Investigative Summary

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Report No.:	271412
Date:	6/4/2018
Order No.	645549
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BACKGROUND

One (1) fractured bellows assembly (see Photo 1) was submitted to our laboratory for a metallurgical investigation.

The bellows assembly is part of a RF power coupler in a larger cryomodule. The bellows was fabricated from resistance seam welded stainless steel sheet by cold forming and brazing - as received it was EDM cut longitudinally (see Photo 2). The bellows was found cracked after transport from Batavia, IL and Menlo Park, CA and back (~4,400 miles) – believed due to the vibration from over the road transportation.

We were requested to verify the fracture mode as fatigue, number of cycles and stress level to failure.

Photo 1: As-received bellows assembly.

Photo 2: Bellows assembly disassembled showing the bellows with an previous EDM cut

PERFORMED TESTING

Visual and Stereoscopic Examination
Scanning Electron Microscope (SEM) Examination
Metallographic (Microstructure) Examination
Micro Indentation Hardness Testing
Chemical Analysis

CONCLUSIONS

1. Based upon the performed tests and examinations, it is our opinion the fatigue fracture initiated on the outside surface at multiple locations at grain boundaries that were infiltrated with braze metal. Secondary fatigue cracking also initiated in the adjacent intrados (without braze metal present) and at the opposite end of the bellows show that the bellows was exposed to overload cyclic stresses enough to cause fatigue initiation at both ends of the bellows.

2. In our opinion, uni-directional bending stresses initiated and propagated the multiple fatigue cracks completely through the bellows wall with no observable stage III fatigue cracking – consistent with zero mean stress level and only the cyclic fatiguing tensile stress of about 40 ksi (half the typical 80 ksi UTS). Radial propagation of the fatigue cracks away from the initiation sites also indicated that the brazed intrados of the bellows did not have associated stress concentration.

3. SEM Fractographic examination of the primary and secondary fatigue fracture surface in the bellows revealed microscopic crack progression markings known as fatigue striations. The fatigue striations initiated at the visually identified fracture initiation sites (some at grain boundaries with braze metal). Fatigue cracks initiate at a sub-micron imperfection in the base stainless steel or infiltrated braze metal - this is stage I fatigue and generally represent over 90% of the fatigue life. Fatigue crack propagation in stage II occurs rapidly producing fatigue striations – small steps of plastic deformation – any change in fatigue crack propagation such as fatigue arrest can lead to “beach” or “clamshell” markings. Fatigue is a progressive failure mode where the crack plastically propagates over time with each cycle of stress. The fatigue crack propagated through approximately 100% of the cross-sectional area and re-initiated at adjacent sites along the intrados as the cyclic stress bearing area decreased and the adjacent structure exposed to ever increasing cyclic stresses as the crack spread around the bellows.

4. The length of a single fatigue striation is about 0.24 µm. The bellows’ wall at the fracture initiation site is 196 µm thick, so it took about 817 cycles of stage II fatigue propagation for the fatigue crack to propagate from the outside surface through the wall of the bellows and terminating on the inside surface of the bellows. Assuming that stage II (the 817 cycles) represents only 5% of the total fatigue life of a single fatigue initiation site is approximately 817/0.05 = ~16,300 cycles.

5. Assuming adjacent fatigue initiation sites became successively active from the center of the 35-mm long crack in the bellows outwards in a sequence of say (1+½+¼+… = 2) then taking half the initiation sites over the 35-mm/2=17.5 mm distance on each side or 8.75mm and assuming a 300 µm spacing of the active fatigue initiation sites gives 8.75 mm/0.3 mm = 29 initiation sites. Hence the approximate total fatigue count is about 29*16,300 = 472,000 cycles to produce the 35-mm long crack in the bellows. For transport of the bellow gives 472,000 cycles / 4,400 miles = 107 cycles/mile or ~1.8 Hz at 60 mph (1 mile/minute).

6. The hardness of the bellows ranged 164 to 224 HV_{500} and 162 to 193 at the heat affected fatigue initiation site. The chemical composition of the bellow conforms to Type 316L stainless steel with a background hydrogen of 4.5 PPM. Austenitic stainless steel is immune to the effect of hydrogen embrittlement.

7. No evidence was observed of pre-existing steel defects, excessive nonmetallic inclusions, or any other detrimental material conditions that could have contributed to the fatigue failure.

SUMMARY of TEST RESULTS

Visual and Stereoscopic Examination

1. Visual and stereoscopic examination of the sample revealed a crack about 35 mm long with a perpendicular EDM cut about 15 mm from the left end of crack (See Photos 3 – 4). The crack is present in the intrados adjacent to the brazed end of the bellows.

