Failure of a Dynamically Loaded Welded Assembly – Case Study

By

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This case study involves the examination of dynamically loaded welded axle housing assemblies to determine the cause of failure. The axle housings cracked in the rectangular structural tubing. They were examined by visual examination, scanning electron microscopic examination, hardness testing, and metallographic examination.

Please note: Many of the characteristics found during this failure analysis are typical of most welded dynamically loaded assembly failures: namely unqualified weld procedures and weld operators.

The equipment on which the axle housing assemblies were used was inspected on a regular basis, and the cracking was discovered prior to any accidents; however, frequent inspection of welded dynamically loaded structures or assemblies does not always occur. Failures, when they occur, usually result in significant losses: of equipment and property, and often lives put in jeopardy. As in this case, the failure may not occur for several years after the equipment is put into service.

Welder certification for a given weld is very important. Because of the expense involved, weld certification is often overlooked, even when it is required in the contract. It is not unusual for a welder to go through three or more qualification tests and many hours of practice prior to being qualified for a given weld.

Visual Examination

Figure 1 – Axle Housing Segment

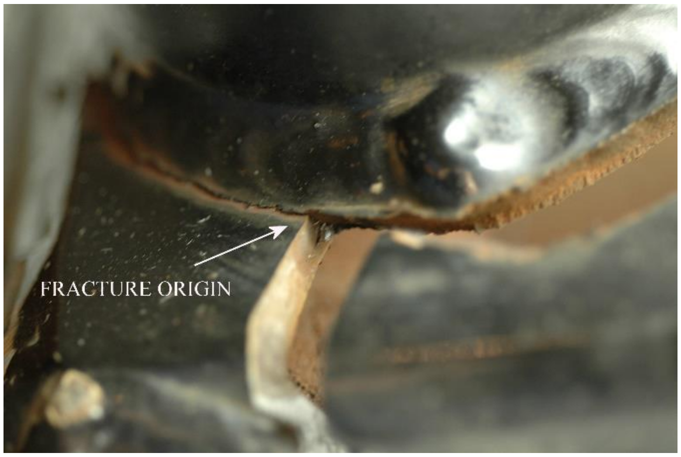

Figure 2 – Fracture Origin - Axle Housing Segment

Figure 1 shows the axle housing segment which was the worst of the housing assemblies examined. There was significant cracking associated with the welds. One of the fractures originated near the weld start-stop location of the circumferential weld. Figure 2 shows the location of the fracture origin near the circumferential weld start/stop. It is difficult to make a weld start/stop that is defect free. To do so requires a highly skilled weld operator.

Figure 3 shows additional weld cracking. There were a number of cracks originating from the weld toes, indicating the weld operator insufficiently skilled for those particular weld types.

Figure 4 shows the fracture origin after removal from the axle housing segment. To the left side of the fracture origin was a fatigue crack, and to the right side the fracture mode was unknown.

