Reversed-bending fatigue tests of quenched and tempered AISI 6150 steel were conducted in dry air and in aqueous 3 pct NaCl. The 3 pct NaCl environment drastically reduced fatigue life but two different shot peening treatments were found to improve the corrosion fatigue life over that of unpeened samples. Multiple fatigue crack initiation occurred at very distinct locations in both the unpeened and the peened specimens fatigued in 3 pct NaCl. Fatigue crack propagation from each initiation site occurred first on flat facets normal to the stress axis and then by a more ductile mechanism after the initiation facets had linked. The average size of the corrosion fatigue initiation facets in the peened specimens was much smaller than that of the unpeened specimens; however, the number of initiation sites was greater in the peened specimens. It is believed that the beneficial effect of the shot peening results from significantly reduced early fatigue crack propagation rates in the compressive residual stress layer at the surface.

In an effort to improve the corrosion fatigue performance of metals, a number of material treatments have been extensively investigated including various heat treatments and metallic coatings. However, although the beneficial effects of shot peening on fatigue performance in a benign environment are well known, such treatment has received only limited attention in connection with corrosion fatigue.

The purpose of the investigation described in this paper was to determine the effects of two different shot peening treatments on the corrosion fatigue behavior of a quenched and tempered low-alloy steel in an aqueous 3 pct NaCl environment. The steel chosen for study (AISI 6150) is one which commonly sees service in high-strength suspension components subjected both to fatigue loading and corrosive environments.

EXPERIMENTAL PROCEDURE

All fatigue tests were conducted in constant amplitude deflection, completely reversed bending at 1800 cycles per min. The round-bar specimen geometry is shown in Fig. 1.

The specimens were surrounded by a cylindrical environment chamber at the critical (reduced) part of their length. The cell enclosure was machined from 50.8 mm diam cast acrylic rod into two cylindrical halves which were joined by gum rubber tubing to allow the cell to flex with the specimen under the bending fatigue loading.

As summarized in Table I, corrosion fatigue tests were conducted on samples shot peened to two different intensities and on unpeened samples in an aerated, aqueous 3 pct NaCl (by weight) solution. For comparison, unpeened samples were also tested in air with less than three ppm moisture content. The NaCl solution (7.5 liters total volume) was circulated through the environmental chamber at a flow rate of 5 liters per h by the use of a gas lift pump activated by compressed air.

All specimens were machined from AISI 6150 low-alloy steel round bar stock of 9.5 mm nominal diam, the composition of which is shown in Table II. After the specimens were machined to the specifications in Fig. 1, they were rough polished with 60 grit emery paper to remove all of the machining marks in the reduced section. Following standard practice, the specimens were austenitized for one h in neutral salt at 866°C and quenched in oil to give a microstructure of 100 pct martensite. They were then tempered at 371°C for one h which resulted in a fine, tempered martensite microstructure with a hardness of Rc 47.5. The salt scale left on the specimens after tempering was removed by a two min pickling treatment in 5 pct (by volume) nitric acid at 90°C. The specimens which were to be tested in the unpeened condition were then polished through 120 grit emery paper with the last marks made parallel to the longitudinal specimen direction. The specimens which were to be

![Fig. 1—Machined specimen geometry (dimensions are in mm).](image)
Table II. Composition of the Steel Tested (AISI 6150)

<table>
<thead>
<tr>
<th>Element</th>
<th>Pct by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.006</td>
</tr>
<tr>
<td>Total Carbon</td>
<td>0.50</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.94</td>
</tr>
<tr>
<td>Copper</td>
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</tr>
<tr>
<td>Manganese</td>
<td>3.85</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.06</td>
</tr>
<tr>
<td>Nickel</td>
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</tr>
<tr>
<td>Phosphorus</td>
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</tr>
<tr>
<td>Silicon</td>
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</tr>
<tr>
<td>Sulfur</td>
<td>0.012</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Table III. Shot Peening Treatments

