Friction Stir Welded Aluminum-Lithium (Al-Li) 2050 Blanks for Spin Forming

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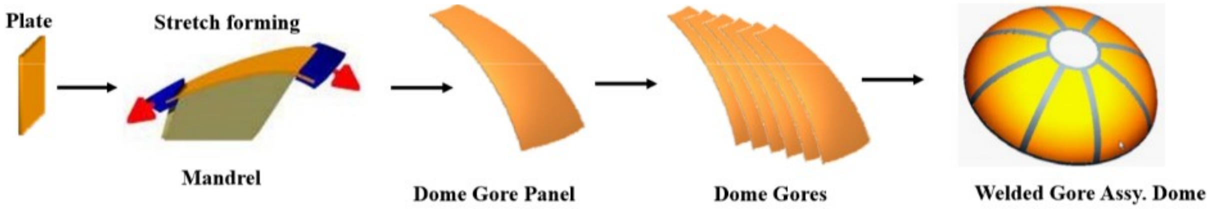
AeroMat 2022 March 15, 2022 Pasadena, CA

Image credit Lockheed Martin unless otherwise indicated

FSW + Spin Forming Background

- **Benefits of FSW + Spin Forming vs. Traditional Gore Construction:**
  - **Improved safety & mission success & lower cost from reduced material quantities, tooling, and production labor**
  - **Reduced part and weld count** (Orion study of single-piece CM shell estimated elimination of over 1,200 inches of welds)
  - **Mass savings from elimination of weld lands** (Orion study estimated elimination of weld lands alone saves 10% mass)
- **Adoption limited by Abnormal Grain Growth (AGG) in FSW zone after post-spin heat treatment**

Traditional Dome/Cone Gore Construction



FSW + Spin Forming Approach

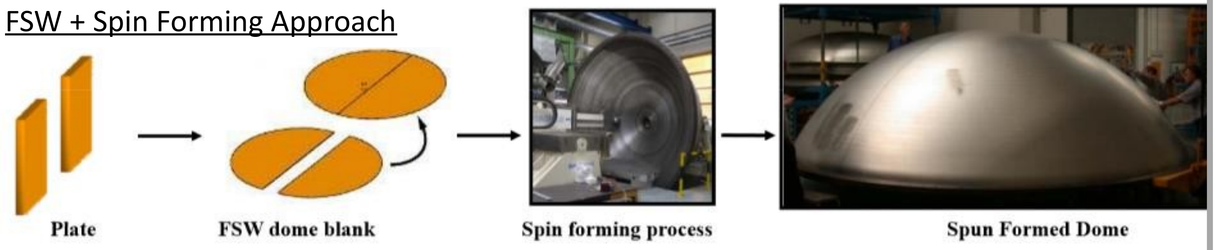
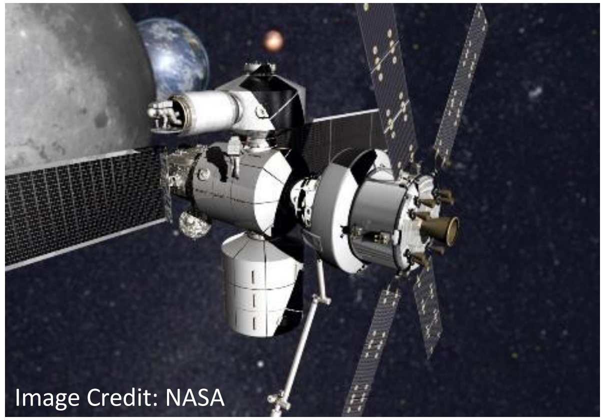


Image Credit: Chen & Russell, NASA-MSFC, 2012

- **Applicable to:**



Crew Vehicle Bulkheads

Orbiting & Surface Habitats

Large Launch Vehicle Domes

2050 Aluminum Lithium Background

- **Benefits of 2050 Al-Li vs. Incumbent Alloys**
  - **2050 plate produced up to a maximum of 6.5” thick per AMS (available up to 8.5” thick)**
    - Compared to 2.25” thick for 2195 Al-Li
  - **2050 has 5% lower density than 2219**
  - **2050-T84 has 27% higher Yield Strength and 17% higher ductility than 2219-T87**
    - For 1.5-2.0” thick plate per MMPDS

Material	LT Ftu (ksi)	LT Fty (ksi)	LT e (%)	ST Ftu (ksi)	ST Fty (ksi)	E (msi)	Density (lb/in^3)
Al 2219-T87 1.5-2” Plate	64	51	6	59	51	10.5	0.103
Al 2050-T84 1.5-2” Plate	73	65	7	71	61	10.9	0.098
Al 2050/Al 2219	1.14	1.27	1.17	1.20	1.20	1.04	0.95

- **Advanced forming of 2050 Al-Li plate**
  - **2-3” thick 2050-T34 plates successfully bump formed and roll formed into cylindrical shapes**
  - **6” thick 2050-T34 plate successfully bump formed into Orion Cone Panel A-F demo article**

Spin Forming of 2050 Al-Li Had Not Been Attempted Prior to This Work

2050 FSW and Post-Weld Heat Treatment (PWHT) Development

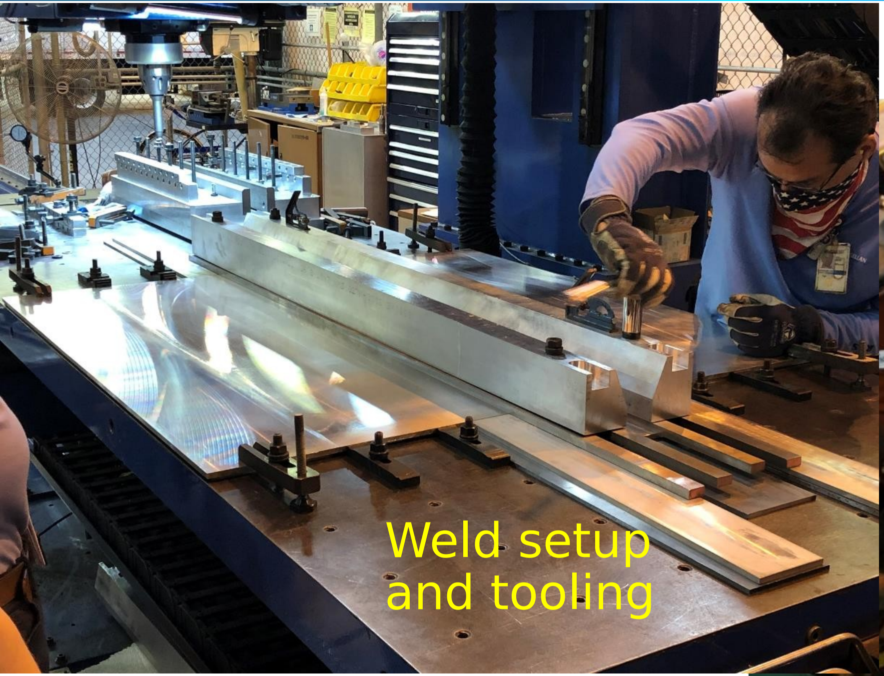
Material	Gauge	Weld Schedule Information	Post Weld Anneal Parameters	UTS (ksi)	YS (ksi)	Forming Range (UTS-YS)	Total Strain (%)	Reference
2050-O	0.320"	A	750°F/3h + air cool	32.6	15.8	16.9	13.2	2020 LM Space IRAD
2050-O	0.320"	A	750°F/3h + air cool	32.7	15.4	17.3	14.2	2020 LM Space IRAD
2050-O	0.320"	B	750°F/3h + air cool	32.4	15.5	16.9	11.2	2020 LM Space IRAD
2050-O	0.320"	B	750°F/3h + air cool	32	15.6	16.4	14.2	2020 LM Space IRAD
2050-O	0.320"	n/a	775°F/1h + air cool (annealed from -T84)	34.2	15.9	18.3	20	2020 LM Space IRAD
2195-O	0.320"	MSFC	750°F/3h + air cool	16.6	11.5	5.1	n/a	Chen & Russell, 2012
2195-O	0.320"	MSFC	Novel parameters developed by NASA	18	9.3	8.7	n/a	Chen & Russell, 2012
2195-O	0.320"	MT Aero	Unknown parameters from MT Aero	22	17.7	4.2	n/a	Chen & Russell, 2012
2195-O	0.320"	MT Aero	Novel parameters developed by NASA	20	11.5	8.6	n/a	Chen & Russell, 2012

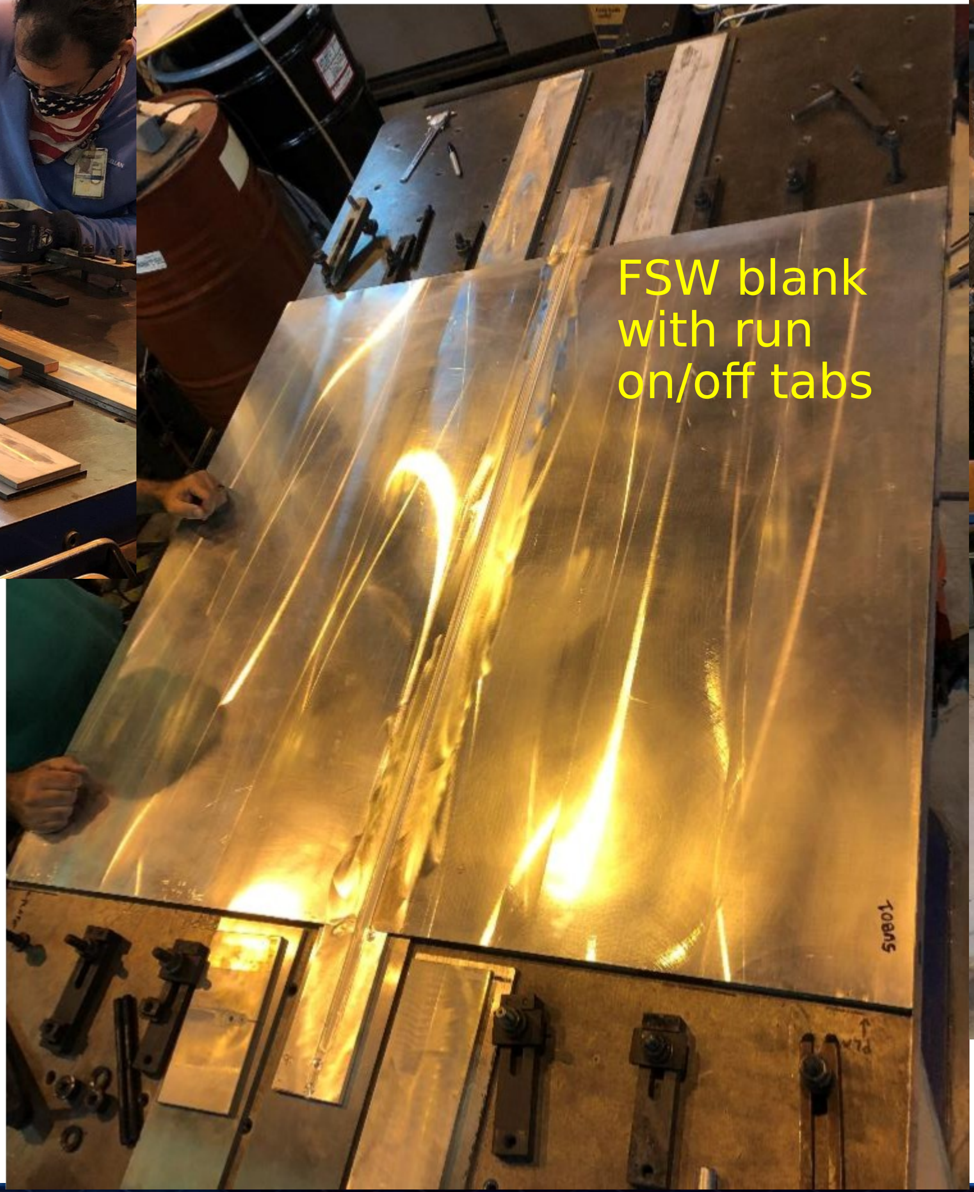
Note: 2050-O coupons tensile tested at 20°C where 2195-O coupons were tested at 200°C

