Integrally Stiffened Cylinder (ISC) Process Development

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Strategic Interchange Meeting
Leifeld Metal Spinning, Ahlen, Germany
January 30, 2015

Space Shuttle External Tank: Traditional Manufacturing Approach

Integrally Machined

- 90% Scrap Rate
- Approx. 250,000 kg. Chips/Tank
- $8M Chips/Tank
- Environmentally Unfriendly

ET LH_2 Barrel

Friction Stir Welded

- Material Property Knockdown
- Potential Weld Defects
- Weld Lands Concentrate Load
- Approx. 800 meters of Welds

Innovative Approach to Manufacturing Launch Vehicle Cryogenic Tanks

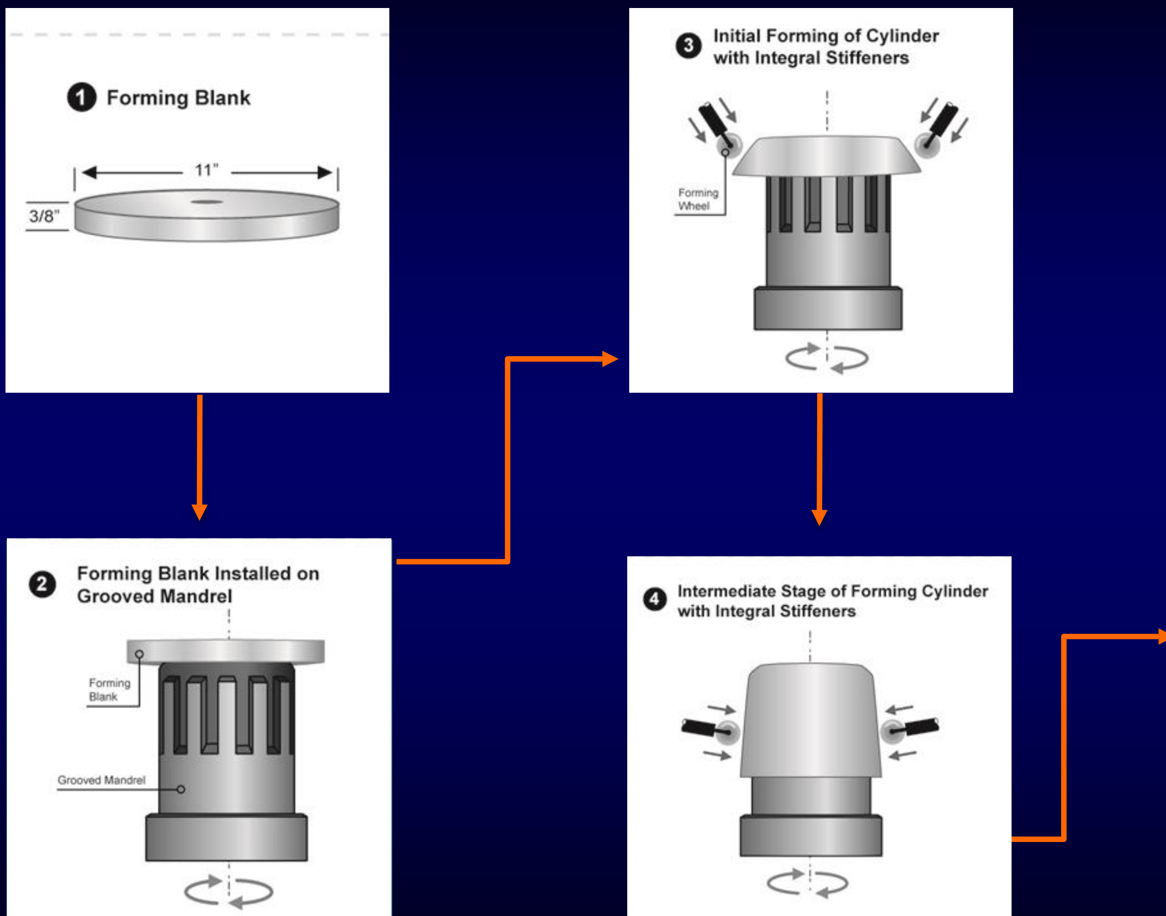
- Use Net Shape Forming Technology to Simultaneously Form Cryogenic Tank Stiffeners and Cylindrical Membrane
- Proven Technology on Small Scale (< 30 cm in diameter) for Commercial Steel Automotive Clutch Housing
- Transition to Aerospace Alloys, Quality and Size
- Benefits: Minimize Welds and Defects
  Reduce NDE
  Reduce Scrap Rate: 90% to < 5%
  Greener Manufacturing

Commercially Produced Steel Clutch Housing

20 cm dia. As-formed, No Machining

Innovative Manufacturing of Cylinders with Integral Stiffeners

- Steel Automotive Clutch Housing -



Commercially Produced Steel Clutch Housing

20 cm dia. As-formed, No Machining

Integrally Stiffened Cylinder (ISC) Process Development

Steel Clutch Housing

20 cm diameter

- Commercial product
- Automotive application
- Steel fabrication

First Ever Forming with Aluminum

20 cm diameter

- Successful transition to Al alloy fabrication

First Attempt at Forming Cryogenic Tank Stiffener Shape

20 cm diameter

- Optimize for cryotank applications

Forming with Multiple Stiffener Shapes

20 cm diameter

- Optimize material flow

Optimize Al-Li Stiffener Height & Spacing for Aerospace Structures

Mandrel Designs with Varied Straight Stiffener Geometry

- Optimize stiffener geometry
- Three groove geometries
  - Height
  - Width
  - Angle