<table>
<thead>
<tr>
<th>Almen Intensity</th>
<th>Cast Shot Size</th>
<th>Coverage</th>
<th>Estimate of Maximum Compressive Residual Stress*</th>
<th>Estimate of Depth of Compressive Layer*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.020-0.022 A</td>
<td>MI-460</td>
<td>100 pct Minimum</td>
<td>793 MPa</td>
<td>0.150-0.41 mm</td>
</tr>
<tr>
<td>0.008-0.010 C</td>
<td>MI-660</td>
<td>100 pct Minimum</td>
<td>993 MPa</td>
<td>0.51-0.61 mm</td>
</tr>
</tbody>
</table>

*Estimated from the material properties and shot peening conditions according to Ref. 27.

tested in the peened condition were not polished after heat treatment but were shot peened to either 0.020 to 0.022 A or 0.008 to 0.010 C Almen intensities as described in Table III.

Just prior to testing, each unpeened specimen was degreased in benzene, pickled in 5 pct (by volume) nitric acid for two min at 90°C to remove the cold-worked surface, and then washed successively in water, acetone, and benzene. This treatment, as well as the polishing steps, the basic specimen configuration, and the testing frequency were used previously by Duquette and Uhlig and Lee and Uhlig. The peened specimens were washed successively in benzene, acetone, and benzene just prior to testing.

RESULTS

The fatigue data resulting from the testing of forty-four specimens is shown in the form of S-N curves in Fig. 2. In keeping with the usual behavior of steels, the dry-air tests of unpeened specimens produced a sharp-kneed S-N curve with a well-defined fatigue limit. As shown, the effect of the 3 pct NaCl solution on the fatigue life of the unpeened specimens was severe and removed all evidence of a fatigue limit.

Both shot peening intensities investigated were effective in increasing the fatigue life of the specimens in 3 pct NaCl. However, as was the case with the unpeened specimens, there was no fatigue limit with the peened samples in the NaCl environment. Each shot peening treatment had about the same effect on the fatigue lifetime.

At the higher stresses considered here, peened specimens had fatigue lives about three times as long as unpeened specimens in 3 pct NaCl; as the test stress decreased the advantage gained by peening increased. At the lower stresses, peened specimens had lives up to ten times longer than unpeened specimens in the same corrosive environment. As noted previously, in neither case was an endurance limit observed.

The specimens fatigued in dry air had no visible corrosion on their surface after testing. On all specimens fatigued in 3 pct NaCl corrosion was apparent, particularly at the reduced section of the specimens where the stress was the greatest. At the reduced section the corrosion appeared to be most concentrated at the top and bottom (180 deg apart) of the specimens as mounted on the fatigue machine. These positions correspond to the regions of highest stress during bending.

At any given test stress the extent of corrosion visible on the peened specimens was independent of the peening treatment. For specimens which had about the same lifetime in 3 pct NaCl, the peened specimens exhibited more severe surface corrosion than did the unpeened specimens. In such cases, of course, the peened specimens had been subjected to a higher stress amplitude.

![Fig. 2—Experimental data.](image1)

![Fig. 3—Macrofractograph of a typical unpeened specimen fatigued in dry air. Fatigue crack growth is from top to bottom.](image2)
Figure 3 is a macrofractograph of an unpeened specimen fatigued in dry-air. Fatigue initiation is at the top of the fracture surface. All of the fractured dry-air specimens exhibited a similar single fatigue area at the top and/or bottom of the fracture surface where the bending stresses were the greatest during testing. Figure 4 is an SEM fractograph of the fatigue area of Fig. 3 showing that fatigue crack growth was transgranular and ductile.

A low-power SEM fractograph of a typical unpeened specimen fatigued in 3 pct NaCl is shown in Fig. 5. The area shown is from the bottom of the specimen where the bending stresses were high. Three distinct corrosion fatigue initiation areas are visible, each lying on a different plane approximately perpendicular to the specimen surface. Such multiple initiation behavior has been previously observed and discussed in the literature in connection with corrosion fatigue of nonpeened samples. Also, as is common in corrosion fatigue, the unpeened specimens fatigued in 3 pct NaCl showed numerous small cracks the fatigue growth of which had been retarded or stopped because of stress shielding by the main crack, i.e. by a reduction in stress intensity factor due to interaction with larger cracks on parallel planes.

