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Welded Arm Assembly Failure

By

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Subject

A failed welded arm assembly was examined to determine the cause of failure. The arm failure was examined by visual examination, chemical analysis, hardness testing, scanning electron microscopic examination, and metallographic examination. The steel specified was ASTM A513 Grade 1008/1010 with yield strength of 45 ksi minimum, and tensile strength of 55 ksi minimum. ASTM A513 is the specification for steel tubing and not steel alloys. It was found that this failure was the result of a lack of understanding of the characteristics of the steel being used, and of the ASTM specifications.

Visual Examination

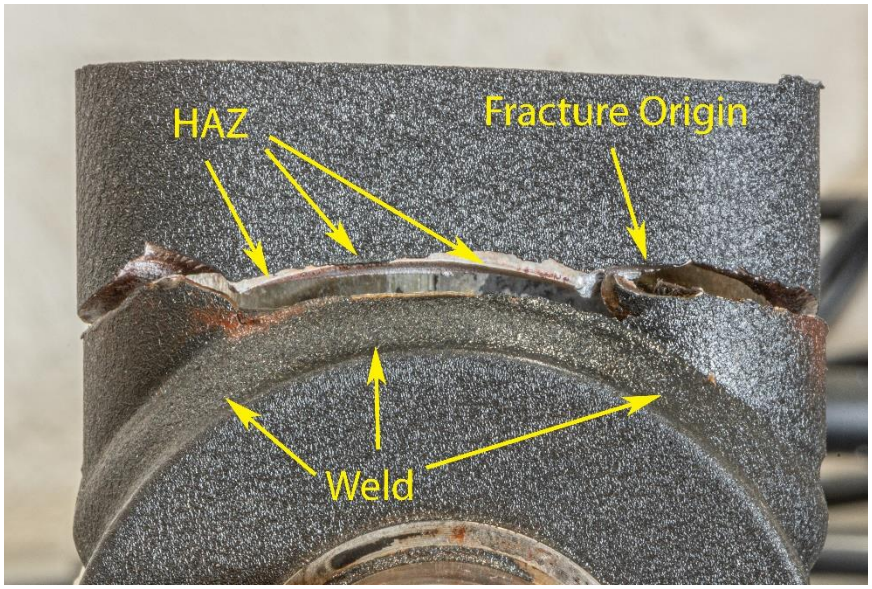

Figure 1 –Welded Arm Assembly

Figure 1 shows the failed arm assembly. The fracture origin is indicated, and the location on the assembly is also shown. The fracture origin was located outside the weld heat affected zone. The fracture progressed in the heat affected zone of the weld joining the arm to the hub. The quality of this weld appeared to be very good.

Figure 2 shows the fracture surface after it had been opened up. The fracture surface had clear indications of fatigue cracking at the fracture origin and along most of the fracture surface.

