Variability in Crack Detectability Due to Load History and Stress State

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Abstract
Practically most nondestructive inspection is performed without detailed knowledge of the loading history, or state of stress, of the component being inspected. A laboratory study has been conducted where complete knowledge of the load history and details of the loading during examination are known. Both eddy current and ultrasound have been used to characterize the material in the vicinity of two cracks induced by specimen geometry and cyclic loading. These specimens have been examined while under different loading conditions to simulate possible variations for practical naturalistic cracks. Finally the specimens were loaded to failure so that the crack fronts could be examined metallographically. The results of this nondestructive materials characterization are discussed as regards the effects on probability of detection results and the ultimate objective of determining the effects of the cracks on performance. The latter being more appropriate for determining the reliability of nondestructive evaluation (RoNDE).

Keywords: Ultrasound, eddy current, scanning, acoustic emission, crack opening displacement, 7075 Al, PoD, RoNDE

1. Introduction

Critical structures and systems in general are designed, constructed, inspected to assure that there are no manufacturing defects, and placed into service. If there is a concern regarding the risk associated with these critical structures or systems the notion of reliability provides a basis for assessing the risk. Unfortunately as computational tools for modelling, and simulating become more sophisticated and the associated analysis become less expensive to perform there is a tendency to presume and assume that the realization of the design is completely consistent with the design with perhaps some reduced reliability due to the fact that the probability of detecting (POD) manufacturing flaws is less than 100% with 100% confidence. A significant part of the less than perfect reliability of nondestructive inspection (NDI) is caused by human factors associated with the inspectors. Actually though the exercise of determining the POD is generally more idealized than the actual circumstances of the inspection in practice, but beyond that other issues not directly related to the NDI are also likely to be less than 100% reliable. The designer always is faced with making assumptions when modelling the structure or system to analyse the performance in order to refine the design. The point here is not to suggest that such assumptions are not reasonable, but rather that these assumptions introduce a reduction in reliability since they might in reality cause the design to be different than the actual structure/system. Variability of material properties (yield strength, ultimate strength, fatigue limit, plane strain fracture toughness, etc.) are less than 100% reliable and when compounded can further reduce the overall reliability. Of course, if human factors affect NDI, human factors must also affect construction. Can nondestructive methods be used to provide data that can help improve the reliability? In this study the focus is upon exploring how crack detection and sizing are complicated by variations in the load history, the state of stress existing when the inspection is performed, and nondestructive characterization of material properties. The intent being to transition the concept of probability of detection to reliability of nondestructive evaluation (RoNDE), where the NDE is the ultimate objective of the NDI, and essential for reliable operation of critical structures.
2. The Study

2.1 Specimen Preparation

Two 0.75 inch (19 mm) thick 7075 T651 Al crack opening displacement (COD) specimens were subjected to constant amplitude cyclic loading from 100-lbs – 1000-lbs, at 15 Hz (450 N-4450 N) to initiate and grow cracks. Ideally with this careful laboratory loading the crack front is straight, resulting in the crack length determined from any point on the crack front being the same; actually as will be obvious from the fracture surfaces the crack fronts do not exhibit a constant length, nor are they symmetric about the mid-plane. Of course actual structures or system components often experience loading spectra which may be nonuniform due to deviation of the components from design as well as geometric details.

Both sides of the specimen surfaces were examined optically after the cracking since both sides of these laboratory specimens were easily accessible, unlike the case for many actual components. The surface breaking crack lengths were measured with optical magnification and the lengths for both specimens were different depending on the surface examined; eventually the entirety of the crack fronts were exposed and examined, Fig. 1.

Fig. 1. Optical images of the finally cracked specimens 1 left, 2 right. The specimens are 0.75-in. (19 mm) thick so the obvious differences between the surface breaking crack lengths can be seen; the difference is as much as 35%.

2.2 Specimen Conditions

The specimens were subjected to different loading histories and conditions while being examined by ultrasonic and eddy current C-scanning. The different load histories and associated nondestructive materials characterization (NDMC) are indicated in Table 1. Specimen 1 was “wedged” by quasi-statically loading to 1500 lbs (6700 N) and shims were placed in the gap to prevent relaxation once the applied load was removed. Specimen 2 was “clamped” by means of a large C-clamp tightened along the centerline of the loading pinholes; the magnitude of the clamping load was not measured. “No load” indicates that no external load was applied; it is unclear whether the crack surfaces were under load.
### Table 1- Loading Histories and NDMC

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Condition</th>
<th>Eddy Current Testing</th>
<th>Ultrasonic Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cracked</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>Cracked</td>
<td>x</td>
<td>x</td>
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<tr>
<td>1</td>
<td>Cracked/wedged</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1</td>
<td>Cracked/wedged/no load</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>Cracked/clamped</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>Cracked/clamped/no load</td>
<td>x</td>
<td>x</td>
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</tbody>
</table>

### 2.3 Ultrasonic C-scanning

A Sonix ultrasonic C-scanning system was used to examine the specimens with different loading histories. The scanning was performed over the plane of the crack through the upper or lower surface of the specimen, an orientation ideal for examining the cracking, but typically not accessible in an actual components. A 15 Mhz transducer with a focal point in water of 1.5 in. (38 mm) was positioned to maximize the reflected echo amplitude from the crack plane. The scanning was conducted, to include the edge of the specimen to afford a reference for measurement, with a step increment of a 0.1 mm.

