

Friction-Stir Welding – Heavy Inclusions in Bi-metallic welds of Al 2219/2195

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Abstract

Heavy Inclusions (HI) were detected for the first time by radiographic examination in aluminum alloy 2219forging/2195plate (advancing/retreating side) Friction Stir Welds (FSW) for the Space Shuttle External Tank (ET) Program. Radiographic HI indications appear as either small (~0.005” – 0.025”) individual particles or clusters of small particles.

Initial work was performed to verify that the HI was not foreign material or caused by FSW pin tool debris. That and subsequent elemental analysis determined that the HI were large agglomerations of Al₂Cu (θ phase), which is the strengthening precipitate in Al2219. A literature search on that subject determined that the agglomeration of θ phase has also been found in Al2219 bead on plate FSW [Ref. 1].

Since this was detected in ET space flight hardware, an investigative study of the effect of agglomerated theta phase particles in FSW Al2219f/2195p was performed. Numerous panels of various lengths were welded per ET weld procedures and radiographically inspected to determine if any HI was detected. Areas that had HI were sampled for room temperature and cyclic cryogenic (-423F) tensile testing and determined no significant adverse affect on mechanical properties when compared to test specimens without HI and historical data.

Fracture surface examination using the Scanning Electron Microscope (SEM) revealed smaller θ phase agglomerations undetectable by radiographic inspection dispersed throughout the Al2219f/2195p FSW. This indicates that θ phase agglomeration is inherent to the Al2219f/2195p FSW process and only rarely creates

agglomerations large enough to be detected by radiography. HI has not been observed in FSW of plate to plate material for either Al2219 or AL2195.

Introduction

Friction Stir Welding for the ET is accomplished with a multiple piece pin tool rotating at several hundred RPM and traversing a butt welded joint of the same design configuration used for fusion welding. A plunge load is imparted through a spindle driven by a FSW machine and reacted against a backside anvil. Frictional heating under the pin tool shoulder and around the pin tip generate sufficient heat to locally plasticize the aluminum alloys to be welded. Tool rotation during the FSW process imparts a material flow in three dimensions within the plasticized weldment, causing complete mixing of the alloys, and consolidation of the weldment occurs via an extruding/forging action under the pin tool shoulder as the pin tool is traversed down the length of the weld. Figure 1 shows a schematic representation of the FSW process and Figure 2 shows the nominal transverse macrostructure of the FSW.

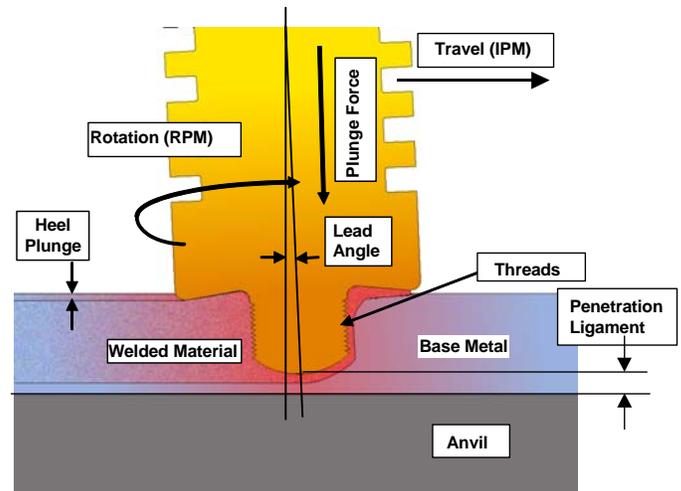


Figure 1: FSW Process

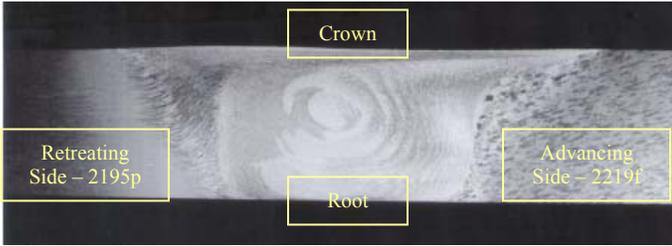


Figure 2: 2219f/2195p FSW

Friction stir welding is performed on longitudinal barrel welds on the ET. Two of those welds are bimetallic welds of Al2219 forging and Al2195 plate with the Al2219 on the advancing side and the Al2195 on the retreating side (2219f/2195p). A Retractable Pin Tool (RPT) is used due to tapering thickness of the weld joint. After barrels are welded, they are inspected by multiple NDE techniques, including radiographic inspection. Radiographic inspection of the Al2219f/2195p FSW has shown scattered HI indications in the thinner gauge sections in some production welds. These HI indications appear bright (higher in density) in the film and typically appear dispersed across the weld in small clusters as shown in Figure 3.

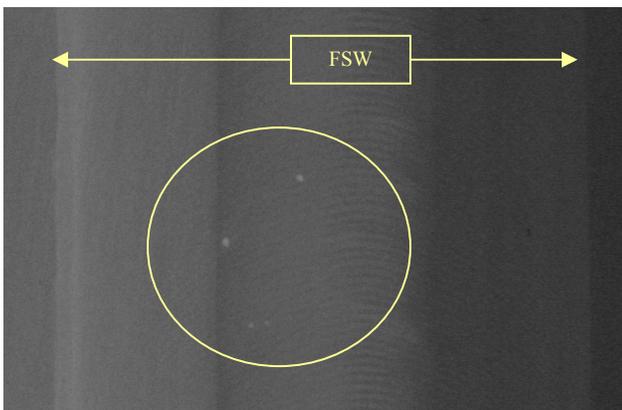


Figure 3: X-Ray film of 99HI-SST prior to machining – digitally enhanced

HI has been a rejectable condition since the implementation of FSW on the ET program and historically has not been observed except for rare instances of foreign debris. An investigation was performed to determine the nature of the observed

HI. Initial work showed that the HI was not foreign material, but a large copper rich phase and was observed only in FSW of Al2219f/2195p.

Investigative Approach

A test plan was generated to recreate and test the HI indications using materials and configurations matching flight hardware. Remnant forged Al2219 material, Al2219 plate and Al2195 plate panels were welded (Figure 4), inspected, and had mechanical property testing performed.