Highlighted parameters selected for implementation on three 48” x 48” x 0.320” subscale blanks

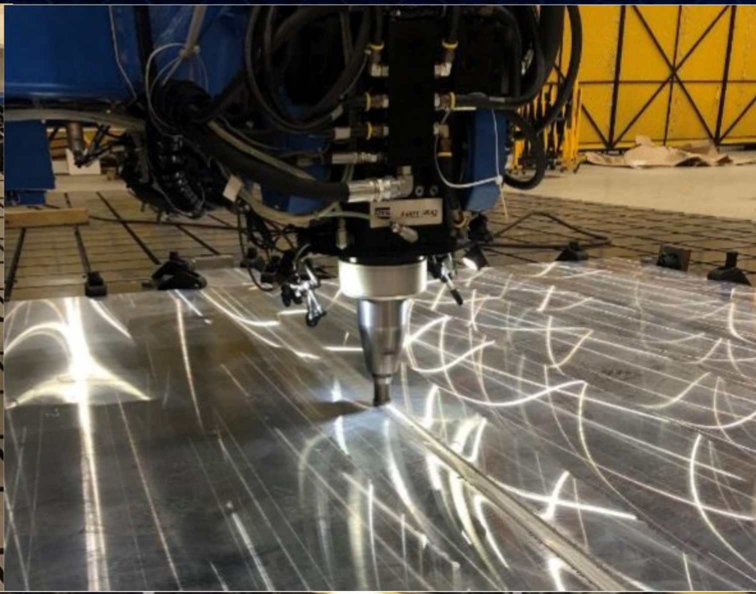
- Improved forming range over 0.320” 2195-O Marshall Space Flight Center (MSFC) weld using identical post weld anneal schedule
- Improved forming range over highest achieved with novel MSFC parameters
- LM “A” schedule performed slightly better than “B” schedule

0.320” 2050-O FSW Subscale Blanks

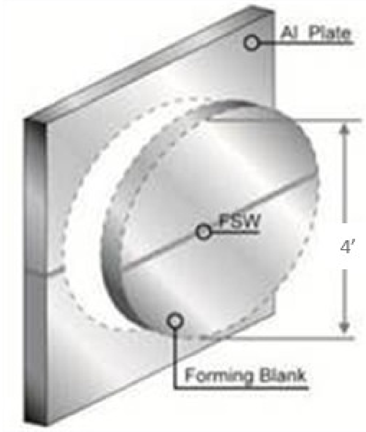


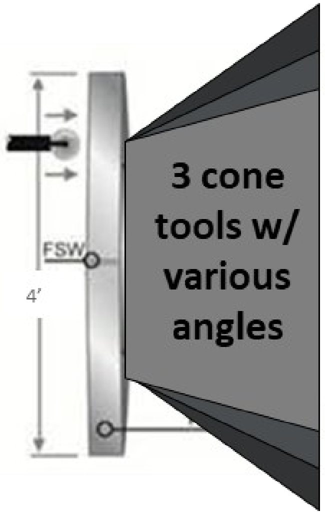


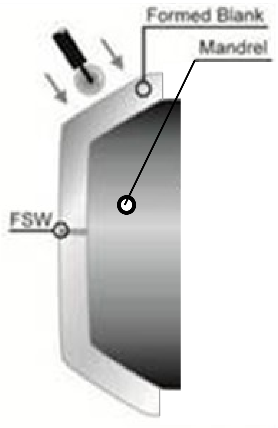
1.5” 2050-T34 Full Scale Blank



2050 FSW Subscale Blank Spin Forming

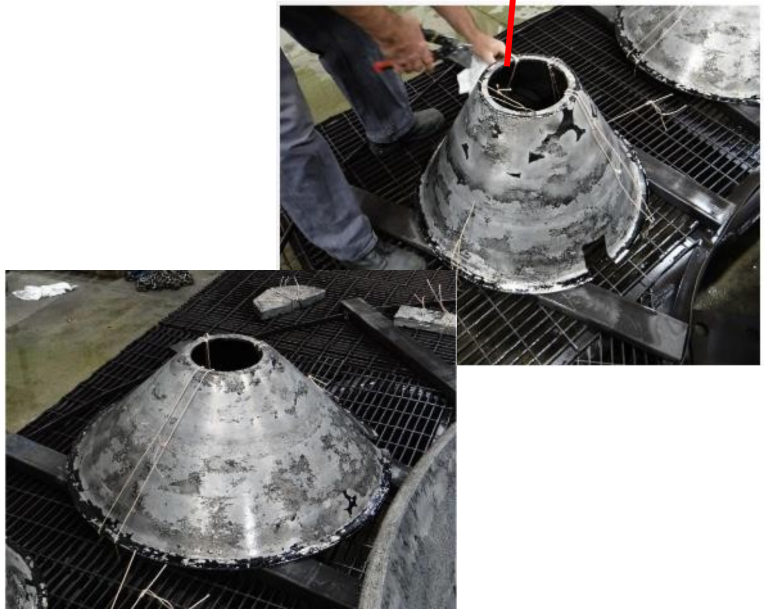




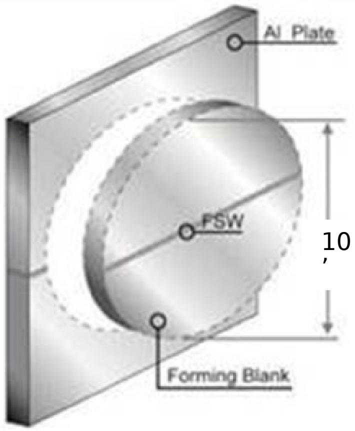


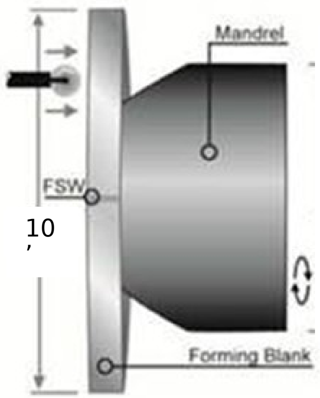
Waterjet Cutting ***(Post-Weld Heat Treating)*** **Tooling Setup** **Spin Forming** **Post-Spin Form Heat Treating**

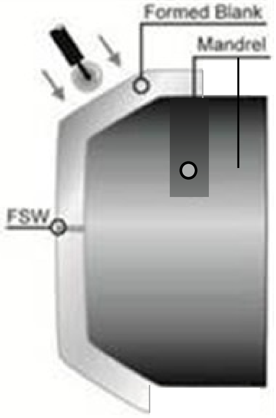
Superficial oxidation caused by long Intermediate Annealing Treatment (IAT) is readily removed by machining

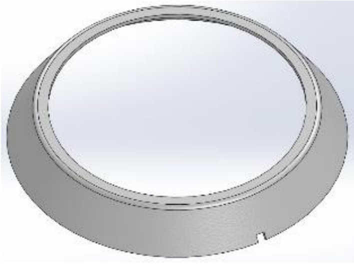


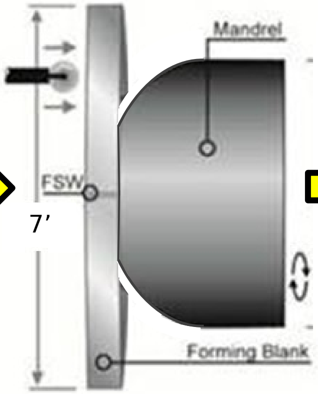
2050 FSW Full Scale Blanks Spin Forming

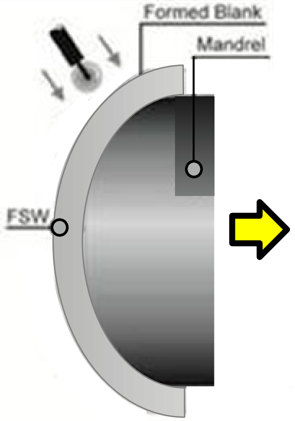












<u>Waterjet Cutting</u> <u>*(Post-Weld Heat Treating)*</u> <u>Tooling Setup</u> <u>Spin Forming [Cone]</u> <u>Waterjet Cutting Dome Blank</u> <u>Spin Forming (Dome)</u> <u>Post-Spin Form Heat Treating</u>

Post-Spin Forming Heat Treating

NASA Langley Research Center (LaRC) leveraged lessons learned from prior spin forming efforts with FSW 2195 blanks to recommend the following:

- Spin forming temperature of 455°F
- Novel Intermediate Annealing Treatment (IAT) developed by NASA; US Patent 9,090,950 (2015)
- Solution Heat Treat (SHT) temperature of 932°F @ 1 hour hold time

LM Space performed internal tensile tests to recommend the following:

- Spin forming temperature of 455°F
- Post Weld Annealing (PWA) of 700°F@ 2 hour hold time

Constellium performed internal tensile testing and fracture toughness of 2050 aged to -T62 to recommend the following:

- Final artificial aging of 320°F @ 24 hour hold time

Processing Sequence of Spin Formed Parts

	2050		2195	
	Temp	Time	Temp	Time
Spin Forming	≥455°F		≥482°F	
PWA	700°F	2 hrs	720°F	2 hrs
IAT	855°F	patented	875°F	patented
SHT	932°F	1 hr	950°F	1 hr
Aging to T62	320°F	24 hrs	340°F	32 hrs*

*Experimental multi-step aging of subscale domes at Spincraft

- Processing temperatures strongly influenced by Cu content
  2195 – 4% Cu
  2050 – 3.5% Cu

2050 FSW Spin Form Subscale Cones vs. 2195 FSW SF Dome Prior Effort

2014 NASA Report on 0.75" thick 2195 FSW SF Dome

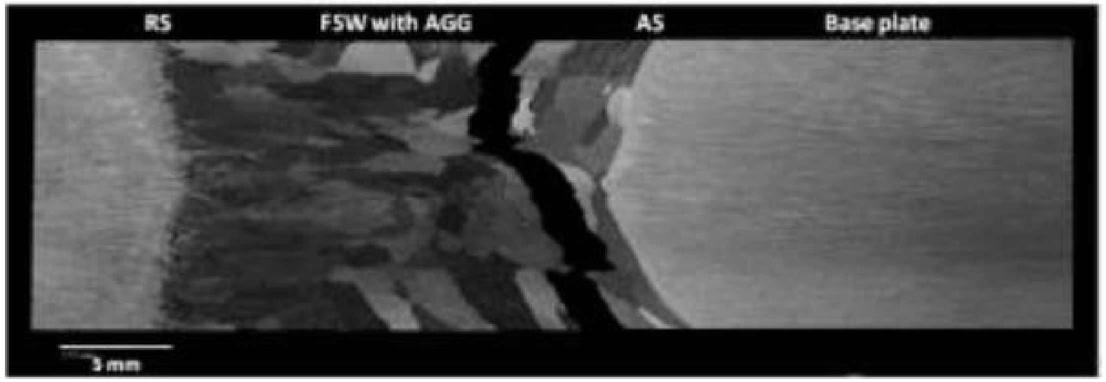
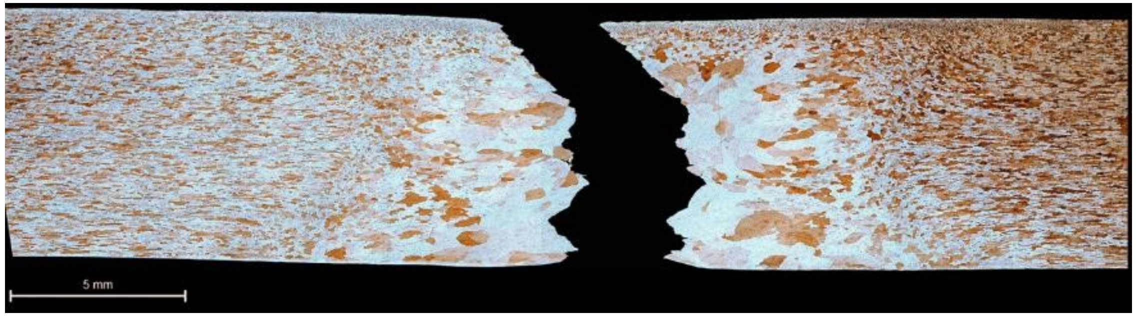


Image Credit: Curreri, *et al.* NASA-TP-2011-216462

Current Work 0.32" thick 2050 FSW SF Dome (60° Strain)



2050 FSW Spin Form Subscale Cones vs. 2195 FSW SF Dome Prior Effort

2014 NASA Report on 0.75” thick 2195 FSW SF Dome

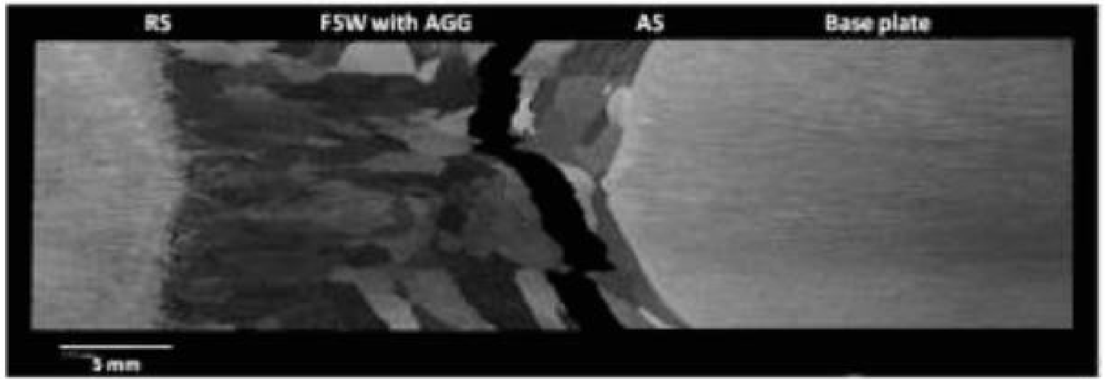
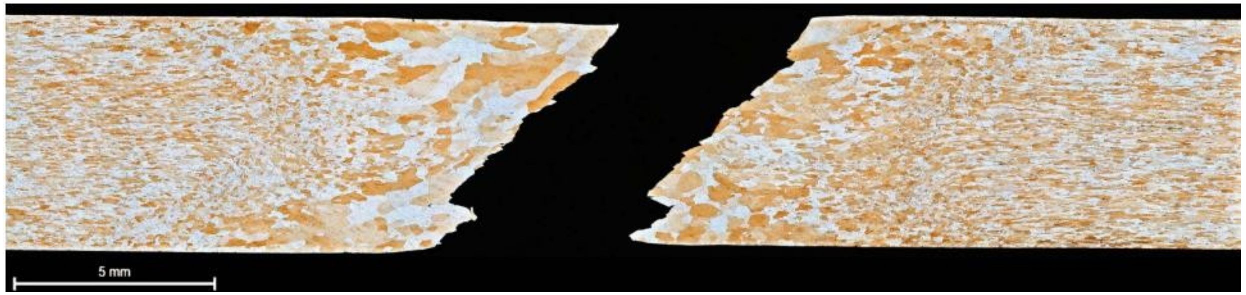


Image Credit: Curreri, *et al.* NASA-TP-2011-216462

Current Work 0.32” thick 2050 FSW SF Dome (45° Strain)



2050 FSW Spin Form Subscale Cones vs. 2195 FSW SF Dome Prior Effort

2014 NASA Report on 0.75” thick 2195 FSW SF Dome

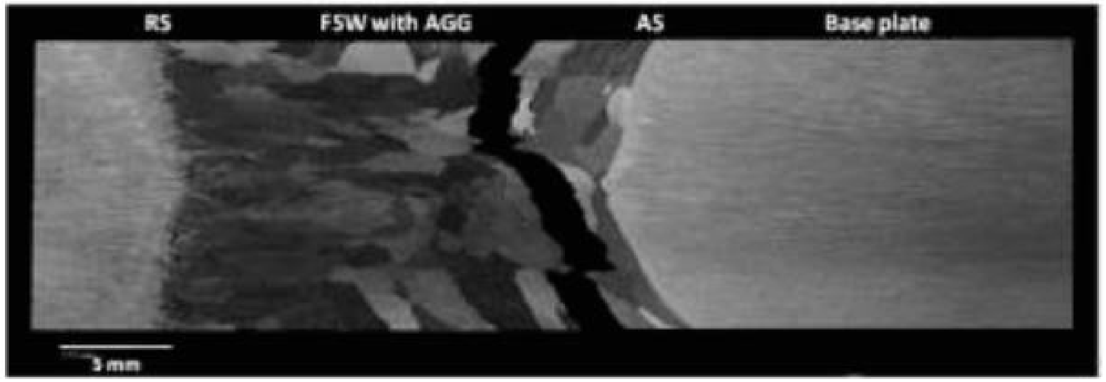


Image Credit: Curreri, *et al.* NASA-TP-2011-216462

Current Work 0.32” thick 2050 FSW SF Dome (30° Strain)

2050 vs. 2195 Subscale FSW Spin Formed Articles

2014 NASA Work 0.75” thick 2195-O FSW Blank

FSW Center Strip

Average of 3 Long Transverse (LT) tensile specimens across the FSW:

SF Dome	UTS (ksi)	YS (ksi)	el. %
2195-T6 FSW	70.0	n/a	**0.65**

Image Credit: Curreri, *et al.* NASA-TP-2011-216462

Current Work 0.32” thick 2050-O FSW Blanks (30°, 45°, 60° strain)

FSW Center Strip (Side A)

FSW Center Strip (Side B)

Average of 4 LT tensile specimens (for each strain level) across the FSW:

SF Cones	UTS (ksi)	YS (ksi)	el. %
2050-T6 FSW 60°	63.7	52.5	**5.1**
2050-T6 FSW 45°	64.4	52.9	**5.9**
2050-T6 FSW 30°	64.1	53.2	**7.0**

