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Effect of jet velocity in co-flow water cavitation jet peening

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ABSTRACT

Water cavitation jet peening (WCP) uses cavitation caused by the shear layer created by two concentric co-flowing jets with large velocity difference to introduce compressive residual stresses in the surface layers of metal components subjected to fatigue loading or a corrosive environment. Mass loss and surface alteration in WCP have been shown to be minimal compared to other mechanical surface enhancement techniques, such as shot peening (SP). This paper investigates the effect of concentric jet velocities in cavitation jet peening in a co-flow configuration on cavitation intensity and peening performance, which are characterized by accelerated erosion on Al 1100-O and Al 7075-T6 and a strip curvature test on Al 7075-T6. Accelerated erosion tests reveal that cavitation intensity and associated erosion (measured by mass loss) are greatly affected by the combination of the inner (V_{in}) and outer (V_{out}) jet velocities and the normalized standoff distance (s_n). Two characteristic erosion patterns are found depending on the relative magnitudes of the jet velocities: one that is focused at the jet center (termed *center regime*) and another that is concentrated in the surrounding annular region (termed *ring regime*). Erosion tests on Al 1100-O and Al 7075-T6 give unexpectedly different results in terms of the maximum mass loss as a function of the jet velocities and standoff distance. When compared to strip curvature tests, it is found that the accelerated erosion tests on Al 1100-O do not capture the influence of inner jet velocity V_{in} and imply misleading trends with regard to outer flow velocity V_{out}. Erosion and curvature tests on Al 7075-T6 are found to be in good agreement and therefore are believed to be better suited to identify the optimum process conditions in WCP. Notwithstanding the higher mass loss density values observed in the center regime, the resultant strip curvature is found to be higher in the ring regime for a higher inner jet velocity V_{in}, potentially leading to higher and deeper compressive residual stresses.

1. Introduction

Peening techniques have been extensively used in industry to improve the fatigue life of components subjected to fatigue and corrosion. The most common among these techniques, namely Shot Peening (SP), employs localized plastic deformation caused by shots of different size and materials to introduce compressive residual stress in metal surfaces, thereby improving their resistance to crack initiation and propagation. However, this technique is also characterized by contamination and substantial surface roughening, which can lead to unexpected failures in low cycle fatigue (LCF) loading situations [1,2]. Over the past few decades a number of alternative peening techniques have been developed to overcome these limitations. Laser shock peening (LSP) is capable of introducing high compressive residual stresses at very large depths with minimal surface modification [3,4], but requires long processing times, special surface preparation, and expensive equipment. Deep rolling has been investigated for a number of different applications [5–7]. While substantial improvements in corrosion and fatigue life are shown for the process, it is limited in its applicability to simple geometric features and not applicable to thin-walled components [8]. Waterjet peening (WJP) has also been evaluated by a number of researchers [9–13]. It employs high speed water droplets as the peening medium, and has shown good results in introducing compressive residual stresses on metal surfaces. Flexibility, limited surface roughening and negligible workpiece contamination are significant improvements of WJP over conventional shot peening [14]. The greatest limitation of this process is its demanding pressure requirements (>200 MPa), which is one order of magnitude higher than the requirement for water cavitation peening (WCP) [15]. Cavitating water jets have been investigated for both cutting and peening applications [15–18]. Cavitation is generated by injecting a high speed jet into a water

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filled chamber. The bubbles created by the strong velocity fluctuations within the mixing layer are delivered to the material surface by the flow, where shock waves and re-entrants jets generated upon bubble collapse cause plastic deformation of the material surface [19,20]. When the exposure time of the metal surface to the cavitating flow is limited to the incubation period [21], no mass loss is observed and instead compressive residual stresses are introduced in the surface layer. A limitation of this technique is the requirement of a submerged environment for the generation of cavitation. Vijay et al. [17] and Soyama [22] overcame this limitation by artificially submerging the high speed jet in a concentric low speed jet. This configuration, which is termed *co-flow*, not only increases the process flexibility, but also has the potential for generating better results compared to cavitation peening in the submerged configuration for a given high speed jet pressure [23].

In the present paper, experiments are conducted to study the effects of inner jet velocity (V_{in}), outer jet velocity (V_{out}) and normalized standoff distance ($s_n = s/D_1$) on the cavitation intensity and material response. First, cavitation aggressiveness is evaluated using accelerated erosion tests on two different materials - soft Aluminum 1100-O and Aluminum 7075-T6 - under different flow conditions in order to identify the best peening parameters. Subsequently, for a selected subset of flow conditions, the peening performance is assessed by performing strip curvature tests on a structural material (Aluminum 7075-T6) shaped in the form of Almen strips.

