USING XRD ELASTIC AND PLASTIC STRAIN DATA TO EVALUATE THE EFFECTIVENESS OF DIFFERENT COLD-WORKING TECHNIQUES IN AEROSPACE MATERIALS

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ABSTRACT
Generating compressive stresses in aerospace materials is an important consideration for enhancing fatigue life. Shot peening and cold expansion of holes are two techniques for imparting beneficial compressive stresses.

X-ray diffraction is a direct method for measuring elastic strains. Diffraction peak widths are an indication of plastic strain. Elastic and plastic strains can be used to better assess the true condition of a component.

This paper presents elastic and plastic strain information from shot peened and cold expanded aerospace materials. Examination of surface data showed which shot peened samples had the deeper layer of compressive stresses. Likewise, elastic and plastic strain data enabled successful ranking of the holes in terms of the maximum amount of cold working.

INTRODUCTION
Studying stresses in aerospace materials helps to address issues important to aircraft sustainment and new materials development. Due to vibrations and inherent cyclic environment, fatigue damage and failures are a primary concern for aerospace structures. For this reason, compressive residual stresses are desirable.

Compressive stresses can be imparted to structures during the manufacturing process. Shot peening is a common practice to impart compressive residual stresses to a wide variety of structures and components. Cold expansion is another method of putting a surface into compression that is commonly employed with structures that contain holes and openings. Both methods were used in this study.

Residual stresses are the stresses that remain in a body after all external loads are removed. These residual stresses are elastic and develop or change as a result of plastic flow in a material. X-ray diffraction (XRD) is an excellent tool for studying residual stresses since it is a direct measurement of elastic strains in a crystalline material. Furthermore, plastic strain can be determined by measuring the diffraction peak width at half the maximum intensity.

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coupling residual stress and diffraction peak width, the effectiveness of cold-working techniques can be evaluated in common aerospace materials.

EXPERIMENTAL PROCEDURE
A. Shot Peening Study
Four aerospace materials were chosen for this study - 4340 and 9310 steels, titanium 6Al-4V (Ti 6-4), and 7075-T73 aluminum. An Almen strip intensity study consisting of variations in impingement angle, air pressure, media flow rate, and stand off/nozzle distance was used to establish desired shot peening parameters for the disks and fatigue specimens used in this investigation. Based on the Almen strip study results, shot peening parameters were selected that would result in a low and high intensity peening condition on the surface of the specimens.

X-ray diffraction was used to evaluate the resulting shot peening-induced residual stresses in the disks and fatigue specimens. Surface measurements were made at the gage section on the fatigue specimens in three equally spaced circumferential locations. The disks were measured at the center and near the edge of the flat surface at 0, 0.03, 0.05, 0.13, 0.18, and 0.25 mm (0, 1, 2, 5, 7, and 10 mils) depths. The subsurface residual stresses were characterized on the disks by alternately performing XRD measurements then electropolishing away layers of material.

B. Cold-Worked Holes Study
The U. S. Air Force supplied TEC with twenty 7075 aluminum samples (203 x 51 x 6 mm) with a centrally located hole. Five of the samples had no cold working while the remaining 15 samples had three different levels of cold working. The initial radius was 2.86 mm. The resulting radius in the cold-worked holes samples ranged from 2.88 to 2.97 mm, representing a 0.89 to 4.00% increase in the radii.

The circumferential stresses generated by the cold expansion were measured by x-ray diffraction at the edge of the hole and at radial distances of 1.27, 2.54, and 3.81 mm (0.05, 0.10, and 0.15") from the edge. Residual stresses and diffraction peak widths were plotted and used to determine the level of cold working.

RESULTS
A. Shot Peening Study
The residual stress (RS) and full width-half maximum (FWHM) data are shown in Figures 1-5. These data represent the average of six separate measurements. V1 and V2 are different vendors while 4A - 12A and 3N - 14N represent A- and N-scale shot peening intensities, respectively.

The 4340 steel surface residual stresses ranged from -488.2 MPa (-70.8 ksi) for V2-12A to -593.0 MPa (-86.0 ksi) for V1-4A. For these samples, the maximum compressive stress occurred at the 0.025 mm (0.001") and 0.051 mm (0.002") depths and ranged from -576.4 MPa (-84.6 ksi) to -610.2 MPa (-88.5 ksi) for the V2-12A and V2-8A intensities.