ISC 2013 Forming Campaign

					Step 1:							
Test Nr.	**Plate Nr**	**Plate thickness [mm]**	**Plate Diameter [mm]**	**Temperature treatment**	**Result Manufacturing step 1.1: Pot shape - bending**	**Result Manufacturing step 1.2: Pot (cone)shape**	**Result Manufacturing step 1.3: Pot shape**	**Result Manufacturing Step 2: Pot shape & stringer 17,5 mm**	**Result Manufacturing Step 2: Pot shape & stringer 20 mm**	**Result Manufacturing Step 2: Pot shape & stringer 25 mm**	**Roller Sets: 1. Combind set 2. Pot pre-form set 3.1. flow forming set 3.2. flow forming set 2**	**Description**
7	**7**	30/20	300	1 Step: 380°C/ 2h 2 Step: 380°C/ 3h	OK	OK	OK	1 path: Stinger height 5,5 - 10mm (1 flow path)	N/A	N/A	2. / 3.	Step 1:pot forming in 3 steps, successful **Step 2: With FF roller set, 300mm feed rate**
8	**8**	30	400	380 C°/2,5 h	Step 1: no bending			N/A	N/A	N/A	2.	Step 1: material is not bending as expected
9	**9**	30/20	300	1 Step: 380°C/ 2h **2 Step: 380°C/ 4h**	OK (1 step)		OK	1 path: Stinger height 6,5-10mm (1 flow path)	N/A	N/A	2. / 3.	Step 1:pot forming in 3 steps, successful **Step 2: With FF roller set, 500mm feed rate**
10	**10**	30/20	300	380 C°/2,5 h	OK (1 step)		destroyed		N/A	N/A		destroyed
11	**11**	30/20	300	**410 C°/5 h**	OK	OK	OK	destroyed	N/A	N/A	2.	new pot programm (no gap, step 1.1-1.3 in one operation)
12	**12**	30/20	300	**410 C°/5 h**	OK	OK	OK	1 path: Stringer height 8-10mm (1st attempt)	N/A	N/A	2. / 3.2	step 1 new pot programm (no gap, step 1.1-1.3 in one operation) step 2 new roller set, adjusted gap
13	**13**	30/20	300	**410 C°/5 h**	OK	OK	OK	N/A	N/A	N/A	2.	new pot programm (no gap, step 1.1-1.3 in one operation)
14	**14**	30/20	300	**410 C°/5 h**	OK	OK	OK	1 path: stiffener 3mm 2 path: stiffener 7-10mm	N/A	N/A	2. / 3.2	step 1 new pot programm (no gap, step 1.1-1.3 in one operation) step 2 flow forming in 2 steps, different roller offset
15	**15**	30/20	300	**410 C°/5 h**	OK	OK	OK	1 path: stiffener height 8-10,5mm	N/A	N/A	2. / 3.2	
16	**16**	30/20	300	**410 C°/5 h**	OK	OK	OK	1 path: stiffener height 8-10,5mm	N/A	N/A	2. / 3.2	
17	**17**	30/20	300	**410 C°/5 h**	OK	OK	OK	N/A	N/A	1 path: stiffener height 8-10,5mm	2. / 3.2	
18	**18**	30/20	300	**410 C°/5 h**	OK	OK	OK	1 path: forward and backward	N/A	N/A	2. / 3.2	
19	**19**	30/20	300	**410 C°/5 h**	OK	OK	OK	1 path: stiffener 10-6mm 2 path: stiffener 10-9mm disrupted siffeners after 2nd flow path	N/A	N/A	2. / 3.2	teared / disrupted siffeners (clamping area)
20	**20**	30/20	300	**410 C°/5 h**	OK	OK	OK	1 path: stiffener height 11-14mm			2. / 1.	changed back to roller set 1 wall thickness reduction 20 to 5mm
Add. Test 0.2 (Mat AA 6061)	**various**	30/20	300	-	for pot program recording			N/A	N/A	N/A	2.	Different flow forming roller set (changed roller a); 1 flow forming path; stiffener height 9-13mm
Add. Test 0.3 (Mat AA 6061)	**various**	30/20	300	410 C°/3 h	OK	OK	OK	1 flow forming path; stiffener height 9-13mm	N/A	N/A	2. / 3.1 / 3.2	Different flow forming roller set (changed roller a)
Add. Test 0.4 (Mat AA 6061)	**various**	30/20	300	410 C°/3 h	OK	OK	OK	1 flow forming path; stiffener height 12,5mm 2 flow forming path; stiffener height 15,2mm	N/A	N/A	2. / 3.1 / 3.2	1 flow forming path: wall thickness reduction 20 to 5,5mm 2 flow forming path: wall thickness reduction 5,5 to 3mm

Integrally Stiffened Cylinders from 2013 Campaign Selected for Analysis (Al-Li 2195)

Best formed cylinder; single pass
(Parameters used in 2014 experiments)

