Investigation of the effects of notch width on eddy current response and comparison of signals from notches and cracks

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INVESTIGATION OF THE EFFECTS OF NOTCH WIDTH ON EDDY CURRENT RESPONSE AND COMPARISON OF SIGNALS FROM NOTCHES AND CRACKS

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ABSTRACT. This paper reports on work conducted to investigate the effect that electrical discharge machining (EDM) notch width has on the eddy current (EC) signal as a function of coil drive frequency. The notch results are also compared to EC signals from laboratory-grown fatigue cracks. This study builds upon previous work with titanium, Inconel and aluminum materials where the signal amplitude was shown to decrease, as expected, as the notch width decreases. The trend was captured well by numerical results and this allowed estimates to be made about the signals from idealized “zero-width” notches. The results indicated that the signal reduction factor from a 0.127mm (0.005 inch) wide, rectangular notch to a theoretical zero-width semi-elliptical notch of the same size ranged from 25 to 42% for low conductivity materials when data was collected at 2MHz. For aluminum, the difference between signals from 0.127mm wide notches and estimated signals for zero-width notches was approximately 50%. However, 2MHz is an uncommonly high frequency for inspecting aluminum alloys so additional work was necessary to investigate the notch width effect at lower frequencies. This study sought to determine how the notch-width effect changed as a function of frequency for high conductivity materials such as aluminum.

Keywords: Eddy Current Inspection, Discontinuity Width, EDM Notch, Fatigue Crack
PACS: 81.70.Ex, 81.05.Bx, 81.40.Np

INTRODUCTION

When conducting an eddy current (EC) inspection for cracks, it is necessary to use a reference specimen with a known discontinuity to setup the equipment. For best results, the discontinuity should resemble the target crack as closely as possible. However, it is often expensive and sometimes impractical to grow representative cracks, so electrical discharge machining (EDM) is often used to place notches in the reference specimen. While EDM notches are not true representations of cracks, they are considered acceptable reference discontinuities for many applications. EDM reference notches commonly produce with widths ranging from 0.076mm (0.003”) to 0.127mm (0.005”) for equipment setup and reference purposes. Some machine shops have recently started producing plunge-cut notches with widths down to 0.0254mm (0.001”) when the depth of the notches are 0.4mm (0.015”) or shallower. Since the width of a notch will affect the
magnitude of an eddy current signal, it is important to develop an understanding of the width/signal strength relationship when setting up an eddy current instrument.

In prior work by Nakagawa et al. [1] the notch width effect was evaluated when a 2MHz differential probe was used to inspect titanium alloy Ti-6Al-2Sn-4Zr-6Mo and nickel-base alloy IN-100 specimens. The eddy current signal amplitude was shown to decrease, as expected, as the notch width decreases; the linear trend being captured well by numerical model predictions. The agreement between the experimental and numerical results allowed signals for idealized zero-width notches to be determined. The results indicated that the signal reduction factor from a 0.127mm (0.005 inch) wide, rectangular notch to a theoretical zero-width semi-elliptical notch of the same size ranged from 25 to 42%. The work was limited to notches that were 0.508mm (0.020”) and 0.762mm (0.030”) long with a 2-to-1 length-to-depth aspect ratio.

In another study, Lo and Nakagawa [2] performed EC crack signal measurements on fatigue cracks grown in Al 6061 and Ti-6Al-4V bars when the cracked surfaces were subjected to mechanical loading. While the EC signals of fatigue cracks in aluminum were found to vary periodically with cyclical loading, the effect of the loading was stronger under tension than under compression. This asymmetry indicated that, while there is noticeable crack opening (volume) effects, the crack closure effects were small for these crack samples and that cracks in aluminum may appear as a mathematical zero-width notch in EC NDE. Interestingly, the in situ measurements of titanium alloy samples showed nominally equal effects between compressive and tensile loading, revealing that both crack opening and closure effects exist in similar strengths for Ti crack measurements. When this is the case, then one must distinguish a crack from the mathematical zero-width notch, taking the morphology effect into account.

In a third study, Larson, Nakagawa and Lo [3] furthered the aforementioned studies by collecting experimental EC data on notches of various widths and low-cycle fatigue cracks. The data from the notches was used to mathematically estimate signals from idealized zero-width notches of various sizes for comparison to the crack signals as illustrated in Figure 1. Signals from the crack specimens were collected under no load, tension and compression loading conditions. The study found that for 6061-T6 aluminum, the signals estimated for the zero-width notches correlated well with the signals from the fatigue cracks. Additionally, it was found that the signals changed very little when the aluminum crack specimens were loaded in tension or in compression, most likely due to the tenacious, insulating oxide layer that forms on aluminum alloys. Therefore, it does seem that experimentally or mathematically determined signals for zero-width notches are comparable to signals similar sized cracks (see Figure 2). For the titanium and iron/nickel-based alloys evaluated, zero-width notch signals correlate well to cracks that are open due to residual stresses or external loading but the stress state and morphological characteristics of the crack must be taken into consideration.

