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Effect of nozzle size scaling in co-flow water cavitation jet peening

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ABSTRACT

Water Cavitation Peening (WCP) employs cavitation to introduce compressive residual stresses in metals while limiting the surface roughening typical of similar surface enhancement processes such as shot peening and laser shock peening. As shown by a number of authors, cavitation intensity is greatly affected by the jet velocity as well as by the nozzle dimensions and shape. This paper reports on an investigation how nozzle dimensions affect cavitation intensity and peening performance in co-flow WCP of Al 7075-T651. Scalability of the process is investigated by comparing co-flow nozzles of increasing size but the same diameter ratios. The results show a substantial increase in cavitation intensity with nozzle size and a considerable decrease in the processing time required for saturation of the strip curvature and residual stress. The observed trends are explained by means of high-speed video imaging analysis and pitting tests, which show that the increase in cavitation intensity is due to an increase in the amount of cavitation when nozzle dimensions increase, while the pit depths and pit shape factor, which are measures of the strength of the cavitation events occurring at the workpiece surface, are largely unaffected. The process yields compressive residual stresses as high as 400 MPa and as deep as 350 μm below the surface, which are both a significant improvement upon previous results reported for shot peening.

1. Introduction

Cavitating jets are used in industrial operations to generate highly localized pressure and temperature pulses. Examples include peening, cutting, cleaning, and rust removal applications. They are widely used due to the relatively low pressures required to produce the cavitation needed to alter the surface properties. In its most common configuration, cavitation is generated by submerging a high-speed water jet in a water-filled reservoir [1]. The cavitation bubbles generated by the turbulence created in the shear boundary layer are transported by the flow to the workpiece surface, where the bubbles collapse, resulting in shock waves and re-entrants jets [2] that create pressure fluctuations on the order of 10 GPa and temperature fluctuations up to 5000 K [3]. Alternatively, a co-flow nozzle configuration, as reported in a few studies [4–6], can also generate cavitation. In the co-flow configuration, a high-speed jet is artificially submerged in a concentric low speed jet to create the condition that allows the cavitation cloud to form and develop, eliminating the need for submerging the part, and thereby enhancing the overall versatility of the process.

Nozzle design is a fundamental aspect of water jetting, playing a key role in both cavitating and non-cavitating jets. While the effect of nozzle geometry on cavitation intensity in the submerged configuration has received some attention from the research community [7–10], its effect on the co-flow configuration has received very little. Vijay et al. [4] investigated the effect of outer flow diameter and nozzle offset on cavitation intensity, but did not generalize the results by adjusting the outer flow rate to compensate for different nozzle geometries. As a result, it is unclear if the observed trends are due to the nozzle geometry or due to change in the outer flow velocity arising from the change in nozzle geometry. Moreover, since their study was focused mainly on cutting applications, and considering the nozzle geometry and flow velocities used, it is fair to assume that the experiments were conducted in the center regime, where the cavitation erosion is focused around the high-speed jet as shown in [6].

Soyama et al. [5,11–13] have reported on cavitation peening using the co-flow configuration. They reported using different nozzles, but did not provide details of the nozzle geometries. Their investigation of the effect of nozzle geometry on cavitation intensity is limited to the identification of the optimum outer diameter of the inner jet nozzle reported in [11]. Finally, flow parameters such as jet velocities and the standoff distance have also been investigated for both submerged [4,14–16] and co-flow configurations [4–6,11]. Unfortunately, the majority of studies fail to report jet

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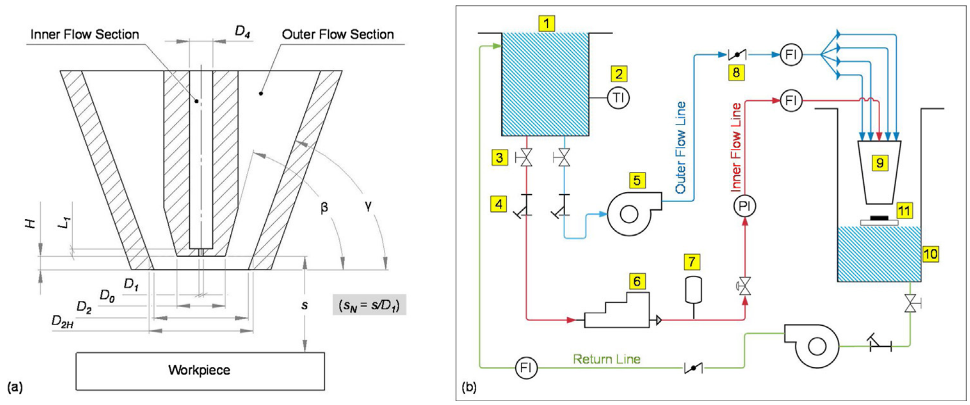

Fig. 1. (a) Co-flow cavitation peening nozzle outlet geometry, (b) schematic of water cavitation peening system consisting of (1) reservoir tank, (2) temperature, flow rate or pressure indicator, (3) valve, (4) strainer, (5) centrifugal pump, (6) positive-displacement pump, (7) pulsation damper, (8) butterfly valve, (9) nozzle, (10) test chamber, and (11) workpiece [6].

