The Fatigue Resistance of Plasma and Oxygen Cut Steel

The fatigue resistance of A572 steel flame-cut surfaces is greater than for A514 steel at lives greater than $2 \times 10^5$ cycles but less at lives under $10^6$ cycles.

BY N-J HO, F. V. LAWRENCE, JR., AND C. J. ALTSTETTER

ABSTRACT. Oxygen-cut specimens of controlled roughness, of gouges, and of gouges repaired by welding and by grinding were prepared for low-alloy, high-strength steel (ASTM A572) and quenched and tempered steel (ASTM A514). A572 plasma-cut specimens were also prepared. Load-controlled fatigue tests were performed using a compression-to-tension stress cycle ($R = -1$). Subsurface microstructures were characterized by metallography and by micro-hardness measurements.

The fatigue resistance of the flame-cut surface was greater for A572 than for A514 at lives greater than $2 \times 10^6$ cycles. For A572 steel, the fatigue lives were found to be somewhat different from specimens having different cutting methods. For A514 steel, the machined surfaces were superior at lives greater than $10^6$ cycles. Heat treatment of the A514 flame-cut surfaces did not much improve their fatigue resistance.

Small gouges on the cut surface were found to have negligible influence on the fatigue resistance compared with the flame-cut surface. However, deeper gouges had a large negative influence on the fatigue resistance: gouges repaired by welding did not have any better fatigue resistance. Grinding out the gouges did not improve the fatigue resistance of the A572 welds.

Introduction

Influence of Oxygen Cutting on Fatigue

Oxygen cutting and plasma-arc cutting have been widely used in industry because they are inexpensive, fast methods of cutting complex shapes from plate stock. In oxygen cutting a preheat flame precedes the oxygen jet, but the major heat input is due to oxidation of the metal. Proper cutting conditions—suitable preheat flame, cutting flame and cutting speed—depend on the gas pressure, nozzle type and type of gas. In plasma-arc cutting, the heat is supplied by a jet of superheated nitrogen or argon-plasma which impinges on the metal. The fatigue properties of oxygen-cut surfaces may be altered as a result of changes in chemical composition, microstructure, residual stress and geometrical features such as roughness, gouges, drag lines and melted edges.

Several investigations on the effect of flame cutting (Ref. 1-5) have shown that the fatigue resistance and other properties of cut surfaces are quite variable due to the use of different materials and cutting conditions. Only the resulting surface roughness has been systematically controlled. The fatigue resistance of the oxygen-cut surface has been found to be strongly influenced by roughness, and differences of as much as an order of magnitude in life have been found between rough and smooth surfaces at the lowest stress levels (Ref. 3).

In practice, flame-cut surfaces of very little or very great roughness are not usual, since they are neither practical nor economical. A reasonably good commercial product might average 0.005 in. (0.13 mm) peak to valley. However, large gouges produced by blow-out, lateral torch instability, etc., are often encountered; these defects may drastically lower the fatigue resistance. When gouges are encountered, the alternatives are: rejection of the gouged part, grinding the gouge to smooth and remove the sharp notch, filling the gouge with weld metal, or leaving the gouge as is. The effectiveness of each of these alternatives is not clear.

Scope of Investigation

The principal objective of the present paper was to evaluate the effect of oxygen cutting on the fatigue resistance of industrially important steels. High-strength, low alloy (ASTM A 572) and quenched-and-tempered (ASTM A 514) steels were investigated at intermediate lives (less than $10^6$ cycles). Surface roughness was controlled to 0.0054 ± 0.0010 in. (0.14 ± 0.025 mm), peak to valley, in order to compare the fatigue resistance of different steels and different cutting methods at the same surface roughness. Surface gouges of various depths were introduced into specimens and were either left as formed, ground off, or filled with weld metal to examine the influence of such conditions on the fatigue resistance.

The fatigue behavior of oxygen-cut specimens was compared with that of plasma-cut specimens and specimens having machined test surfaces. Several tests were performed on specimens heat treated after oxygen cutting. The microstructures and hardness profiles were determined for each steel and cutting method.

Experimental Procedures

Two structural steels—one comparable to ASTM A572 grade 42 (0.22% max. carbon, 42 ksi min. yield strength), and a

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<th>Table 1—Chemical Composition, Wt.-% (a)</th>
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<td>C</td>
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(a) Composition supplied by manufacturer.