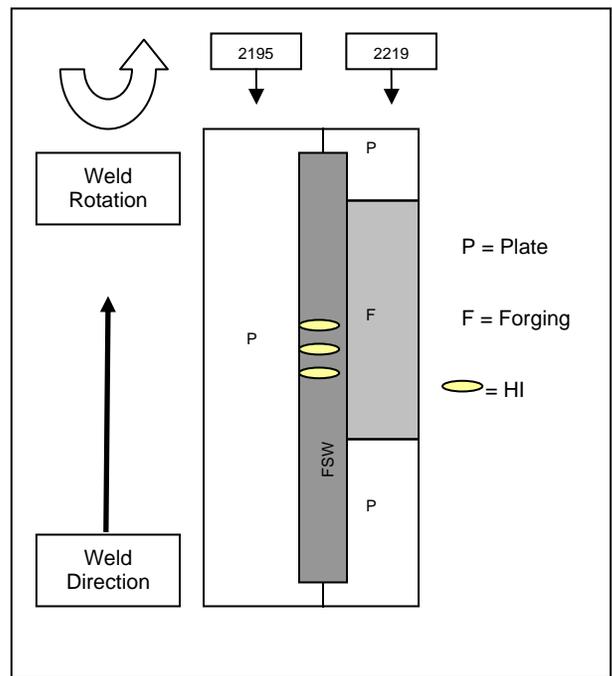


Figure 4: FSW top view layout for Test Panels

Two ~17ft Al2219f/2195p panels were FS welded and radiographically inspected to determine the presence of HI. After initial radiography, and post weld prep to remove flash, additional radiographic and phased-array ultrasonic inspections were performed prior to test specimens being excised.

Due to the limited number of HI clusters created, three Room Temperature (RT) tensile specimens and two Simulated Service Test (SST) cryogenic (-423F) specimens with radiographic HI were excised. Five other RT tensile specimens without radiographic HI were also excised to be

used as a control, while also using historical data for comparison. All test specimens were proof tested up to ~32ksi at room temperature and had post-proof NDE performed to determine if any changes to the HI or surrounding material were detected (i.e. crack growth). Following proof test and NDE, the RT tensile specimens were tested to ultimate fracture. Following proof test and NDE, the SST specimens were cycled through 4 mission lives at -423F, had post mission cycle NDE, and then tested for residual tensile strength at -423F.

Certain specimens were selected to have Scanning Electron Microscopy (SEM) examination including Energy Dispersive Spectroscopy (EDS) and metallographic examination to further characterize the HI and determine if any detected HI was involved in the fracture path.

Results / Discussion

Room temperature results showed that all HI specimens were in family with the tensile specimens without HI. No post proof NDE (radiography and penetrant) changes/indications were noted.

Specimen 95HI was chosen to be examined in the SEM to see if the HI was involved in the fracture path due to its fracture through the weld as shown in Figure 5. Typically aluminum alloy FSW's fracture in the Heat Affected Zone (HAZ) as in Figure 6.

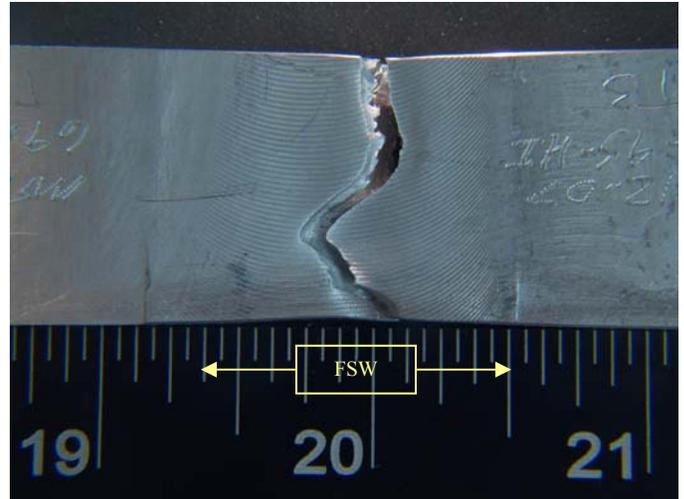


Figure 5: 95HI Crown Side View Post Fracture – weld fracture

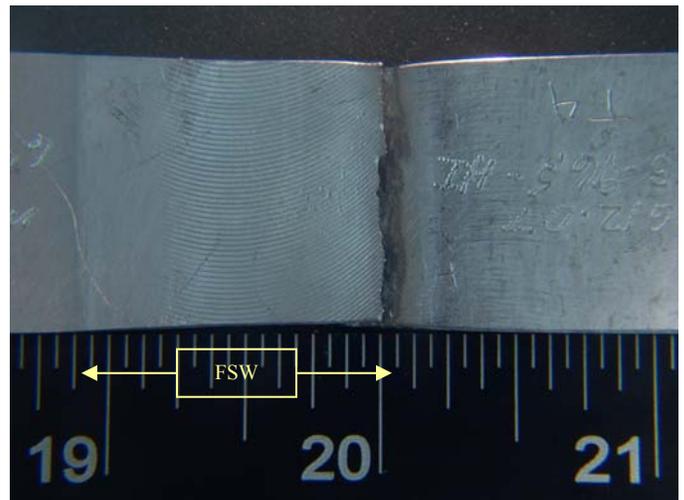


Figure 6: 95.5HI Crown Side View Post Fracture – HAZ fracture

Backscattered Electron (BSE) SEM examination of the fracture surfaces of 95HI showed several regions of higher density agglomerated material that followed the FSW flow pattern as shown in Figures 7-9. EDS analysis (Figure 10) identified the agglomerated material as Al_2Cu (θ phase). However, these regions do not correspond with the radiographic indications. The larger radiographic HI (agglomerated θ phase) were not involved in the fracture. What was observed in the SEM is agglomerated θ phase that is undetectable by radiographic inspection due to its size.

