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Comparison between cavitation peening and shot peening for extending the fatigue life of a duralumin plate with a hole

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ABSTRACT

In order to demonstrate the advantages of cavitation peening, in which the impact due to cavitation bubbles collapsing is used to mechanically treat a surface, compared with shot peening, the fatigue lives of peened specimens comprising duralumin plates with open holes were evaluated. In the present experiment, cavitation bubbles were generated by injecting a high speed water jet into a water filled chamber, producing what is known as a cavitating jet. The specimens, which had either a chamfered or rounded edge hole, were treated by cavitation peening and shot peening, then tested using a tensile fatigue test. The fatigue life of the shot peened specimen was equal to or less than that of the as machined specimen, whereas cavitation peening extended the fatigue life. When the cavitating jet was injected in such a way that the cavitation bubbles collapsed at the wall surrounding the hole, the fatigue life at a maximum tensile stress, $\sigma_{\max}$, of 150 MPa was extended by more than a factor of ten. It was also demonstrated that cavitation peening introduced compressive residual stress of about 300 MPa into the wall surrounding the hole.

1. Introduction

A peening method that uses cavitation impact can enhance the fatigue strength of metals in the same way as shot peening. Since shot is not required, this method is called “cavitation shotless peening” (Soyama et al., 2002), or simply “cavitation peening” (Soyama, 2014a). As shot is not used in cavitation peening, there are no solid objects bombarding the workpiece. Thus, if used to introduce compressive residual stress into a material, the increase in surface roughness is much smaller after cavitation peening compared to conventional shot peening (Soyama et al., 2004). The other advantage of cavitation peening is that it can be used to treat remote areas. That is, cavitation peening can introduce compressive residual stress into areas that are inaccessible to shot peening (Soyama et al., 2008). However, since cavitation is a hydrodynamic phenomenon, the peening effect depends upon the flow pattern in the region where the bubbles collapse, and this needs to be carefully considered to obtain the desired results.

Crack propagation around fastener holes in aircraft components causes serious problems, as it affects the lifetime of these components. However, the introduction of compressive residual stress around the fastener holes, for example by cold expansion (Phillips, 1973), can extend the lifetime. Surface mechanical treatments such as shot peening and laser peening have also been proposed for extending the fatigue life. It has been shown that shot peening can prevent crack propagation near the edge of an aluminum alloy specimen (Cerny et al., 2014). It has also been demonstrated that laser peening is an effective technique for improving the fatigue life of aluminum alloys with fastener holes (Yang et al., 2001). Moreover, Tan et al. (2004) has shown that laser peening introduces compressive residual stress and inhibits crack propagation in aluminum alloy. Cuellar et al. (2012) investigated the effect of the laser peening pattern on the fatigue performance of an aluminum alloy specimen with a hole in it. Furthermore, Achintha et al. (2014) showed that a laser peened 5 mm thick specimen of aluminum alloy had better fatigue performance than a 15 mm thick specimen that had been shot peened.

Although a plate bending fatigue test has been used to show that cavitation peening improves the fatigue strength of duralumin plates with open holes (Soyama, 2014a), a tensile fatigue test should be applied to aircraft components, as some components with fastener holes are applied by not only bending stress but also tensile stress. In the case of cavitation peening, cavitation bubbles can be generated by injecting a high speed water jet into a water filled chamber (Soyama et al., 1995). This sort of submerged water jet is

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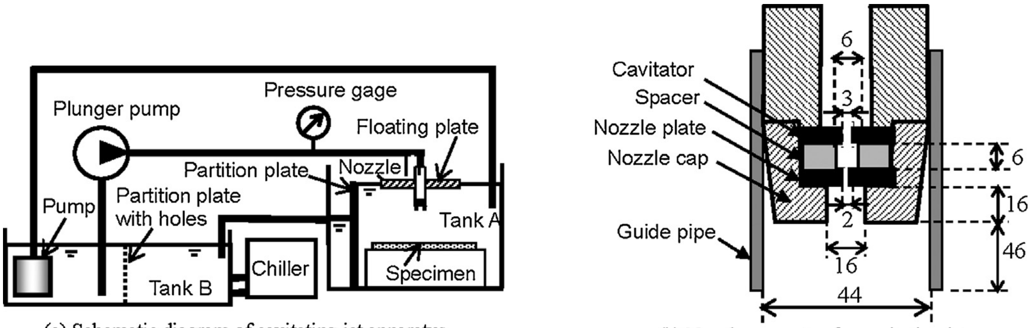

(a) Schematic diagram of cavitating jet apparatus

(b) Nozzle geometry for cavitating jet
(All dimensions quoted in mm)

Fig. 1. Schematic diagram of cavitation peening system (a) schematic diagram of cavitating jet apparatus, (b) Nozzle geometry for cavitating jet (all dimensions quoted in mm).

