ABRASIVE WATER JET DRILLING OF COOLING HOLES IN AEROENGINES: PRELIMINARY EXPERIMENTAL STUDY

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This paper addresses an experimental investigation on the feasibility of using abrasive water jet (AWJ) for the drilling of small-diameter holes in aeroengines components. These components are sprayed with ceramic thermal barrier coating (TBC). The required holes are typically 0.5 to 1 mm in diameter with a drilling angle of 30 to 90 deg. The parameters of the AWJ were varied to study their effects on both quantitative and qualitative hole drilling parameters.

KEYWORDS

abrasive water jet, drilling, thermal barrier coating

1 INTRODUCTION

The efficiency of the modern gas-turbine engine (the aeroengine) can be improved by increasing the working temperatures inside the engine. Superalloys based on nickel have been developed for the manufacture of aeroengine parts such as blades, guide vanes, afterburners and casings. These materials combine toughness, creep strength, oxidation and hot-corrosion resistance at high temperatures. [Yeo 1994]

However, the temperature of the combustion gases within modern aeroengines can reach temperatures beyond the melting points of the superalloys. Thus, a quantity of air that is not used for combustion is introduced into the engine through thousands of very small cooling holes in the combustion chamber to cool the walls of the flame tube by means of effusion cooling. Rows of cooling holes are also drilled into the turbine blades and vanes to make use of impingement cooling using air from other parts of the engine. [McNally 2004]

Drilling through these tough superalloys by conventional methods is very difficult. Therefore, engine manufacturers have been forced to look for alternative drilling methods to achieve very small holes having difficult geometry [McNally 2004]. The most used technique is laser drilling [Kamallu 2002].

Laser can drill TBC cooling holes in a few seconds and are much faster than AWJs. However, the laser process introduces heat to the component. This heat causes the TBC component to expand thermally. And, since the TBC and the metal substrate have different thermal expansion coefficients, the differing expansion causes delamination of the TBC from the substrate [Sezer 2006]. Although it is unknown if this delamination is detrimental to the component, it is viewed as unfavourable. [Hashish 1991]

Advantages of the AWJ for drilling include the following [Hashish 2009]:

- No thermal, mechanical, or metallurgical effects are produced.
- A wide range of materials can be drilled.
- A wide range of TBC and substrate thicknesses can be drilled.
- Holes with relatively large length-to-diameter ratios can be drilled.
- It is useful for drilling shaped holes and slots.

2 EXPERIMENTAL PROCEDURE

2.1 Abrasive water jet drilling system and process parameters

The experimental facility used to determine possibility to drilling holes to thermal barrier coating by abrasive water jet consisted essentially of a high-pressure water supply system and X-Y cutting table for traversing of the abrasive water jet cutting head over stationary sample.

High-pressure water was supplied to the cutting head by a high-pressure pump PTV75-60 with two pressure intensifiers capable to deliver up to 7.8 l·min-1 of water at operating pressure from 40 to 400 MPa (maximum power 75 kW). X-Y cutting table PTV WJ2020-2Z-1xPJ – 2D with inclinable cutting head specially designed for cutting with water and abrasive water jets was used to traverse the abrasive water jet cutting head. The working area of the table was 2000x2000 mm.

The standard commercially available cutting head PTV Slice I equipped with water nozzle 0.33 mm in diameter (Fig. 1) and focusing tube Roctec 100 (Kennametal) 0.91 mm in diameter and 76.2 mm long was used during the experiments.

Figure 1. Cutting head Slice I (diameter of the water nozzle 0.33 mm)

Indian garnet 80 MESH and Australian garnet GMA 200 MESH were selected to evaluate the influence of abrasive grain size on exit holes diameter and holes quality. Figures 2 and 3 show individual grains of both types of garnet abrasives (both pictures of abrasives are in the same magnification).