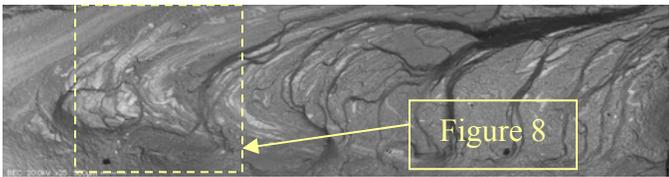


Figure 7: Composite BSE SEM image of 95HI at 25x original magnification

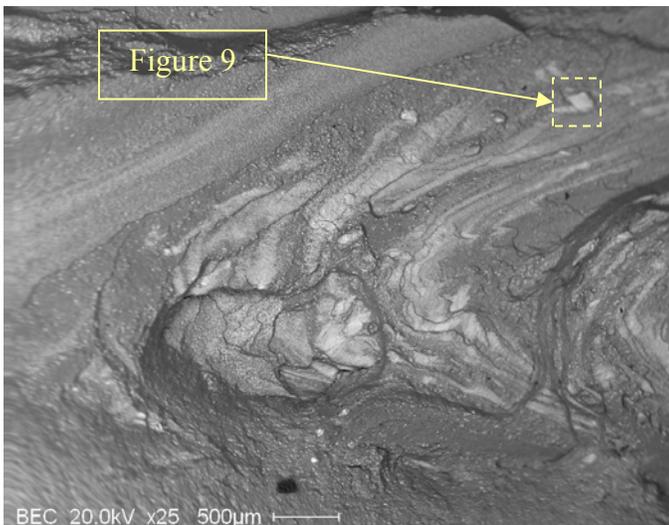


Figure 8: BSE SEM image of 95HI at 100x original magnification

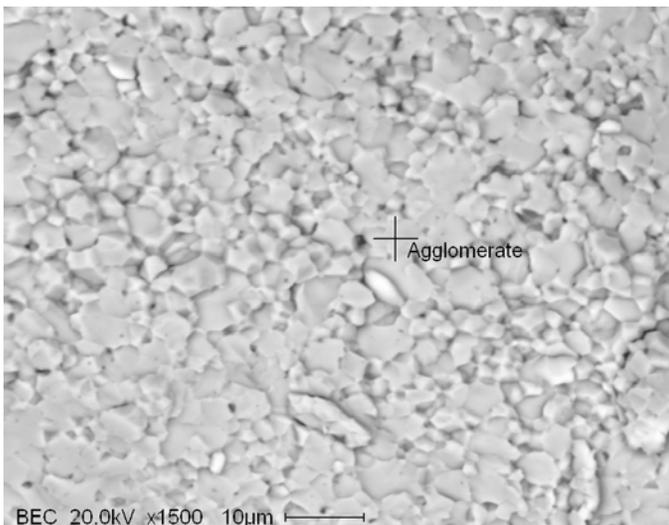


Figure 9: BSE SEM image of 95HI at 1500x original magnification

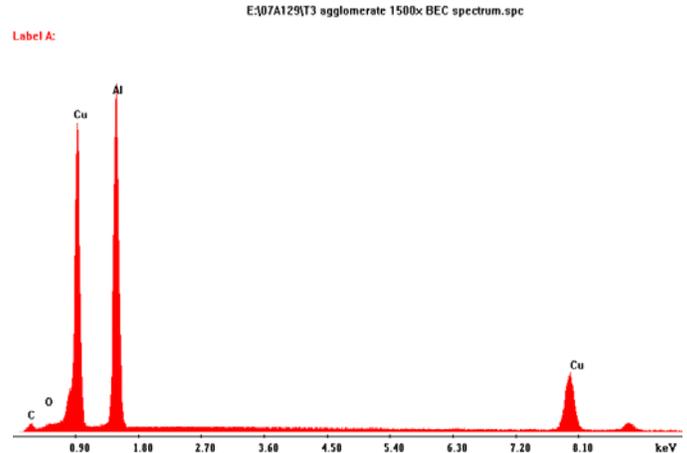


Figure 10: EDS Spectra of 95HI agglomerate (Figure 9)

RT specimen 125.5, which had no radiographically detectable HI was machined to force a fracture through the FSW in order to use as a control for the SEM examination (Figure 11). This specimen also showed streaks of agglomerated θ phase, but to a much lesser extent as shown in Figures 12 & 13. EDS spectra were similar to those in Figure 10. Thus, a dispersion of agglomerated θ phase may be normally present throughout bimetallic FSW using Al2219 forging on the advancing side.