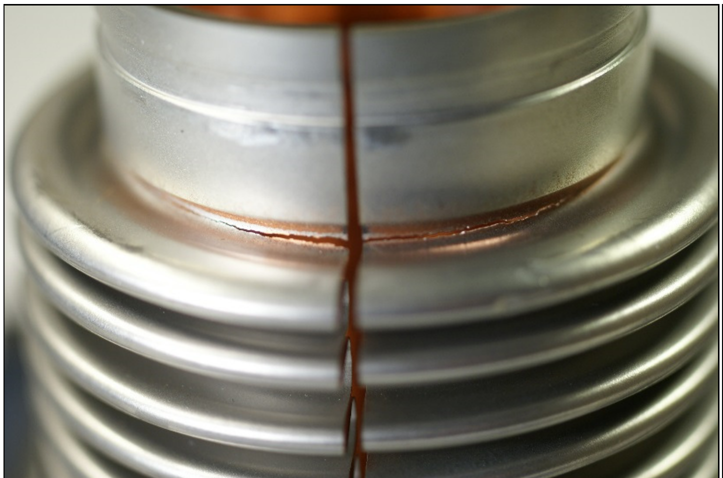
Photo 3: Crack in intrados adjacent to brazed end of bellow

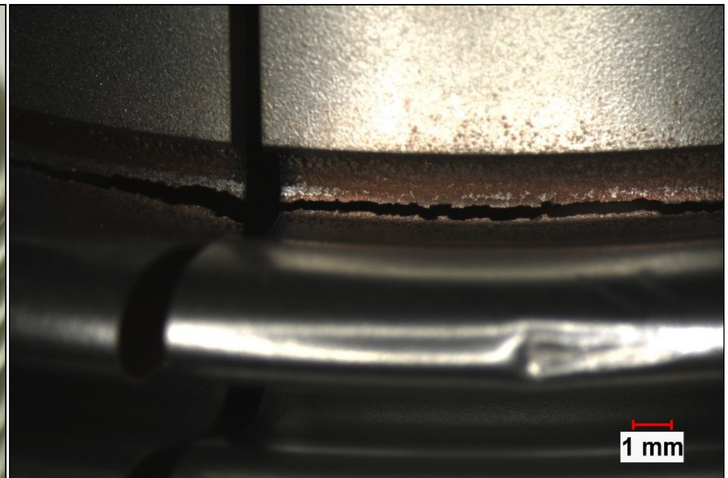

Photo 4: Close-up of crack from outside.

2. The exposed fracture surface as observed from inside end of the bellow shows a fracture surface consistent with fatigue fracture surface as indicated by “ratchet marks” separating multiple fatigue initiation sites (see Photo 5).

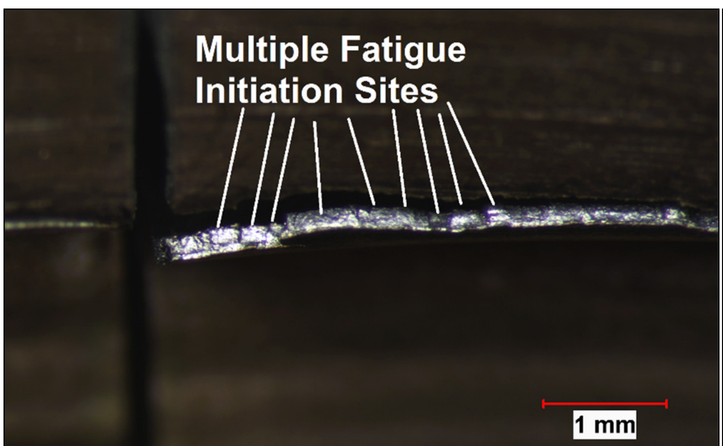

Photo 5: Close-up of crack from inside.

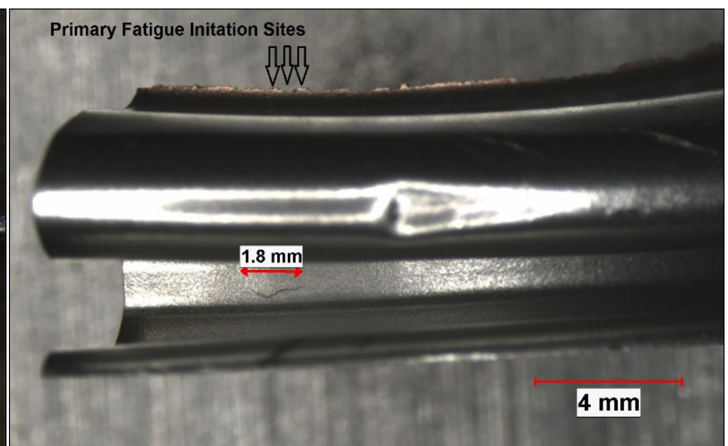

Photo 6: Secondary crack about 1.8 mm in adjacent intrados of the fold in the bellows.

3. A secondary fatigue crack was found in the adjacent intrados of the bellows and in line with the middle of the primary fatigue crack consistent with cyclic stress along this longitudinal section of the bellows (see Photo 6).