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<th>Table 2—Mechanical Properties</th>
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<tr>
<td>$S_y$, ksi</td>
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<td>$S_m$, ksi</td>
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quenched-and-tempered steel which conformed to ASTM A514 grade C (0.20% max. carbon, 0.005% max. boron, 100 ksi min. yield strength) — were obtained as 1 in. (25.4 mm) thick plates. The chemical composition and the mechanical properties of these steels are given in Tables 1 and 2. The series of test specimens that were prepared is shown in Table 3.

All specimens were cut with the loading direction perpendicular to the rolling direction. Specimens of series 1 to 4 were cut to the dimensions shown in Fig. 1. Because of the gougles, the specimens of series 5 to 7 were cut to the dimensions shown in Fig. 2. Specimens of series 2 and 3 were flame cut from blanks by moving them beneath a cutting torch which was oscillated at constant amplitude (0.0054 in., i.e., 0.14 mm, peak to valley) and at a constant frequency by a cam mechanism (Ref. 3). The cutting parameters (Table 4) were carefully controlled to minimize resolidification deposits on the melted edge (Ref. 3). A torch tip to metal separation of 0.25 in. to 0.5 in. (6.4-12.7 mm) was used. After cutting most specimens, the hot-rolled surfaces were machined to a 0.01 in. (0.25 mm) depth keeping the tool marks parallel to the loading direction. Series 3 was subsequently heat treated to obtain the same microstructure and hardness as the quenched-and-tempered steel throughout its thickness. Specimens in series 4 were plasma-arc cut by Caterpillar Tractor Co. using a nitrogen plasma gas and a cutting speed of 30 ipm (12.7 mm/s). Half of these specimens had their hot-rolled surfaces removed by machining.

For Series 5, gougles of various depths were made by suddenly moving the torch laterally or letting a thin sheet of steel pass through the cutting jet. The cutting conditions were the same as series 2 and 3 except that the torch was not continuously oscillated. In series 6, the gougles were cleaned and repaired by welding using E6013 covered electrodes for A572 and E11018 covered electrodes for A514 and then milled smooth. Specimens of series 7 had the gouges removed by grinding them to a generous radius (3 in., i.e., 76.2 mm), to a depth just sufficient to remove the gouge. All cut surfaces were brushed by hand before surface contour profiling and testing. The contour of the flame-cut surface and gouge of each specimen was measured using an LVDT profilometer (Ref. 3) with a tungsten carbide stylus inclined 30 deg from the normal surface. Profile traces (Fig. 3) were recorded at the upper edge, midthickness and lower edge to determine if the specimens were within tolerance (0.0054 ± 0.0010 in. peak to valley average roughness).

Selected specimens of each series were sectioned and mounted for optical metallography. Microhardness profiles were determined using a Vickers indenter and a 100 g load. Fatigue test specimens were mounted in an MTS machine with self-aligning grips and were fatigued using a compression-to-tension stress cycle \((R = -1)\) under load control at 3-5 Hz. After fatigue testing, the fracture surfaces were examined with a scanning electron microscopy (SEM).

Results

Metallography and Microhardness

Flame cutting produces an altered microstructure and variations in microhardness. All flame-cut specimens had a large heat-affected zone at the torch (upper) side of the specimens due to the larger heat input from the cutting nozzle. The heat-affected zones of the upper edges are two to three times deeper than those of the lower (bottom) edges of the specimens.

A572 Flame-Cut Specimens. The microstructures at the midthickness of the flame-cut surface resemble those reported by Goldberg (Ref. 4) and the Netherlands Group (Ref. 5). At the cut surface, a 25-50 \(\mu\)m thick carbon-enriched zone consisted of spots of ledeburite on top of a thin layer of pearlite, followed by plate martensite, mixed with retained austenite.

The plate martensite and retained austenite were always formed at the surface of the root of serrations behind the cutting flame. The hardness of the plate martensite and retained austenite mixture was over 800 VHN (Fig. 4). The fine pearlite under the ledeburite was around 500-450 VHN (not apparent in Fig. 4). The microstructure at the peak of the serration due to cutting consisted mainly of various amounts of fine pearlite growing at austenite boundaries with ledeburite spots at the tip of the serration. Below the fusion line to a depth of 0.5 mm (0.02 in.) was a zone containing lath martensite and/or bainite. To a depth of 0.4 mm (0.016 in.) below this zone was an inhomogeneous mixture of pearlite and fine ferrite. At an additional depth of 0.4 mm (0.016 in.) a subcritical heat-affected zone consisted of partially spheroidized pearlite and ferrite. Finally, original pearlite and ferrite substructure was found.