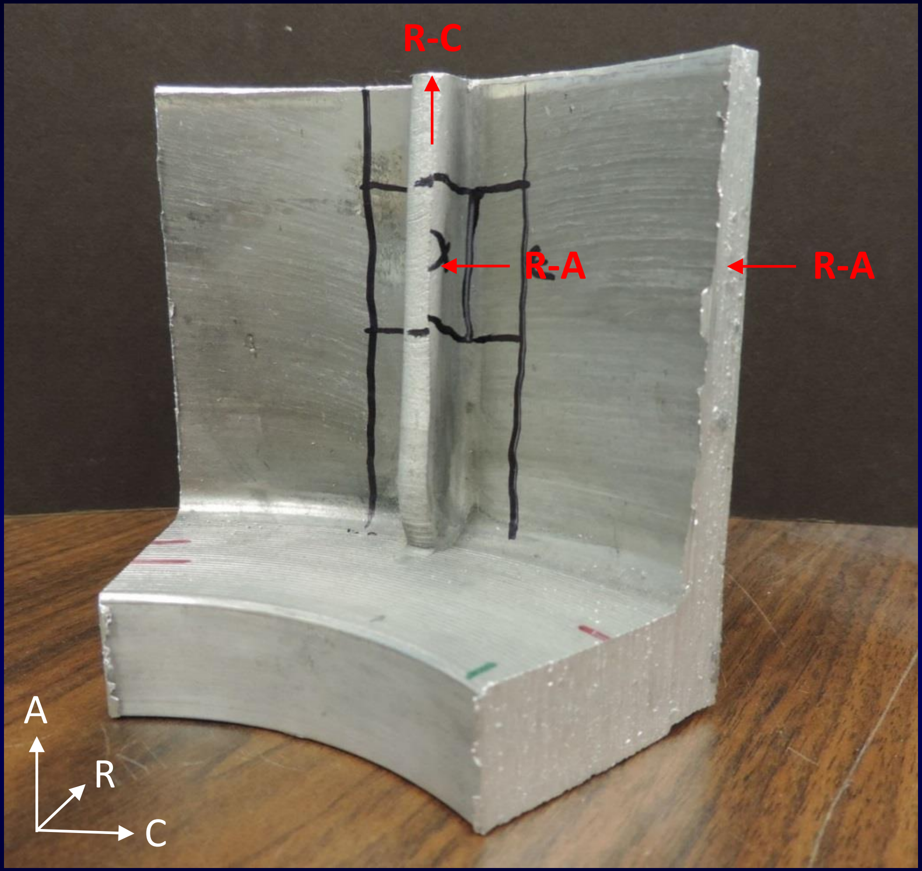
Two passes in alternate directions

Reduced pre-heat temperature

Cylinder Dimensions

	Wall	Stiffener	
Cylinder	Thickness (mm)	Height (mm)	Width (mm)
20	6	14	5
18	5.3	10	5
7	5.5	5	6

Al-Li 2195 Integrally Stiffened Cylinders from 2013 Campaign - Analysis Plan



- Processed to T6 temper
  - SHT 510°C / 1 hour / Water quench
  - Age 160°C / 30 hours
- Locations examined:
  - Stiffener
    - R-C and R-A
  - Cylinder Wall
    - R-A
- Analysis Methods
  - Optical Microscopy
  - EBSD Texture
  - Hardness

Test #20: Al-Li 2195-T6

Best Formed Cylinder, Baseline for 2014 Forming Campaign

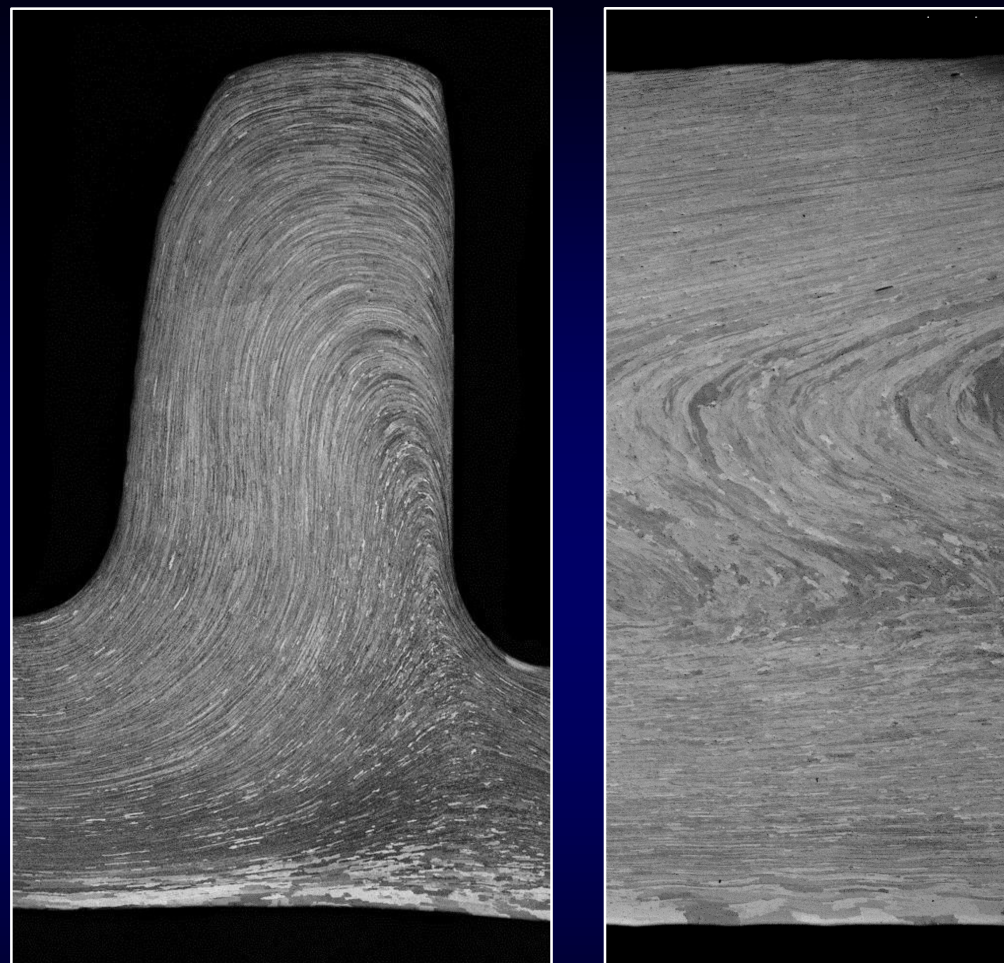
Direction of material flow during forming

