Short communication

Peening the tip of a notch using ultrasonic cavitation

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\begin{abstract}
A peening technique using ultrasonic cavitation was proposed to peen the tip of deep notches. The working theory of the present peening technique for the notch tip was described and numerically demonstrated. An experiment using a deep notch shape and an ultrasonic loading with a frequency of 20 kHz achieved noticeable compressive residual stresses at the notch tip.
\end{abstract}

1. Introduction

Notches introduced in mechanical components substantially degrade structural durability due to the stress concentration when the components are subject to tension. To improve the durability, the tensile stress concentration at the tip needs to be mitigated. Shot peening, which is to impact the surface with shot streams and produce a compressive residual stress layer, has been used to relieve the tensile stress concentration. However, for deep and narrow notches, shot peening becomes less suitable to peen the tips of the notches due to the difficult geometries, which are challenging to access.

To address the challenges to peen deep notches, we propose a shot-less peening approach using ultrasonic cavitation. When water is ultrasonically excited, cavities form and grow. When the cavities reach a volume where energy can no longer absorbed, they collapse violently generating shockwaves. Early works using the shock waves demonstrated compressive residual stresses on flat metal surfaces or increases of the fatigue limit\cite{1–3}, which implies that ultrasonic cavitation is able to provide surface treatment like shot peening. The present approach makes use of the shock waves in producing a compressive residual stress layer at the notch tip.

In this work, we presented the working theory to enable the proposed approach using ultrasonic cavitation to peen the tip of deep notches. A finite element analysis and a peening experiment were carried out to verify the working theory. Also, the residual stresses achieved at the notch tip produced from the experiment were measured and discussed.

2. Working theory

The converging geometry of notch is the key feature to achieve intensive cavitation leading to generate compressive stresses at the notch tip. As shown in Fig. 1, the notch shape tends to focus the applied ultrasound as the rigidity of the sidewalls prevents ultrasonic energy from being transmitted from water to the steel part at the interface. As the ultrasound is focused at the tip, the ultrasonic intensity reaches the maximum at the tip of the notch, intensifying ultrasonic cavitation as illustrated in Fig. 1. Thus, the peening effect by cavitation is significantly enhanced at the tip as desired.

The degree of the intensity concentration at the tip scales with severity of the notch; with the notch angle and the notch tip radius decreasing, the intensity concentration is scaled up. Thus, it can be claimed that, based on the scalability of the intensity concentration effect, the ultrasonic cavitation peening approach becomes more preferable to peen the tips of deep notches which are fairly challenging to access.

In the present work, a finite element simulation and an experiment were carried out to verify the theory using the configuration of a peening system shown in Fig. 2. The present notch was introduced with the depth of 28 mm and the opening angle of 30°. The sides were covered to further confine the ultrasonic filed. The vibration probe was directed to the notch tip.

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3. Acoustic finite element analysis

The present finite element simulation aims to verify the validity of the assumption that the rigidity of the steel sidewall affords to fully constrain the ultrasonic field leading to concentration of ultrasonic intensity at the tip. The dimensions of the notch in the simulation model were set as given in Fig. 2. The properties of elements comprising the steel part and the water part were given in Table 1. The water part of the simulation model adopted the 8-node linear brick acoustic elements from Abaqus while the steel part used the 8-node linear solid continuum elements [4]. At the interfaces between water and solid, the nodes of the steel part were coupled with the corresponding nodes of the water part. To simulate vibration to ultrasonically excite the water, the vibration loading with the amplitude of 35 μm was set to a frequency of 20 kHz. The simulation was run on steady state dynamic analysis.

### Table 1

<table>
<thead>
<tr>
<th>Material constants</th>
<th>Steel</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg m(^{-3}))</td>
<td>7860</td>
<td>1000</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>210</td>
<td>-</td>
</tr>
<tr>
<td>Bulk modulus (GPa)</td>
<td>-</td>
<td>2.2</td>
</tr>
<tr>
<td>Acoustic impedance (kg m(^{-2}) s(^{-1}))</td>
<td>(47.2 \times 10^9)</td>
<td>(1.45 \times 10^9)</td>
</tr>
</tbody>
</table>

Fig. 1. Notch peening using ultrasonic cavitation. Ultrasound is focused in the zone of the notch tip inducing cavitation, which, in turn, produces the compressive stresses at the metal surface.

Fig. 2. Schematic of the present peening system. Steel covers are added on the side to enhance the intensity concentration.