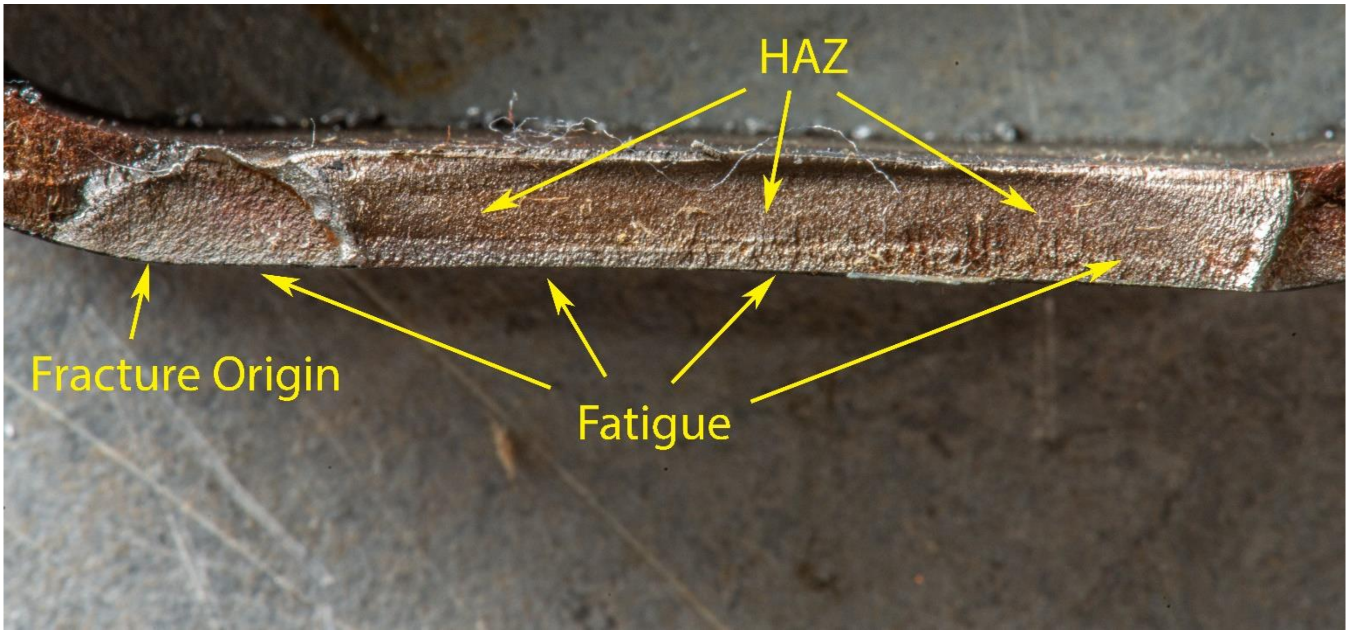

Figure 2 – Fracture Origin Arm Assembly

The visual examination showed that the primary failure mode was fatigue.

Chemical Analysis

The chemical analysis was done according to the following ASTM Specifications: ASTM E1019 for carbon and sulfur, and ASTM E415 for the other elements. The results of the chemical analysis for the tube material used for the arm assembly are given in the table that follows.

The chemical analysis shows that the steel used for the arm was ASTM A1008/A1008M Grade DDS, a drawing quality steel with low levels of carbon and manganese. 1008/DDS steel is sold with a yield strength range of 17 to 29 ksi. Based on the chemical composition of the arm's steel, it can be assumed that the fracture toughness is very low, and that the ductile brittle transition temperature is greater than 100^{o} C. The fatigue endurance limit of 1008/DDS steel is a function of the grain size, and not of the tensile and yield strength, which is characteristic of most steel alloys. The estimated fatigue endurance limit is 2.8 ksi. The typical fatigue endurance limit of 22.5 ksi is expected for steel having the tensile and yield strength specified for this tubing. The fatigue value was taken from the Wadd Technical Report 60-42, ADA280890, published by Curtiss-Wright Corporation in 1960. 1008/DDS is not appropriate for use in applications subjected to cyclic loading.

Chemical Analysis of Tube Steel Welded Arm Assembly (Percent by Weight)			
Element	Tube	1008/DDS	1010
Carbon	0.03	0.06 Max	0.08 - 0.13
Manganese	0.17	0.50 Max	0.30 - 0.60
Phosphorous	0.013	0.020 Max	0.035 Max
Sulfur	0.008	0.025 Max	0.035 Max
Silicon	<0.005		
Nickel	0.01		
Chromium	0.03		
Molybdenum	<0.005		
Copper	0.02		
Aluminum	0.04	0.01 Min	0.01 Min

Hardness Testing

The hardness testing was done according to ASTM E384, using a Vickers indenter and a 500 gram load. The results of the testing are given in the table that follows.

Hardness Test Data (Rockwell B Scale)					
Sample	Vickers	STD DEV	MAX VALUE	MIN VALUE	HARDNESS
HAZ	112.00	3.65	117.00	107.00	63.20
Tube	129.00	4.98	134.00	122.00	71.72
Fracture Origin	129.00	6.22	134.00	119.00	71.60

When using 1008, or 1008/DDS drawing quality steel in welded assemblies, it is necessary to use the minimum yield strength of the steel as the primary strength design parameter. The reduced hardness in the weld heat affected zone illustrates that this was likely not applied during the design process. The minimum yield strength for 1008/DDS is 17 ksi. The reason for this is that the steel in the weld heat affected zone is annealed and not strengthened because of the low carbon and manganese content. The compression yield strength of annealed 1008/DDS is approximately 10 ksi.