Visual and Stereoscopic Examination (cont.)

4. Stereoscopic examination shows there are several independent shallow fatigue cracks in the adjacent intrados of the bellows consistent with fatigue initiation at the outside surface of the intrados (see Photos 7 - 8). These fatigue cracks are well into stage II fatigue crack propagation and were most likely arrested when the primary fatigue crack above (i.e. closer to the braze joint) propagated enough to shift the cyclic load away arresting secondary fatigue.

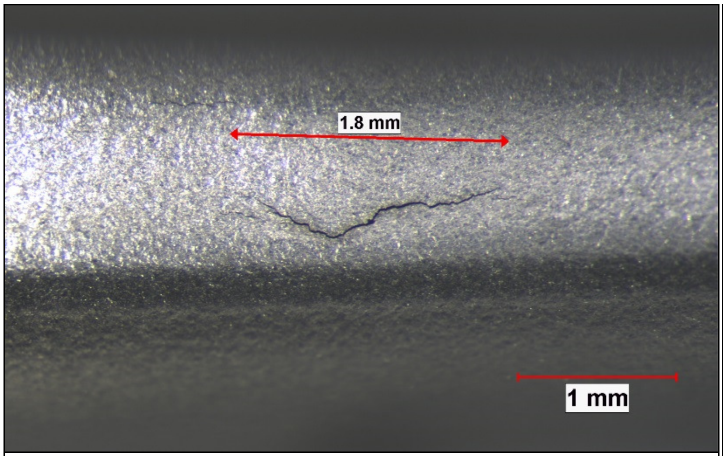

Photo 7: Secondary fatigue crack in adjacent intrados fold of bellows.

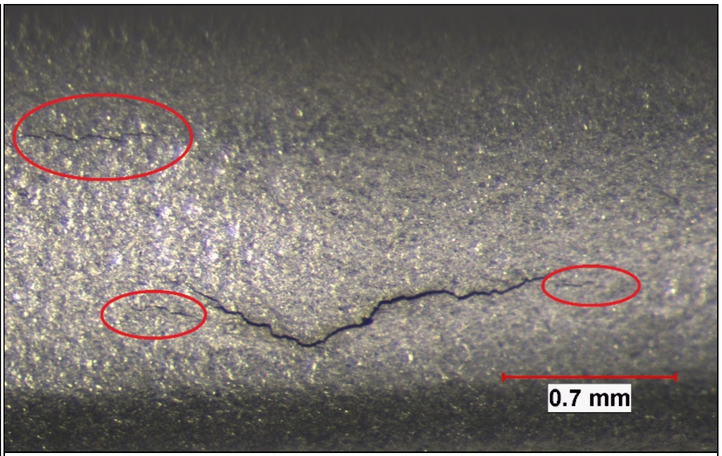

Photo 8: Three more independent fatigue cracks (circled in red) around the secondary fatigue crack.

5. Stereoscopic examination also shows three additional cracks found at the opposite end of the bellows. One long crack exposed when cutting out the chemical analysis sample – longitudinally in line with primary and secondary fracture initiation sites documented above (see Photo 9). Two more cracks at the 180° opposite the primary fracture initiation sites (see Photo 10).

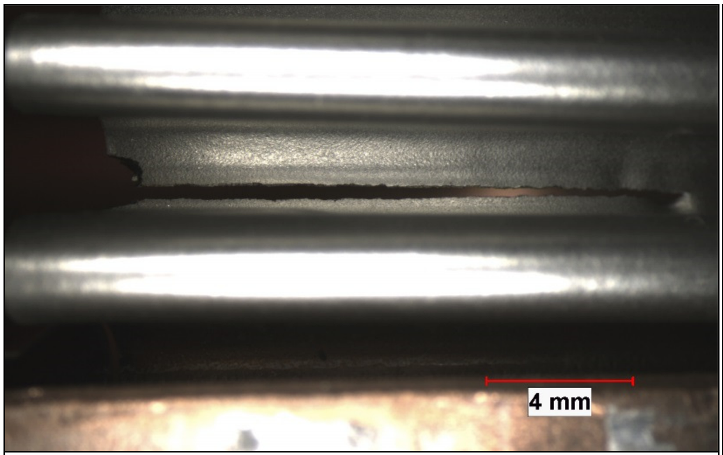

Photo 9: Tertiary fatigue crack found on the opposite end of the bellows exposed when removing chemical analysis sample.