Figure 2. Grains of Indian garnet 80 MESH used during experiments

Figure 3. Grains of Australian garnet 200 MESH used during experiments

2.2 *Material characterisation*

The thermal barrier coated samples used in this study were provided by Honeywell corp. The material system used for experimentation consisted of plates of 1 mm thick Ni-base superalloy which was air plasma sprayed with an yttria stabilised zirconia thermal barrier coatings, approximately 320 µm thick and nickel aluminide bond coat of approximately 130 µm thickness (see Fig. 4). The compositions of the bond coat and top coat used are listed in Tab. 1.

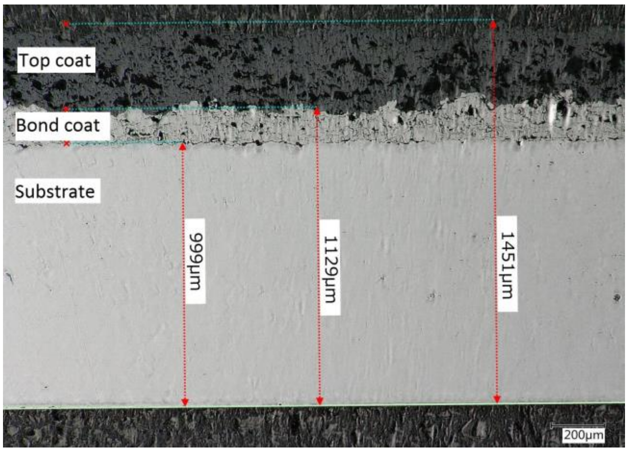


Figure 4. The typical microstructure of cross-sectional view of the thermal barrier coating used in this study

Coating type	Material	Composition (wt.%)					
		Ni	Cr	Al	Y	ZrO_2	Y_2O_3
Bond coat	NiCRAlY	57.5	31	11	0.5		
Top coat	Stabilized zirconia					92	8

Table 1. Chemical composition of TBC

2.3 *Hole analysis*

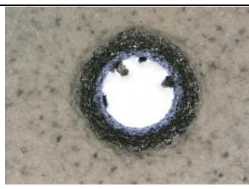
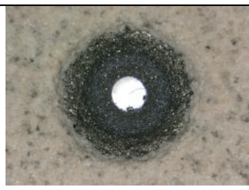
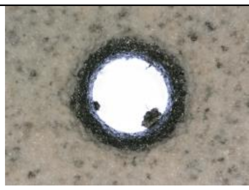
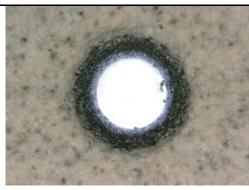
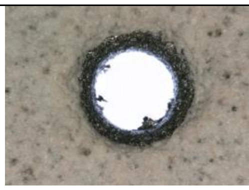
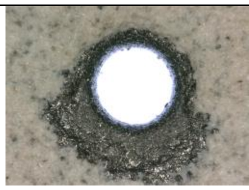
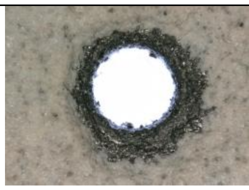
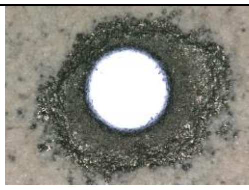
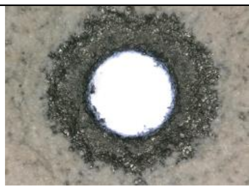
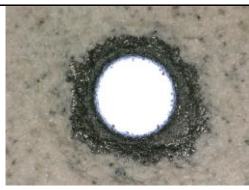
Optical microscope Keyence VHX 5100 was used for measurement exit holes diameter. Microscopy analyses were carried out to identify the delamination of TBC and burrs at the exit side of the holes for different AWJ drilling parameters.

3 RESULTS

3.1 *Influence of water pressure*

The water pressure has a great effect on the drilling time and thus on the economy of the process. Increasing the pressure reduces the drilling time but increases the risk of delamination of TBC, which is undesirable. The first experiment was therefore aimed at finding a maximum level of water pressure, where TBC delamination from the substrate did not occur.