The depth of compression from maximum to minimum for the different shot peening conditions was V2-12A, V1-8A, V2-8A, V2-4A, and V1-4A.
The diffraction peak widths (FWHM) ranged from 2.84° to 3.17°. For all cases, the maximum FWHM was at the surface. The largest to smallest FWHM values for the different shot peening intensities were V2-12A, V1 and V2-8A, V2-4A, and V1-4A.

Figure 1. Residual Stress and Peak Width Profile for 4340 Steel

Trends for the 9310 steel followed the pattern for the 4340 steel; however, the compressive stresses were higher. The depth of compression from maximum to minimum was V2-12A, V1-8A, V2-8A, V2-4A and V1-8A. The maximum to minimum FWHM order was V2-12A, V2-8A, V1-8A, V2-4A, and V1-4A. Allowing for slight differences in vendor processing, the trend still followed the maximum to minimum shot peening intensities.

Figure 2. Residual Stress and Peak Width Profile for 9310 Steel
The Ti 6-4 samples were shot peened to both A- and N-scale intensities. The A-scale intensities resulted in deeper levels of compression with the maximum to minimum depth of compression order being V1-11.5A, V2-14A, V1-8A, and V1-4A. For these samples, the FWHM order was V2-14A, V1-11.5A and V1-8A, and V1-4A. There was a slight variation in depth of compression and FWHM trends that again can be attributed to vendor shot peen processing differences.

For the Ti 6-4 N-scale intensities data, the compressive stresses approached neutral between 0.025 mm (0.001") and 0.051 mm (0.002") for the lower intensity shot peening and prior to the 0.127 mm (0.005") depth for the higher intensity. The maximum to minimum compression level was V1-14N, V1-11N, V1-5N, and V1-3N. The FWHM data exhibited the same trend as the stress data.
The 7075-T73 aluminum samples remained in compression to 0.254 mm (0.010"). At that depth, the residual stresses for the 10A, 12A, and 14A intensities ranged from -218.6 MPa (-31.7 ksi) to -295.8 (-42.9 ksi). The order of maximum to minimum compressive stresses was V1-14A, V1-12A, V2-10A, V2-12A, V1-10A, and V1-4A. Here the surface FWHM was V1-14A, V1-12A, V1-10A, V2-12A and V2-10A, and V1-4A. Since there was no significant difference in the subsurface stresses for V1-12A, V2-10A and V2-12A, the trend of larger surface FWHM for more compressive depth holds.

Figure 5. Residual Stress and Peak Width Profile for 7075-T73 Al

Although it is outside the scope of this paper, it is interesting to note that the best fatigue response in most cases did not come from the samples with the highest intensity shot peening. In many cases, the best fatigue performance was associated with the minimum intensity shot peening.

B. Cold-Worked Holes Study
The residual stresses and peak width data are shown in Fig. 6-9 and summarized in Table 1. Initial review of the data indicated that four groups of five samples were a logical ordering. Being a blind study, there was no indication that the samples were processed in groups of five or if the samples each represented a different level of coldworking. Once the four groups of five samples each were established, an attempt was made to order the samples within the group. The samples were ranked according to the level of compression at the hole and away from the hole relative to the diffraction peak width.

The ordering of the samples from least to most cold working is as follows:

AF5, AF2, F4, AF3, AF1 (no or minimal cold working)
AF9, AF6, AF8, AF7, AF10
AF13, AF12, AF15, AF11, AF14
AF16, AF18, AF17, AF19, AF20 (maximum cold working)
Table 1. Circumferential Residual Stress and Average Peak Width from Cold-Worked Holes