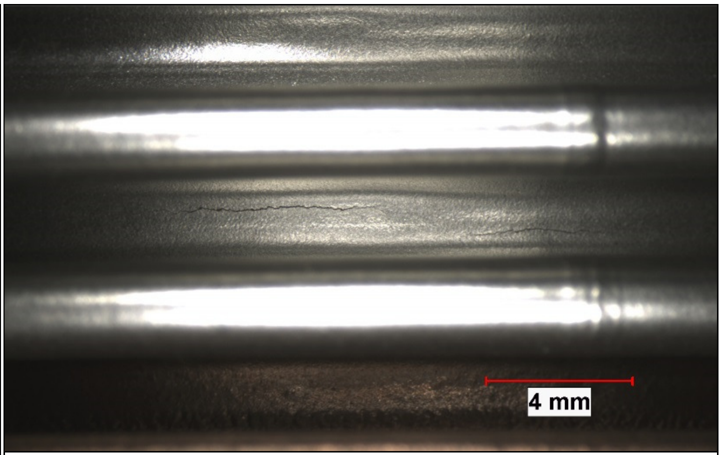

Photo 10: Another set of two cracks on the opposite end of the bellow 180° from the other cracks and adjacent to the weld seam.

Scanning Electron Microscopy Examination

1. SEM examination revealed multiple fatigue initiation sites along the intrados of the bellows bend closest to the braze joint. Red arrows indicate the direction of stage II fatigue crack propagation completely though the bellows' wall (See Photo 11) with no observed stage III fatigue (final overload fracture), which is consistent with a low nominal stress in the bellows. The stage II fatigue cracks propagate radially from the initiation sites. This is consistent with unidirectional cyclic bending fatigue with no stress concentrations present in the bellow at this location (see Photo 12).

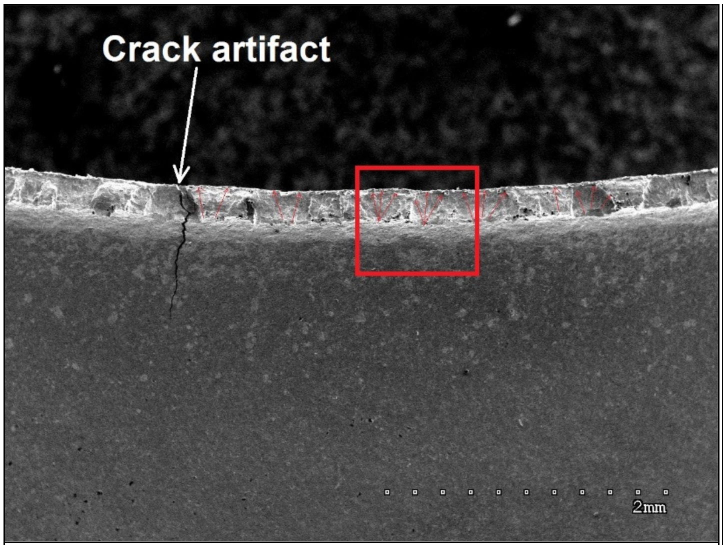

Photo 11: SEM image Mag: 20X
Multiple fatigue initiation sites along intrados fold of the bellows

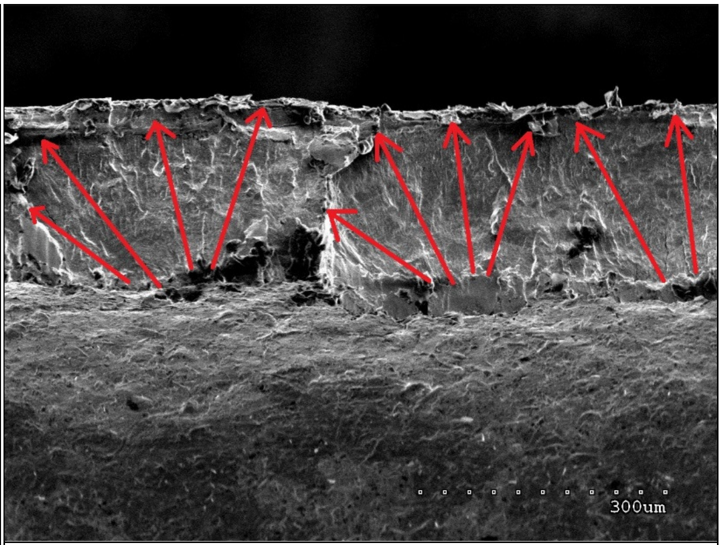

Photo 12: SEM image Mag: 120X
Red boxed area showing radial fatigue crack propagation through the bellow wall.

2. SEM examination revealed fatigue striations on the stage II fatigue surface. Stage II crack propagation extended though the bellows wall to the inside surface (See Photos 13). The length of a single fatigue striation is about 0.24 µm. The bellows' wall at the fracture initiation site is 196 µm thick so it took about 817 cycles in stage II fatigue for the fatigue crack to propagate from the outside surface through the wall of the bellows, terminating on the inside surface of the bellows.

SEM Examination (cont.)