The following parameters were used for this experiment: drilling time 5 s, abrasive mass flow rate 100 g·min^{-1}, stand-off distance 4 mm. The results of this experiment are shown in Tab. 2.

p [MPa]	80 MESH	200 MESH
40		
80		
120		
180		
220		

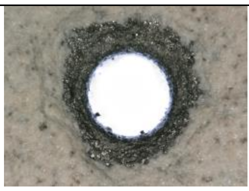
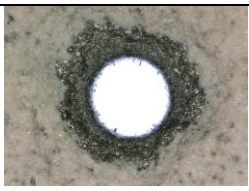
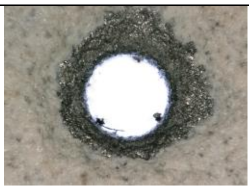
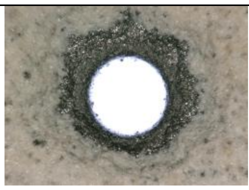
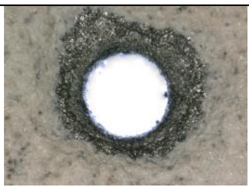
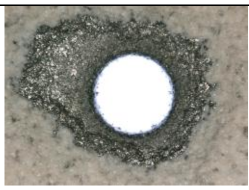
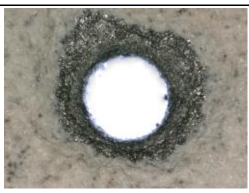
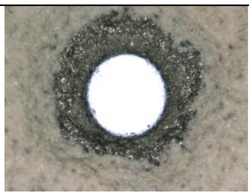
260		
310		
350		
400		

Table 2. Effect of water pressure on delamination of the TBC (drilling time 5 s, abrasive mass flow rate 100 g·min^{-1}, stand-off distance 4 mm)

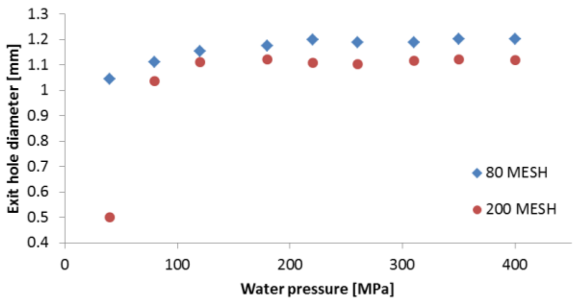


Figure 5. Influence of water pressure on the exit holes diameter for two sizes of abrasive grains

Figure 5 shows the relationship between the used water pressure, exit holes diameter, and abrasive grain size. For water pressure higher than 100 MPa, the exit holes diameter is approximately constant. Thus, the water pressure has a negligible effect on the resulting exit holes diameter. The size of the used abrasive grains has stronger effect on the exit holes diameter. Indian garnet 80 MESH (i.e. abrasive with bigger grain size) produce higher exit holes diameter compared to Australian garnet 200 MESH.

3.2 *Influence of stand-off distance*

During AWJ drilling some areas on real components may be less accessible, so it is important to know how the stand-off distance will affect the diameter of the drilled hole.

The following parameters were used for this experiment: drilling time 5 s, abrasive mass flow rate 100 g·min^{-1}, water pressure 80 MPa. The results of this experiment are shown in Tab. 3.