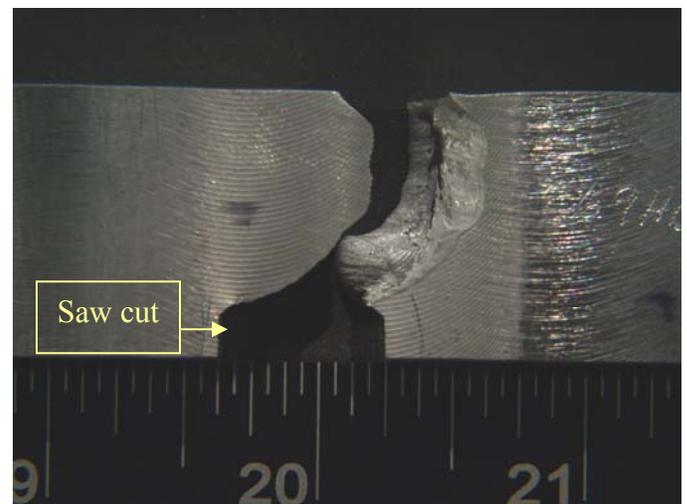


Figure 11: 125.5 Crown Side View Post Fracture

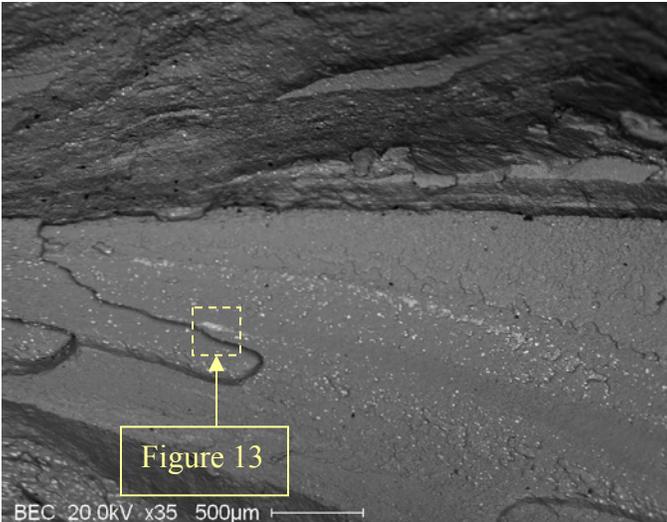


Figure 12: BSE SEM image of 125.5 at 35x original magnification

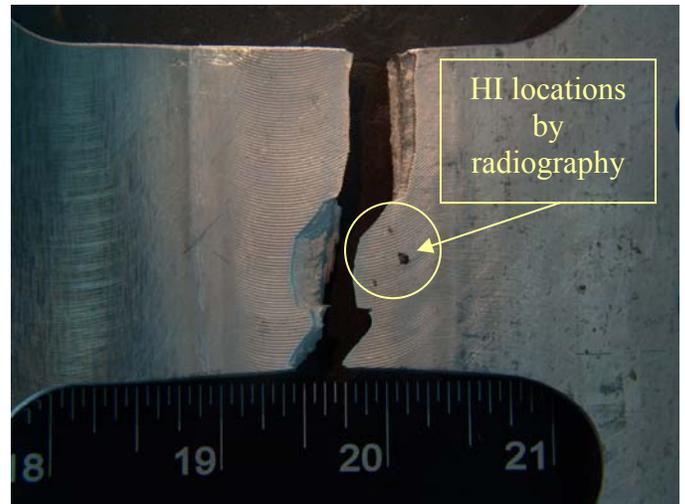


Figure 14: 99HI-SST Crown Side View Post Fracture

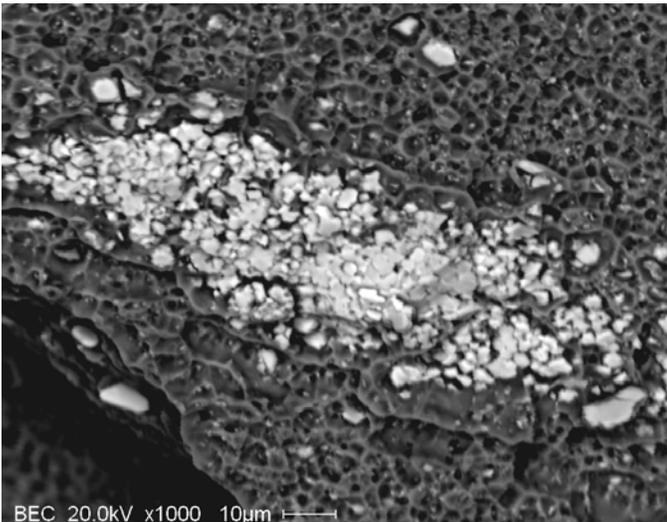


Figure 13: BSE SEM image of tensile 125.5 at 1000x original magnification

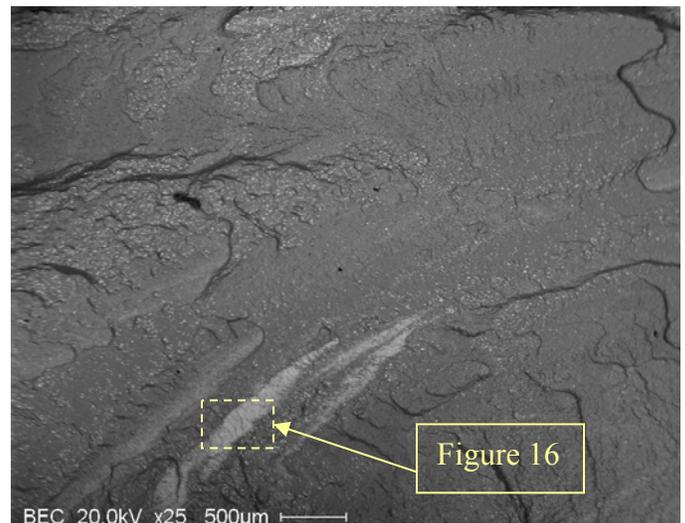


Figure 15: BSE SEM image of 99HI-SST at 25x original magnification

Simulated Service Test (SST) residual strength results were in family to typical Al2219f/2195p FSW cryogenic (-423F) results. SEM/EDS examination showed that one region of agglomerated θ phase on the fracture face correlated to the radiographically detected HI as seen in Figures 14-17.

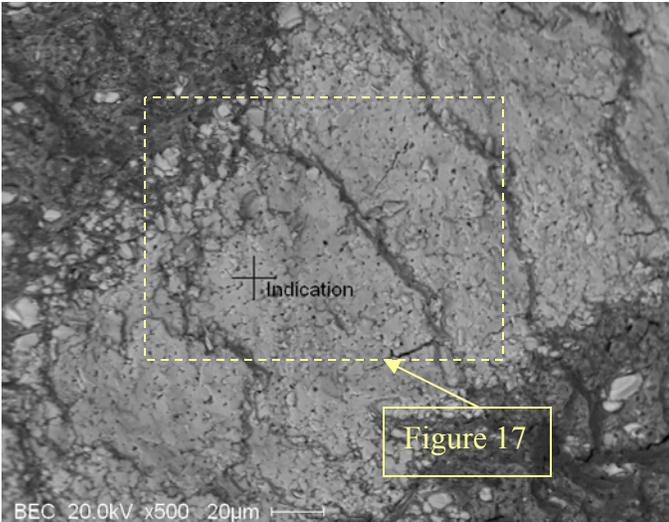


Figure 16: BSE SEM image of 99HI-SST at 500x original magnification

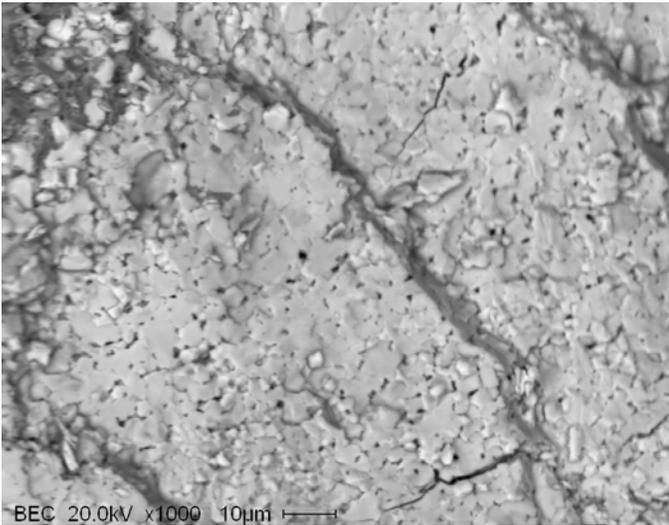


Figure 17: BSE SEM image of 99HI-SST at 1000x original magnification

Metallurgical examination revealed that other radiographically detected HI were not involved in the fracture, but created a secondary surface crack as shown in Figures 18-20. Since no post proof or post-cycle indications were noted by penetrant, the surface crack likely initiated at stresses close to ultimate fracture of the FSW.