Direction of material flow about circumference during forming

R
C

IML

OML



Direction of material flow during forming

R
A

1 mm

- Non-uniform material flow into groove
- Strain induced recrystallization at OML

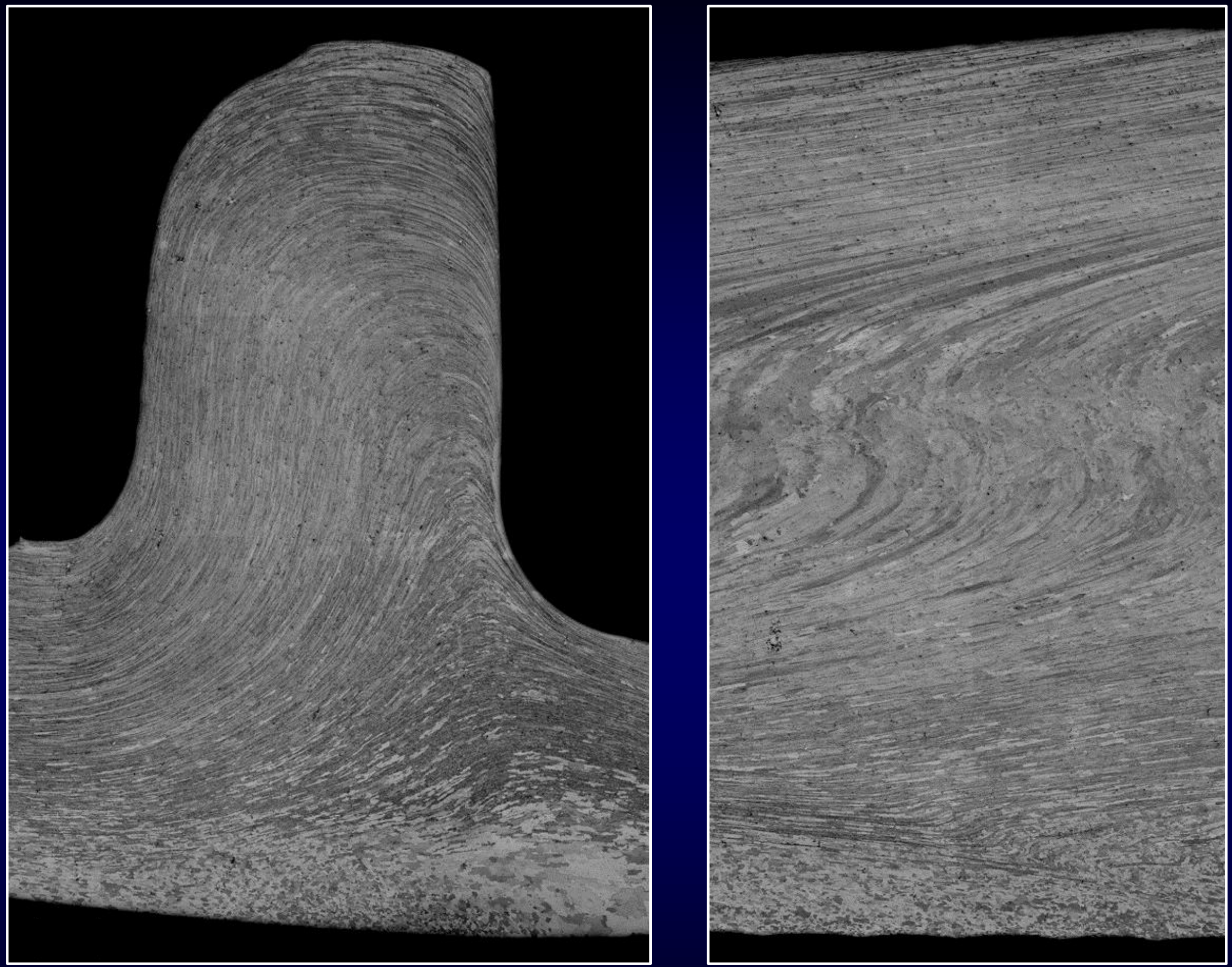
Test #18: Al-Li 2195-T6
Two Passes in Opposite Directions

IML

Direction of material flow during first forming pass

Direction of material flow about circumference during first forming pass

R
C



Direction of material flow during first forming pass

R
A

1 mm

OML

- More recrystallization at OML
- Generally finer recrystallized grain size; Local region of large grains