8-10X Improvement in Ductility with ≤9% Lower Strength vs. 2195 Prior Work

2050 vs. 2219 Full Scale Spin Formed Dome

Prior 2015 NASA Work 2” thick 2219-F Blank

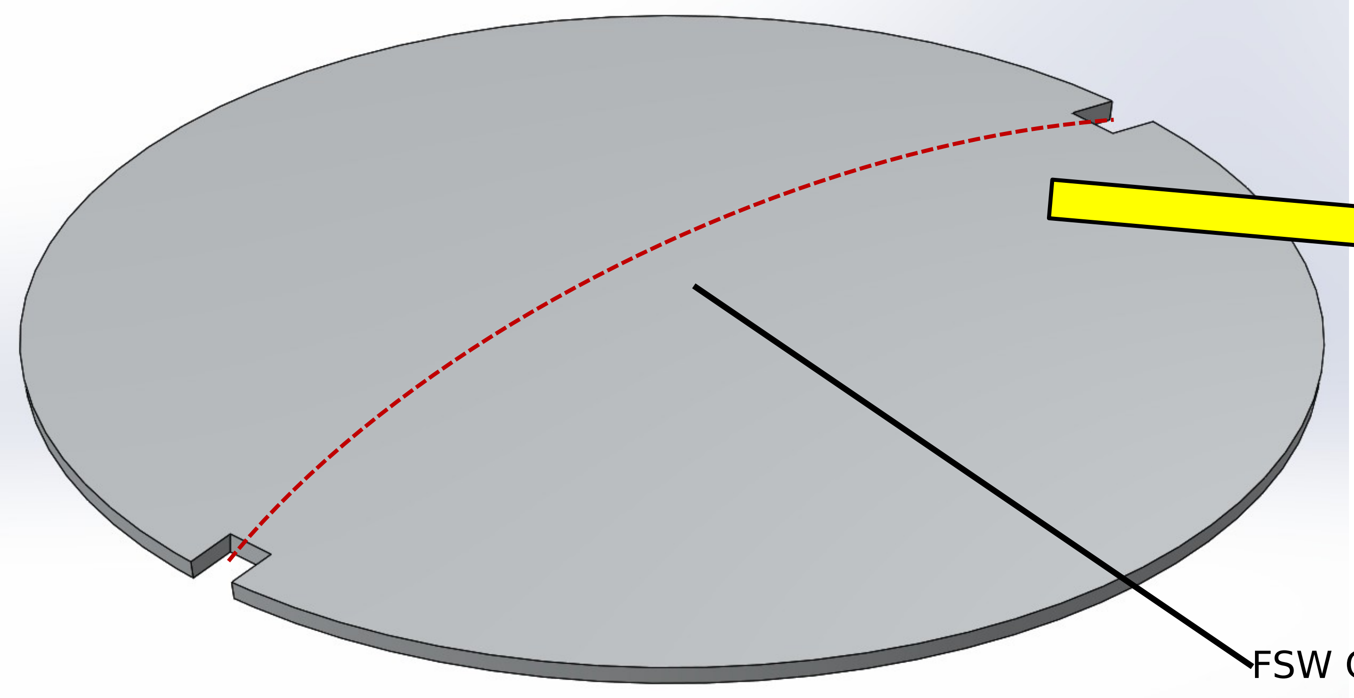
Image Credit: Hoffman, *et al.* NASA/TP-2015-218674.

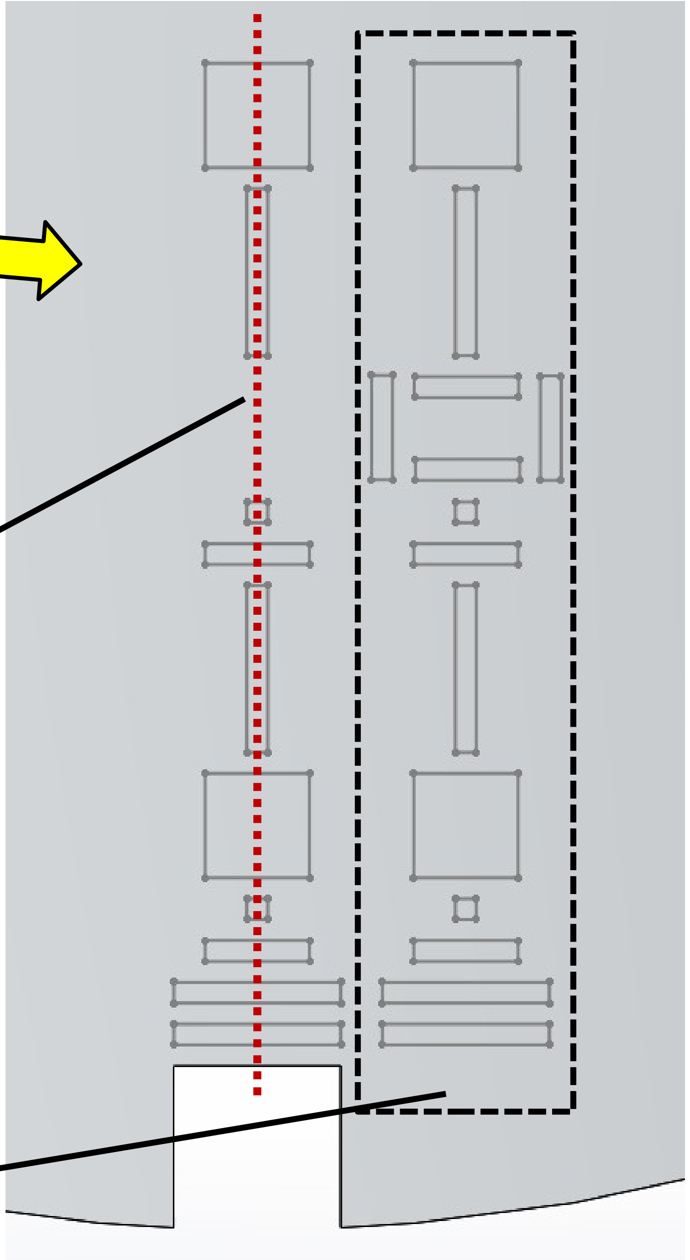
- **Spin forming of Orion Aft Bulkhead Dome**
- **Annealed from –F temper before spinning**
- **Solution heat treated, quenched, and aged to -T62**
- **This blank was <u>not</u> friction stir welded**

Current Work 1.5” thick 2050-T34 FSW Blank

- **Spin forming of Dome**
- **Post-weld annealed from -T34 temper before spinning**
- **Solution heat treated, quenched, and aged to -T62**
- **Utilized *<u>different</u>* spinning mandrel as 2015 Orion Aft Bulkhead**