Figure 3 – Fracture Origin - Axle Housing Segment

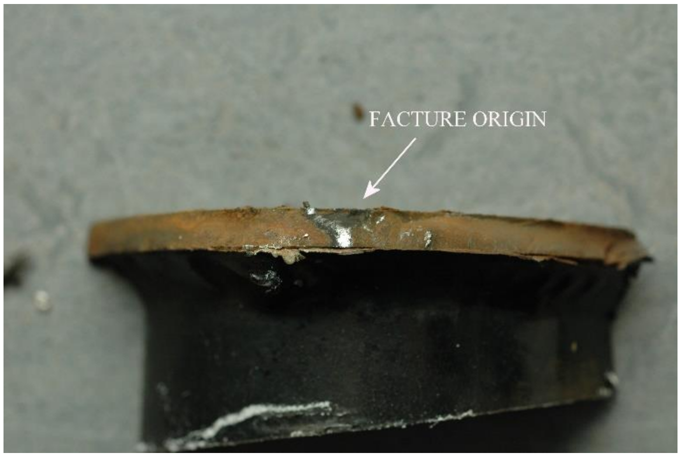

Figure 4 – Fracture Origin

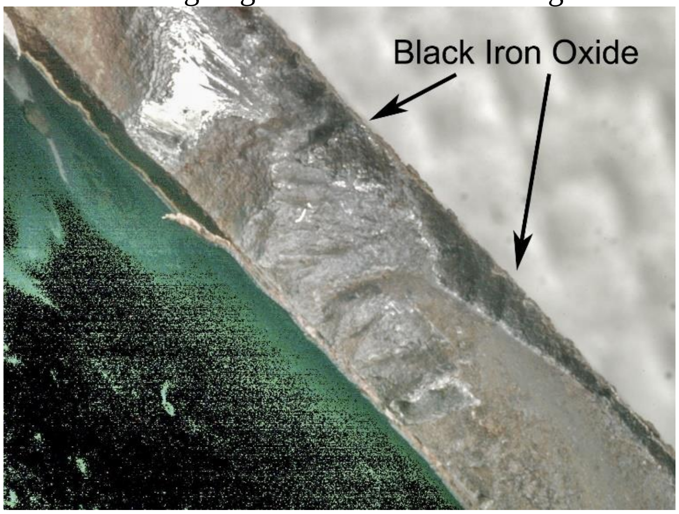

Figure 5 – Fracture Origin after Cleaning

The fracture origin is shown after cleaning was done prior to scanning electron microscopic examination, Figure 5. The presence of black iron oxide reveals an area where there was a lack of root fusion during welding. Black iron oxide forms at temperatures greater than 900^{o} F.

Scanning Electron Microscopic Examination

The fatigue section of the fracture in the axle housing segment was so badly corroded that the only information that could be obtained from the scanning electron microscopic examination was that the fracture was actually fatigue, Figures 6 and 7. The amount of corrosion prevented the measuring of the fatigue striation spacing, which is necessary in estimating the applied cyclic stress.

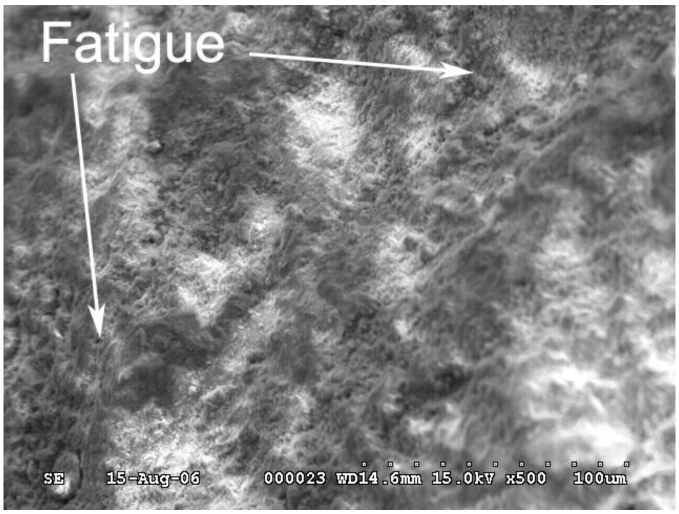

Figure 6 – 500X Fatigue Fracture - Axle Housing Segment

Figure 7 – 180X Fatigue Fracture - Axle Housing Segment

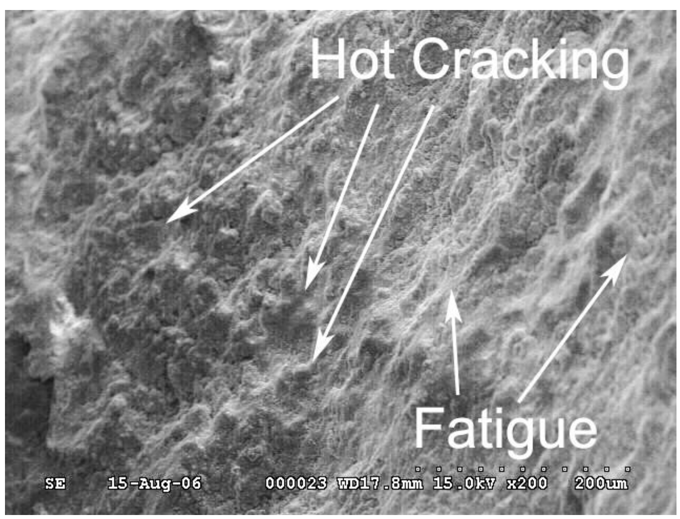

Figure 8 – 200X Hot Cracking and Fatigue - Axle Housing Segment

The fracture mode nearest the fracture origin, Figure 8, appears to have been hot cracking, which was indicated by apparent intergranular fracture and melting. Again, the amount of corrosion was significant enough that a definite evaluation was not possible. The extent of the corrosion is a clear indication that the crack had been open for a considerable amount of time.

Hardness Testing

The hardness testing was done according to ASTM E384, using a Knoop indenter and a 500 gram load.