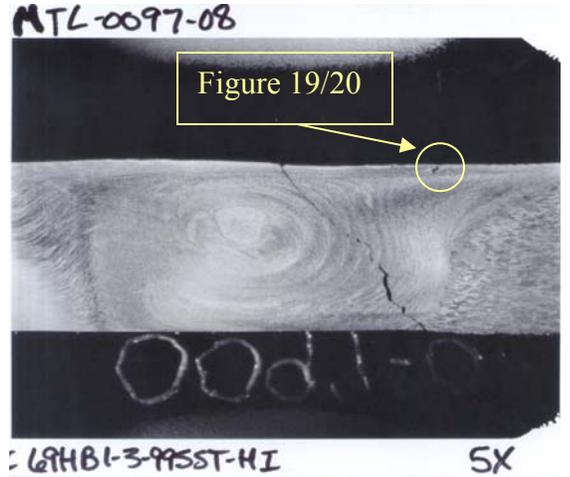


Figure 18: Macro cross section of 99HI-SST post fracture – Keller’s etch 5x



Figure 19: cross section of 99HI-SST post fracture showing HI near crown surface – Scale is 0.005” – Keller’s Etch 100x



Figure 20: cross section of 99HI-SST post fracture showing HI near crown surface – scale is 0.002” - Keller’s Etch 200x

Conclusions

The Friction Stir Welded test panels successfully recreated HI as observed in flight hardware radiographic inspections of Al2219f/2195p Friction Stir Welds.

HI has only been detected by radiographic inspection in FSW that have forged Al2219 material on the advancing side of the butt joint. This is likely due to the fact that Al2219 forgings have higher % copper at the surface and can have larger θ phase precipitates.

The HI was shown to be large agglomerations of θ phase precipitates created from the homogeneous θ phase present in the Al2219 forging and is typically near the crown side surface of the FSW.

Based on fracture surface examination smaller θ phase agglomerations which are not detectable by radiographic inspection are dispersed throughout the Al2219f/2195p FSW. This indicates that θ phase agglomeration is inherent to the Al2219f/2195p FSW process and only at times creates agglomerations large enough to be detected by radiography.

The radiographically detectable HI did not noticeably affect mechanical properties of the FSW or significantly reduce residual strength of simulated service specimens. Secondary cracking at HI locations appear to occur at stresses near ultimate as no post proof cracking was observed.

Acknowledgements

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References

1. G. Cao & S. Kou: "Friction Stir Welding of 2219 Aluminum: Behavior of θ (Al_2Cu) particles", The Welding Journal, pg 1-s – 8-s, Jan 2005



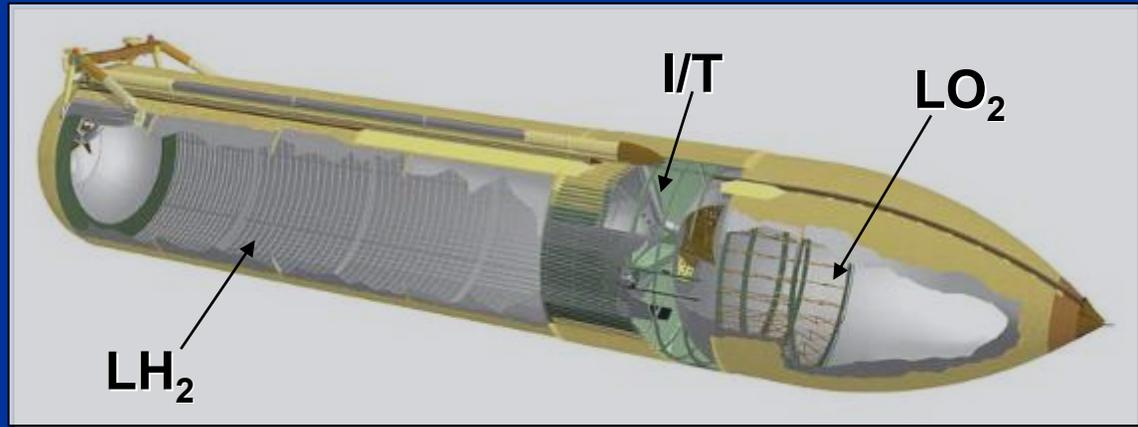
Trends in Welding Research 2008

Friction-Stir Welding – Heavy Inclusions in Bi-metallic Welds of Al 2219/2195



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Space Shuttle External Tank



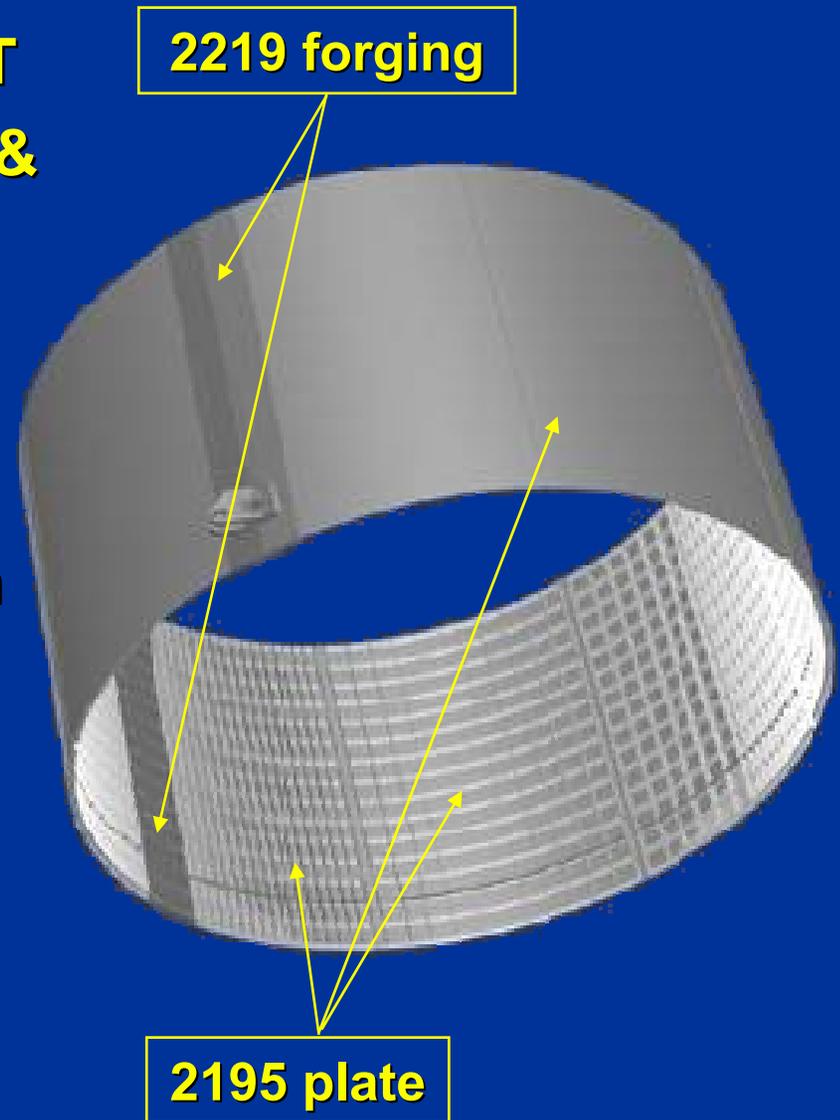
- Built in New Orleans, LA
- External Tank is the Structural backbone of the Space Shuttle System
 - Absorbs 7.8 Million lbs of Load at liftoff
- Consists of a LH₂ tank (383k gal), LO₂ tank (143k gal), and a structural intertank.
- Propellant tanks are welded structures (FSW and fusion)