Scanning Electron Microscopic Examination

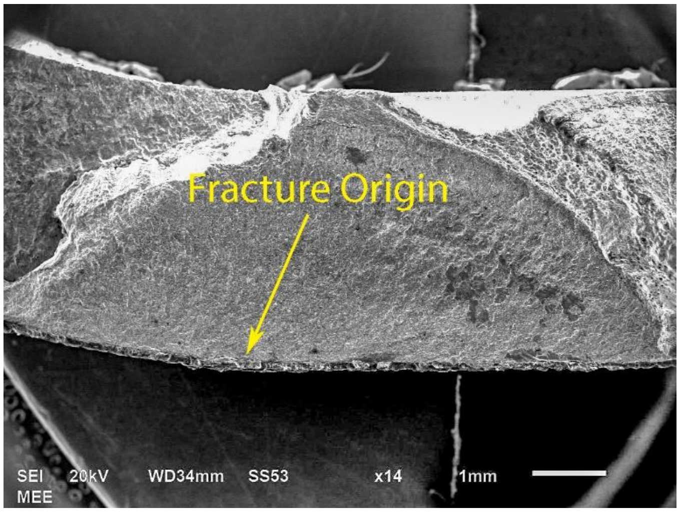

Figure 3 – 14X Fracture Origin Arm

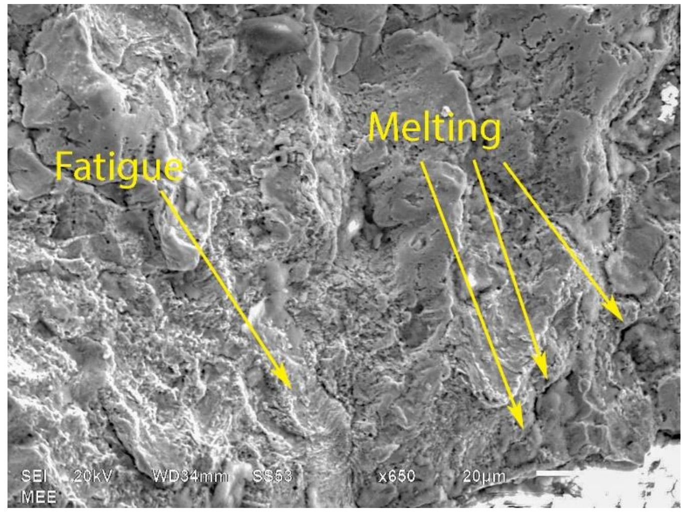

Figure 4 – 650X Fracture Origin Arm

The fracture origin of the arm, as viewed with the scanning electron microscope, is shown in Figure 3. A much closer view is shown in Figure 4, which shows two failure modes, fatigue and localized melting. The melting was the result of localized heating in excess of 2600^{o} F. The cause of melting could have been an arc strike during the welding process. No evidence was found to directly identify the cause. The left side of the sample in this photo shows cracking, which is an indication that the tensile strength of the steel had been exceeded.

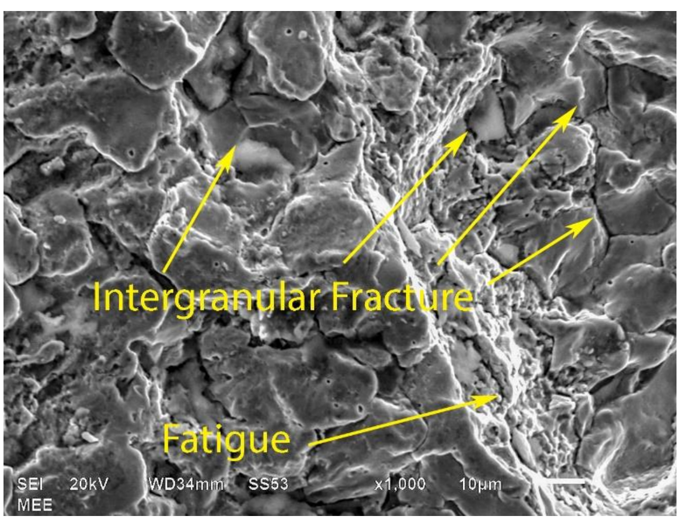

Figure 5 – 1000X Near Fracture Origin Arm

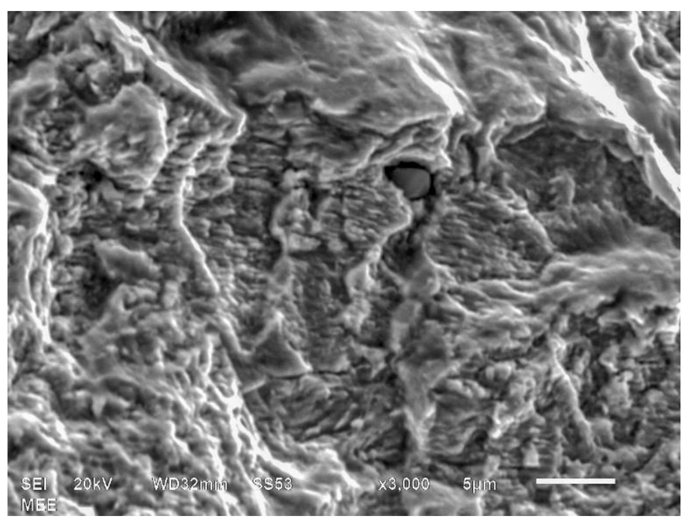

Figure 6 – 3000X Fatigue Arm

Figure 5 shows mixed mode fracture, fatigue and intergranular, next to the fracture origin. The intergranular fracture was likely the result of low ductile-brittle transition temper for the 1008/DDS steel.