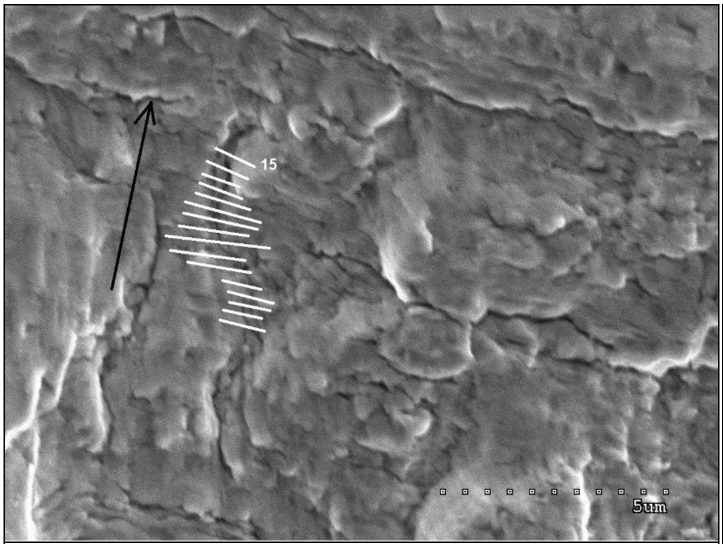

Photo 13: SEM image Mag: 6400X
Fatigue striations on stage II fatigue fracture surface marked with parallel white lines. The black arrow indicates the direction of fatigue crack propagation.

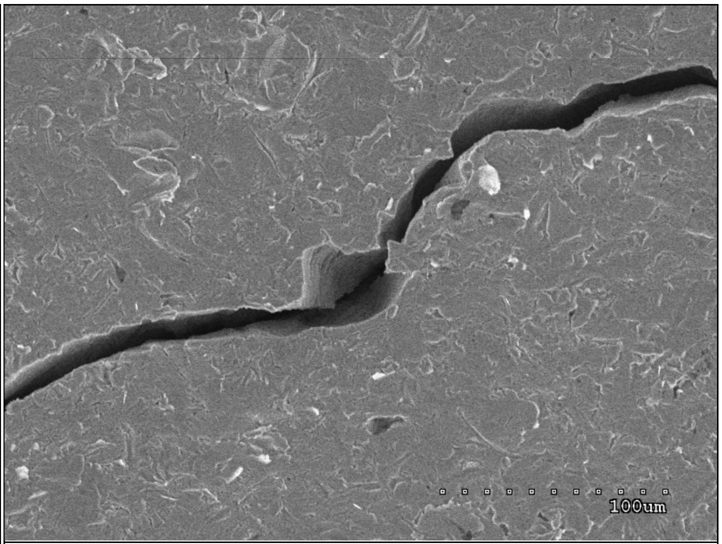

Photo 14: SEM image Mag: 320X
Secondary fatigue crack in adjacent intrados with small section of surface missing and most likely becoming micro fatigue debris.

3. SEM examination revealed the secondary fatigue crack confirmed that it is a fatigue crack as indicated by the observed fatigue striations inside the crack (see Photos 14 – 15). Cutting out the 1.8 mm crack and opening it for direct SEM examination revealing fatigue striations on the order of those observed and measured on the primary fatigue fracture surface (see Photo 16).

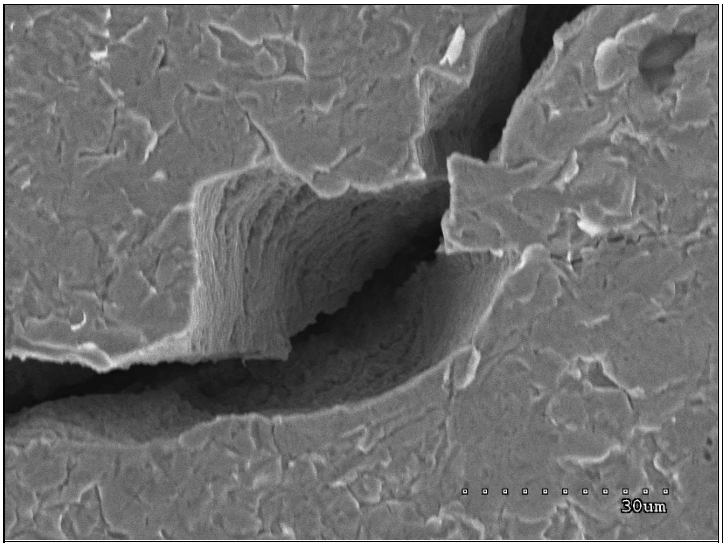

Photo 15: SEM image Mag: 1000X
Close-up showing fatigue striations in secondary fatigue crack.