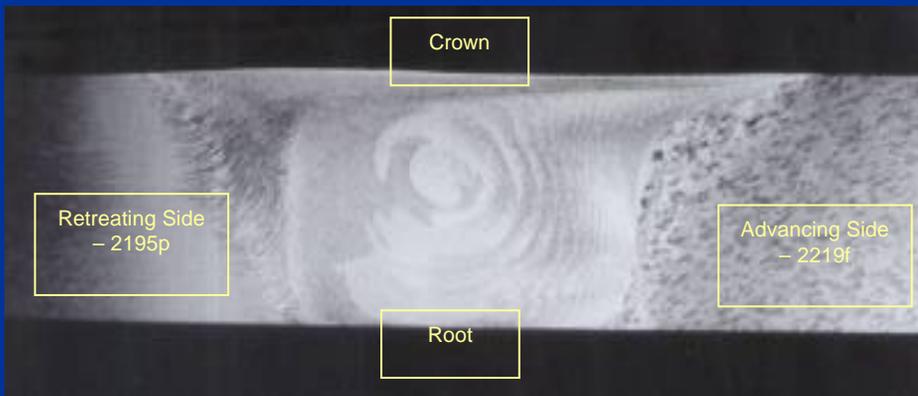
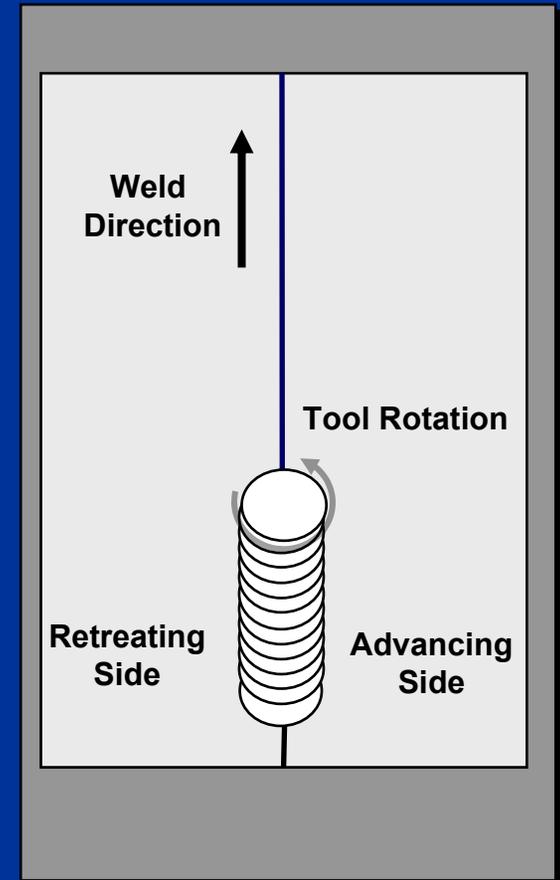
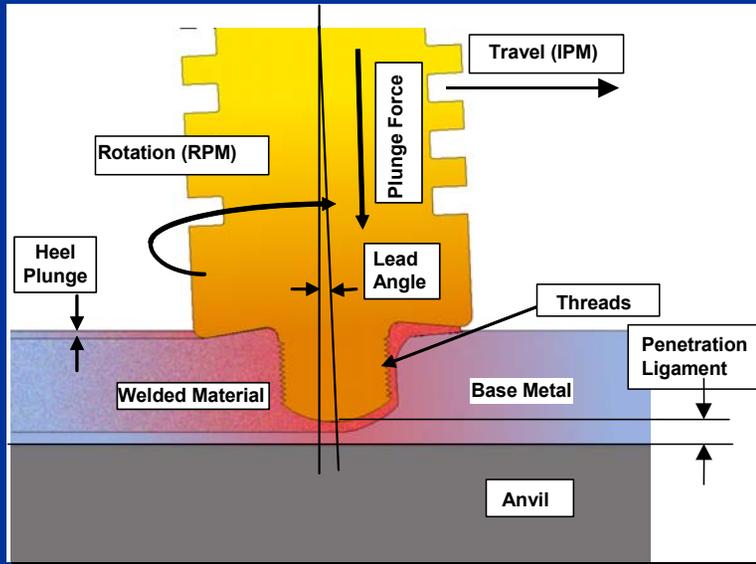
FSW on the External Tank



- Longitudinal welds only on ET
 - 2195p/2195p, 2195p/2219f, & 2219f/2195p welds
- Over 120 welds completed to date!
 - 16 were bimetal welds
- Today's discussion is only on bimetal welds
 - 2219f/2195p (adv/ret)
 - f = forging
 - p = plate



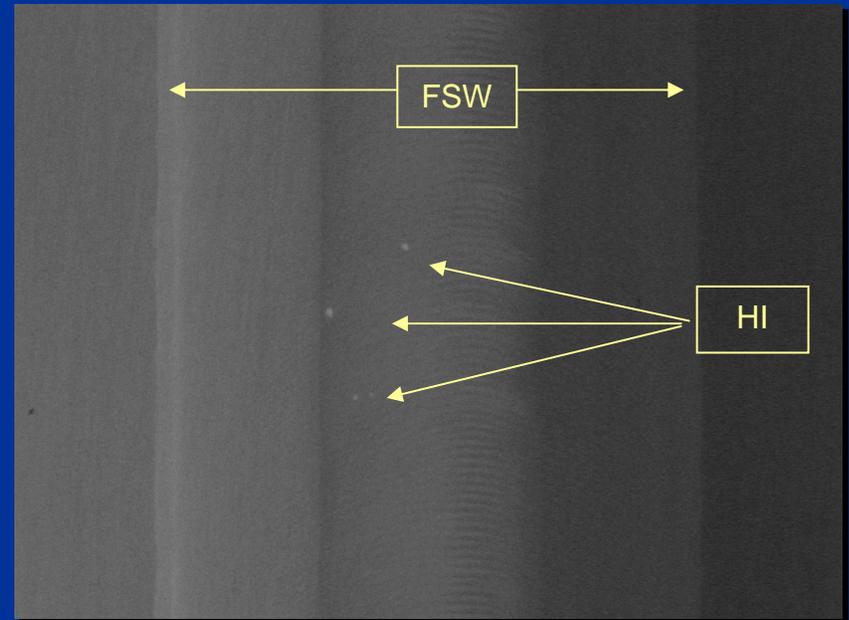
FSW on the External Tank (2)



