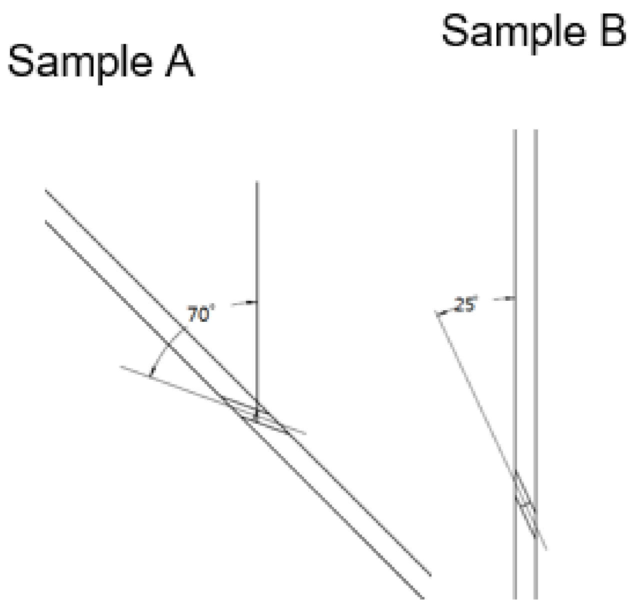
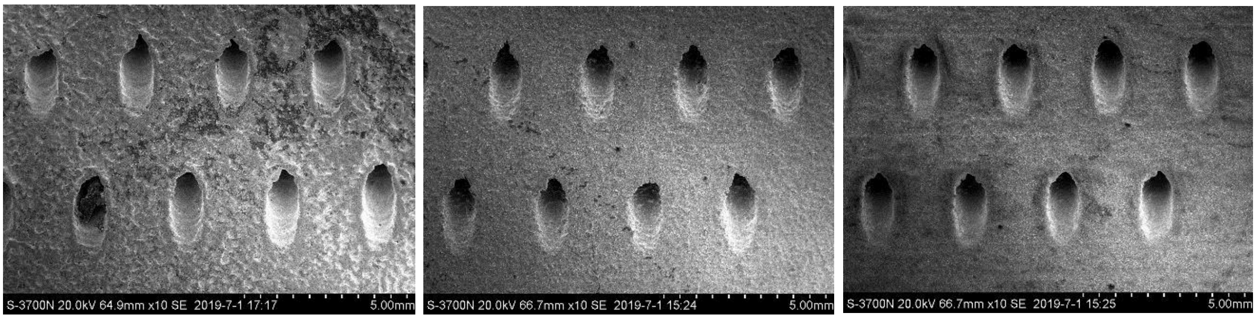


Figure 9 –The β of samples

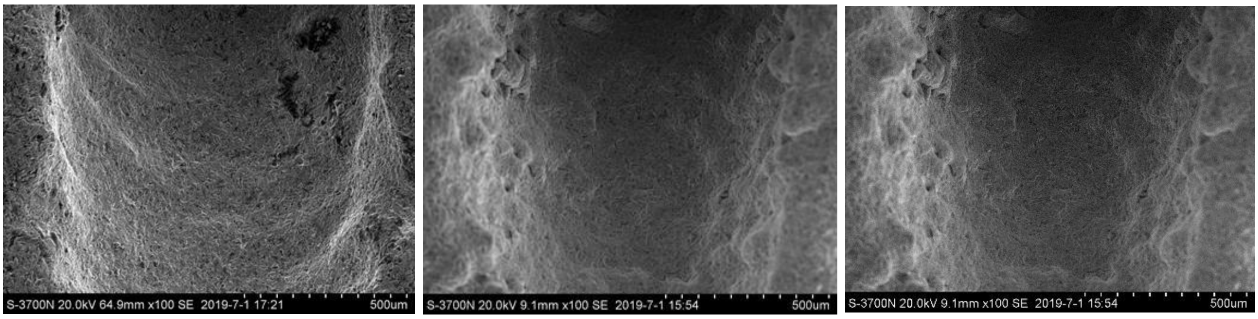
Furthermore, the three samples are analyzed by electron microscopy and the analysis results are shown in Figures 10 and 11. From the electron microscopy results, the formability of test piece A is poor, the roughness is Ra10.6 and there are burrs and wrinkles in the surface. The formability of the test pieces B and C is much better, but the wrinkled surface can still be found. The surface roughness is Ra5.3 and Ra2.66 respectively. From the electron microscopy results, the folds and protrusions of the flow channel surface in the hole of test piece A are higher and the surface is rough. The roughness of the flow channel surface in the hole can effectively affect the airflow heat transfer of the hole and increase the contact area. However, it could also reduce the airflow velocity in the hole, which can result in the decrease in the outlet airflow velocity and a reduction in the coverage of the outlet film of the shaped holes.