2050 Full Scale Spin Formed Dome Coupon Locations

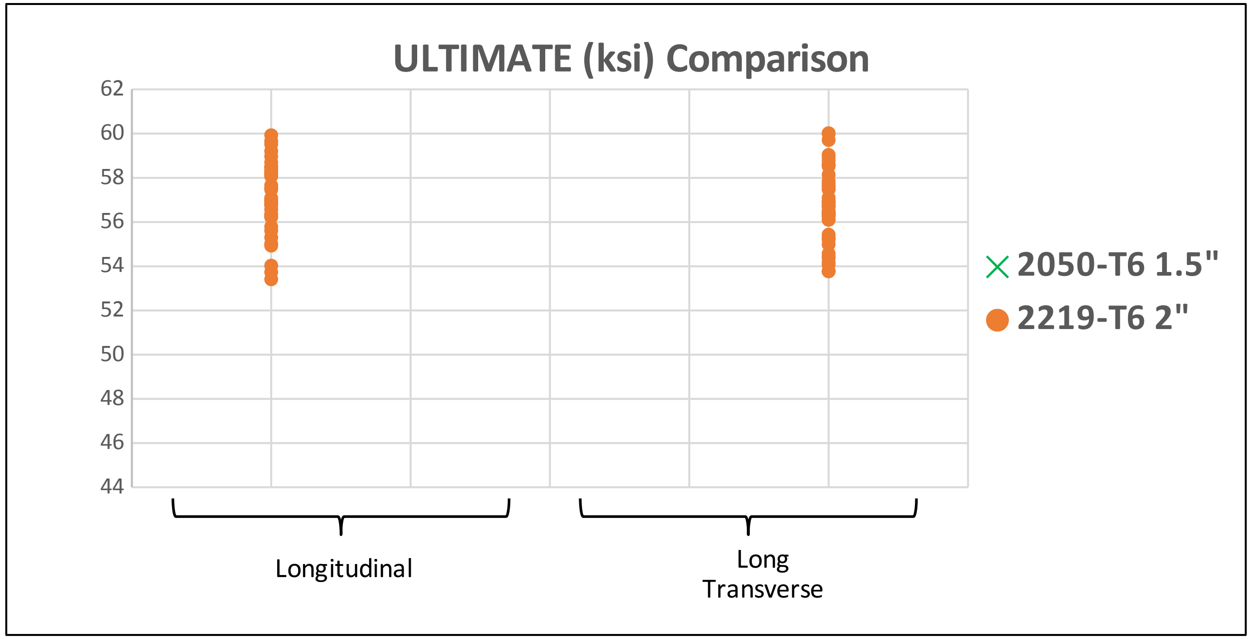


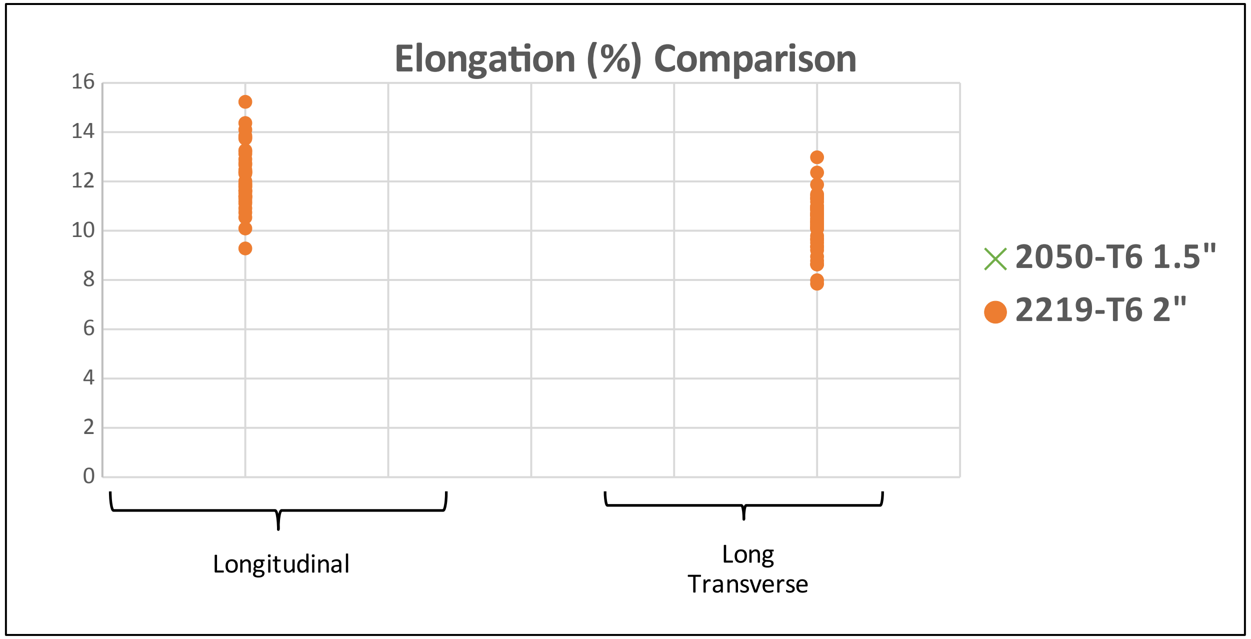


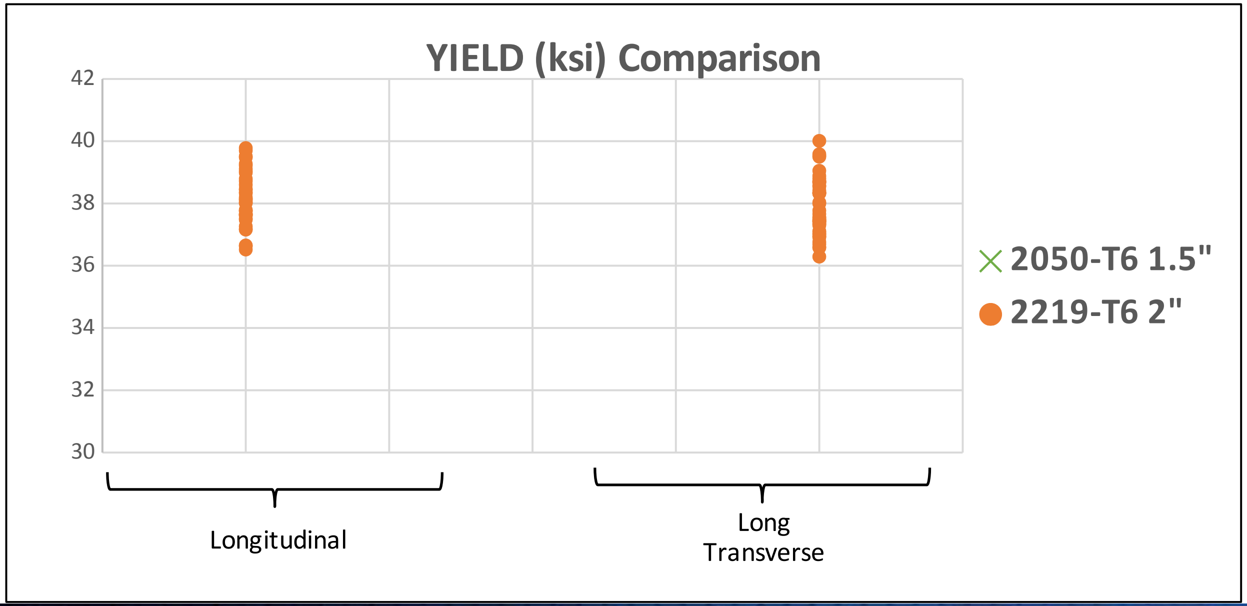
FSW Centerline

Considering Parent Material Properties for Dome Comparison

2050 vs. 2219 Full Scale Spin Formed Dome – Parent Material Comparison



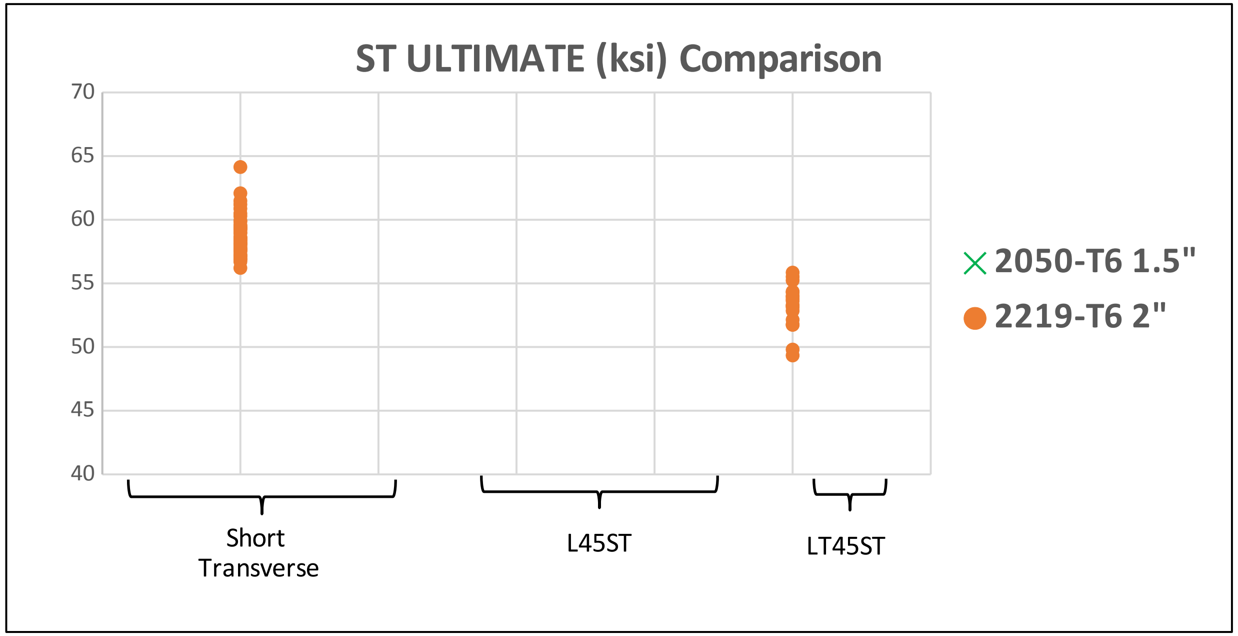


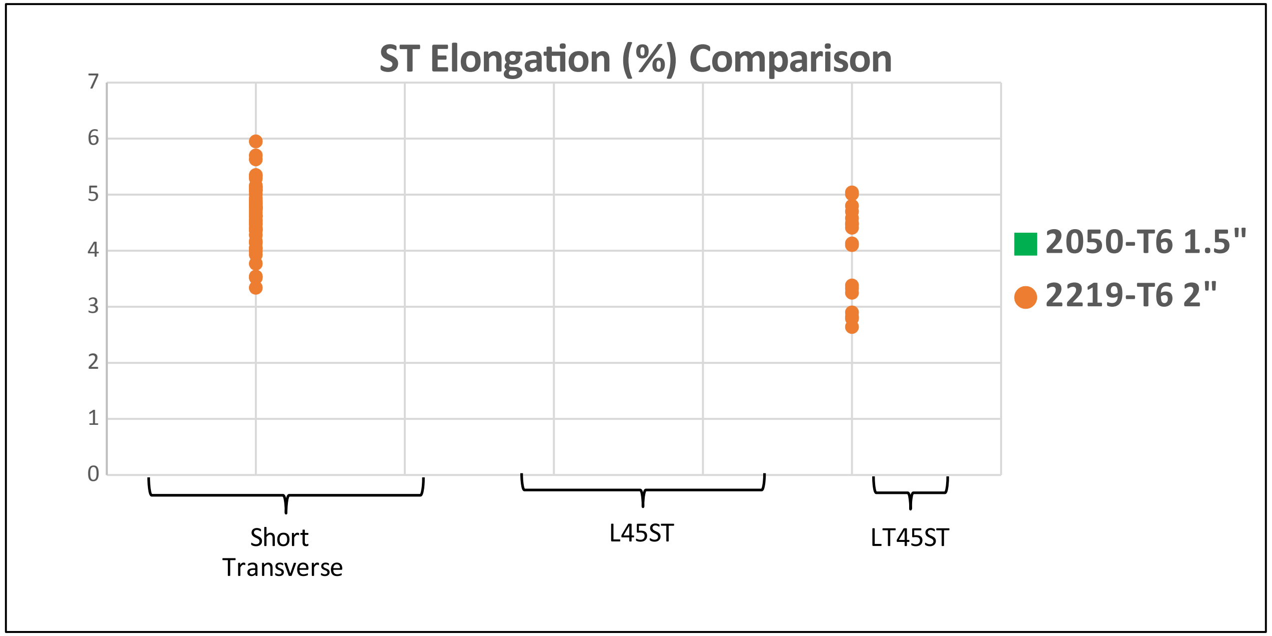


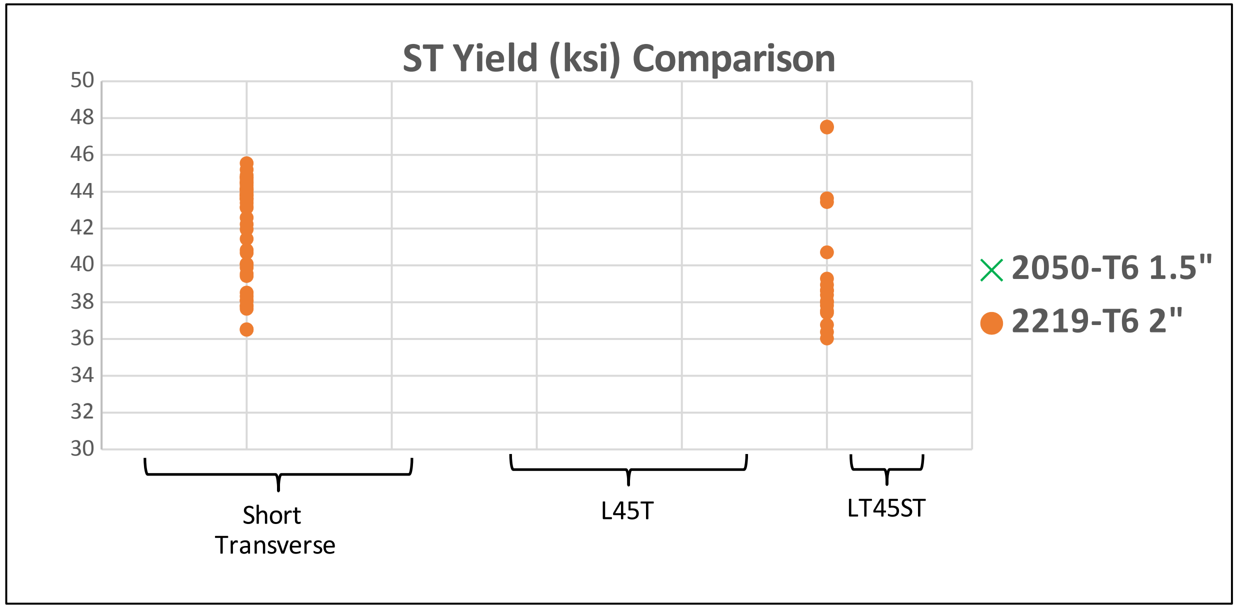
Longitudinal	Min. 2219-T6 2” thick Parent Material	Min. 2050-T6 1.5” thick Parent Material	% Change
Uts (ksi)	53.4	73.5	38% Increase
Yts (ksi)	36.5	62.6	72% Increase
Elongation (%)	9.3	10	Comparable