X-Ray Heavy Inclusions (HI)



- **PROBLEM:** scattered heavy inclusions (~0.005" – 0.025") were detected in our first production 2219f/2195p welds by X-Ray
- HI are rejectable in FSW on the ET program
- HI were not pin tool / foreign debris
- Never detected HI on 2219plate/2195plate FSW development work

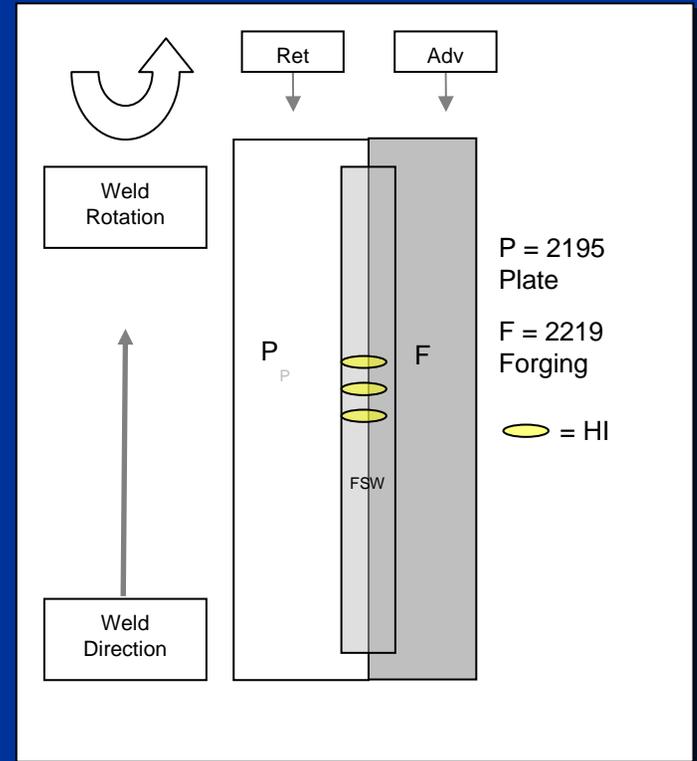


Digitized X-ray Film showing HI



Test Approach

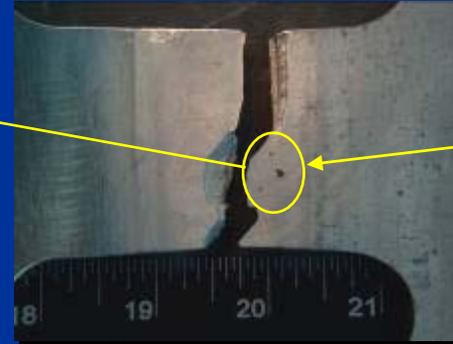
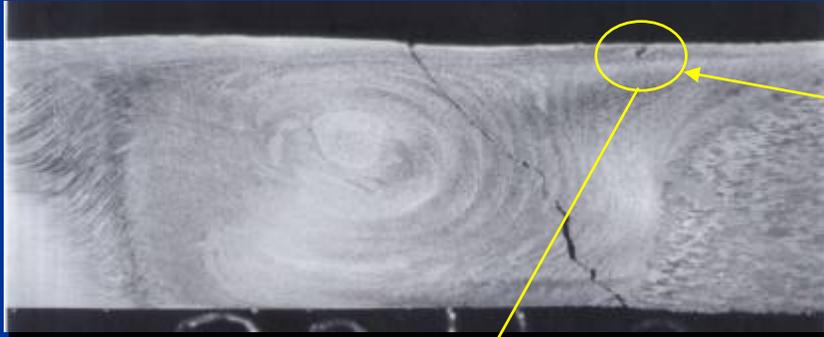
- 2 ~17ft panels were welded
 - Post weld NDE on each
 - Areas of HI were sectioned for testing
 - 3 RT Tensiles
 - 2 -423F Simulated Service Tensiles
 - Selected test specimens were examined in SEM and using metallographic methods



Simplified test panel layout



Metallographic Results



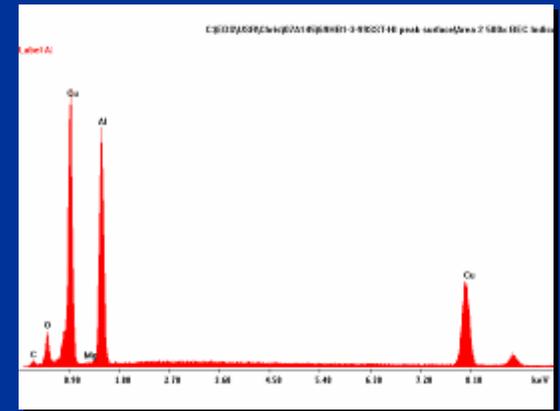
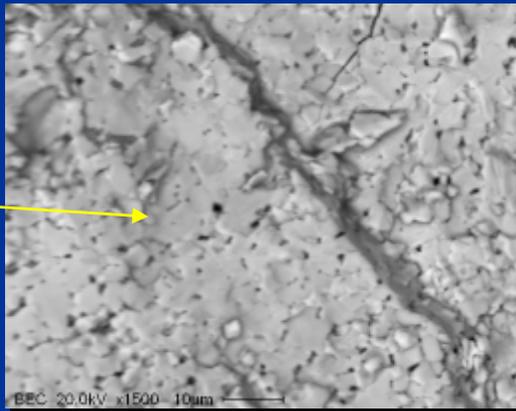
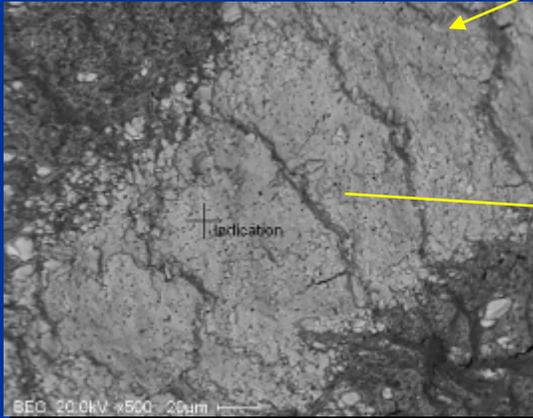
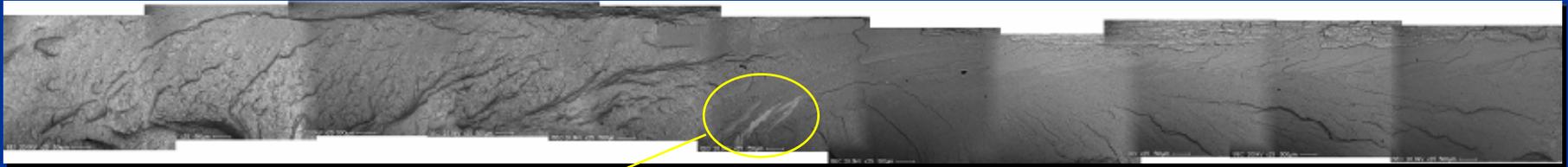
X-Ray HI's