Hardness Test Data – Tubing Right Front Axle Housing Segment (Rockwell B Scale)				
Sample	Knoop	Std. Dev.	Range	Hardness
Tubing Base Metal	165.00	2.30	163.00 - 169.00	80.42 RB
Tubing Base Metal*	198.00	15.27	180.00 - 216.00	89.04 RB
Tubing HAZ	162.00	4.72	157.00 - 169.00	79.16 RB
Tubing HAZ	168.00	1.67	166.00 - 170.00	81.16 RB

*Near Bend in Tubing

The welding did not appear to have much effect on the mechanical properties of the rectangular tubing. The hardness of the tubing is within the expected range for ASTM A500 structural tubing.

To better define the fracture mode, micro-hardness profiles using a 50 gram load were taken perpendicular to the various fracture surfaces.

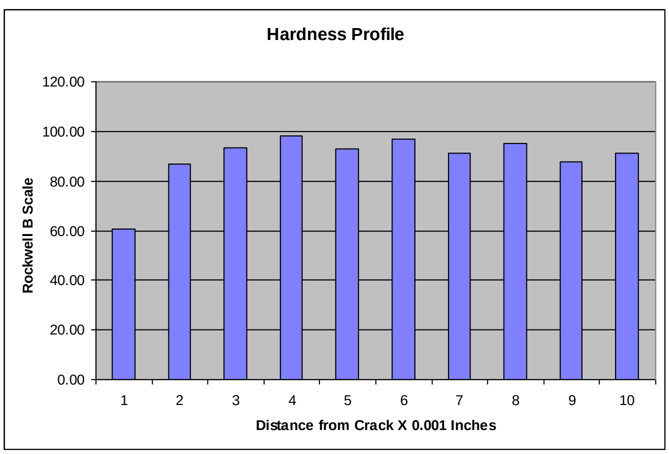

Figure 9 – Hardness Profile Starting at Fatigue Crack - Axle Housing Segment

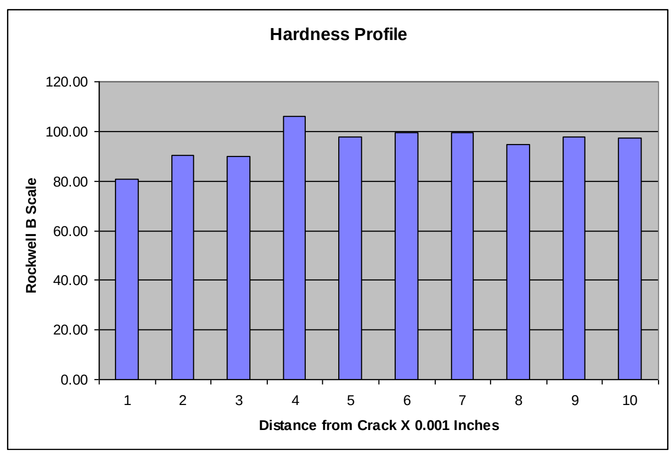

Figure 10 – Hardness Profile Starting near Hot Crack End - Axle Housing Segment

The two hardness profiles starting on either side of the fracture origin have characteristics similar to those produced by fatigue cracks, Figures 9 and 10. The two profiles indicate plastic strain to about 0.004 inches of the crack. The size of the plastic radius can be used to estimate the cyclic fatigue stress associated with the fracture. Using the plastic radius is not as accurate as using the fatigue striation spacing.

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Metallographic Examination

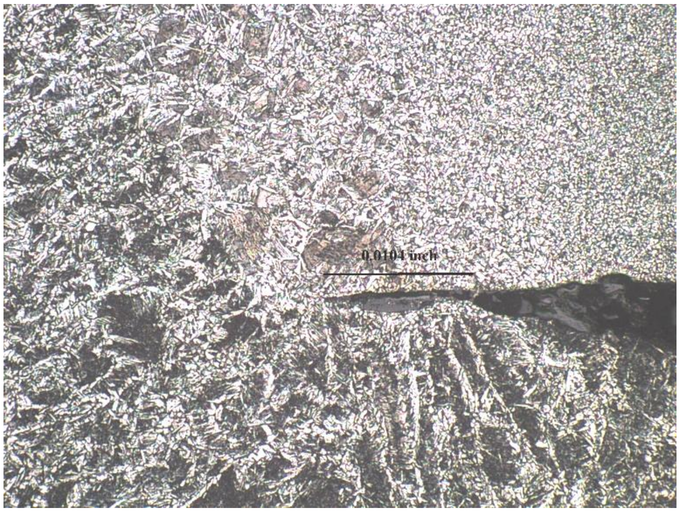

Figure 11 – 100X Lack of Fusion in Root of Circumferential Fillet Weld - Axle Housing Segment