### 2.4 Eddy Current C-scanning

A Zetec MIZ-40 Eddy Current unit was used to generate either a 100 kHz, 200 kHz, 300 kHz, or 400 kHz excitation of a 3-mm diameter eddy current probe. The horizontal output, which nominally provided a component of the complex impedance, was recorded when C-scanning of the top or bottom surface of the specimen where the first step was positioned to coincide with the eddy current probe centered over a line orthogonal to the crack plane and the notch tip. The step increment of the scan used was 0.1 mm. The “horizontal” component of the sampled eddy current signal, sampled at 400 samples/s, was collected using a National Instruments Compact RIO (cRIO 9014 wFPGA).

### 2.5 Acoustic Emission Monitoring

Acoustic emission was monitored during the final fracturing of the specimens. A Physical Acoustics Corporation (PAC) wide-band differential (WD) transducer (AE04) connected to a PAC 2/4/6 preamplifier was further amplified using a Tektronix 1A7A High Gain Differential amplifier bandpassed filtered between DC and 1 MHz. Finally the signal was directed to an HP 3400B RMS Voltmeter and the DC output was collected using a National Instruments Compact RIO (cRIO 9014 wFPGA).

### 2.6 Fracture of Specimens

To allow direct examination of the crack surfaces the specimens were loaded quasi-statically to failure while the crack opening displacement, applied load and AE RMS voltage were monitored.
3. Experimental Results and Discussion

The ultrasonic C-scans for Specimen 1 in the wedged condition and the unwedged condition are shown in Fig. 2. The images suggest that the crack face is larger when wedged, but the differences when the actual crack faces are examined, see Fig. 1, are more likely due to improved reflectivity of the surfaces when separated due to wedging. Clearly as would be expected if the crack is loaded so as to separate the crack surfaces the detectability using ultrasound is improved, however, the nature of this loading is not determined during non-destructive inspection (NDI).

Fig. 2. The top ultrasonic C-scan is for Specimen 1 in the unwedged condition and the bottom is for Specimen 1 in the wedged condition.

Fig. 3. The optical image of the Specimen 2 crack surface and the associated ultrasonic C-scan
Fig. 3 shows that the ultrasonic C-scan made with an optimal orientation with respect to the crack surface shows how the crack length varies across the crack surface and indicates that the length on neither surface is the largest value. The fact that the crack has grown at different rates for different points across the crack front suggests that knowledge of the state of stress and properties of the material across the crack front are not uniform even for controlled laboratory testing.

Fig. 4 shows two different sets of data for scans of the same specimen surface but at two different frequencies. For simplicity of data collection only one component of the complex impedance is collected as the probe is scanned in C-scan fashion over the surface. The large excursions correspond to when the probe passes over the crack. The peaks occur every scan which are 0.1mm apart. The different indicated lengths are no doubt due to the different depths of penetration of the eddy current field interaction with the subsurface crack face, but which crack length is being determined?

Fig. 5. The AE RMS signal and load are plotted versus time for Specimen 1 left and Specimen 2 right during the loading to fracture the surface.

Fig. 5 shows that the AE response of the two specimens which were subjected to different loading history subsequent to fatigue crack initiation and growth are quite different before the cracks begin to grow. The result of loading Specimen 1 in order to wedge the crack open can be seen from the delay in the AE activity upon loading, but once crack growth begins the AE in both cases is copious. However, if the load versus crack opening displacement is considered, Fig. 6, it becomes clear that nature of loading is different due to the intervening loading of Specimen 1 to 1500 lbs (6700 N) in order to wedge the crack. This overloading, not unlike what might actually happen in a bridge structure when a large truck crosses, shows how the crack tip can be blunted altering the nature of the subsequent crack growth.
4. Conclusions

A study was conducted to explore how different loading histories and states of stress during NDI alter the detectability of cracks in 7075 Al. It was shown that ultrasonic C-scanning optimally oriented with respect to the crack surface gives different indications of the crack front if the state of stress along the crack front is different due to the crack being loaded in tension. In addition the eddy current responses at different frequencies for a crack with a nonuniform crack front, the typical naturalistic situation, are different since the different depths of penetration and interaction with the nonuniform crack front are different; the response suggests a different crack length than the surface breaking length measured optically.

Finally, the growth of cracks due to different load histories is not obvious from NDI of unloaded cracks, although AE monitoring offers some insight for 7075 Al.