Long Transverse	Min. 2219-T6 2” thick Parent Material	Min. 2050-T6 1.5” thick Parent Material	% Change
Uts (ksi)	53.8	70.5	31% Increase
Yts (ksi)	36.3	60.8	67% Increase
Elongation (%)	7.9	10	Comparable

2050 vs. 2219 Full Scale Spin Formed Dome – Parent Material Comparison







Short Transverse	Min. 2219-T6 2" thick Parent Material	Min. 2050-T6 1.5" thick Parent Material	% Change
Uts (ksi)	56.2	69.2	23% Increase
Yts (ksi)	36.5	57.2	57% Increase
Elongation (%)	3.3	3.9	Comparable

Longitudinal-45°-Short Transverse	Min. 2219-T6 2" thick Parent Material	Min. 2050-T6 1.5" thick Parent Material	% Change
Uts (ksi)	49.3	58.8	19% Increase
Yts (ksi)	36.0	51.4	43% Increase
Elongation (%)	2.6	1	Comparable

2050 vs. 2219 Full Scale Spin Formed Cone – Parent Material Comparison

Prior 2014 NASA Work 1.5” thick 2219-T34 FSW Blank

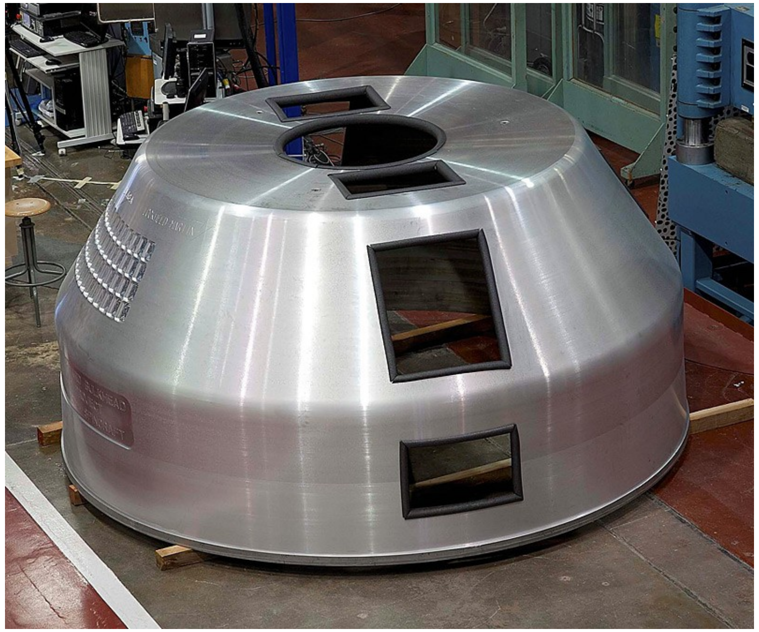


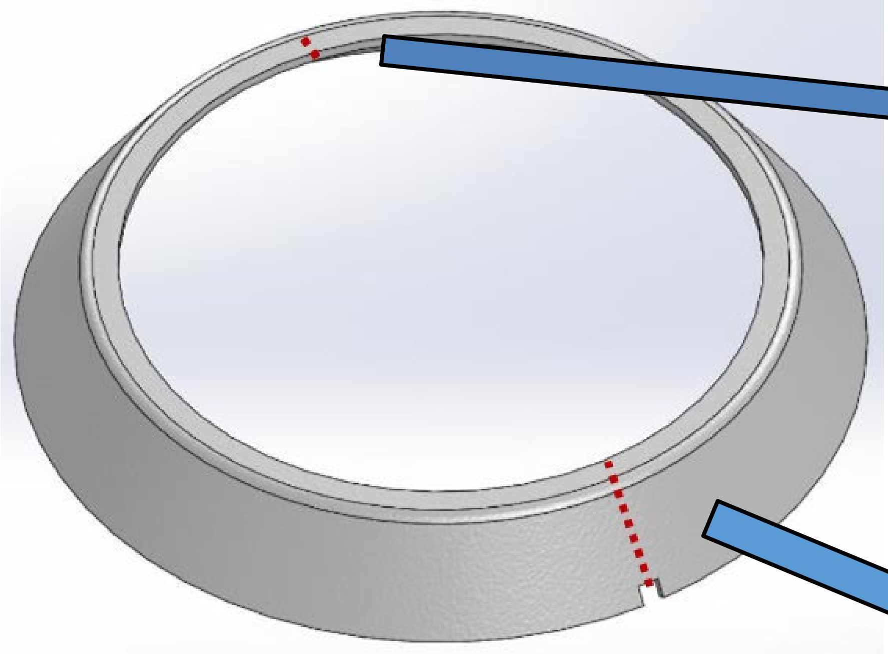
Image Credit: Domack, *et al.* NASA-TM-2014-218163

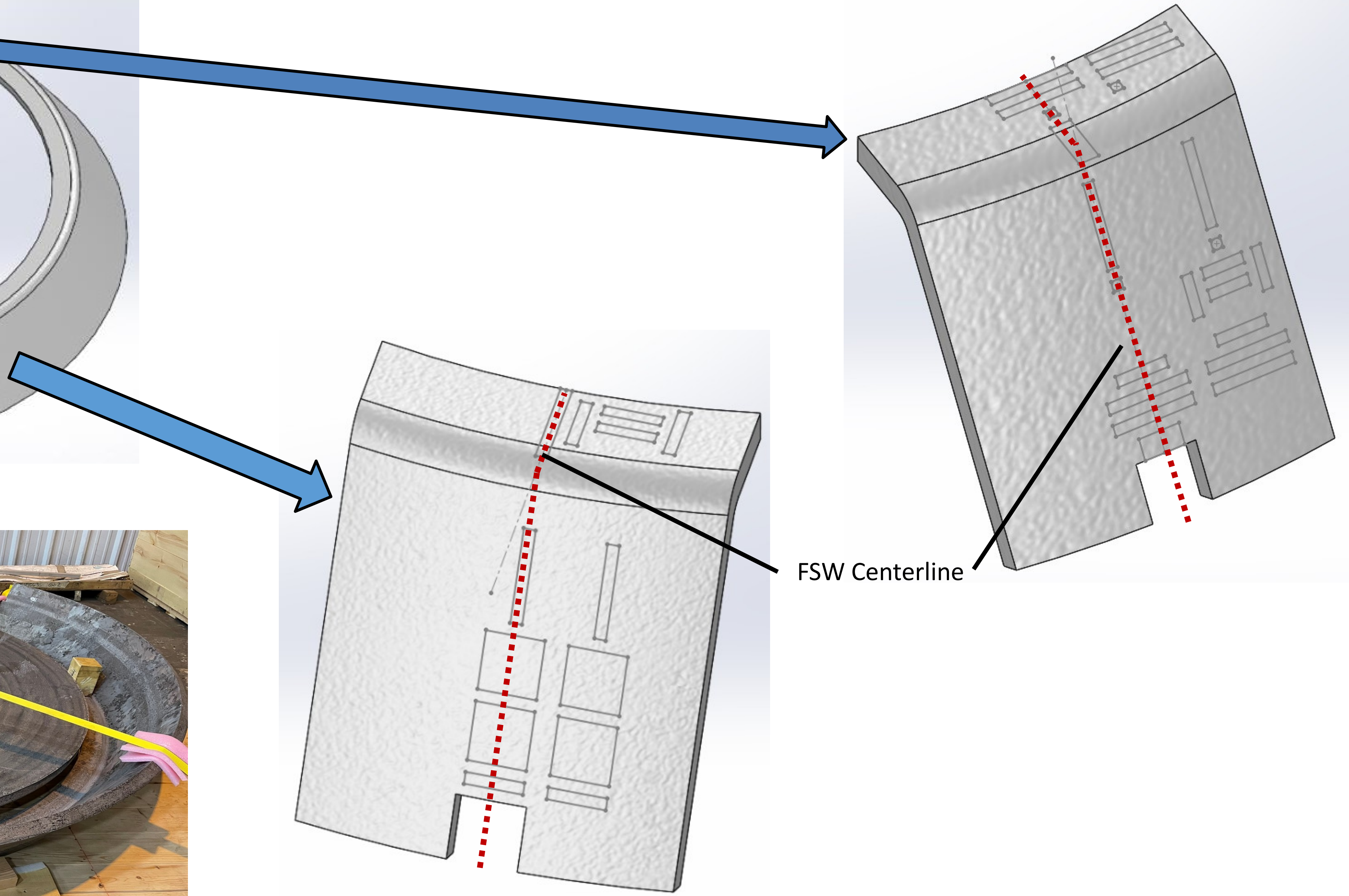
- **Article included Forward Bulkhead, Cone, and Barrel (132” max diameter)**
- **Post-weld annealed before spinning**
- **Solution heat treated, quenched, and aged to -T6**

Current Work 1.5” thick 2050-T34 FSW Blank

- **Article included just Forward Bulkhead and Partial Cone Segment (112” max diameter)**
- **Post-weld annealed before spinning**
- **IAT before solution heat treat, quench, and age to -T6**
- **Utilized *<u>same</u>* spinning mandrel as 2014 FPVBH article**

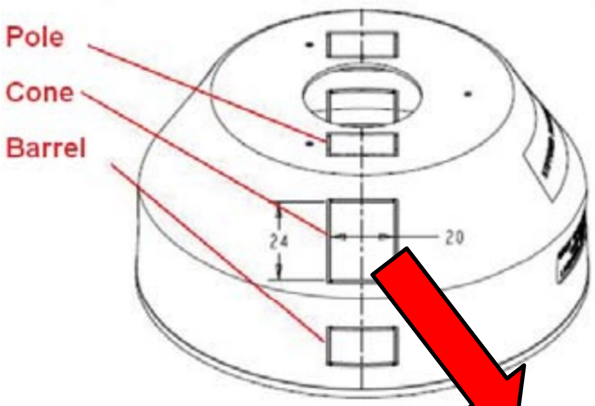
2050 Full Scale Spin Formed Cone Coupon Locations





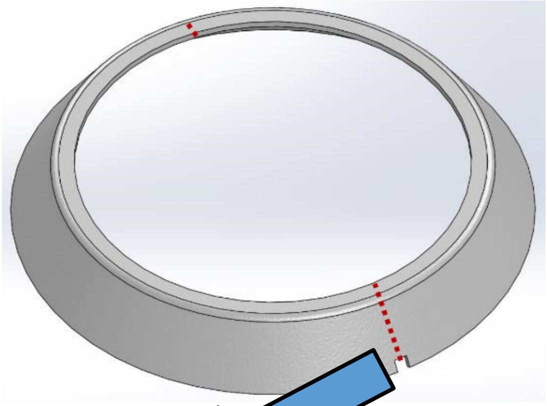
2050 vs. 2219 Full Scale Macrographs

2219-T6 FSW SF Cone



- AGG still present in 2050 FSW SF cone article
- Reflected by low ductility values recorded
- Spin roller experienced a bump and was heard acoustically as it moved over 2219 FPVBH FSW
- Bumping was not witnessing in spin forming of 2050 articles and behaved as a singular plate