Test #7: Al-Li 2195–T6
Lower Pre-heat Temperature

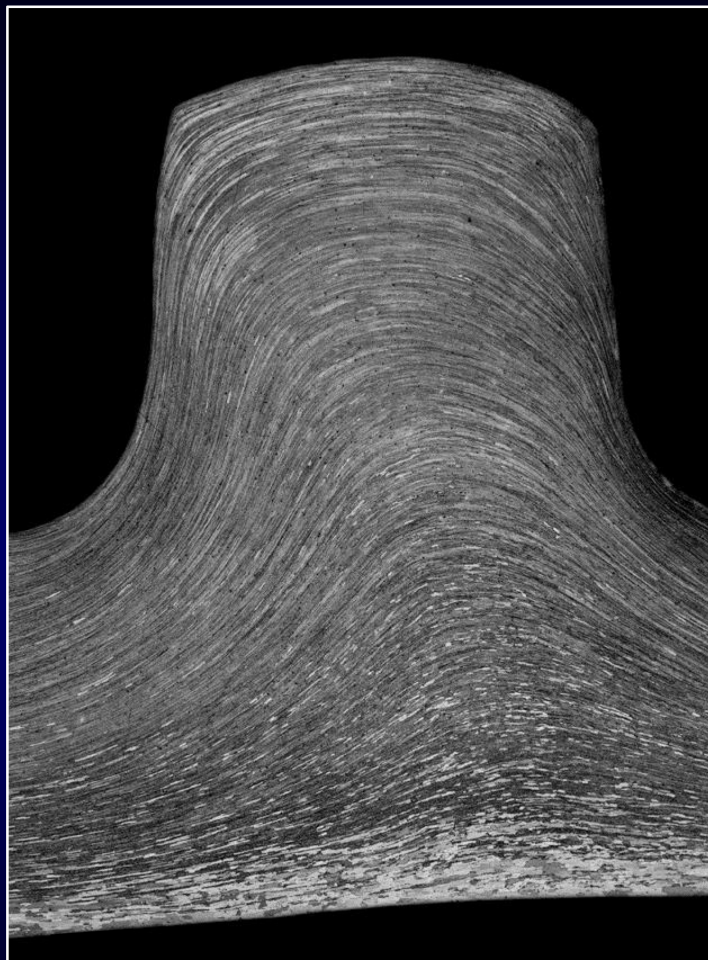
IML

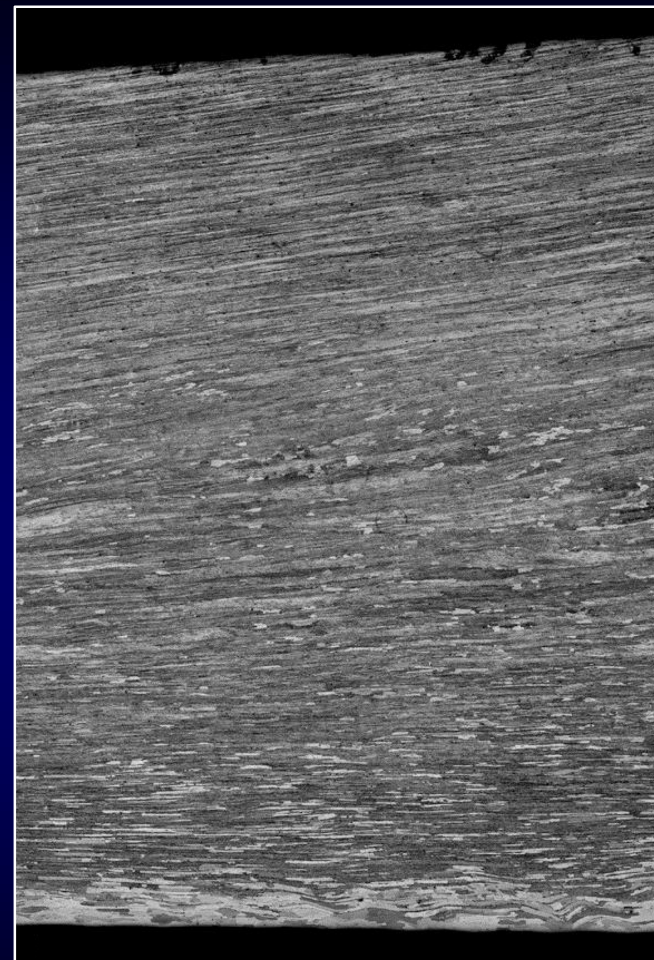
⊗ Direction of material flow during forming