The common characteristic of the circumferential fillet weld associated with the axle housing segment was lack of fusion in the root. **The weld would not have been acceptable to any welding code that I am aware of,** because of the lack of weld fusion shown in Figure 11. Tubular branch connections such as the ones that failed are some of the most difficult welds to properly design and weld. They require very highly qualified welder operators, and often very elaborate weld procedures to produce defect free welds. This particular branch connection does not meet AWS D1.1:2000 criteria for a pre-qualified structural weld subject to fatigue loading. The manufacturer would need to develop and qualify a welding procedure for this branch connection to produce a weld that meets all of the requirements for a fatigue loaded branch connection. Any personnel welding this connection would need to be qualified to that procedure. These records should be supplied with each axle housing assembly.

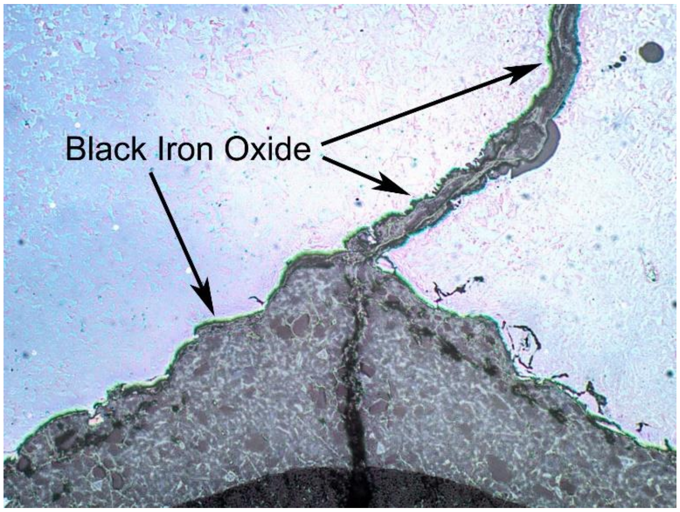

Figure 12 – 200X Hot Crack in Root of Axle Housing

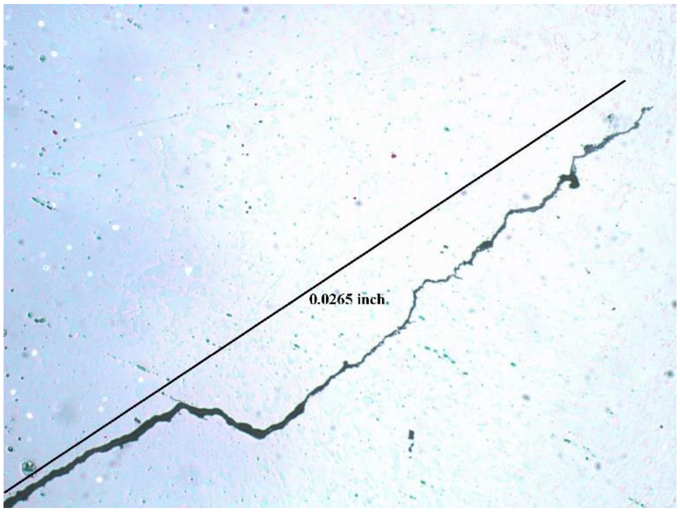

Figure 13 – 200X Hot Crack Extension from Root of Axle Housing

The side of the crack in the axle housing segment that was designated as a hot crack had two types of oxide scale present, Figure 12. A black, high temperature oxide was caused by heat from the weld process. This assembly had failed prior to leaving the weld shop, and shows that there was no quality control, or likely even inspection of finished welded assemblies. Figure 13 shows extension of the hot crack. The end of the crack was likely the result of fatigue.