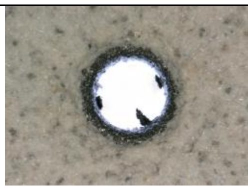
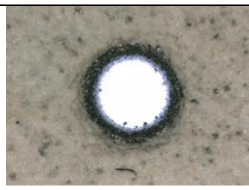
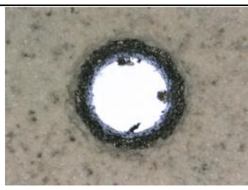
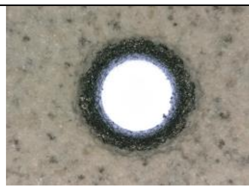
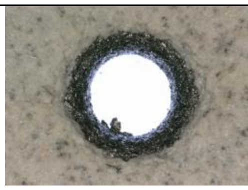
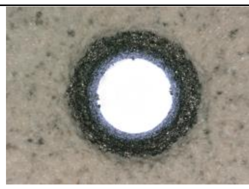
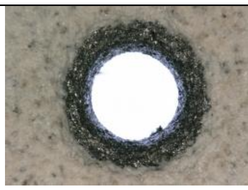
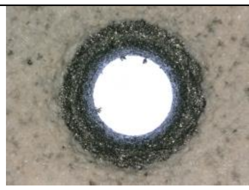
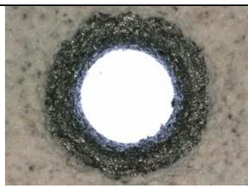
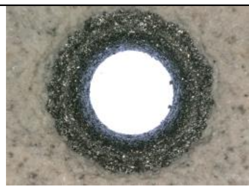
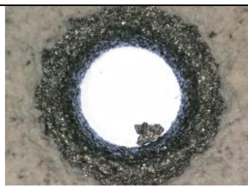
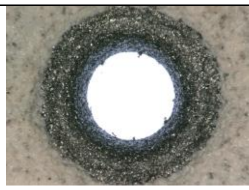
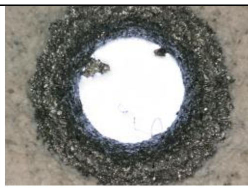
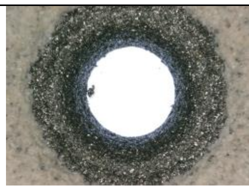
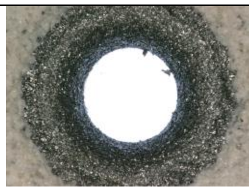
z [mm]	80 MESH	200 MESH
2		
4		
6		
8		
10		
12		
14		
16		
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Table 3. Effect of stand-off distance on hole diameter (drilling time 5 s, abrasive mass flow rate 100 g·min^{-1}, water pressure 80 MPa)

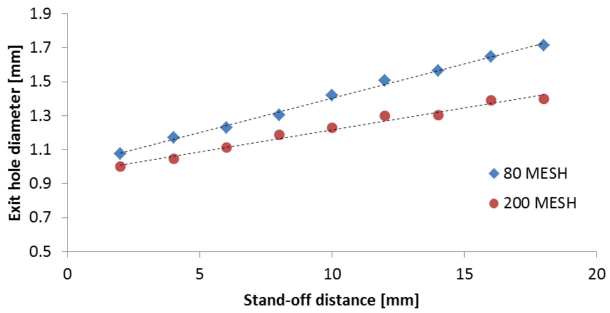

Figure 6. Influence of stand-off distance on the exit holes diameter for two sizes of abrasives

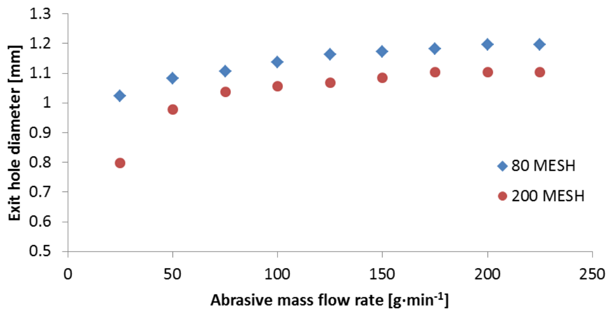

Figure 8. Influence of abrasive mass flow rate on the exit holes diameter for two abrasives grain size

Results presented in Figure 6 show that the influence of stand-off distance on the exit holes diameter can be linearly correlated. The exit holes diameter increases with the increasing stand-off distance. This is due to the expanding of abrasive water jet after the exit of the focusing tube. An optimal stand-off distance is in the range of 2 to 4 mm.

3.3 *Effect of drillng time*

A typical aeroengine component will have several thousand cooling holes [McNally 2004] in order to facilitate the proper cooling pattern. Drilling time relates directly to production speed and, therefore, has impact on the economics of AWJ processing.

The following parameters were used for this experiment: abrasive mass flow rate 100 g·min^{-1}, water pressure 80 MPa, stand-off distance 4 mm, drilling time of 2.5 to 60 s. Fig. 7 shows the relationship between exit hole diameter and drilling time.