2050-T6 FSW SF Cone



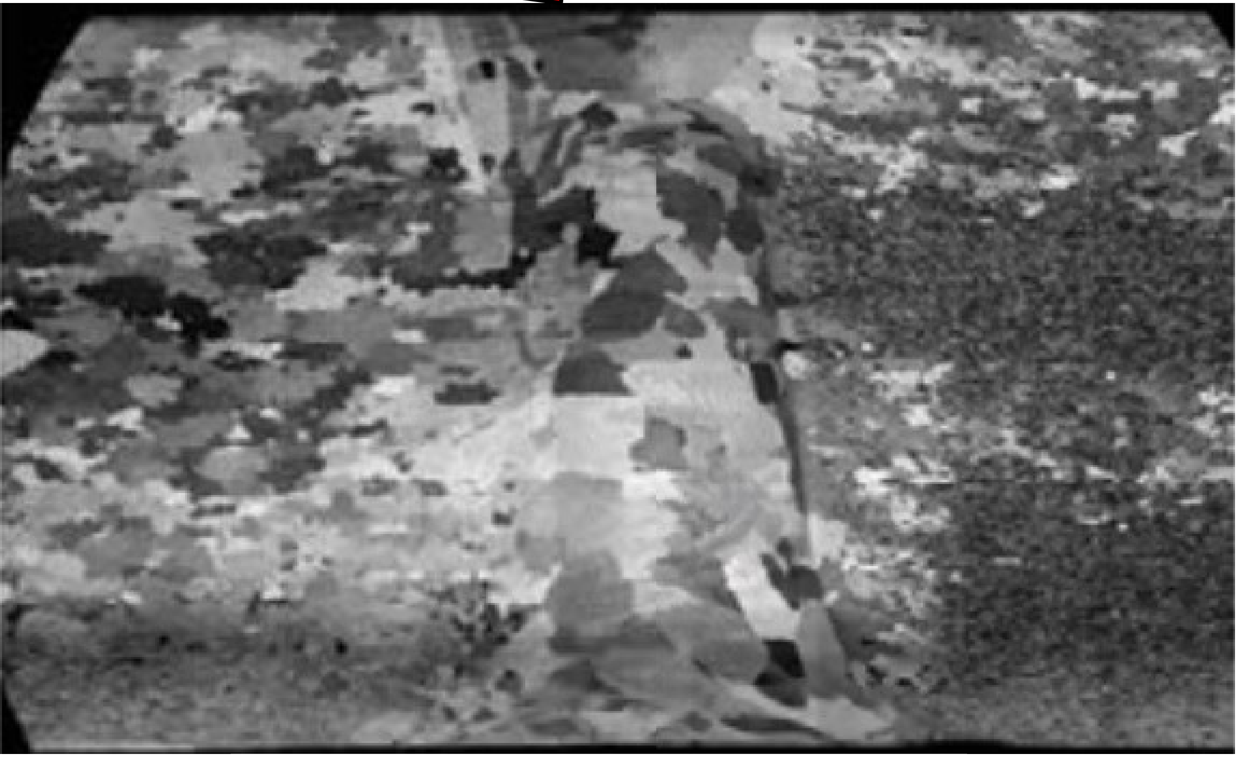
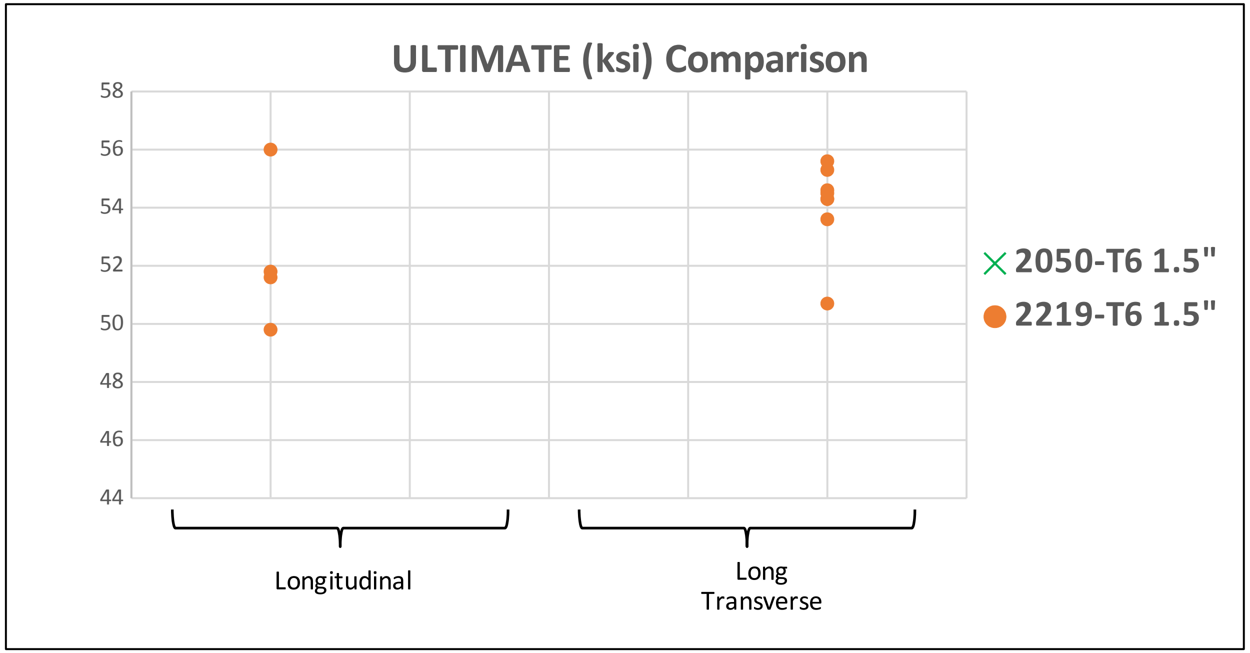
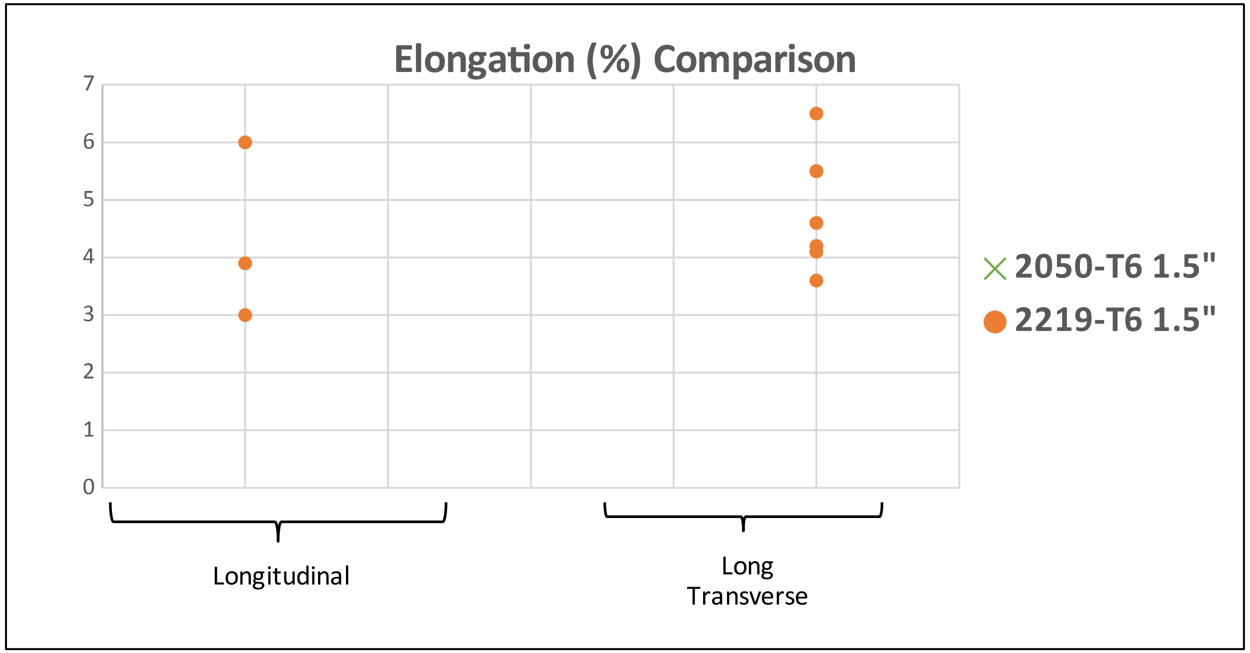
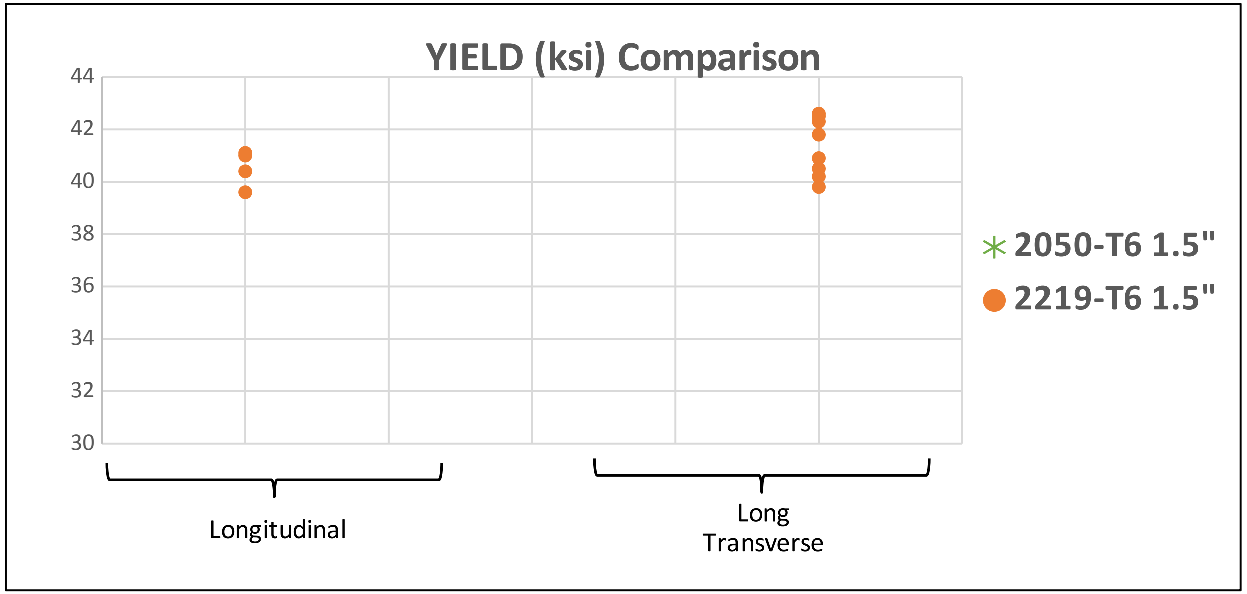