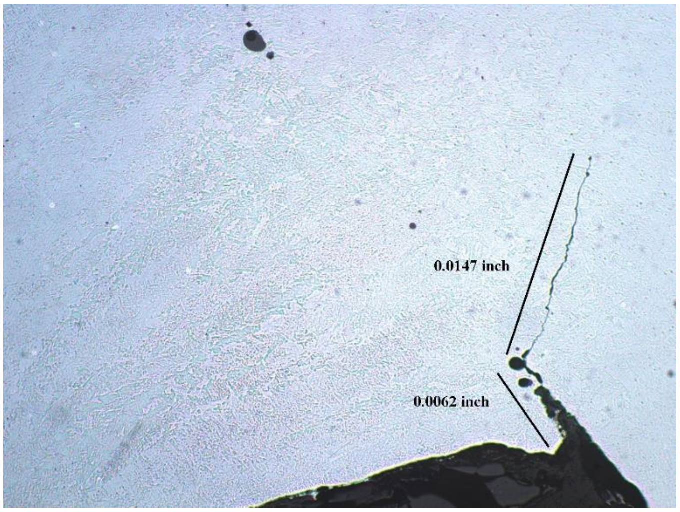

Figure 14 – 100X Crack in Weld Toe - Axle Housing Segment

Figure 14 shows the crack at the weld toe of the start-stop location. There is lack of fusion at the weld toe that was the result of the weld puddle running ahead of the arc, which is an operator error. The crack extends into the rectangular tubing material along the weld base metal interface. The quality of this weld was extremely poor.

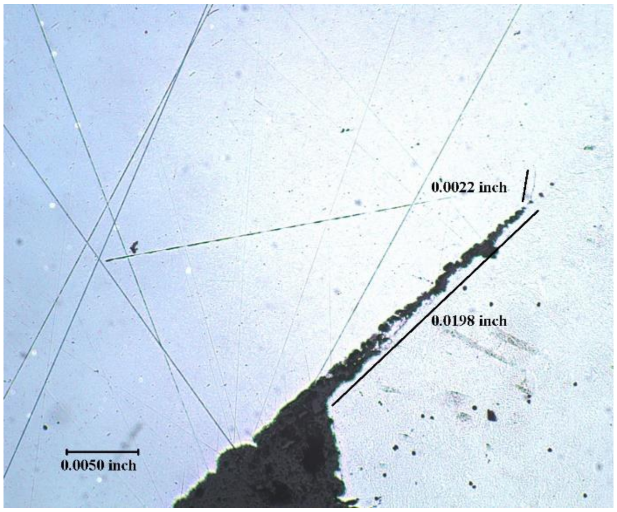

Figure 15 – 100X Lack of Fusion and Crack at Weld Toe - Axle Housing Segment

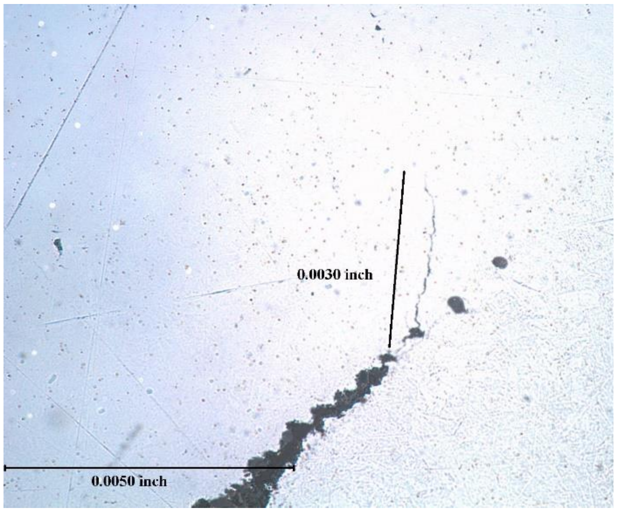

Figure 16 – 400X Crack Extension - Axle Housing Segment

The weld start-stop location on the axle housing segment had lack of fusion at the weld toe, Figure 15. At the root of the lack of fusion was an extension crack penetrating about 0.030 inch into the tube wall, Figure 16. This was another very poor quality weld.

The metallographic examination clearly showed that the circumferential fillet welds used for the branch connection were of extremely poor quality, and were the initial cause of cracking in the axle housing assembly even prior to being put into service.

Fracture Mechanics

Fracture mechanics were used to estimate the stress levels that were on the parts at the time of fracture. The following equation was used to estimate the cyclic stress at the two locations: $\Delta\sigma = \frac{\sigma_{ys}\sqrt{2\pi r}}{\mathrm{Y}\sqrt{a}}$. The definitions for the terms are given below.

$\Delta\sigma$	Cyclic fatigue stress
σ_{ys}	Yield strength
r	Plastic radius
Y	Constant equal to 2.1
a	Distance from the start of the fracture

The plastic radius as determined by micro-hardness testing was 0.004 inches. This yields a cyclic stress of 6700 psi. AWS D1.1 limits the cyclic stress load for similar designs to 7000 psi. Without other contributing factors, namely, stress risers caused by poor quality welding resulting from an improper welding procedure and a weld operator not qualified to the procedure, this connection should not have failed.