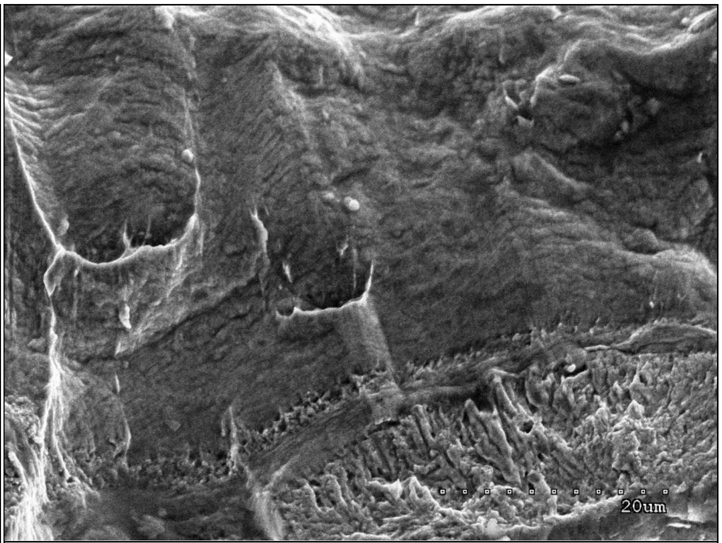

Photo 16: SEM image Mag: 1600X
Fatigue fracture surface of secondary fatigue crack after opening the secondary fatigue crack by cutting.

Metallographic Examination

1. A metallographic cross section though the middle of the primary fatigue initiation site (see Photos 17 – 18) revealed braze metal infiltration into the austenitic grain boundaries with some braze metal present on the fracture surface near the initiation site (see Photos 19 – 20).

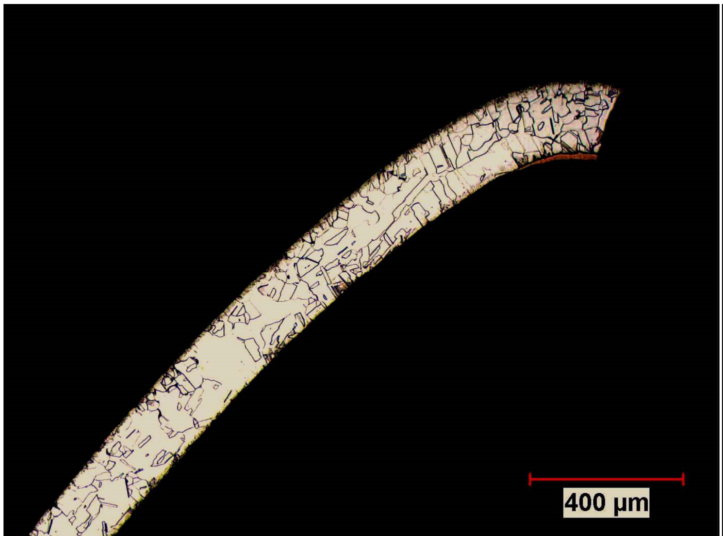

Photo 17: Magnification: 50X; Etchant: Acetic Glyceregia
Cross section through middle primary fracture bellows side.

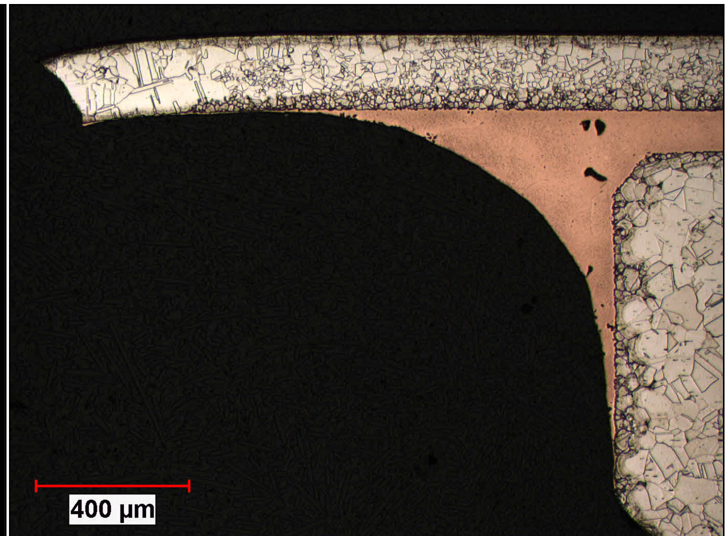

Photo 18: Magnification: 50X; Etchant: Acetic Glyceregia
Cross section through middle primary fracture braze side.

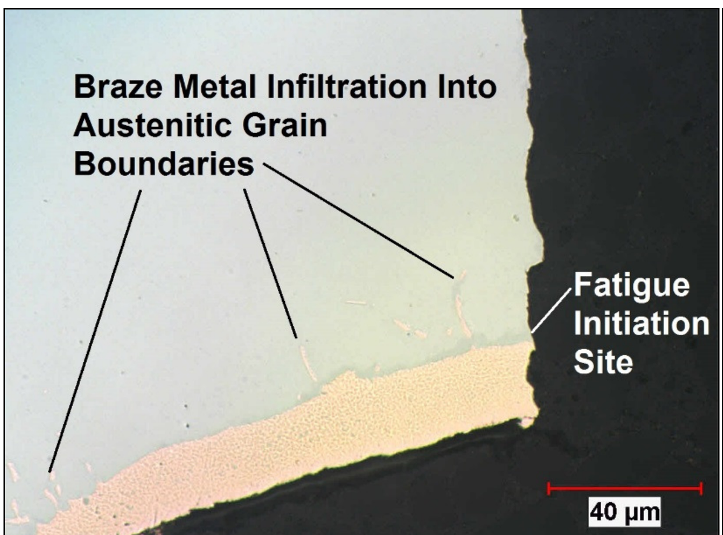

Photo 19: Magnification: 500X; Unetched
Cross section of primary fatigue initiation site on bellows side of fracture.