<table>
<thead>
<tr>
<th>Sample</th>
<th>Circumferential Residual Stress, MPa (ksi)</th>
<th>Average Peak Width,°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.05&quot; from Edge of Hole</td>
<td>0.10&quot; from Edge of Hole</td>
</tr>
<tr>
<td>AF1</td>
<td>$-155.1 \pm 12.4$ (22.5 ± 1.8)</td>
<td>$-117.9 \pm 12.4$ (17.1 ± 1.8)</td>
</tr>
<tr>
<td>AF2</td>
<td>$-65.5 \pm 8.3$ (-9.5 ± 1.2)</td>
<td>$-42.7 \pm 10.3$ (-6.2 ± 1.5)</td>
</tr>
<tr>
<td>AF3</td>
<td>$-141.3 \pm 13.8$ (-20.5 ± 2.0)</td>
<td>$-131.7 \pm 13.1$ (-19.1 ± 1.9)</td>
</tr>
<tr>
<td>AF4</td>
<td>$-118.6 \pm 13.8$ (-17.2 ± 2.0)</td>
<td>$-115.8 \pm 15.2$ (-16.8 ± 2.2)</td>
</tr>
<tr>
<td>AF5</td>
<td>$-33.1 \pm 7.6$ (-4.8 ± 1.1)</td>
<td>$-19.3 \pm 9.7$ (-2.8 ± 1.4)</td>
</tr>
<tr>
<td>AF6</td>
<td>$-217.9 \pm 13.1$ (-31.6 ± 1.9)</td>
<td>$-113.1 \pm 12.4$ (-16.4 ± 1.8)</td>
</tr>
<tr>
<td>AF7</td>
<td>$-237.9 \pm 13.8$ (-34.5 ± 2.0)</td>
<td>$-157.2 \pm 13.8$ (-22.8 ± 2.0)</td>
</tr>
<tr>
<td>AF8</td>
<td>$-219.3 \pm 9.7$ (-31.8 ± 1.4)</td>
<td>$-180.0 \pm 14.5$ (-26.1 ± 2.1)</td>
</tr>
<tr>
<td>AF9</td>
<td>$-164.9 \pm 15.9$ (-23.9 ± 2.3)</td>
<td>$-64.1 \pm 14.5$ (-9.3 ± 2.1)</td>
</tr>
<tr>
<td>AF10</td>
<td>$-271.0 \pm 20.7$ (-39.3 ± 3.0)</td>
<td>$-153.1 \pm 11.7$ (-22.2 ± 1.7)</td>
</tr>
<tr>
<td>AF11</td>
<td>$-286.8 \pm 23.4$ (-41.6 ± 3.4)</td>
<td>$-214.4 \pm 12.4$ (-31.1 ± 1.8)</td>
</tr>
<tr>
<td>AF12</td>
<td>$-285.5 \pm 16.5$ (-14.4 ± 2.4)</td>
<td>$-217.9 \pm 14.5$ (-31.6 ± 2.1)</td>
</tr>
<tr>
<td>AF13</td>
<td>$-204.8 \pm 15.9$ (-29.7 ± 2.3)</td>
<td>$-120.7 \pm 13.8$ (-17.5 ± 2.0)</td>
</tr>
<tr>
<td>AF14</td>
<td>$-318.5 \pm 17.9$ (-46.2 ± 2.6)</td>
<td>$-208.9 \pm 15.9$ (-30.2 ± 2.3)</td>
</tr>
<tr>
<td>AF15</td>
<td>$-243.4 \pm 11.7$ (-35.3 ± 1.7)</td>
<td>$-191.0 \pm 8.3$ (-27.7 ± 1.2)</td>
</tr>
<tr>
<td>AF16</td>
<td>$-264.8 \pm 15.2$ (-38.4 ± 2.2)</td>
<td>$-208.2 \pm 9.7$ (-30.2 ± 1.4)</td>
</tr>
<tr>
<td>AF17</td>
<td>$-246.2 \pm 16.5$ (-35.7 ± 2.4)</td>
<td>$-153.8 \pm 13.1$ (-22.3 ± 1.9)</td>
</tr>
<tr>
<td>AF18</td>
<td>$-288.9 \pm 18.6$ (-41.9 ± 2.7)</td>
<td>$-167.5 \pm 28.3$ (-24.3 ± 4.1)</td>
</tr>
<tr>
<td>AF19</td>
<td>$-272.4 \pm 16.5$ (-39.5 ± 2.4)</td>
<td>$-201.3 \pm 17.2$ (-29.2 ± 2.5)</td>
</tr>
<tr>
<td>AF20</td>
<td>$-231.7 \pm 22.1$ (-33.6 ± 3.2)</td>
<td>$-222.7 \pm 22.8$ (-32.3 ± 3.3)</td>
</tr>
</tbody>
</table>
Figure 6. Samples AF1-AF5 Residual Stress and Peak Width Distribution

Figure 7. Samples AF6-AF10 Residual Stress and Peak Width Distribution
Circumferential Residual Stress (RS) and Full Width-Half Maximum (FWHM) from Cold-worked Holes AF11 - AF15

Figure 8. Samples AF11-AF15 Residual Stress and Peak Width Distribution

Circumferential Residual Stress (RS) and Full Width-Half Maximum (FWHM) from Cold-worked Holes AF16 - AF20

Figure 9. Samples AF16-AF20 Residual Stress and Peak Width Distribution

DISCUSSION

Compressive residual stresses are generally associated with extended fatigue life. These stresses, however, must extend beneath the surface to be effective. Superficial compressive residual stresses can be negated by tensile stress spikes just beneath the surface if the surface stress fades or if a small crack or defect penetrates into the tensile region. For these reasons, methods that

impart a significant compressive layer beneath the surface or around a hole are important for improving fatigue life.