Figure 6 shows well formed fatigue striations that have a spacing of 14.9 X 10^{-6} inches.

Fracture Mechanics

Fracture mechanics can be used to estimate the stress levels that were on the parts at the time of the fracture. Knowing the location and spacing of the fatigue striations permits the estimation of the cyclic fatigue stress by the following equation: $\Delta\sigma = \dfrac{E\sqrt{\dfrac{spacing}{6}}}{Y\sqrt{a}}$. The terms are defined below:

$\Delta\sigma$	The applied cyclic stress.
E	The modulus of elasticity equal to 30,000,000 psi for steel alloys.
a	The distance the fatigue striations progressed from the fracture origin.
Y	A constant equal to 2.1. It is defined by the shape of the crack.

The value for "*a*" is the tube wall thickness of 0.143 inches.

The estimated cyclic stress at the location shown in Figure 6 was 59.5 ksi. This load far exceeds the strength of the 1008/DDS steel.

A major contributing factor to the failure is the very low compressive strength of 1008/DDS steel. Once the compression yield strength has been exceeded, any additional or repeated loading will be tensile loading.

Metallographic Examination

Figure 7 shows the ferrite microstructure of the arm steel. There is an occasional carbide in a grain boundary. The presence of grain boundary carbides likely indicates embrittlement. The grain size of the steel was determined to be ASTM 9, which is very fine grained steel.

Figure 8 shows the microstructure of the weld heat affected zone, which is an acicular ferrite. The grain size was found to be ASTM 7.5, which is still fine grained. The fine grained steel in the heat affected zone is the result of the steel being aluminum killed.

The carbon level in this steel was 0.03 percent, which means that quench age embrittlement was not likely to have occurred, accounting for the low hardness in the weld heat affected zone.