In summary, the deviation of the cooling efficiency of flat fan-shaped holes in different growth directions is large, which could be attributed to the angle β between the centerline of the cooling hole and the vertical surface of the printing growth. When the angle β is large, the forming quality of the orifice is poor and the flow channel surface in the hole is rough, which affects the adhesion of the outlet gas film and reduces the cooling efficiency of the fan-shaped holes.



（1）A Ra10.6　（2）B Ra5.3　（3）C Ra2.66

Figure 10 –Electron microscopy analysis result of the entrance position of the shaped hole



（1）A （2）B （3）C

Figure 11 –Electron microscopy analysis results of the inner flow channel of shaped hole

The cooling efficiency test was conducted for samples B and D, the comparison of the test results is shown in Figure 12. The result shows that the test piece printed with the outlet of the fan-expanded section down (Sample B) has a higher cooling efficiency and a longer film coverage distance.

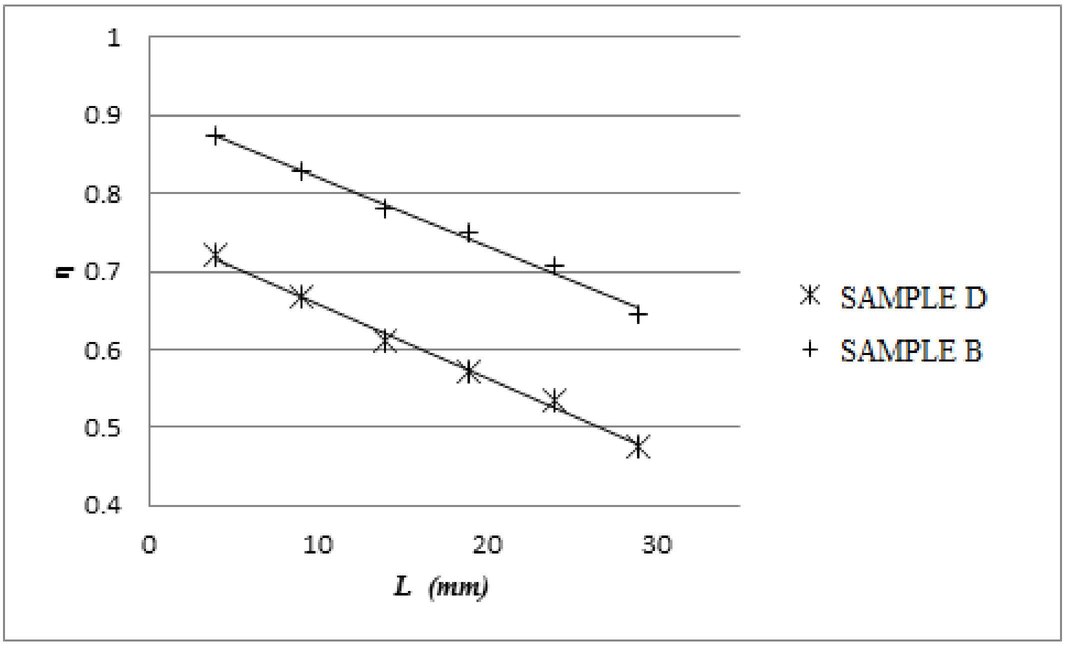
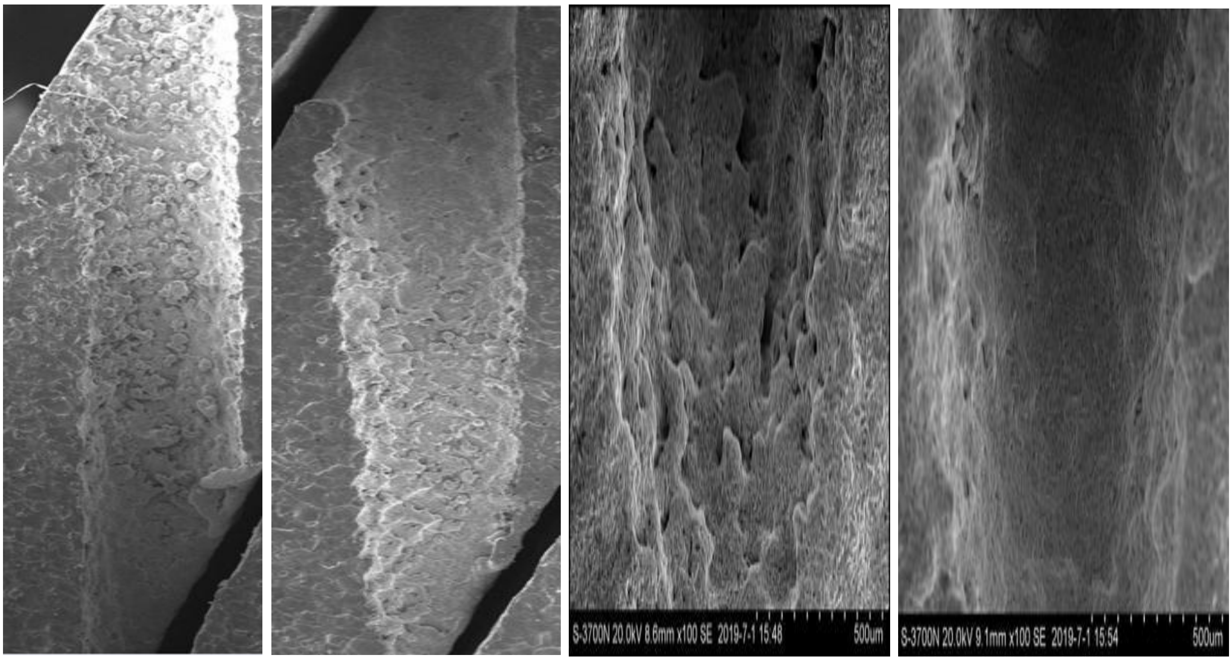