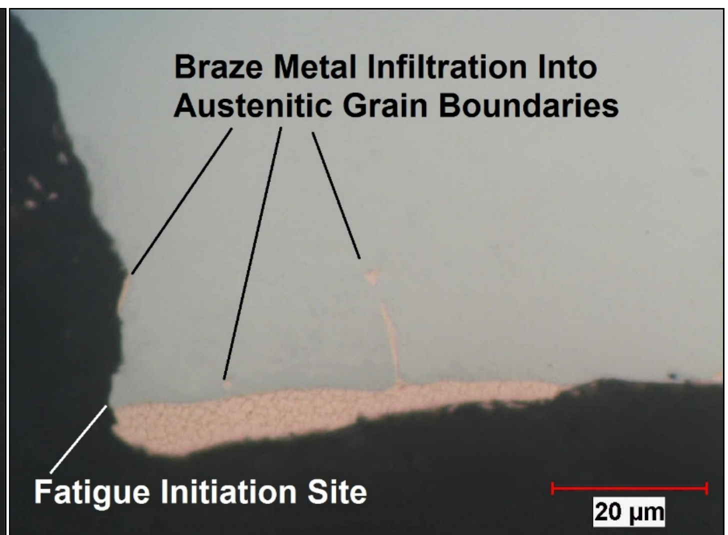

Photo 20: Magnification: 1000X; Unetched
Cross section of primary fatigue initiation site on brazed side of fracture with braze metal present on fatigue fracture surface.

2. The thickness of the bellows walls varied from the thickness at the fatigue initiation site of 196 µm (see Photo 21) to the thinnest walls of 112 µm in the middle of the bellows' bend (see Photo 22).

Metallographic Examination (cont.)

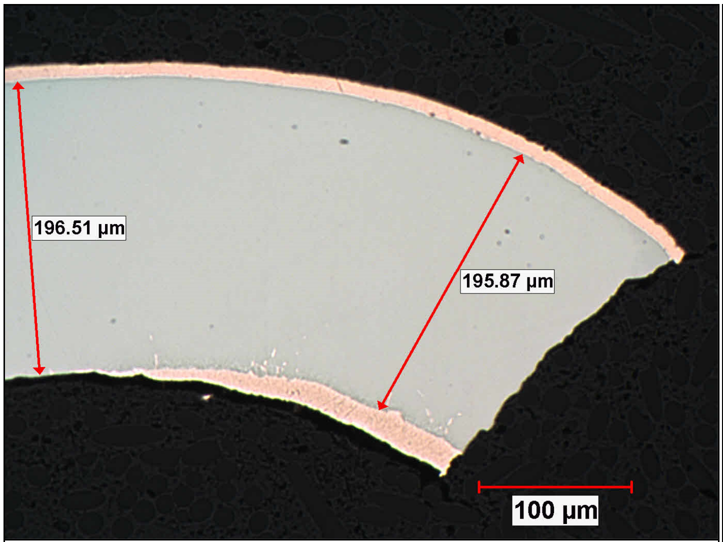

Photo 21: Magnification: 200X; Unetched
Thickness of bellow at fracture initiation site (bellows side of fracture).

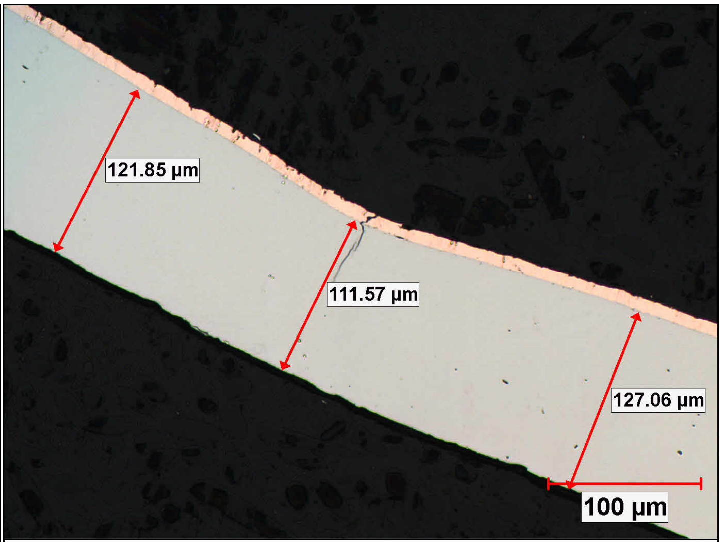

Photo 22: Magnification: 200X; Unetched
Thinnest bellows wall observed in middle of 180° bend with short crack initiating on inner wall – most likely an artifact from cutting.