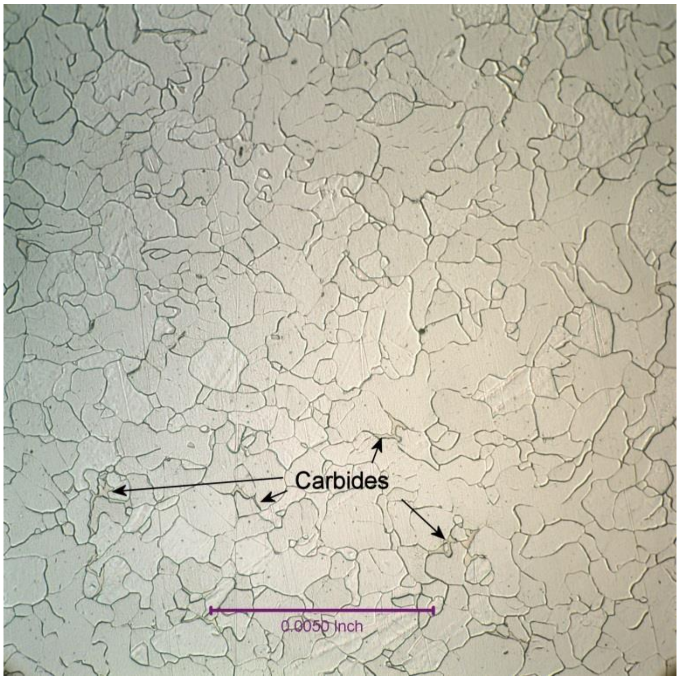

Figure 7 – 400X Microstructure Arm

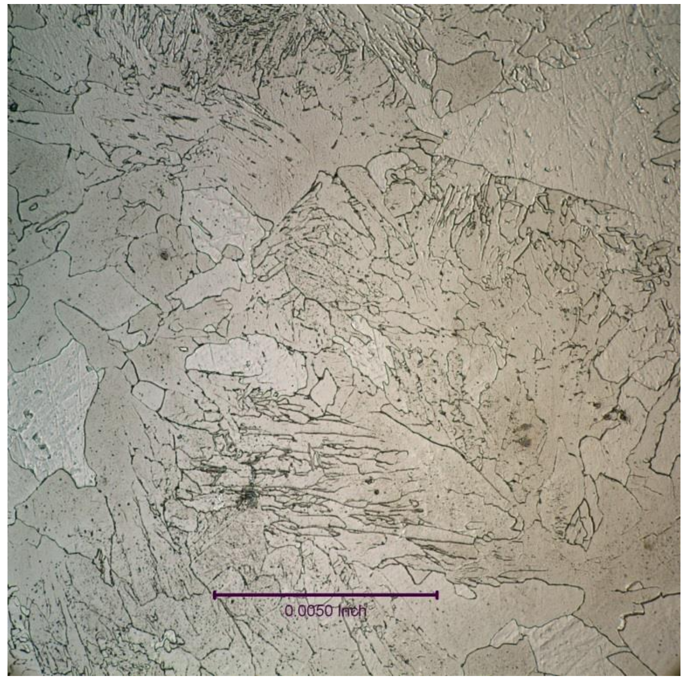

Figure 8 - 400X Weld HAZ Arm

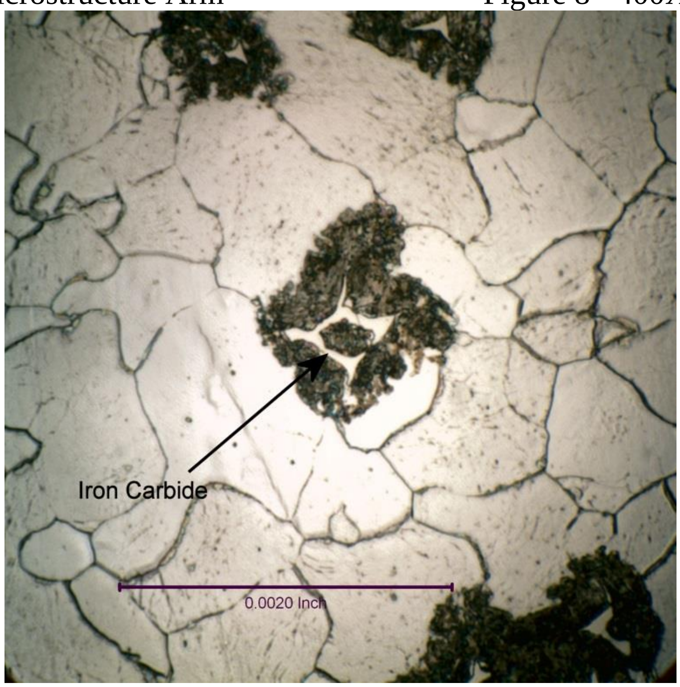

Figure 9 – 1500X Carbide Precipitation Arm

Figure 9 shows the microstructure next to the heat affected zone. The carbon has precipitated as very fine pearlite, carbide, and Bainite. The microstructure was the result of very rapid cooling after welding.

Discussion

The evaluation of this assembly shows that there are major concerns with the steel tubing and the welding process used to fabricate the arm assemblies for the equipment.

There are metallurgical considerations with the steel tubing, which is specified as 1008/1010 steel. The chemical analysis showed 1008/DDS was the steel used for the tubing. There are several problems inherent to welding 1008/DDS steel. If the carbon content is 0.05 percent, the heat affected zone will be embrittled. If the carbon content is between 0.04 and 0.12 percent, any portion of the tube heated to over 1400^{o} F. by welding is subject to quench age embrittlement. Sections of the tube that have been heated to between 400 and 700^{o} F. are subject to Blue Brittleness, especially portions that have been formed or cold worked. 1008/DDS has other problems: the ductile-brittle transition temperature is much higher than room temperature when the manganese content is very low, as in the case of the welded arm assembly. The low manganese appears to have resulted in embrittlement, which is very common in 1008/DDS steel. The fatigue strength in 1008/DDS steel is based on the grain size: 1008/DDS steel with a grain size of ASTM 7 and finer has an endurance limit of 2.8 ksi. This is very low for steel. The endurance limit for most carbon steels is 50 percent of the yield strength. The compression strength of the steel is about 10 ksi in the annealed condition. 1008/DDS is not a good steel to use for dynamically loaded welded assemblies. The use of 1010 would be better suited for this unit, 1015 would be better yet for weldability. These steels should be aluminum killed to prevent grain growth in the weld heat affected zones.