A higher-magnification SEM fractograph of the flat corrosion fatigue initiation area visible to the left in Fig. 5 is shown in Fig. 6. Comparison of Fig. 6 with Fig. 4 shows that fatigue crack growth within the initiation facets was much less ductile than was propagation in the standard dry-air samples. However, outside of the early-growth (microcrack) regions the fatigue fracture surfaces from the corrosive and dry-air environments appear quite similar. Figure 5 also shows secondary cracking on the fracture surface which was characteristic of unpeened specimens fatigued in 3 pct NaCl.

Fig. 6—Higher-magnification SEM fractograph of the corrosion fatigue initiation facet shown to the left in Fig. 5 (nominal crack growth from bottom to top).

Fig. 7—Low-power SEM fractograph of a peened specimen (0.020 to 0.022 A Almen intensity) fatigued in 3 pct NaCl. Note the large number of initiation facets (nominal crack growth from top to bottom).
DISCUSSION

Almen reported that the beneficial effect of shot peening on bending fatigue strength in air increases to a maximum as the shot peening intensity increases up to an optimum value \( (i_0) \) as indicated schematically in Fig. 9. As the intensity increases beyond the optimum value, the peening has less beneficial effect and eventually contributes adversely to the fatigue strength. A peening treatment with an intensity greater than \( i_0 \) in Fig. 9 produces such a deep surface layer of residual compressive stress that the required balancing residual tensile stress in the interior grows to a harmful magnitude. As a result, fatigue failures initiate in the interior. A well-preserved fracture surface of a specimen subjected to a peening treatment of intensity greater than \( i_0 \) should indicate that the fatigue failure initiated at a point below the surface. Presumably, such an initiation mode would not be sensitive to the specimen environment.

In the present study the shot peening treatment of 0.008 to 0.010 C Almen intensity was significantly more intense than the treatment of 0.020 to 0.022 A Almen intensity (see Table III), yet both had about the same effect on fatigue life in 3 pct NaCl. It might be concluded that the two treatments lie on opposite sides of \( i_0 \) on the curve in Fig. 9, with 0.020 to 0.022 A on the left and 0.008 to 0.010 C on the right. However, inspection of fractured specimens which had been peened with the 0.008 to 0.010 C treatment yielded no obvious evidence of subsurface initiation. A possible explanation is that Fig. 9 is simply not applicable to fatigue in a corrosive environment since, where corrosion fatigue is involved, factors other than stress distribution may play an important role. For example, as peening intensity increases, surface deformation and surface corrosion activity are also increased and crack initiation may be facilitated even though the deeper compressive residual stress would inhibit early fatigue crack growth. The resultant fatigue lifetime is a function of these competing factors.

In general corrosion fatigue fracture can be divided into stages of fatigue crack initiation, micro- and macro-fatigue crack propagation, and final fast-fracture, each of which may be affected differently by the environment. As the fatigue stress decreases, a larger percentage of the total fatigue life is involved with initiation. Thus, since peening increased the corrosion fatigue lifetime more at the lower stresses it might be suspected that peening has an inhibiting effect on crack initiation. However, the fractographs which were previously described do not support this explanation. Rather, the residual compressive stress near the surface which resulted from peening must have decreased the early (micro) fatigue crack propagation rates. This early crack propagation which occurs immediately after initiation is closely related to initiation on a fracture time scale but is a distinctly separate process. Similarly, Burck, Sullivan, and...
Wells observed dramatically reduced early crack propagation rates in glass-bead peened nickel-base superalloy specimens tested in air but as the cracks grew larger the propagation rates quickly approached those of unpeened samples. They concluded that an increase in the fatigue life of the peened specimens was due primarily to the inhibition of early crack propagation by the large compressive residual stress at the surface and not to a suppression of crack initiation. In the present case the absence of an endurance limit for the peened samples in NaCl, together with the large number of fatigue crack initiation sites and secondary fatigue cracks, is evidence of a similar phenomenon.