**FIGURE 1.** Illustration showing the two step approach to relating open EDM reference notches to actual cracks. The first step is to develop an algorithm that accurately captures the notch width effect and use this to calculate a signal for an idealized crack. The second step involves relating the calculated signal from the idealized crack to an actual crack with its morphology effects.
The graph shows that for aluminum alloy 6061-T6 plate the empirically derived curve (dashed line) for zero-width notch of various sizes compares well with the experimental data for low-cycle fatigue cracks (diamond markers with log-fit trend line). The data from notches of various widths, which was used to derive the zero-width curve, is shown with the heavy, solid lines.

The work reported on here looks at how the notch width effect changes as a function of eddy current coil drive frequency for the aluminum alloy. Since the previously mentioned work was conducted at 2MHz, which is an uncommonly high for inspecting high conductive materials such as aluminum, data at lower frequencies was desired. The notches and cracks were scanned at frequencies ranging from 50kHz to 1MHz using an absolute pencil-type probe. The peak magnitude of each scan was recorded for comparison. Specifics on the procedures, results and additional work plans are presented in the following sections.

MATERIALS AND PROCESSES

Specimen Description and Experimental Procedure

The aluminum alloy used in this study was 6061-T6, which had an electrical conductivity 27.74 MS/m (47.8% IACS). This material was used because previously produced notch specimens and low-cycle fatigue crack specimens in this alloys was available for testing. Notches ranging from 0.51mm (0.020") to 3.05mm (0.120") were included. Unfortunately, 0.025mm (0.001") wide notches could not be manufactured for notches deeper than 0.38mm (0.015") due to EDM limitations.

The notch width specimens were prepared by plunge cutting EDM notches of different sizes and shapes in flat specimens of the subject materials. The focus of this work was on thumbnail-shaped notches but a few rectangular-shaped notches were also produced. The notches were characterized using image-based measurement software to determine the length, depth and width of the notches directly or through the use of replication. Notch shape and dimensional information is provided in Table 1.
The low-cycle fatigue cracks specimens were produced in three-point bending with a max load of 80% of yield strength and an R ratio of 0.1. An EDM starter notch was used to initiate the crack. The surface was then milled and ground to remove the starter notch and loading was resumed to grow the crack to final size. A number of cracks were fractured open to determine that the crack grew with a length-to-depth aspect ratio of 2.8:1. All the specimens were 15cm (6.0") long, 1.27cm (0.5") thick and 2.54cm (1.0") wide for the Al and Ti, and 3.8cm (1.5") wide for Inconel. Crack dimensional information is provided in Table 2.

Experimental data were collected using a pencil-type, differential probe with an outside diameter of the coil of approximately 1.5mm. The probe had a design operating frequency of 1MHz. A commercial eddyscope instrument was used to drive the probe at 1MHz, 500kHz, 200kHz, 100 kHz and 50kHz. A computer-controlled motion and data acquisition system was used to perform raster scans at an increment of 0.05mm and to record the eddyscope output voltage. The peak-to-peak signal magnitude was obtained from the raster scan data. A photo of the experimental setup is shown in Figure 3.

**TABLE 1.** Summary of notch shape and dimensional information for EDM notch specimens.

<table>
<thead>
<tr>
<th>Specimen/Notch ID</th>
<th>Shape</th>
<th>Notch Dimensions, mm (inch)</th>
<th>Length</th>
<th>Depth</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>22927 1B</td>
<td>Thumb</td>
<td>0.5232 (0.0206) 0.1727 (0.0068) 0.0305 (0.0012)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22927 1C</td>
<td>Thumb</td>
<td>0.5105 (0.0201) 0.1651 (0.0065) 0.0813 (0.0032)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22927 1D</td>
<td>Thumb</td>
<td>0.5105 (0.0201) 0.1727 (0.0068) 0.1245 (0.0049)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22927 1E</td>
<td>Rectangular</td>
<td>0.5131 (0.0202) 0.1727 (0.0068) 0.1270 (0.0050)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22927 2B</td>
<td>Thumb</td>
<td>0.7696 (0.0303) 0.2540 (0.0100) 0.0305 (0.0012)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22927 2C</td>
<td>Thumb</td>
<td>0.7544 (0.0297) 0.2591 (0.0102) 0.1270 (0.0050)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22927 2E</td>
<td>Thumb</td>
<td>2.2987 (0.0905) 0.7671 (0.0302) 0.0838 (0.0033)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22928 1B</td>
<td>Thumb</td>
<td>1.5113 (0.0595) 0.5080 (0.0200) 0.0813 (0.0032)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>22928 1C</td>
<td>Thumb</td>
<td>1.4986 (0.0590) 0.5080 (0.0200) 0.1321 (0.0052)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22928 1D</td>
<td>Rectangular</td>
<td>1.5265 (0.0601) 0.5080 (0.0200) 0.1295 (0.0051)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22928 2B</td>
<td>Thumb</td>
<td>3.0429 (0.1198) 1.0135 (0.0399) 0.0787 (0.0031)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22928 2C</td>
<td>Thumb</td>
<td>3.0556 (0.1203) 1.0109 (0.0398) 0.1295 (0.0051)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22928 2D</td>
<td>Rectangular</td>
<td>3.0556 (0.1203) 1.0211 (0.0402) 0.1295 (0.0051)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 2.** Summary of low-cycle fatigue crack dimensions.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Notch Dimensions, mm (inch)</th>
<th>Length</th>
<th>Estimated Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>02-700</td>
<td>0.762 (0.030) 2.721 (0.011)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02-701</td>
<td>1.829 (0.072) 0.653 (0.026)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02-738</td>
<td>1.524 (0.060) 0.544 (0.021)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02-757</td>
<td>1.600 (0.063) 0.571 (0.022)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02-764</td>
<td>1.499 (0.059) 0.535 (0.021)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02-782</td>
<td>2.819 (0.111) 1.007 (0.040)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02-784</td>
<td>2.083 (0.082) 0.744 (0.029)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02-788</td>
<td>2.489 (0.098) 0.889 (0.035)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>02-789</td>
<td>3.099 (0.122) 1.107 (0.044)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