Image Credit: Domack, *et al.* NASA-TM-2014-218163

2050 vs. 2219 Full Scale Spin Formed Cone – FSW Comparison



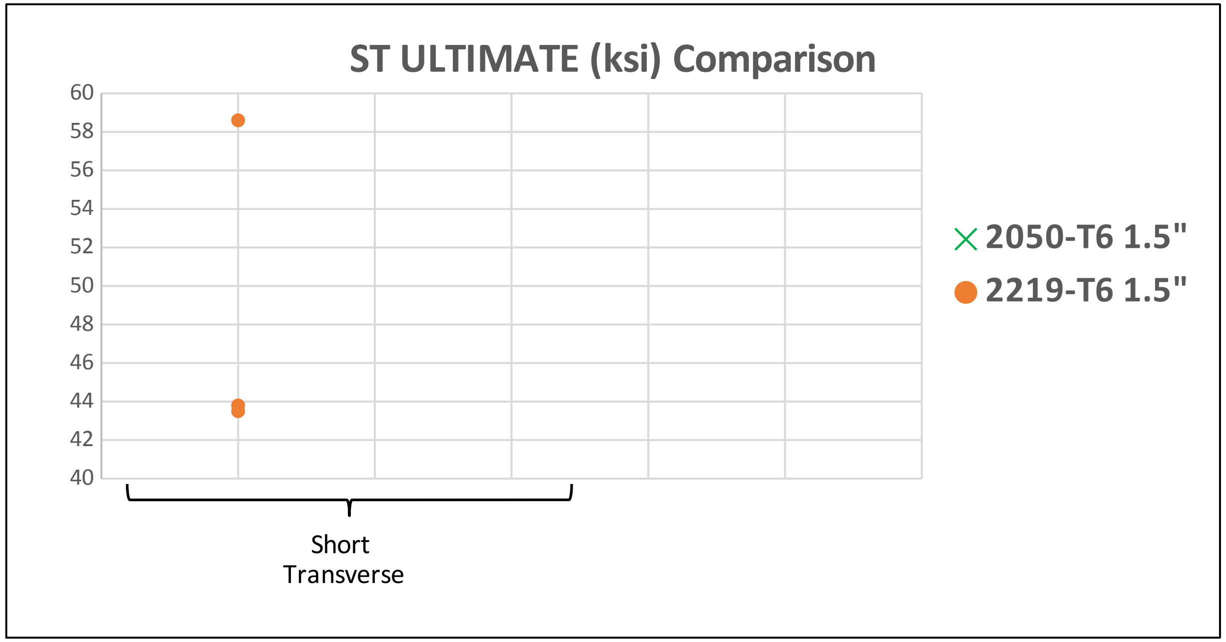


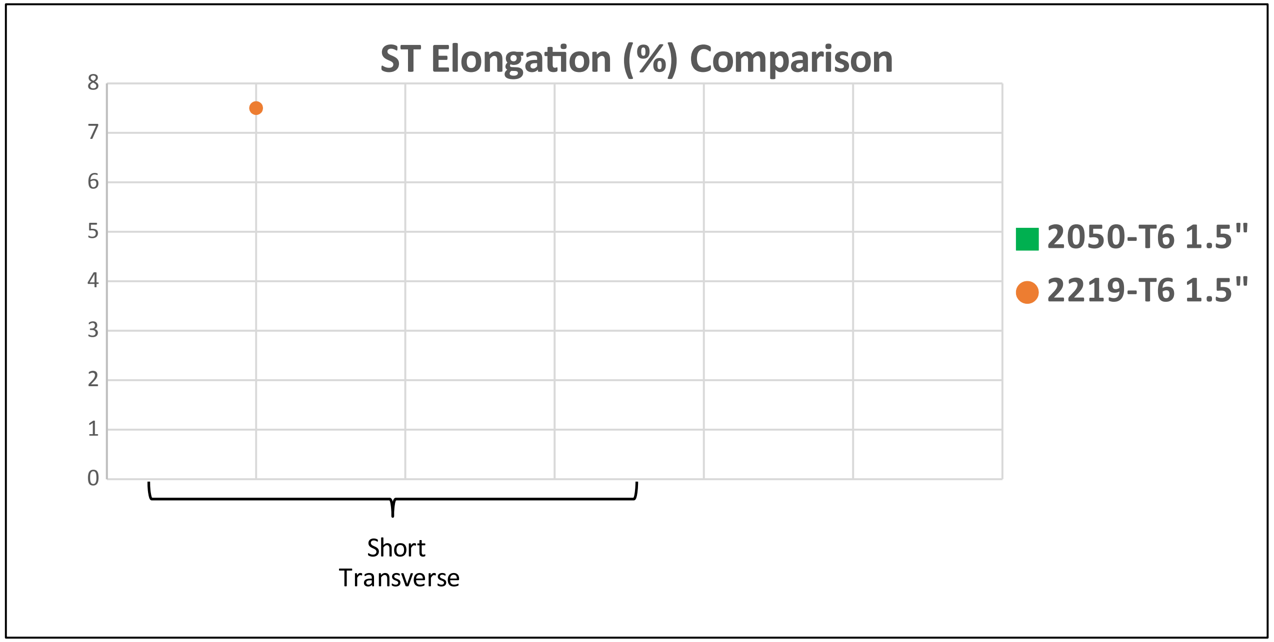


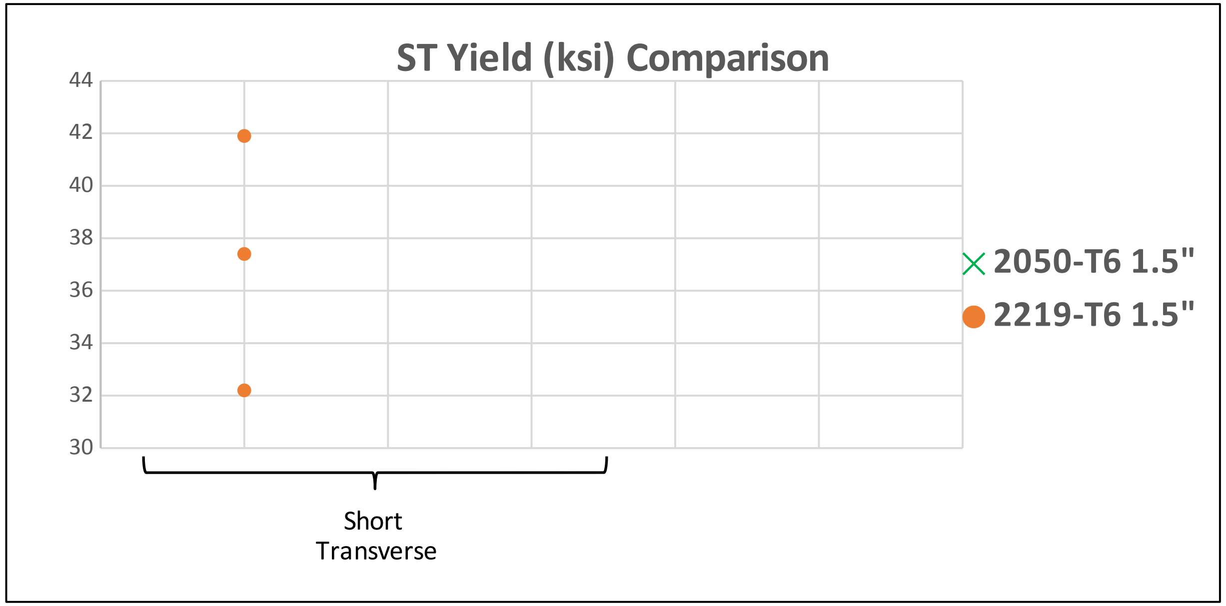
Longitudinal	Min. 2219-T6 1.5” thick FSW	Min. 2050-T6 1.5” thick FSW	% Change
Uts (ksi)	49.8	57.2	15% Increase
Yts (ksi)	38.4	55.3	44% Increase
Elongation (%)	3	2	Comparable

Long Transverse	Min. 2219-T6 1.5” thick FSW	Min. 2050-T6 1.5” thick FSW	% Change
Uts (ksi)	50.7	58.8	16% Increase
Yts (ksi)	39.8	54.3	36% Increase
Elongation (%)	3.6	3	Comparable

2050 vs. 2219 Full Scale Spin Formed Cone – FSW Comparison







Short Transverse	Min. 2219-T6 1.5" thick FSW	Min. 2050-T6 1.5" thick FSW	% Change
Uts (ksi)	43.5	55.9	59% Increase
Yts (ksi)	40.3	49.9	42% Increase
Elongation (%)	7.5*	6	Comparable

*Two ST tensile tests in 2219 FSW failed outside gage length – no %el. recorded

Conclusions

- **2050 subscale cones exhibited <u>8-10X improvement</u> in FSW ductility over 2195 prior art**
  - Significant reduction in AGG formation, improving with larger strain input
  - Subscale cones witnessed same PWA, IAT, SHT, quench, and age as full-scale articles
  - Near elimination of AGG attributed to FSW methods and/or attributed to thinner gauge w/higher strain input

- **2050 full scale cone and dome exhibited <u>36-72% improvement</u> in Yield Strength over 2219 prior art**
  - Ductility values were comparable in parent material and FSW
  - 2050 spin formed components present mass savings opportunity over 2219 for crew vehicles/structures

- **Future work required for qualification of large FSW blanks for flight**
  - Determine impact of IAT on AGG and other potential heat treatment improvements
  - Target higher spin forming strains and/or subsequent deformation processing to mitigate AGG formation
  - Apply novel FSW methods used in subscale to full scale articles in future FSW blanks for spin forming

Questions?

LOCKHEED MARTIN

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Standex