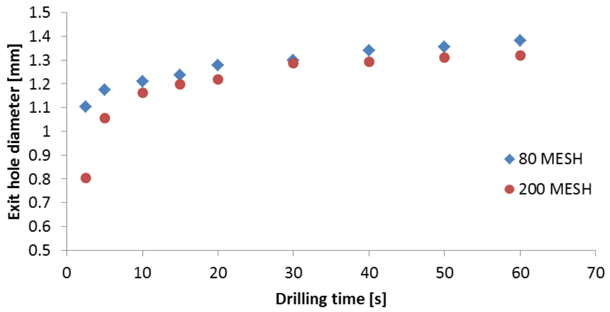

Figure 7. Influence of drilling time on the exit holes diameter for two sizes of abrasive grains

It is found that drilling time has strong influence on exit holes diameter in first 10 s of drilling process. Then there is an approximately linearly increasing of exit holes diameter up to the drilling time of 40 seconds. Drilling time longer than 40 seconds has no effect on the exit holes diameter.

3.4 *Effect of abrasive mass flow rate*

Another parameter that influences the economy of the process is the mass flow rate of the abrasive. The aim of this experiment was to find an optimal mass flow rate.

The following parameters were used for this experiment: drilling time 5 s, water pressure 80 MPa, stand-off distance 4mm. The results of this experiment are shown in Fig. 8.

The relationship between the abrasive mass flow rate and the exit holes diameter is similar to the one in previous case. Exit holes diameter is strongly affected by the abrasive mass flow rate up to 75 g·min^{-1} only a slight increase of diameter can be observed for higher values of abrasive mass flow rate.

3.5 *Effect of abrasive grain size*

Two sizes of abrasive grains were used in the previous experiments (see Fig 2 and 3). Fig. 9 shows example of comparison between these two types of abrasives.

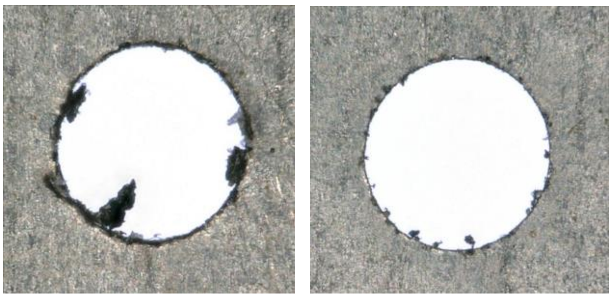

Figure 9. Magnified picture of cooling holes on the metal side. Left picture – Indian garnet 80 MESH, right picture –Australian garnet GMA 200 MESH (both picture: drilling time 5 s, water pressure 80 MPa, stand-off distance 2 mm, abrasive mass flow rate 100 g·min^{-1})

From all experiments we can draw the following conclusions:

- Finer abrasive significantly reduces the burrs at the exit side of the holes.
- Finer abrasive produce cooling holes with smaller exit diameter.
- Finer abrasive produce cooling holes with higher quality of surface.
- Finer abrasive has a slightly lower drilling performance.

4 CONCLUSIONS

In this study, characterization of cooling holes created on thermal barrier coated samples using abrasive water jet drilling was carried out. The following conclusions can be made from this study:

- Water pressure - undesirable delamination of TBC from the substrate occurs for water pressure higher than 100 MPa. 80 MPa water pressure was used for following experiments.
- Stand-off distance – the best results were achieved for stand-off distance of 2 to 4 mm.
- Drilling time – optimal drilling time is in the range of 3 to 7 s for 80 MPa of water pressure.

- Abrasive mass flow rate – one old Czech proverb says, "less is sometimes more". The optimal mass flow rate is 100 g·min^{-1} in this case. A higher mass flow rate has no benefit.
- Abrasive grain size – finer abrasive significantly reduces the burrs at the exit side of the holes, produces holes with higher quality of surface and smaller diameter of exit hole, however has a slightly lower drilling performance.

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