X-ray diffraction can non-destructively measure surface stresses. This technique, however, effectively measures stresses in the top few atomic layers of a material. Residual stresses, by definition, are calculated from the elastic strains measured. The diffraction peak width indicates the amount of plastic strain in the part. Coupling surface residual stresses and diffraction peak width can provide information about the effective layer of compressive stresses.

The shot peening study showed that deeper compressive stresses were regularly associated with the higher intensity shot peening. The exceptions were on the Ti 6-4 A-scale intensity samples and the 7075-T73 aluminum samples. For the Ti 6-4 samples, the V1-11.5A shot peening intensity produced a slightly greater residual compressive stress with depth than the V2-14A intensity. And for the 7075-T73 aluminum, the compressive stress in the V2-12A intensity sample was similar but not greater than the V2-10A sample. Although the number of samples tested was small, vendor shot peen processing differences may be the reason these particular samples did not follow the general trend.

The cold-worked holes study showed higher compressive stresses for the samples that were more heavily cold worked. The magnitude of the compressive stresses was greater away from the hole edge for the samples that had a higher level of cold working. Based solely on residual stresses, the two groups that had the highest amount of cold working were similar. Only when the peak width was compared to the residual stress level at all measured distances from the hole was it possible to determine which samples had the maximum amount of cold working.

Assuming that the cold-worked hole samples represented four distinct levels of cold working indicates scatter in the data among the five samples in each group. This scatter is attributed to a combination of the processing and the x-ray diffraction measurements. Processing variables could include non-uniformity in 1) the metallurgy of the blank samples, 2) the drilling and preparation of the hole, and 3) the hole expansion technique. Furthermore, the cold expansion variability is related to the tolerances in starting hole diameter (±0.0015"), sleeve thickness (–0.0 + 0.006") and major diameter of the mandrel (±0.002"). The split sleeve mandrel cold expansion process is designed to give a minimum required level of expansion.

X-ray diffraction residual stress theory assumes that samples have a fine-grained, randomly oriented structure. This condition is rarely found in engineered materials although many materials can be precisely measured if the degree of preferred orientation is low and the structure is relatively fine-grained. The presence of larger grains, preferred orientation, and stress gradients produce non-linear d-spacing versus sin^2 ψ plots. This non-linearity can be translated into measurement uncertainty. In this study, measurement uncertainty ranged from 6.9 to 28.3 MPa (1.0 to 4.1 ksi). Since all reported stress values were calculated from the measured data using the same x-ray elastic constant, this parameter was not considered in the error analysis although it may be the largest source of measurement inaccuracy.

7 Private communication with Michael Landy of Stresswave, Inc.
Aluminum alloys have a face-centered cubic structure. Preferred orientation and/or larger grains often occur based on the processing employed in manufacturing components. These properties, in turn, may affect the uniformity of the plastic strain that results from cold expansion. These factors also affect the uncertainty in x-ray diffraction measurements. If one assumes that the samples with no cold working were uniformly processed, then x-ray diffraction would be the largest source of uncertainty. Experience indicates, however, that introducing a hole into a component may not always result in uniform stresses around the hole. Although care was taken to make measurements at the same distance from the edge of the hole, the exact location of the measurements is another potential source of error especially with the presence of stress gradients extending in a radial direction from the hole. Consideration of all the above factors makes it difficult to quantify the uncertainty of the measurements and rank the sources of error.

Furthermore, no mathematical models were developed during this study. The rankings of the samples were subjectively made by grouping them according to stress level at the edge of the hole, the persistence of the compressive stresses away from the hole, and the diffraction peak width. Additional studies are recommended to 1) quantify sources of error and 2) develop mathematical models to objectively rank cold-worked holes based on elastic and plastic strains.

CONCLUSION

Shot peening a sample or cold working a hole in a sample imparts compressive stresses in the sample. These plastic deformation processes increase the diffraction peak width relative to the amount of the plastic deformation. The XRD technique nondestructively measures elastic (residual stress) and plastic (diffraction peak width) strains at the surface of a sample. When the level of residual stress is compared to the peak width, the depth of compressive stresses can be qualified.