2. Materials and methods

2.1. Cavitation peening apparatus

The water cavitation peening apparatus used in this study was designed and built in-house. A schematic of the system can be seen in Fig. 1, while the nozzle used for the erosion and peening experiments is shown schematically in Fig. 2. The nozzle consists of two distinct sections. The inner flow section is for the high speed jet, a plunger pump delivering 2.8×10^{-4} m^3/s and 34 MPa was chosen in order to achieve the high pressure required by the flow conditions. The flow velocity is controlled by a variable frequency drive. The outer flow section is for the supporting fluid, which is used to locally submerge the high speed jet, thereby producing cavitation. Given the high volume required, a centrifugal pump delivering 3.8E-3 m^3/s at 392 kPa was selected, and an upstream flow regulator valve was used to control the flow velocity in the section. To ensure flow homogeneity, the outer flow line was connected to the cavitation nozzle through four inlets spaced 90° apart and located at the top of the nozzle. The inlets and the nozzle main cross section area were dimensioned with the goal to keep the average outer flow velocity inside the nozzle below 0.5 m/s. A system of gates and meshes ensured flow homogeneity and minimized the swirl inside the nozzle, with a 0.25 m long straight nozzle section between the last mesh and the nozzle outlet. The nozzle dimensions are listed in Table 1. The ratio D_0:D_1:D_2 was chosen based on [24], while diameter D_4 and dimension L were selected based on [25].

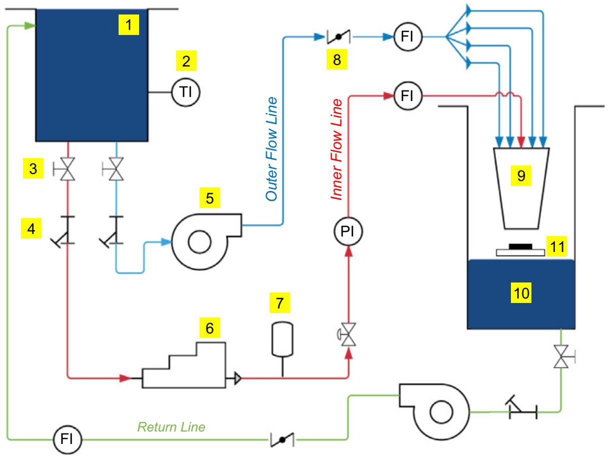

Fig. 1. Water cavitation peening (WCP) apparatus. (1) Reservoir tank (2) temperature, flow rate or pressure indicator, (3) valve, (4) strainer, (5) centrifugal pump, (6) positive-displacement pump, (7) pulsation damper, (8) butterfly valve, (9) WCP nozzle, (10) test enclosure and (11) test sample.

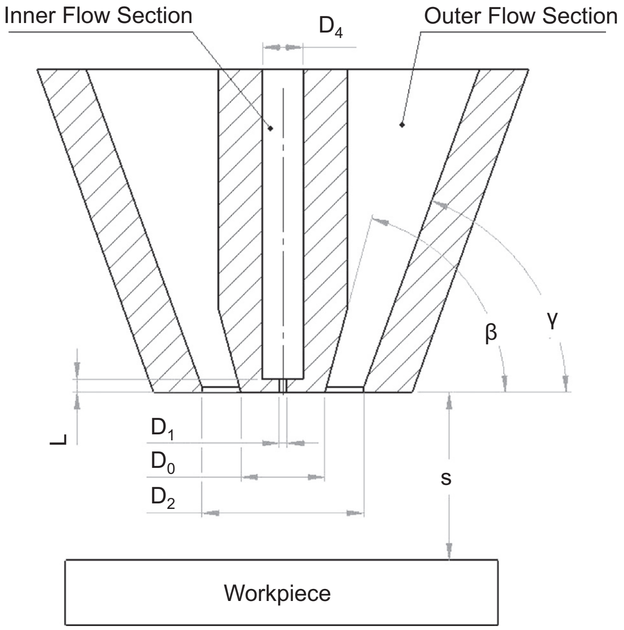

Fig. 2. Co-flow cavitation peening nozzle details.

Table 1
Nozzle dimensions.

D_0	12.8 mm
D_1	0.85 mm
D_2	24 mm
D_4	$8 \times D_1$
L	$3.5 \times D_1$
β	75°
γ	70°

2.2. Experimental procedure

2.2.1. Accelerated erosion tests

Cavitation aggressiveness is evaluated indirectly by exposing samples of soft aluminum Al 1100-O and Al 7075-T6 to the cavitating flow for an extended period of time (beyond the incubation period [21]) and measuring the corresponding mass loss. It should be noted that mass loss is an undesirable effect in peening processes. However, it serves to quantitatively establish the flow conditions that yield the most intense cavitation. Once cavitation aggressiveness is established through the accelerated erosion tests, actual peening is performed by exposing the surface to the cavitating jet for a short duration (*saturation time* [15]) to induce residual stresses without any mass loss. This method was initially developed and adopted by many researchers in the field of cavitation to evaluate the cavitation erosion resistance of engineering