Figure 12 –Test results of cooling efficiency of up-down fan-expansion section

Electron microscope was applied to analyze the flow path surface of the shaped holes of test samples B and D, the results are shown in Figures 13. The outlet fan-expanded section down is better in the formation of the flow path in B. Because it can maintain a rectangular flow channel surface(a). While the sample D hole flow path of the expansion section with the opening facing upward is poorly formed. And there is shrinkage at the lower end, the overall hole flow path is trapezoidal(b). The flow channel of the hole guides the speed of the airflow in the hole. The inlet of the hole with the fan-expansion section facing up is a narrowing shape resulting in the concentration of the airflow velocity in the hole. Meanwhile, due to the high velocity in the center of the hole axis and the large jet depth, the film adhesion at the outlet is poor. Although the roughness of the outlet surface of the D expansion hole is Ra3.2 (d) and that of B is Ra6.3(c), the cooling effect of scheme B is better. This is due to the roughness of fan-expanded section facing down, especially the orifice hole inlet part, which is smaller than that in the hole with the fan-expanded downward. For fan-shaped holes studied in this paper, the process quality of the inlet port of the round hole is decisive for the cooling efficiency. Thus, the influence of process quality of small holes on cooling efficiency should be considered firstly in the process.



(a)	(b)	(c)	(d)
Cross-section of B	Cross-section of D	Surface roughness of B expansion part (Ra=6.3)	Surface roughness of D expansion part(Ra=3.2)

Figure 13 –Electron microscopy analysis results of shaped hole flow channel

5. CONCLUSION

In this paper, the cooling efficiency of AM fan-shaped hole plates with different growth directions was studied. And the cooling efficiency measurement was performed on each test piece with the cooling efficiency test system. The conclusions are summarized as follows:

（1）With the increase of the blowing ratio M, the cooling efficiency of the AM fan-shaped holes increases. When M increases to a certain degree, the cooling efficiency remains constant;

（2）The discrepancy in the cooling efficiency of the AM fan-shaped holes in different printing growth directions is large. The main reason for this difference is the angle between the center of the hole and the direction of printing growth. When the angle is smaller, the hole formability will be better. At the same time, the roughness in the hole will be smaller, and the cooling efficiency will be higher.

（3）For the AM fan-shaped hole, the orifice section of the inlet hole has a greater impact on the cooling efficiency than the fan-expansion section of the outlet. The forming quality of the inlet orifice section is better, the cooling efficiency of the AM fan-shaped holes is better.

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