Friction stir welding is a solid state welding process used in the fabrication of various aerospace structures. Self-reacting and conventional friction stir welding are variations of the friction stir weld process employed in the fabrication of cryogenic propellant tanks which are classified as pressurized structure in many spaceflight vehicle architectures. In order to address damage tolerance behavior associated with friction stir welds in these safety critical structures, nondestructive inspection and proof testing may be required to screen hardware for mission critical defects. The efficacy of the nondestructive evaluation or the proof test is based on an assessment of the critical flaw size. Test data describing fracture behavior, residual strength capability, and cyclic mission life capability of friction stir welds at ambient and cryogenic temperatures have been generated and will be presented in this paper. Fracture behavior will include fracture toughness and tearing (R-curve) response of the friction stir welds. Residual strength behavior will include an evaluation of the effects of lack of penetration on conventional friction stir welds, the effects of internal defects (wormholes) on self-reacting friction stir welds, and an evaluation of the effects of fatigue cycled surface cracks on both conventional and self-reacting welds. Cyclic mission life capability will demonstrate the effects of surface crack defects on service load cycle capability. The fracture data will be used to evaluate nondestructive inspection and proof test requirements for the welds.
Damage Tolerance Behavior of Friction Stir Welds in Aluminum Alloys

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NASA Human Space Flight Requirements

- NASA safety requirements call for fault tolerance or a minimum risk approach for human rated flight hardware
- Damage tolerance is one element of a minimum risk approach
- Basic philosophy behind damage tolerance is mitigating risk associated with a part failing from a crack or crack-like defect

Damage Tolerance is a Multi-Disciplined Endeavor

- Design, analysis, NDE, process control, quality control, acceptance testing (proof testing) and material behavior
- Particular interest in behavior of material with cracks or crack-like defects

Damage Tolerance Approach

- Process Control
- Residual Strength Behavior
- Nondestructive Evaluation
- Proof Test
Applications

Space Shuttle External Tank

- Pressurized Structure
- Conventional Friction Stir Welds
  - ET 132, ET133 through ET 138
    - 2195/2195 Longitudinal Hydrogen Tank Barrel Welds
  - ET134 through ET 138
    - 2195/2195 Longitudinal Oxygen Tank Barrel Welds
    - 2219/2195 Longitudinal Longeron to Hydrogen Tank Barrel Welds

Reference: Kinchen, 2008
Applications

Constellation Ares I Propellant Tanks
- Pressurized Structure

Manufacturing Demonstration Article
17.5 foot diameter

• Conventional FSW
• Self-Reacting FSW
• Self-Reacting FSW with Termination Hole
Applications

Space Launch System Multi-Purpose Crew Vehicle Stage Adaptor

- Dry Structure – stability critical
- 2195/2195 Barrel Panel to Barrel Panel Longitudinal Conventional Friction Stir Welds
- 2219/2195 Forward and Aft Ring to Barrel Panel Self-Reacting Circumferential Friction Stir Welds
- 16 foot diameter aft end
- 18.5 foot diameter forward end
- Pathfinder in Work
- Structural Test Article in Work
- Engineering Flight Test Article in Work
Applications

Space Launch System Propellant Tanks

- Pressurized Structure
- Liquid Hydrogen Tank
- Liquid Oxygen Tank
- 100% Friction Stir Welded
- Weld Process in Work
- Design in Work
Conventional Friction Stir Weld

Processes

Friction Stir Weld in Progress
Reference: Kinchen, 2008

Nominal Transverse Cross Section

Ref: Nunes, 2011
2195/2195 Conventional Friction Stir Weld with Lack of Penetration Defect, $t = 0.320''$

Test sample with fracture across LOP

Ref: Kinchen, 2000
Self-Reacting Friction Stir Weld

Processes

Nominal Transverse Cross Section

Self-Reacting Weld Tool

Ref: Schneider, 2010
Defect Sizes: 0.013” x 0.010”; 0.007” x 0.010”; 0.010” x 0.005”

2195/2195 Self Reacting Friction Stir Weld with Wormhole Defect, t = 0.327”

Defect Size
0.025” x 0.013”

2219/2014 Self Reacting Friction Stir Weld with Wormhole Defect, t = 0.208”

Defect Sizes: 0.013” x 0.010”; 0.007” x 0.010”; 0.010” x 0.005”
Processes

Friction Pull Plug Weld
Processes

Self-reacting Friction Stir Weld Termination Hole

Hole Enlarged to Accommodate Pull Plug

Pull Plug at “zero” Displacement

Pull Plug at “full” Displacement

Pull Plug after Final Machining
Friction Pull Plug Weld

Base Metal

Plan View of Region Shown in Macro

Plug – Base Metal Interface

Cross Section A-A
Plug - Base Metal

Cross Section B-B
Plug - Friction Stir Weld
Defects in Friction Pull Plug Welding

Liquid Penetrant indications

Ref: Kinchen, 2009
Testing

Surface Crack Tension Test Sample

Failure path in surface crack tension plug panel.

Ductile tearing during simulated proof cycle

Fracture surface in conventional friction stir weld
Friction Stir Weld Pull Plug Residual Strength vs Flaw Size
2014-T6 to 2219-T87

Circled data failed adjacent to flaw.

\[0.45 < \frac{a}{2c} < 0.60\]
Friction Stir Weld Pull Plug Residual Strength vs Flaw Size
2195-T8 to 2195-T8

Normalized Ultimate Strength vs a/t

- 70 F
- -320 F

0.45 < a/2c < 0.60
Normalized Strength vs Surface Crack Length
2195-T8 Self-Reacting and Conventional Friction Stir Weld Various Flaw Locations, 0.250" and 0.320" Thick
70 F, -320 F, and -423 F
0.25 < a/2c < 0.75

Residual Strength/Average Room Temperature Strength

Surface Crack Length (in)

RED = 70° F
BLUE = -320° F
VIOLET = -423° F
Diamond = Self Reacting
Square = Conventional (Ref: Kinchen, 2000)
2195/2195 Conventional FSW LOP
Nominally Zero Peaking and Mismatch
ET and ARES I Upper Stage Test Data

Residual Strength/Average Room Temperature Strength

- 0.320" < t < 0.380"
- 0.250" < t < 0.500"

70 F
-423 F
Conclusions

• Expanding fracture database for friction stir welds and friction plug welds.

• In general residual cryogenic strength of friction stir welds and friction plug welds is higher than residual ambient strengths.

• Critical surface flaws can be reliably detected with liquid penetrant nondestructive evaluation.

• Critical volumetric flaws can be reliably detected with Phased Array Ultrasonic nondestructive evaluation.

• Damage Tolerance Approach
  • Nondestructive Evaluation
    • PAUT
    • Etched Visual

  • Cryogenic toughness greater than room temperature toughness so room temperature proof testing is a viable option for screening mission critical defects.

• Process Control