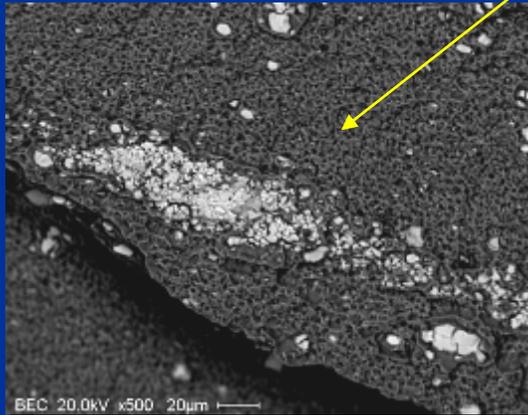
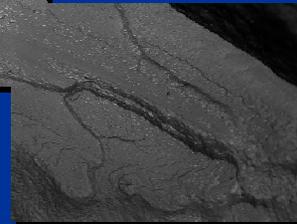
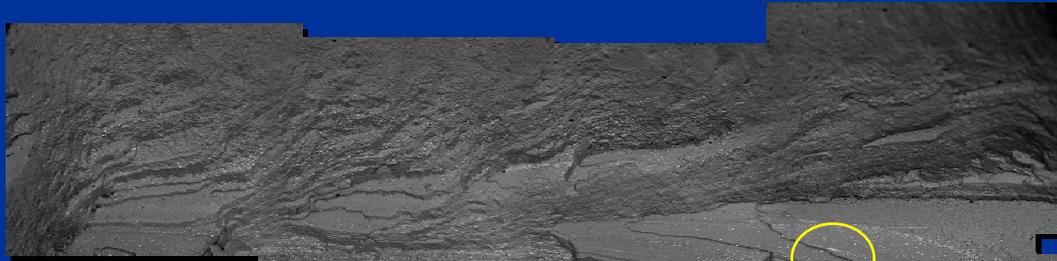
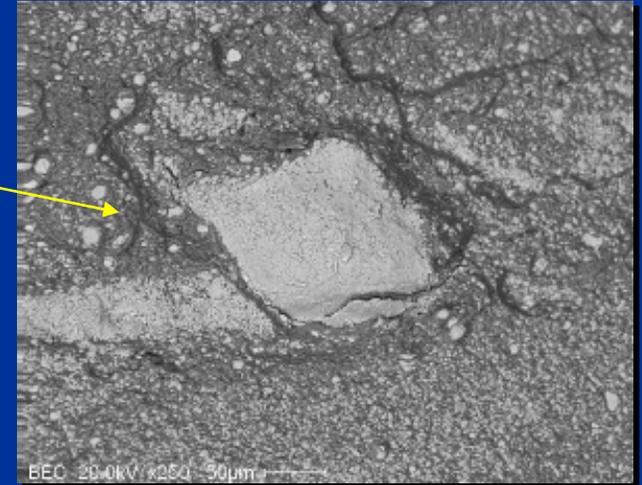
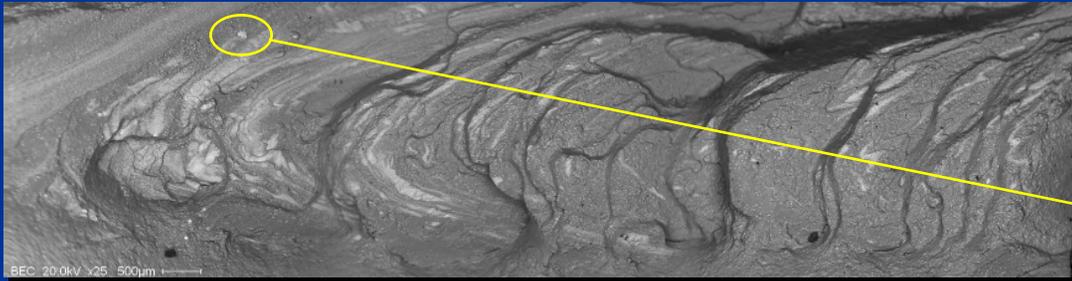
Agglomerated θ phase



SEM Results - -423F SST



SEM Results – RT Tensiles



• Agglomerated θ phase (to a lesser extent) in fracture surface with no corresponding X-ray indication!



Tensile Results (Room Temp)



- **Proof tested to ~32ksi @ RT**
- **Post proof NDE (X-Ray & Penetrant) to verify no change in HI (crack growth)**
- **HI showed no affect on mechanical properties**



Simulated Service Results



- **Proof tested to ~32ksi @ RT**
- **Post proof NDE (X-Ray & Penetrant) to verify no change in HI (crack growth)**
- **4 Mission Lives for load spectrum @ -423F (simulating ET service x4)**
- **Post mission NDE (X-Ray & Penetrant) to verify no change in HI (crack growth)**
- **Test to UTS @ -423F to test residual strength**
- **HI showed no affect on properties**



Conclusions



- Radiographic HI only observed in FSW of 2219 forging / 2195 plate (adv/ret) on our tooling configuration starting approx 8-10 feet into the weld
- HI is agglomerated θ phase
- θ phase agglomeration is a natural part of the FSW process
 - Can cause agglomerations large enough to be detected in X-ray
- Radiographically detected HI does not affect mechanical properties (tensile / fracture)