→ Direction of material flow about circumference during forming

R ↑ → C

OML





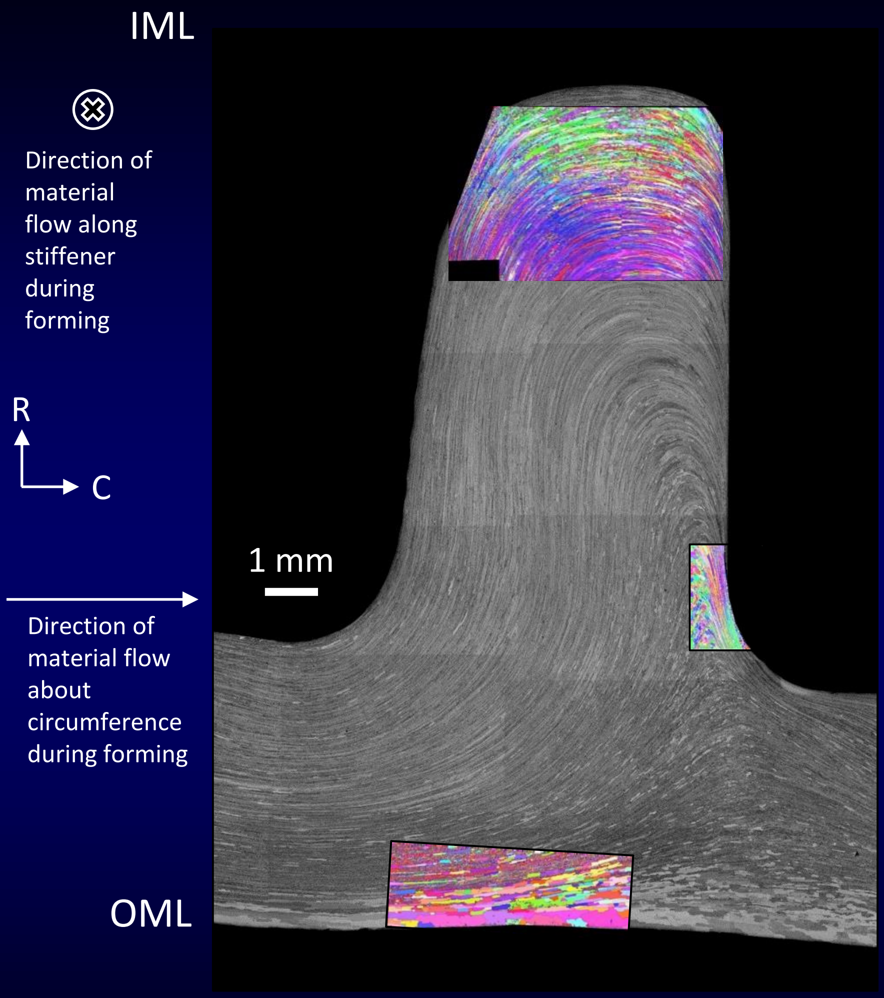
→ Direction of material flow during forming

R ↑ → A

1 mm

Flow lines more symmetric in stiffener

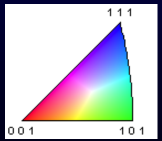
Test #20: Al-Li 2195-T6
Variability in Grain Size and Morphology in Stiffener



Top of Stiffener
- Similar to plate grain size and morphology
- Material flow leads to change in crystal direction from <111> in the center of the stiffener toward < 110> at the top
- Overall weak texture

Stiffener / Cylinder Interface
- Equiaxed recrystallized grains develop where flow reverses
- At outer edge elongated thin grains are pushed up from base plate wall region
- Grain size ranges from ~100 μm^2 to 1,000μm^2
- Changes in the flow and associated crystal rotations within this vicinity do not allow for strong textures to develop

OML Surface
- Small unrecrystallized grains (~100 μm^2)
- Large, recrystallized grains develop along OML surface (grain size > 20,000 μm^2)
- Recrystallized grains show no preferred texture

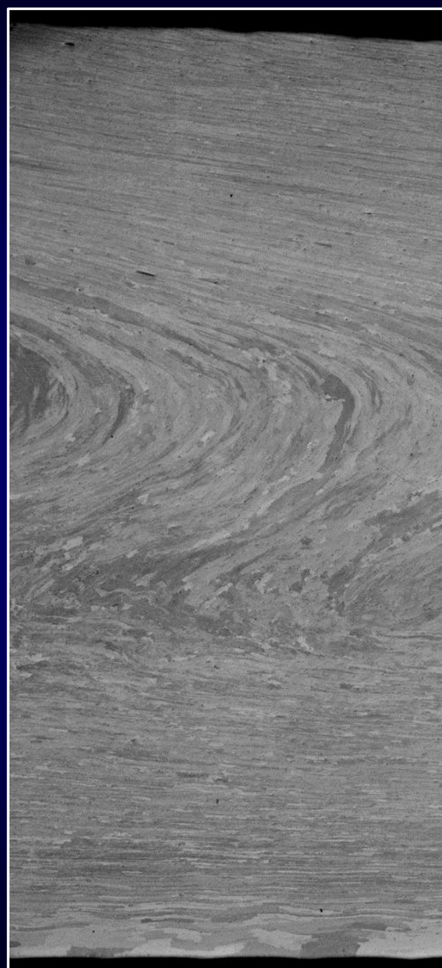


Test #20: Al-Li 2195-T6
Variability in Grain Size and Morphology in Stiffener

Optical Micrograph

IML

Direction of material flow along stiffener during forming



Stiffener

Wall

OML

EBSD Map

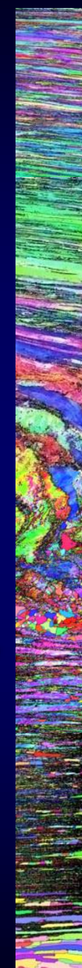
R

A

Stiffener

Wall

1 mm



Unrecrystallized with regions of heavy substructure; Similar to rolled plate

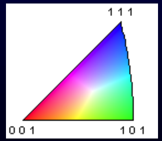
Elongated grains where the boundaries are now aligned in the R direction due to changes in flow path

