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Winter 2012

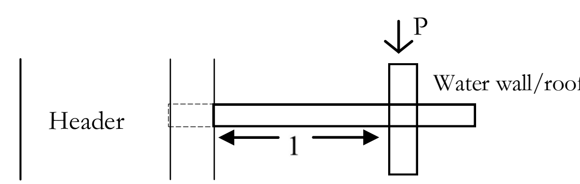
Signs of Aging in Old Boilers

Beginning at the initial start-up, boilers "age" until replacement is necessary at the "end of useful life" for individual components. However, not all components grow old together. If water chemistry control has been good, economizers usually last longer than radiant superheaters. The degradation process is caused by exposure to high temperature for the materials of construction to operate in the creep range, for thermal fatigue to be a significant degradation mechanism, and, of course, for microstructural changes to develop. For purposes of the present discussion, no wastage or wall thinning will occur; ignore fireside fuel ash corrosion, flyash or sootblower erosion, water/steam oxidation and corrosion. Wall thickness surveys will find these problems and tube replacements will be made as needed. Concurrent with microstructural changes are decreases in hardness, strength, and ductility. These changes include spheroidization of carbides in Cr-Mo steels, graphitization in carbon and C-Mo ferritic steels, and sigma phase formation and sensitization in austenitic stainless steels.

For high temperature SH and RH outlet headers, creep and thermal fatigue interact in a unique fashion, often called creep fatigue, at the stub tube-to-header welds toward the ends of the headers. For headers with steam temperatures below the creep range, simple thermal fatigue at these locations may develop. Differential expansion between the hotter header and cooler water walls leads to a deflection of the stub tubes between water walls and header. The bending or deflection is greatest at the ends of the header, assuming the expansion is symmetrical, about the mid-point in length.

The form of damage, creep fatigue or thermal fatigue, depends on the temperature of the individual stub tube. Microstructural analysis of the cracks is usually necessary to establish the cause. Not all tubes operate at the average steam temperature in the header. T-2 tubes in an intermediate header with a steam temperature of 850° F may be high enough to be in the creep range, even though at this temperature, they are not usually expected to fail by creep at Code allowable stress levels.

Estimate of the stresses imposed by differential expansion on the stub tube welds at or near the header may be calculated from simple beam theory. Assume the load on a flexible stub tube is a point at the water wall/roof penetration, thus:



and sigma phase, refer to **Figure 5**. The appearance of sigma phase suggests this pendant or end of several pendants may have operated above the design temperature of a fair portion of the 33 year service. It may also imply a U shape to the temperature distribution within the superheater (other pendants have to be examined to confirm). At the OD next to the weld metal and HAZ, are the expected intergranular creep or creep-fatigue cracks, Figure 6, the result of the combined tensile stresses (from bending and the DMW).

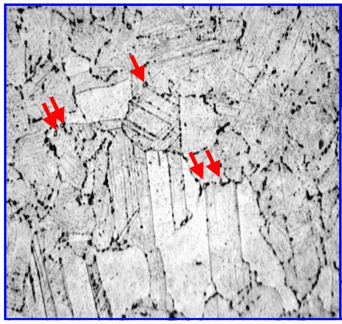


Figure 5 - The microstruture of the 321H is austenite, as expected. The grain boundaries are well covered with both carbides (sensitized) and sigma phase, the large black spots on the grain boundaries. 400x, etched

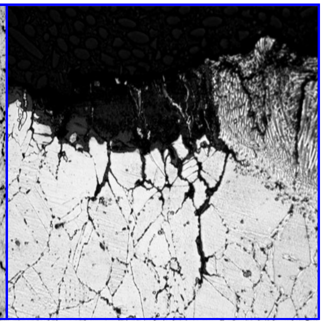


Figure 6 - The OD at the toe of the DMW contains the early stages of creep or creep-fatigue damage, the intergranular cracks. 200x, etched.

Also noted near the cracks are twin boundaries, the straight black lines across some austenite grains, evidence of plastic strain from the tensile stresses.

A small step or change in diameter, a stress raiser or "notch", at the edge of the weld metal. The 321H oxidizes more rapidly than the nickel weld metal (similar in composition to Inconel 625). Over the service life, the stress raiser further increases the effective tensile stress.

In summary, the damage in stub tube-to-header welds as a result of differential expansion between header and roof may be explained by stresses estimated from simple beam theory, expected operating stresses on weld alloys and conditions used during fabrication. More important, however, is the help provided in knowing just where to look for the first signs of damage, the precursor to failure, as steam generators pass the 25 year mark. The careful inspection required to find these cracks requires thorough pre-cleaning which is time consuming. In addition to careful visual inspection, other inspection techniques such as liquid penetrant, magnetic particle and replications are suggested.

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Signs of Aging in Old Boilers (continued)

The deflection is given by:

EQ1: $\delta = \frac{Pl^3}{3EI}$

Where: δ is the deflection (caused by the differential expansion), in l is the length of the stub tube between header and water wall, in E is Young's Modulus, about 22×10^6 psi at 1000° F
I is the Moment of Inertia, $\frac{\pi}{64}(OD^4 - ID^4)\ in^4$,

for pipes and tubes is given by
P is the load necessary to cause the deflection, lbs. in simple bending.