Table 1
Chemical composition of the material under test.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.68	0.53	3.8	0.46	0.56	0.01	0.09	0.02	RE

Table 2
Mechanical properties of the material under test.

Yield stress	258 (MPa)
Tensile strength	410 MPa
Elongation	21.7%

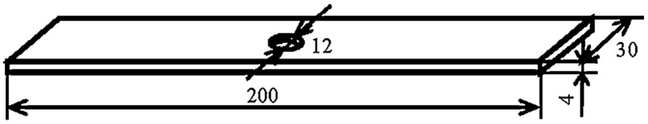

Fig. 2. Geometry of test specimen (all dimensions quoted in mm).

called a cavitating jet. Although Soyama (2004) has demonstrated the introduction of compressive residual stress using a cavitating jet in air, the air was drawn into the cavitating jet when a specimen with an open hole was treated, and the cavitation bubbles around the jet were unable to produce the necessary impacts. Thus, a normal cavitating jet, i.e., a cavitating jet in water, was used in the present experiment.

Water jet peening is a process in which a high speed water jet introduces compressive residual stress as a result of the impact of water droplets at the jet center. Chillman et al. (2007) demonstrated the plastic deformation of aluminum alloy using a water jet at 600 MPa and Azhari et al. (2013) demonstrated work hardening of aluminum alloy using a water jet at 50–150 MPa. Note that a cavitating jet with an excessively high injection pressure cannot introduce large compressive residual stress (Demma and Frederick, 2006). A submerged water jet at high injection pressure introduces compressive residual stress by a similar mechanism to water jet peening, and this allows us to jointly classify cavitation peening and water jet peening. Soyama (2015) proposed a classification map for cavitation and water jet peening using the relationship between the optimum standoff distance, where the aggressive intensity of the jet has a maximum, and the cavitation number, which is defined by the injection pressure and the downstream pressure of the nozzle. Thus, it is necessary to demonstrate the extension of the fatigue life by cavitation peening by showing evidence of the cavitation impacts.

In order to demonstrate that the fatigue life of duralumin plates with fastener holes can be extended further by cavitation peening than by shot peening, specimens of duralumin plates with open holes were treated by cavitation peening and shot peening, and the fatigue life was evaluated by a tensile fatigue test. As mentioned above, optimizing the flow pattern around the peening area is very important to get better fatigue performance in the case of cavitation peening; thus, two different processes were carried out in order to make the cavitation bubbles collapse at the wall surrounding the hole by changing with the way in which the cavitating jet was injected. As residual stress is one of the important parameters in fatigue performance, the residual stress in the wall surrounding the hole was measured by an X-ray diffraction method.

2. Experimental

Fig. 1(a) shows a schematic diagram of the cavitating jet apparatus used for cavitation peening. Water, which is stored in tank B through an ion-exchange resin, is pressurized by a plunger pump with a maximum pressure of 35 MPa. The maximum discharge is 3.0×10^{-2} m^3/min, and this is injected into a water filled chamber, i.e., tank A, through a nozzle which is shown in Fig. 1(b). The nozzle has a cavitator and a guide pipe whose geometries have been optimized previously (Soyama, 2014b). The nozzle throat diameter of the nozzle plate d is 2 mm. In the present experiment, the injection pressure of the cavitating jet, $p1$, is 30 MPa and the standoff distance from the upstream edge of the nozzle plate to the specimen surface was chosen as 262 mm, which was optimized by measuring the arc height of the Duralumin plate (Soyama, 2014b). In the present experiment, the cavitation number was 0.0033 and the standoff distance, normalized by the nozzle throat diameter, was 131. Note that the present conditions are cavitation peening conditions (Soyama, 2015).

The material used for the fatigue test was Duralumin Japanese Industrial Standards JIS A2017-T3. The chemical composition and mechanical properties of this are shown in Tables 1 and 2, respectively. The specimens were 200 mm in length, 30 mm in width and 4 mm thick with a 12 mm diameter hole at the center, as shown in Fig. 2. In order to investigate the effect of the edge profile of the hole, the edge was chamfered with a 0.5 mm chamfer or rounded with a radius of 1 mm. To investigate the effect of cavitation peening and shot peening on the fatigue life, a tensile fatigue test was carried out with the frequency of 30 Hz. The specimen was clamped by a hydraulic clamping system and the clamped length of the specimen was 30 mm in length. The stress ratio between the maximum tensile stress, σ_{max}, and the minimum tensile stress, σ_{min}, was 0.1.