Narrow band of small, equiaxed recrystallized grains

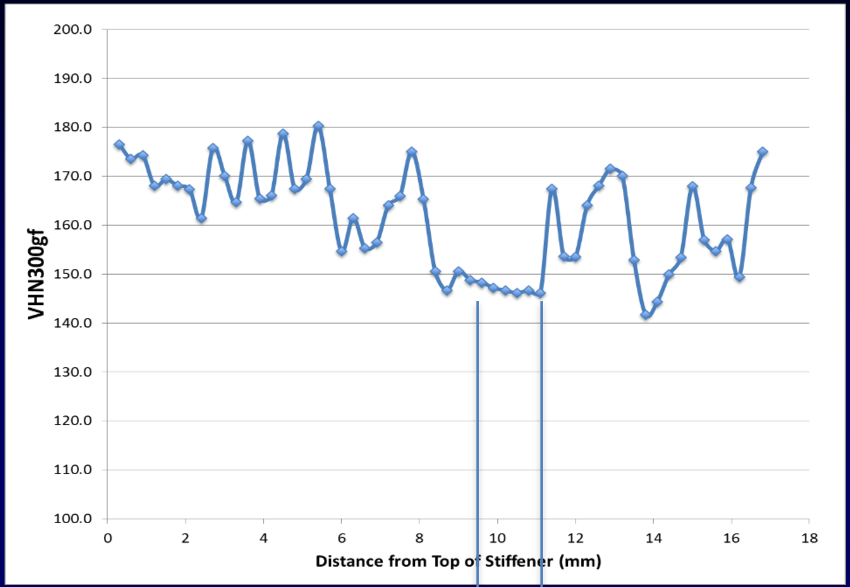
Unrecrystallized zone

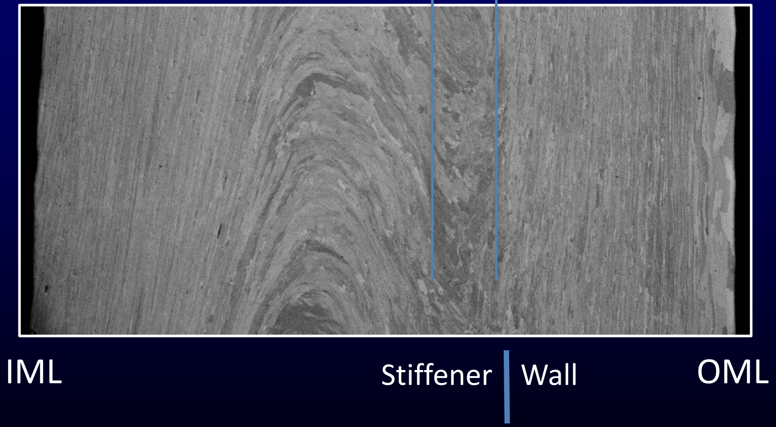
Highly deformed region with substructure; Intermittent recrystallized grains

