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Power dissipation investigation of bespoke De-Laval nozzles for rapid Plasma Figuring process

Nan Yu[1], Renaud Jourdain[1], Mustapha Gourma[2], Paul Shore[1, 3]

[1]*Precision Engineering Institute, Cranfield University, UK*
[2]*Power Engineering Centre, Cranfield University, UK*
[3]*Loxham Precision Ltd, UK*

nan.yu@ucd.ie
Building 90, Cranfield University, Bedford, MK43 0AL, United Kingdom

Abstract

The work supports the development of the Plasma Figuring technology. The figuring method utilises a plasma torch equipped with bespoke nozzles. In this work, ten De-Laval nozzles were designed and fabricated based on a numerical analysis previously carried out in the Precision Engineering Institute at Cranfield University. The work focused on energy dissipation of novel nozzle. The investigation of these nozzles was carried through two series of experiments where flows and temperatures of coolant were measured to determine the energy dissipation of each bespoke nozzle. The first series of measurements was carried out on nozzles impinging a substrate at a stand-off distance of 6 mm. Whereas in the second series of experiments, nozzles were investigated without the substrate. The predicted power dissipated values from coolant in each nozzle is provided. The nozzle that dissipated the less amount of power was determined.

Plasma torch, plasma figuring, power dissipation

1. Introduction

In 2012, plasma figuring was proven to be a cost-effective method for the correction of large scale ultra-precise optical surfaces [1]. The process was exceptionally rapid but residual errors were observed. Figure errors were mainly due to the footprint of the sub-aperture tool. Thus, the work addresses this issue by seeking an enhanced tool footprint that would provide both narrower footprint and higher material removal rate. Previously, a CFD model was created for the investigation of the design rules of De-Laval nozzles used for the bespoke ICP torch [2, 3].

In this paper, first the mechanical construct of the novel nozzles is presented. Second, a power dissipation investigation of the plasma torch is presented. The experimental work was carried out using the RF power up to 800 W. Power dissipation measurements of each nozzle were carried out three times, and average values were obtained. Thus, the entire series of bespoke nozzles was characterised. Therefore, experimental results were used for the derivation of the power dissipation values of the nozzle for a RF power set to 1200 W. Hereafter, the original and the bespoke nozzles are presented.

2. Design and fabrication of enhanced nozzles

This section presents the mechanical design of the nozzles mounted on an inductively coupled plasma (ICP) torch. The work focus on the original (section 2.1) and a series of bespoke nozzles (section 2.2).

2.1. Original nozzle design

The original nozzle (Fig. 1) is composed of three parts: aluminium ring, copper nozzle and outer shell. The quartz tube of the ICP torch is mounted into the aluminium ring. Copper was chosen for the water cooled De-Laval nozzle because of its thermal diffusivity. Thus, the plasma stream (thousands of degrees Celsius) can flow throughout without occurring neither melting nor surface integrity degradation. Indeed, the surrounded area of the nozzle was chilled by coolant (20 degree Celsius). The cooling channel (spiral) was located between the copper nozzle body and its outer shell.

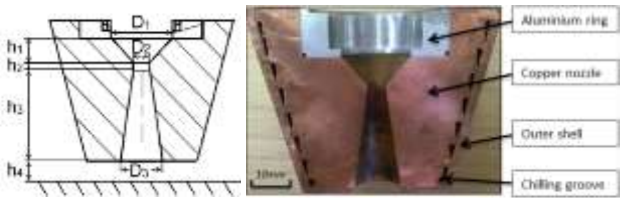

Figure 1. Parameters of the nozzle (Left), cross section of existing nozzle (Right)

The hydrodynamic characteristics of the original De-Laval nozzle depend on seven parameters (Figure 1, left). Some of these parameters were altered for seeking the enhancement of the plasma jet performance from a material removal viewpoint.

A past study concluded that the distinguishing physical characteristics of this type of nozzle is the ratio of the divergent area to the throat area. Thus, the series of bespoke nozzle was designed bearing in mind this finding (section 2.2).

2.2. Bespoke nozzle design

The bespoke nozzle design was mounted onto an existing ICP torch flange (Fig. 3). So the dimensional design parameters of the nozzle at the junction were constrained. Also, the inner diameter of the aluminium ring, the diameter D_1 of the convergent section, the position of the chilling entering apertures were unchanged.

The investigation of the effects of changing the inner parameters on the hydrodynamic characteristic led to a mechanical design made of two distinguished sets of parts. This mechanical solution enables a convenient mounting of the De-Laval ring (Fig. 2). Using a screw fastening means, the De-Laval ring was screwed in and off to be replaced by another one.

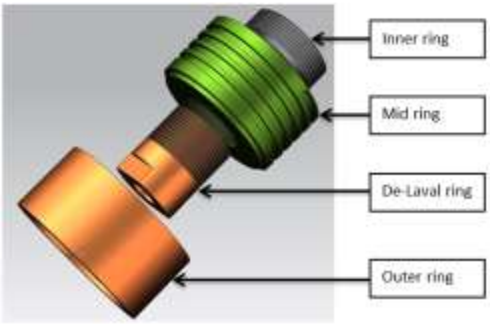

Figure 2. Four parts of the new nozzle

The two set of parts of the bespoke nozzle have different purposes. The De-Laval ring was used for transporting plasma stream. The mid ring served as a heat exchanger. Figure 3 illustrates the bespoke nozzle assembly.