Fig. 3. Alternating pressure amplitude contours. The quarter symmetry was used in the simulation.
The alternating pressure amplitude shown in Fig. 3 demonstrates that the intensity i.e. the pressure amplitude continues to elevate and reaches the maximum at the tip as predicted in the working theory. This proves that the steel sidewalls, whose acoustic impedance is far greater than that of water as given in Table 1, are fully rigid to be able to constrain the ultrasonic field leading to the concentration of the pressure amplitude.

It should be noted that the pressure presented at the notch tip from the simulation is sensitive to the dimensions of the elements near the tip so that the pressure will continue to increase with the mesh more refined at the tip, in other words, since the tip radius of the notch is not given in the present model, the pressure field would come to be singular at the notch tip by refining the mesh. Thus, for the result to be more accurate, a proper tip radius needs to be properly implemented. However, the present finite element simulation only aims to collectively understand the pressure distribution inside the notch so that a full evaluation of the individual accuracies of the pressure values near the notch tip were not conducted here.

4. Experimental procedure and results

An experiment was conducted to measure residual stresses at the notch tip which was produced by the cavitation resulting from the concentrated ultrasonic field in the notch. The experimental set-up was shown in Fig. 4. A SPCC steel strip was assembled on the side of the working sample as shown in Fig. 4, which was to collect the stress by the cavitation and be removed after the experiment for the ex-situ stress measurement by the X-ray diffraction (XRD) method on the exposed side surface. Each X-ray diffraction measurement involved a slender irradiated area of 2 mm wide by 10 mm. The slender irradiated area was oriented in parallel with the notch tip line, which moved away from the notch tip by an increment of 2 mm to capture the stress variation over the immediate area of the notch tip.

The stress values from the measurements revealed that appreciable compressive residual stresses were locally produced near and at the notch tip (Fig. 5). The maximum compressive residual stress was found at the notch tip, as expected. The residual stress rapidly decreased with distance away from the notch tip. The local stress field indicates that intensive cavitation was locally produced at the tip as a result of the pressure concentration shown in Fig. 3. It is possible that the residual stress was further raised by the geometric discontinuity associated with the notch shape, which was, however, not counted in the ex-situ measurement [5]. The ex-situ stress measurement was carried out on the surface of the strip after it was removed from the notch configuration. Thus, when they were measured, the residual stresses especially at the tip could be less than the actual ones by the stress concentration factor associated with the geometric discontinuity.

5. Visualization of cavitation

In order for the concentration of ultrasonic intensity to be visually confirmed, the images of cavitation inside the notch were recorded during the process. The steel cover was replaced with a glass cover, which is transparent to visualize cavitation produced inside the notch. From the recorded image shown in Fig. 6,
intensive cavitation was observed near the tip during the process as expected from the pressure concentration. Fig. 6 indicates that the residual stress field shown in Fig. 5 was built up as far as the local cavitation appeared.

Also, from the recorded images, migration of cavities was inspected. As well as the notch tip, cavities formed directly underneath the vibration probe and subsequently displaced by circulation flows known as acoustic streaming. However, no prominent contribution from the migration to the formation of the cavity cluster at the notch tip was observed. Thus, this observation demonstrates that the intensive cavitation at the tip mainly resulted from the pressure concentration, not from collection of the cavities which were displaced from elsewhere.

6. Discussion and conclusion

We successfully peened the tip of the deep notch using ultrasonic cavitation. Appreciable compressive residual stresses were achieved in the area near the notch tip by the ultrasonic vibration loading. The locally concentrated stress field at the notch tip indicates that intensive cavitation was produced at the notch tip from the pressure concentration, which is induced by the converging geometry of the notch shape. It is also visually confirmed that the intensive cavitation at the tip mainly resulted from the pressure concentration, not from collection of the cavities which were displaced from elsewhere. The concentration feature offers the potential to repair deep notches or flaws which are challenging to reach.
An extensive parametric study will be carried out to assess efficacy of the present approach for various notch dimensions including notch tip radius and opening angle. In addition to residual stress, strain hardening and surface roughing will be investigated. The vibrator's loading amplitude, shape and dimensions of the ultrasonic tip, duration time, and, types and conditions of cavitating liquids will be optimized to further improve the residual stresses at the notch tips. Models of cavitation and jet flows induce by the vibrator tip will be integrated in the numerical simulation to improve the accuracy of the results.

In addition, the ultrasonic cavitation combined with the notch configuration can be useful in the applications of nano powders preparation and mechanical alloying of powder materials. Early works [6,7] reported that ultrasonic cavitation can play to increase the reaction rates of the processes. Thus, as the chemical effect of ultrasonic cavitation was proven, the notch configuration can serve as a platform able to significantly enhance the activity by providing an amplified ultrasonic intensity.

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