3. The microstructure at the primary fatigue initiation site showed transgranular fracture through the coarse austenitic grains with cold working slip bands (see Photos 21 – 22).

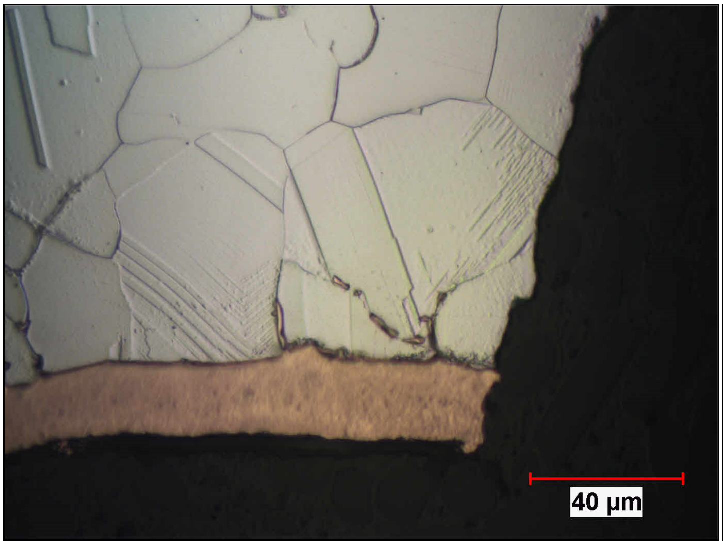

Photo 23: Magnification: 500X; Etchant: Acetic Glyceregia
Cross section through middle primary fracture bellows side.

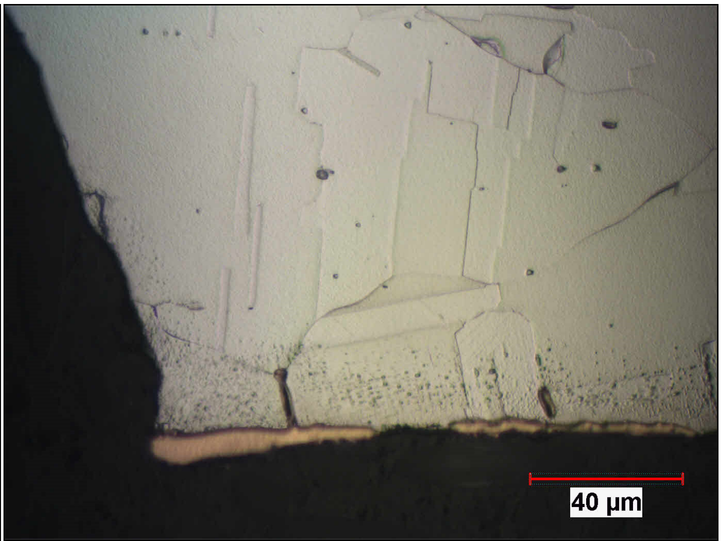

Photo 24: Magnification: 500X; Etchant: Acetic Glyceregia
Cross section through middle primary fracture braze side.

Micro Indentation Hardness Testing

1. Micro indentation hardness testing using a Vickers diamond indenter with 500g load (per ASTM E384) revealed the thin cold worked stainless steel bellows measured hardness ranged from 164 HV_{500} on the straight sections to a high of 224 HV_{500} at the deformed (bent) corners. The fatigue initiation site measured 193 HV_{500}.

2. The measured hardness of the thin stainless steel at the fractured brazed end ranged from 162 HV_{500} at the fracture initiation site to a lower 156 HV_{500} at the brazed joint.

3. The stainless steel base ring brazed to the bellows measured 134 HV_{500}.

Chemical Testing

1. Chemical testing revealed the sample conforms to Type 316L stainless steel per ASTM A240.

2. The results are shown in Table 1 below in weight percent in an iron matrix.

Table 1 – Chemical Testing*

Element	Bellows	T316L
Carbon	0.025	0.030 max
Manganese	1.60	2.00 max
Phosphorus	0.034	0.045 max
Sulfur	<0.005	0.030 max
Silicon	0.40	0.75 max
Nickel	10.24	10.0 – 14.0
Chromium	16.87	16.0 – 18.0
Molybdenum	2.06	2.00 – 3.00
Copper	0.54	--
Hydrogen	4.5 PPM	--

* Hydrogen, carbon and sulfur analysis performed in accordance with ASTM E1019.
Other elements determined by ICP-MS per ASTM E1479.

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