Shot peening produces not only a compressive residual stress at the surface but also a layer of highly cold worked material, the effects of which must be considered with respect to corrosion fatigue behavior. Although uniform cold working usually increases the fatigue strengths of steels in benign environments, it has little, if any, benefit in corrosion fatigue. Similarly, martensitic strengthening of steels is not effective in increasing the corrosion fatigue lifetime. In particular, McAdam found that a chromium-vanadium spring steel, which was quite similar to the AISI 6150 steel of the present study, had a slightly longer fatigue lifetime in fresh water when fully annealed than when hardened to almost twice the annealed tensile strength. Thus, in the present case it is believed that the beneficial effects of shot peening on corrosion fatigue lifetime derive exclusively from the compressive residual stress at the surface. Similar effects have been reported for nitrided surfaces which are also in residual compression although the general surface corrosion rate is also decreased in nitrided samples. The greater number of crack initiation sites for the peened as compared to the unpeened samples in NaCl solution is attributed to two factors. First, the cold worked, damaged, high residual stress surface layer of the peened material is more susceptible to corrosive attack and thus to crack initiation and, secondly, the compressive residual stresses from peening significantly retard the fatigue crack growth rates during the very early stages of propagation, thus allowing more time for additional fatigue cracks to initiate before stress shielding by a major crack occurs. The retardation of early fatigue crack growth rates in the peened samples also accounts for the increased fatigue lives of the peened specimens in spite of their apparently decreased resistance to surface corrosion and fatigue crack initiation.

The secondary cracks evident on the initiation facet of the corrosion fatigue shot peened sample of Fig. 8 are quite different from the branch cracks observed in the corrosion fatigue areas of unpeened specimens. The cracks of Fig. 8 are most likely the result of the slow initial crack propagation rate in the peened specimens. Such a slow crack propagation rate, which is a consequence of the compressive residual stress, would subject highly stressed crack tip elements to the environment for a long period of time. In the unpeened specimens tested in 3 pct NaCl, the material in the crack-tip region is replaced more rapidly due to the faster crack propagation rate. Also, as mentioned previously, the cold-worked surface of the peened specimens led to increased corrosion activity. The total effect of these factors was to increase the environmentally assisted component of the fracture process relative to the environment insensitive component in the peened specimens.

The distinct transition in corrosion fatigue crack propagation mode which occurs after the initiation facets have linked apparently corresponds to a critical stress intensity factor range or, equivalently, to a critical crack growth rate. When the individual initiation facets link, there is a rather sudden increase in stress intensity factor because of the geometrical change from several individual penny cracks to a single edge crack. Because shot peening results in more corrosion fatigue crack initiation sites, the initiation facets are more closely spaced, and therefore smaller, when linking occurs. Thus, the transition to the more ductile fatigue crack growth mode occurs at shallower crack depths in the peened specimens than in the unpeened samples. Despite this behavior, peening increases corrosion fatigue lifetimes because the growth rates of the facets are sufficiently reduced in the compressive surface layer before linking occurs.

CONCLUSIONS

A 3 pct NaCl environment drastically reduced the fatigue lives of unpeened AISI 6150 steel specimens. Two shot peening treatments of different Almen intensity (0.020 to 0.022 A and 0.008 to 0.010 C) increased fatigue life in 3 pct NaCl by a factor of from three to ten depending on test stress. Although there was a large difference in peening intensity, both treatments had about the same effect on corrosion fatigue lifetime. No evidence of a fatigue limit in the 3 pct NaCl environment was observed for either unpeened or peened specimens.

The fracture surfaces of dry-air-tested specimens exhibited single fatigue crack initiation sites. The fracture surfaces of unpeened specimens fatigued in 3 pct NaCl had fracture surfaces which featured three to five flat corrosion fatigue initiation sites and/or secondary surface cracks which also indicated multiple crack initiation. The fracture surfaces of all of the peened specimens (both treatments) exhibited ten to twenty flat corrosion fatigue initiation facets for each major fatigue crack. These initiation areas were much smaller, although more numerous, than those observed on the unpeened specimens fatigued in 3 pct NaCl.

The peening treatments did not appear to hinder the initiation of corrosion fatigue cracks. Rather, the increase in corrosion fatigue lifetime exhibited by the peened specimens is attributed to a reduced early fatigue crack propagation rate in the surface compressive residual stress layer.

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