A572 Plasma-Arc Cut Specimens. The microstructure of the plasma-arc cut surface at the lower edge is different from that of oxygen-cut specimens. There was no evidence of selective oxidation or carburization produced by a plasma gas jet. There was no hard carburized layer to be seen.

At the cut surface, there was a martensite matrix to a depth of 0.3 mm (0.012 mm) below the surface. However, within this zone, the martensite at the cut surface was less hard than that below the
cut surface (Fig. 5). This effect may be due to loss of carbon from the molten material. Under the martensite matrix zone was a fine ferrite plus high carbon austenite. Beyond this was ferrite and very small spheroidized pearlite adjacent to the original pearlite-ferrite structure.

A514 Flame-Cut Specimens. At the midthickness of the cut surface, the microstructure and microhardness (Fig. 6) for the A514 oxygen-cut specimens was similar to the A572 oxygen-cut specimens. Ledgeubrite, plate martensite, retained austenite and pearlite at the cut surface, and lath martensite matrix zone below the fusion line were found. They extended to a 0.5 mm (0.02 mm) depth.

For the A572 steel, a hard layer and high carbon region were found. Further below was coarse-grain tempered martensite, then there was a layer of many small pearlite nodules spreading at the grain boundaries. This coincided with the abrupt drop of microhardness (see Fig. 6) and probably represents the intercritical heat-affected zone.

A514 Quenched-and-Tempered After Cutting Specimens. There was a straight boundary between light and dark-etching regions beneath the cut surface. This straight boundary was believed identical to the fusion line seen on the as-cut surfaces. Within the light region at the top there were many spheroidized fine carbides suggesting that carbon was picked up during cutting and was spheroidized upon subsequent heat treatment.

Fatigue Test Results

The results of the fatigue tests are plotted in S-N diagrams, Figs. 7 to 11. Some specimens failed at undesired locations and hence were not included in the S-N diagrams. The lines in Figs. 7 to 11 were fitted to the test data using the least-squares method.

Discussion

Fatigue Crack Initiation Sites

Fatigue crack initiation of the flame-cut A572 specimens occurred at the edge of the flame-cut surface. For the flame-cut A514 specimens, initiation occurred either close to the upper edge or at the midthickness of the cut surface. The A514 usually had multiple points of initiation. In A514 specimens, quenched-and-tempered after cutting, the fatigue cracks initiated at points on the flame-cut surface, mainly at the most severe notches.

All flame-cut surface failures were at the roots of serrations. It seems that geometry is more important than microstructure in determining the fatigue crack initiation site. For the plasma-arc cut A572 specimens, the fatigue crack initiation point was mainly at the upper edge, as Goldberg reported (Ref. 4). In those specimens with unground hot-rolled surfaces, the crack always initiated on the hot-rolled surfaces probably as a result of surface decarburization, rolling defects, or unfavorable residual stresses.

Influence of the Flame-Cut Surface Roughness

The geometry or surface roughness of the flame-cut surface is one of the important factors which control fatigue resistance. A model for the effect of the flame-cut surface was developed by assuming that surface contour can be approximated as a series of notches (Ref. 3). The fatigue notch factor Kf is defined as the ratio of fatigue strength of unnotched to notched specimens at long lives and is usually less than the theoretical stress concentration factor Kt (which is defined as the ratio of the maximum longitudinal stress at the tip of the notch to the average, remote stress) because of plasticity effects. Peterson (Ref. 6) found that these effects can be empirically accounted for by the relationship:

$$K_f = 1 + K_t - 1 \left[ \frac{1}{1 + 2a} \right]$$  \hspace{1cm} (1)

where $r$ = radius of the notch; $a$ = material property.