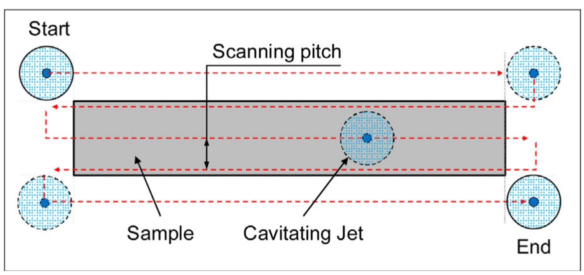

Fig. 2. Peening (scan) path.

Table 1
Dimensions of the standard peening nozzle.

Feature	Dimension	Ratio ($/D_1$)
D_1	0.85 mm	1
D_0	12.8 mm	15
D_2	24.0 mm	28.2
D_4	6.80 mm	8
L_1	2.98 mm	3.5
H	0	0
β, γ	75°, 70°	–

velocities along with the nozzle geometry details. A detailed discussion of the effect of jet velocity on cavitation intensity in co-flow WCP was recently reported by the present authors [6].

Water cavitation peening has already proven capable of matching the performance of established processes such as shot peening [17]. Therefore, the ability to scale the process and reduce processing time and associated costs will dictate the future of this technology in modern manufacturing environments. This paper reports the results of experiments designed to study the effects of co-flow nozzle size, or dimensions, on the cavitation intensity and the workpiece surface properties. First, cavitation intensity is evaluated by means of accelerated erosion tests on Aluminum 7075-T651. Subsequently, peening tests are carried out to evaluate strip curvature, which serves as a quick measure of the residual stress change in the workpiece surface. Finally, pitting tests and high-speed video imaging are used to analyze and explain the results obtained.

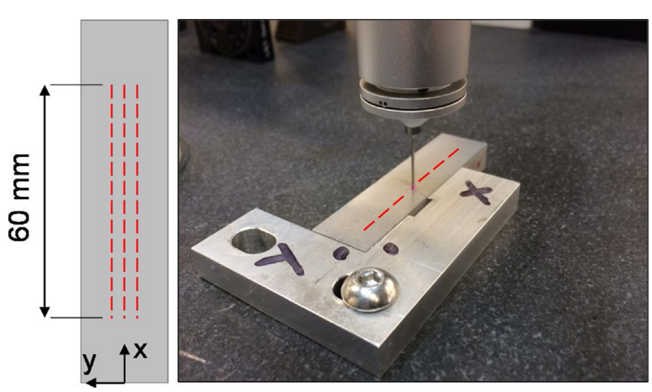

Fig. 3. Strip curvature measurement.

2. Materials and methods

2.1. Co-flow nozzle geometry

The schematic of the co-flow nozzle used in the experiments is shown in Fig. 1a. The design of the overall apparatus (Fig. 1b) is identical to that used in the authors' prior work [6]. The nozzle is made up of two concentric sections. The inner section of the nozzle is for the high-speed jet, which is produced by a plunger pump delivering 2.8×10^{-4} m^3/s at 34 MPa in order to achieve the high pressures required by the flow conditions. The outer flow section is used to locally submerge the high-speed jet, and thereby enables cavitation. A centrifugal pump delivers water at a flow rate of 3.8×10^{-3} m^3/s at a pressure of 392 kPa. The outer flow velocity is controlled via a flow regulator valve located upstream of the nozzle.

The inlets and the primary nozzle cross-section were designed to yield an average outer flow velocity less than 0.5 m/s. Dimensions of the standard nozzle geometry are listed in Table 1. A detailed description of the co-flow cavitation peening apparatus can be found in the authors' prior work [6].

2.2. Experimental procedure

2.2.1. Accelerated erosion tests

Cavitation intensities produced by different nozzle geometries were evaluated by exposing fixed locations on samples of Aluminum 7075-T651 to cavitation for a period of time in excess of the *incubation period* [18], according to the ASTM standard G134 [19], till the onset of erosion (and therefore mass loss). Although mass loss is not desirable in peening, it serves to quantify the nozzle's effectiveness in producing cavitation. After establishing the cavitation intensity produced by the nozzle, actual peening tests were carried out by exposing the workpiece surface to the cavitating flow for a short time period (less than the *saturation time* [14])