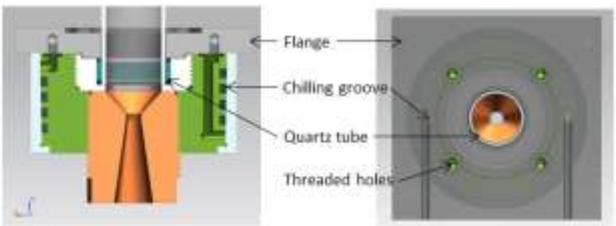

Figure 3. Assembly diagrams of the new nozzle and existing flange. Left: section view; Right: top view

Table 1 and Figure 1 (left) illustrates the dimensions of all the nozzles designed, fabricated and tested. The critical parameters ($D_{1\text{-}3}$ and $h_{1\text{-}3}$) and λ (angle of divergence) are written in Table 1. According to the one-factor-at-a-time (OFAT) method, D_1 was kept constant, D_2 was varied for nozzles 4-5 & 10, D_3 was varied for nozzles 2-10, h_3 was varied for nozzles 6-8, while λ was kept constant at 24.7° for nozzles 7-9.

Table 1 Critical parameters of the De-Laval nozzle designs

No.	D_1	D_2	D_3	h_1	h_2	h_3	λ
Ori	D_{1i}	D_{2i}	D_{3i}	h_{1i}	h_{2i}	h_{3i}	λ_i
1	D_{1i}	D_{2i}	D_{3i}	h_{1i}	h_{2i}	h_{3i}	λ_i
2	D_{1i}	D_{2i}	12.0	h_{1i}	h_{2i}	h_{3i}	λ_i
3	D_{1i}	D_{2i}	11.4	h_{1i}	h_{2i}	h_{3i}	λ_i
4	D_{1i}	4.7	11.4	h_{1i}	h_{2i}	h_{3i}	λ_i
5	D_{1i}	4.3	11.4	h_{1i}	h_{2i}	h_{3i}	λ_i
6	D_{1i}	D_{2i}	11.4	h_{1i}	h_{2i}	20.6	λ_i
7	D_{1i}	D_{2i}	11.4	h_{1i}	h_{2i}	14.6	24.7
8	D_{1i}	D_{2i}	N	h_{1i}	h_{2i}	20.6	24.7
9	D_{1i}	D_{2i}	16.7	h_{1i}	h_{2i}	h_{3i}	24.7
10	D_{1i}	3	11.4	h_{1i}	h_{2i}	h_{3i}	λ_i

3. Power dissipation results

The set of bespoke nozzles were tested using the power dissipation method detailed in [4, 5]. Two types of experiments were carried out for the assessment of the energy dissipated values. The first type of experiments required to set a nozzle-to-substrate distance to 6 mm. Thus, nozzles 6, 7 and 8 were not tested because the distance h_3 was much shorter and the vertical stroke of the motion system was too short. The second series of experiments required the substrate to be removed. Temperature measurements of each nozzle were carried out three times. Results were averaged and processed to derive the power dissipated by the nozzle when operated at 1.2 KW. Figure 4 illustrates the predicted power dissipated values. Through, those two sets of results (Fig. 4 grey and striped columns), two findings were highlighted.

First, the powers dissipated by each of the bespoke nozzle was lower than that of the original torch nozzle. The difference was about 15%. Bespoke nozzle 1, which has the same internal dimensions than the original De-Laval nozzle, enabled to do a like for like comparison. The difference was attributed to coolant channel design, thermal resistance between De-Laval and mid rings and the inner surface quality (roughness and oxidation) of the De-Laval ring.

Second, the power dissipated by a torch positioned at a set distance from a substrate was systematically higher than that without it. The reason was thought to be the thermal radiation of the substrate and temperature of the surrounding environment. However, there is one exception in the measurement of nozzle 9. A more robust explanation requires further investigation.

Nozzle 3 had the smallest power dissipation when a substrate faced the torch, and the second smallest value when no substrate faced the torch. Nozzle 7 (shortest h_3 value) has the smallest power loss when there was no substrate.

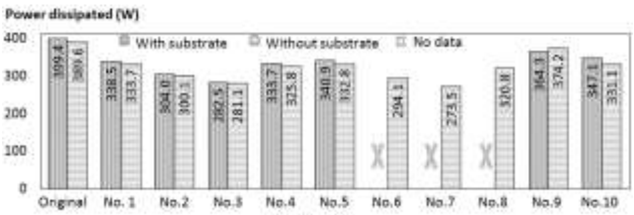

Figure 4. Predicted power dissipated of enhanced nozzles when RF power is set to 1.2 KW

4. Conclusion

A unique power dissipation analysis of bespoke nozzles was carried out. The results enabled to identify the nozzle design that had a higher efficiency from a power dissipation viewpoint. Results showed that the power dissipated from the series of bespoke nozzles was systematically lower than that the one measured onto the original nozzle. Amongst the ten bespoke nozzles, nozzle 7 had the smallest amount of power dissipated when tested in conditions similar to Plasma Figuring process. Further work is now being undertake to characterise the nozzles from a material removal viewpoint.

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