For steel, the value (a) can be related to the ultimate strength $(S_u)$:

$$a = 0.001(300/S_u)^{1.8}$$  \hspace{1cm} (2)
Fig. 5—Microhardness at the lower edge of A572 plasma-cut steel

Table 4—Oxygen Cutting Parameters for 1 in. Steel Plate Using Propylene Gas

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<thead>
<tr>
<th>Material</th>
<th>Gas pressures, psig:</th>
<th>Preheat oxygen</th>
<th>Cutting oxygen</th>
<th>Average cutting speed, ipm</th>
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<tr>
<td>A572</td>
<td>3.5</td>
<td>6</td>
<td>48</td>
<td>14</td>
</tr>
<tr>
<td>A514</td>
<td>4.5</td>
<td>7</td>
<td>50</td>
<td>14</td>
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Cutting tip = "Oweswell 14238." (a) Estimated from hardness measurements averaged from surface to 0.1 mm (0.01 mm) depth. (b) From tensile test. (c) Averaged values.

where \( (S_w) \) is given in ksi and \( (a) \) is in inches.

As can be seen from the surface profiles of Fig. 3 and the idealizations of Fig. 12, the roughness of the surface may be approximated as a series of semicircular notches (even though the notches more nearly resemble semicircular notches). Unfortunately, the \( K_f \) of a series of semicircular notches is not available. The \( K_f \) for a single elliptical notch is:

\[
K_f = 1 + 2 \sqrt{D/(W/2)}
\]

where \( D \) = depth of the notch; \( W \) = width of the notch.

The \( K_f \) of a semicircular notch at the cut surface is smaller than that of a semicircular notch, because \( W \) is greater than \( D \), yet it was assumed that \( K_f \) for a series of semicircular notches will be the same as that found for semicircular notches. Using the model for a series of semicircular notches, \( K_f \) values were determined (Ref. 7) using average values of \( D \) and \( D/W \) for each group of specimens—Table 5.

Ultimate strength \( (S_u) \) values were estimated for each steel from hardness data. The fatigue notch factor, \( K_n \), was then calculated using eqs. (1) and (2). The values calculated are shown in Table 5 and compared with experimentally determined values. The machined specimen results were taken as the smooth specimen fatigue strength at the value of stress which caused failure in 10^6 cycles.

The close agreement in Table 5 between measured and calculated values of \( K_f \) for A514 suggests that the differences between machined and flame-cut results can be attributed to geometry and surface roughness effects alone. This is not the case with the A572 results. Possibly residual stress has had more influence on A572 than on A514.

Residual Stress

Surface residual stresses alter the mean stress which, in turn, greatly influences the fatigue crack initiation life. The stress amplitude, mean stress level and cycles to failure are related through the relation (Ref. 8):

\[
N_i = \frac{1}{b} \left( \frac{\sigma_i - \sigma_0}{\sigma_0} \right)^{1/b}
\]

where \( N_i \) = cycles to failure; \( \sigma_0 \) = stress amplitude; \( \sigma_0 \) = mean stress; \( b \) = fatigue strength exponent (negative value).

Compressive residual stresses reduce the mean stress level so that the fatigue life is longer, and the fatigue strength is higher. Tensile residual stresses shorten the fatigue life. The Netherlands Group (Ref. 5) showed this effect for flame-cut surfaces. However, these surface residual stresses only play important roles in the fatigue crack initiation, and are presumed to have little effect on the propagation stage due to large crack tip plasticity which eliminates any residual stress. The residual stresses on the flame-cut surface depend on cutting parameters in a very complicated way; even with the same cutting conditions, the residual stresses are never exactly the same from specimen to specimen.

The results of residual stress measurements by the Caterpillar Tractor Co. using x-ray diffraction methods indicated that the longitudinal residual stresses in one specimen of A572 steel were entirely compressive on the flame-cut surface, while in a specimen of A514 steel small tensile residual stresses were observed on one surface—Fig. 13. From eq. (4), the fatigue life of A514 should be less influenced by the residual stress than the A572 which has a smaller \( \sigma_0 \). These compressive residual stresses of the same level should have a stronger influence on A572 than on A514. This is thought to be the reason why the measured \( K_f \) value is smaller than that of the calculated \( K_f \) value for A572 steel.

The Effects of Gouges

Whether gouges have a strong influence on the fatigue strength depends on the gouge depth and the stress concentration factor caused by the gouge. The width of the gouge cannot be smaller than 0.125 in. (3.2 mm), the diameter of the cutting jet. Thus, it is difficult to make very sharp gouges by cutting. It is not practical or possible to make very deep gouges by suddenly moving the cutting nozzle laterally without losing cutting action.