The experimental results are presented in Figures 4 and 5. The charts in Figure 4 show the signal magnitude versus notch width for a number of different frequencies. The chart on the left shows the results for notches that are 0.51mm (0.02”) long and the chart on the right shows the results for notches that are 3.05mm (0.12”) long. The value for the zero width values was determined by extrapolating the trend line and the data was then normalized to highlight the slopes of the lines. It can be seen from the data that the eddy current signal decreases as expected with decreasing notch width. The trend is basically linear, which is consistent with numerical calculations. It can also be seen that the slope of the data set lines increases with frequency. At lower frequencies, the lines tend to be flatter, indicating a smaller signal magnitude change due to the notch width. This trend is somewhat weak at the 0.51mm notch length but strengthens with increasing notch length.

In the set of charts shown in Figure 5, the eddy current signal magnitude is plotted as a function of discontinuity length. Here data for thumbnail- and rectangular-shaped notches and low-cycle fatigue cracks are presented. These charts highlight the effect that the probe drive frequency has on the notch width effect. In these charts it can be seen that at any given discontinuity length, the signal decreases as notches changes from 0.127mm wide rectangular- to thumbnail-shaped and the width of the notches decrease. The dashed lines with the circle markers represent the predicted zero-width notch signals, which were obtained by extrapolating the empirical data. One important observation from the charts is that the predicted zero-width notch signals correlate well to the fatigue crack signals. The fatigue crack signals are indicated by the diamond markers and the black lines are linear trend lines for this data. The collection of charts in Figure 5 also illustrates nicely how the notch-width effect decreases with decreasing frequency. At the higher frequencies, the
FIGURE 4. Charts showing the signal magnitude versus notch width for a number of different frequencies. The chart on the left is for normalized data from 0.51mm (0.02") thumbnail shaped notches. The chart on the right is for normalized data from 3.05mm (0.12") thumbnail shaped notches.

FIGURE 5. Charts showing the signal magnitude as a function of discontinuity length for notches of various widths and for low-cycle fatigue cracks. The solid gray lines indicate data from notches of various widths. The dashed line represents the estimated zero-width notch signals determined by extrapolating the empirical data. The green diamond markers indicate the signals from low-cycle fatigue cracks and the solid black lines are trend lines for the crack data.
lines representing the different width notches and the trend line for the cracks are well separated. Unfortunately at this point, it is only possible to directly compare zero-width cracks to 0.003” wide notches because narrower notches cannot be produced for the longer notch lengths. Nevertheless, as the frequency is lowered, the lines start to move closer together indicating a smaller notch-width effect.

In previous work it was determined that at 2MHz the estimated signals for zero-width notches were approximately fifty-percent lower than signals from 0.127mm wide notches. The preliminary data collected in this study indicates that the reduction factor appears to be between ten- and thirty-percent for a frequency of 100kHz. Additional data collection and numerical modeling is necessary to narrow this range.

SUMMARY

This study was conducted to investigate the relationship between the eddy current signals from EDM calibration notches and fatigue cracks in aluminum. It was found that the signals from low-cycle fatigue cracks were smaller in magnitude than the signals from similar sized EDM notches, as expected. The investigation determined that the signals from the fatigue crack specimens correlate well to the predicted zero-width notch signals that were established by extrapolating the experimental data from notches that were nominally identical except for their width. It was also determined that the difference in signal magnitude between the notch signals and the predicted zero-width notch or crack signals decrease as the test frequency was decreased. The data indicates that the reduction factor appears to be between ten- and thirty-percent for a frequency of 100kHz. Additional data collection and numerical modeling is necessary to confirm these preliminary results.

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