The tensile stress on the surface is given by:

EQ2: $S = \frac{Mc}{I}$

where: S is the maximum stress in the outer fiber, psi
M is the bending moment, in-lb, and is equal to Pl
c is the distance from the neutral axis to the surface, in
I is the moment of inertia, in^4

What is to be calculated is the stress, S psi, from the deflection at the cracked tubes near the ends of the header. Solve EQ1 and EQ2 for P; thus:

EQ 1a: $P = \frac{3\delta EI}{l^3}$

EQ2a: $P = \frac{SI}{lc}$

Set the two equations equal to each other and then solve for S, gives:

EQ3: $S = \frac{3\delta Ec}{l^2}$

Perusal of EQ3 suggests the stress from differential expansion that causes creep fatigue or thermal fatigue damage decreases as the stub tube gets longer (more flexible/less stiff), and increases as the deflection increases (longer header, larger temperature difference between water wall and header), and stub tubes get larger in diameter.

The deflection is estimated from the differences in thermal expansion between an outlet header at 1000° F and the water wall roof at 650° F, T° F, hence:

EQ4: $\Delta\ (header\ expansion) = \propto TL$

where: $\propto$ is the coefficient of expansion, in/in/° F L is length from header midpoint to end tubes, in

$\propto$ for T-22 from 70° F to 1000°F is 7.97×10^{-6} in/in/° F

$\propto$ for 210 A1 from 70° F to 650° F id 7.35×10^{-6} in/in/° F

This simple approach does indicate that the first and thorough inspection to be performed on the tubes at the ends with the shortest length.

The following example, from the files of DNFM from a 33 year old boiler, illustrates some of these concepts. As a bonus it provides an illustration of a true rarity, a DMW made with a nickel-based welding alloy that failed on the stainless steel side.

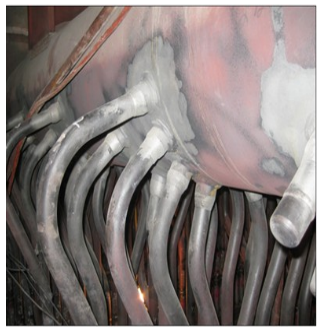

Figure 1 - Photo of the new end row of tubes, grit blasted for ease of examination. The last pendant was removed at start-up to balance steam temperature and the capped tube at the right is part of the modification.

Inspection of the high temperature SH outlet header found significant cracks at the inner tubes of an eight-tube array, see **Figure 1**. A close-up view of the damaged region is presented in **Figure 2**; note the crack removal areas are in the smaller diameter tube and are on the half toward the end of the header. The deflection of the tube from differential expansion would put the tension portion of the tube facing the header end. The two tubes here are specified as 2 ¼" OD X 0.460" MWT T-22 and 1 ¾"OD X 0.260" MWT 321H. Where the damage occurs (T-22 at the header, T-22 HAZ of the DMW, or the 321 HAZ of the DMW) depends on several factors. Those factors include: tube diameters, length to the roof (i.e., bending moment), shape of the DMW and T-22 tube-to-header weld (i.e., stress raisers due to poor weld geometry), and the welding alloy used in the DMW.

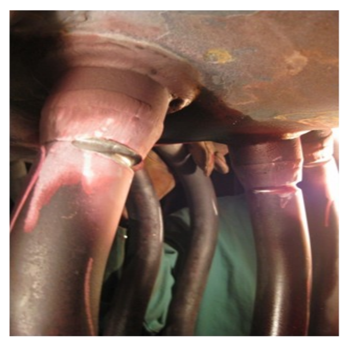

Figure 2 - Close up of the crack removal area since the crack was ground away prior to repair welding at the 321H HAZ

Historically DMWs were made with stainless steel welding alloys, often E-309. Failure would occur in the HAZ on the T-22 side. The coefficient of thermal expansion of stainless steel is about 30% larger than ferritic steels similar to T-22. That difference places a large thermal strain in the T-22 at the edge of the fusion zone. The modern practice is to use a nickel-based alloy. Now the weld metal and T-22 thermal expansion are nearly equal, and the thermal strain is transferred to the stainless steel HAZ. Under normal operation the stainless side is strong enough to resist failure.

In the present example the failure is in the 321H. Since the tensile stresses are additive, the stress from bending of the stub tube (from differences in expansion between roof and header) adds to the stress in the HAZ (from differences in expansion between 321H and the weld metal). The result is failure in the smaller diameter 321H tube as noted in **Figure 2**.

No dimensional measurements on header length or stub tube length were provided, so estimates of actual stress levels could not be calculated. The point may be moot, however, as stress relaxation would likely occur as the tubes operate at high enough temperature and at long enough times to effectively "stress relieve" the strains during service. Therefore, the likely reason is that the damage takes so long to develop.

A second row stub tube was sent to DNFM for metallurgical analysis and is shown in **Figure 3**. A close-up is presented in **Figure 4**. The DMW is well-made with a smooth transition between the tubes of differing diameters. Metallographic analysis of the DMW in a plane where damage, if any, is to be expected displays four interesting microstructural details:

Figure 3 - As-received stub tube sample.

Figure 4 - Close-up of the DMW and the T-22 stub. Note the smooth transition by the weld between the 2 ¼" OD T-22 and 1 ¾" OD 321H.the 2 ¼" OD T-22 and 1 ¾" OD

The microstructure of the 321H is equiaxed austenite with the grain boundaries decorated with both carbides