For both steels investigated, small gouges (approximately less than 0.02 in., i.e. 0.51 mm, depth average) and some large gouges (0.06 in., i.e. 1.5 mm average) did not reduce the fatigue strength; failure initiated on the flame-cut or hot-rolled surfaces. For the A572 steel, only three specimens failed at gouges which had depths over 0.02 in. (0.51 mm) average; but in these cases, the fatigue strength was reduced only slightly compared with the flame-cut specimens of the same dimension without gouges. For A514 steel, only those specimens with gouge depths over 0.06 in. (1.5 mm) failed at the gouge. Other gouge specimens failed at the flame-cut surfaces and had fatigue lives very close to those of the flame-cut surface without a gouge.

Gouge-welded specimens of A572 steel which failed at the weld had somewhat poorer fatigue behavior than prepared gouged specimens (Fig. 8), yet
Comparison of Flame-Cut, Plasma-Cut and Machined Surfaces

As seen in Fig. 7 for A572 specimens with 1 in. (25.4 mm) width, there is only a small difference between the flame-cut, plasma-cut and machined surfaces. It seems that the plasma-cut surface has a smoother surface and a little higher fatigue resistance than the others. As seen in Fig. 10 for 2 in. (50.8 mm) wide gouge-ground specimens, failure always occurred at the flame-cut and hot-rolled surfaces. None of these failed on the ground surface (machined surface). It seems that the fatigue resistance of the flame-cut surface depends on the effects of residual stress, geometry and, to a minor extent, microstructural alteration.

Several specimens with the original hot-rolled surface failed at the surface. The fatigue results showed that the hot-rolled surface had the same fatigue resistance as a machined surface (Fig. 11). From this result, it would seem that it is not necessary to remove the hot-rolled surface.

The superiority of the A514 machined surfaces is seen in Fig. 9. Most of the flame-cut and quenched-and-tempered specimens failed at the flame-cut surface other than the machined surface on the lateral sides. However, all three types of surfaces give the same fatigue resistance at shorter lives ($10^4$ cycles). Comparing those of the A514 which failed at the weld roots had a poorer fatigue resistance than gouged specimens (Fig. 10). The reason for this is thought to be that, while repair welding the deeper gouges in the A514 steel, complex residual stresses may have been formed and weld defects such as lack-of-fusion and slag at the weld root were introduced.

Gouges could be repaired by grinding, too, if the gouge is not very deep. The results showed that grinding does not seem to have beneficial effects for the A572 steel.
Effects of Different Dimensions and Materials

In Fig. 14, the fatigue resistance of flame-cut specimens with different widths is shown. Wider specimens had a lower fatigue resistance for both steels. On the average, the fatigue strength was decreased 5 ksi for 2 in. (50.8 mm) wide specimens compared with the 1 in. (25.4 mm) wide. All specimens were in plane strain condition so that this effect may result from differences in residual stresses along the cut surface caused by different preheat and cooling rates for the different widths.

In Fig. 14, it is seen that A572 had higher fatigue resistance of the flame-cut surface than A514 beyond 2 X 10^6 cycles. Previous work (Ref. 3) also showed this tendency beyond 10^6 cycles for the smooth surface and beyond 2 X 10^5 cycles for the rough surface at stress ratio, R = 0. The A514 exhibited a greater notch sensitivity than A572.

Conclusions

1. For the A572 steel, the differences in the fatigue resistance resulting from different cutting methods are very small. For the A514 steel at lives greater than 1.5 X 10^6 cycles, the machined surface has greater fatigue resistance than the flame-cut and quenched-and-tempered (after cutting) surfaces. Heat treatment of the flame-cut surface does not much improve fatigue resistance.

2. The difference in fatigue resistance between flame-cut and small gouged surfaces is negligibly small for both steels. Big surface gouges have a negative influence on the fatigue resistance. Neither grinding nor repairing gouges by welding increases the fatigue resistance compared with the gouged surface for both steels.

3. At lives greater than 2 X 10^6 cycles, A572 flame-cut surfaces have greater fatigue resistance than A514, but at lives less than 10^5 cycles the fatigue resistance of A514 flame-cut surfaces is greater than that of A572.

Acknowledgments

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References