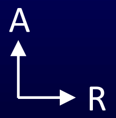
Fully recrystallized layer at OML



Hardness Profile of Cylinder from Test #20



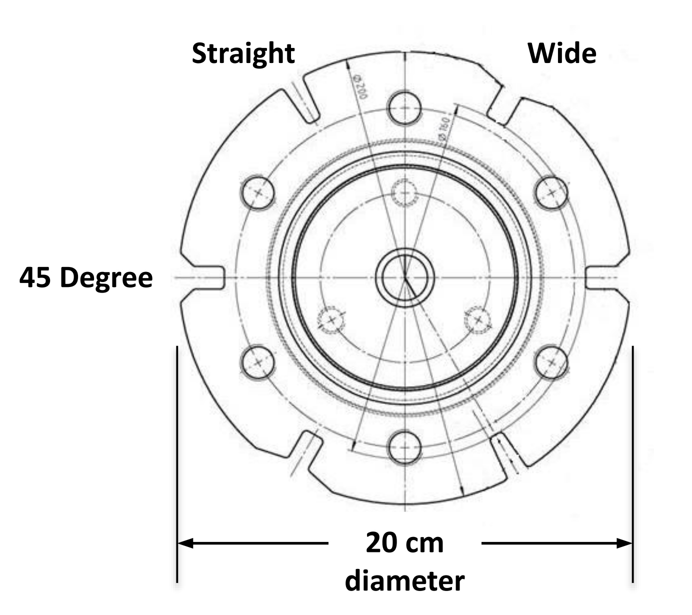




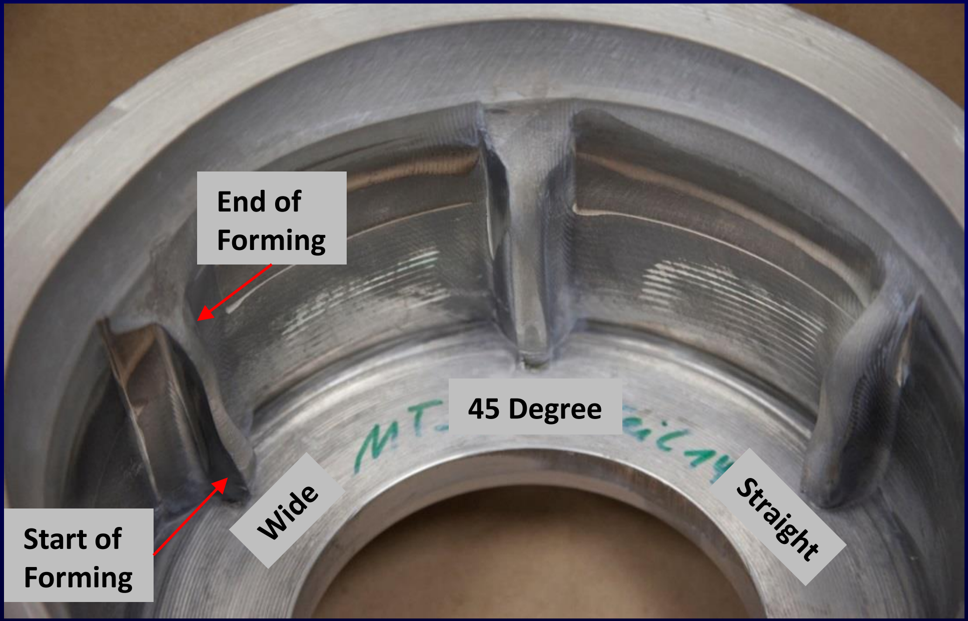
- Hardness decreases overall from top of stiffener to OML
- Hardness is lowest in band of recrystallized grains
  - Suggests reduced tensile strength in this region

Optimize Material Flow into Grooves

- Designed and fabricated new mandrel with three different shaped stiffener grooves
  - Entry angle varied to optimize material flow into stiffener groove
  - All stiffener grooves are 20 mm deep
- Successfully fabricated stiffeners representative of cryogenic tank barrels
  - Fully filled all stiffener grooves near the start of forming
  - Straight stiffener groove resulted in most complete fill along the length of the stiffener



Mandrel with Three Stiffener Groove Shapes



Cylinder with Three Stiffener Shapes

ISC 2014 Forming Campaign

		Pot Forming					Stiffener Forming				
Teil	Test	Blank Configuration	Roller Set	Pot Forming Tool	Preheat	Parameters	Roller Set	Pot Forming Tool	Preheat	Parameters*	Maximum Stiffener Height
4	7	Dia. 300 mm t 30 mm	2	Mandrel 1	5 hrs 410°C	1 manufacturing step Axial and rotation speed fixed	1	Mandrel 2	5 hrs 410°C	Rot/axial speed 1:3 Rot constant; vary axial	14.7 mm
5	8	Dia. 300 mm t 30 mm	2	Mandrel 1	5 hrs 410°C	1 manufacturing step Axial and rotation speed fixed	1	Mandrel 2	5 hrs 410°C	Rot/axial speed 1:3	19.9 mm
6	9	Dia. 300 mm t 30 mm	2	Mandrel 1	5 hrs 410°C	1 manufacturing step Axial and rotation speed fixed	1	Mandrel 2	5 hrs 410°C	Rot/axial speed 1:4	15.9 mm
7	10	Dia. 300 mm t 30 mm	2	Mandrel 1	2.5 hrs 410°C	1 manufacturing step Axial and rotation speed fixed	1	Mandrel 2	5 hrs 410°C	Rot/axial speed 1:3	16.6 mm
8	11	Dia. 300 mm t 30 mm	2	Mandrel 1	2.5 hrs 410°C	1 manufacturing step Axial and rotation speed fixed	1	Mandrel 2	5 hrs 410°C	Rot/axial speed 1:1	11.7 mm
9	12	Cylinder	2	NA	NA	NA	2	Mandrel 1	5 hrs 410°C	Same as Test #8	7.7 mm
10	13	Cylinder	2	NA	NA	NA	1	Mandrel 1	5 hrs 410°C	Same as Test #8	11.7 mm
11	14	Cylinder	2	NA	NA	NA	1	Mandrel 2	5 hrs 410°C	Same as Test #8	11.3 mm
12	15	Dia. 300 mm t 37 mm	2	Mandrel 1	2.5 hrs 410°C	1 manufacturing step Axial and rotation speed fixed	1	Mandrel 2	5 hrs 410°C	Same as Test #8	20 mm
13	16	Dia. 300 mm t 37 mm	2	Mandrel 1	2.5 hrs 410°C	1 manufacturing step Axial and rotation speed fixed	1	Mandrel 2	5 hrs 410°C	Same as Test #8	20 mm
14	17	Dia. 300 mm t 37 mm	2	Mandrel 1	2.5 hrs 410°C	1 manufacturing step Axial and rotation speed fixed	1	Mandrel 2	5 hrs 410°C	Same as Test #8	20 mm

Parameters	
Axial speed	200 - 800 mm/min
Rotation / axial speed ratio	1:1 - 1:4
Feed rate	Bite taken in sequence by three offset forming rollers

Analysis Goals

- Effect of starting blank geometry
  - Thin vs thick machined taper vs cylinder
  - Compare cylinders 8, 14, and 17
- Characterize material flow into different groove shapes
  - Mandrel 1 vs mandrel 2
  - Compare cylinders 13 and 14
- Effect of forming parameters
  - Change in feed rate (only adjust roller c) – compare cylinders 7, 8, and 10
  - Effect of rot./axial speed ratio - compare cylinders 8, 9, and 11

Integrally Stiffened Cylinders from 2014 Campaign Selected for Analysis (Al-Li 2195)


Test #8

- Best of the parameter optimization series (7-11)
- Thinner tapered blank; formed pot
- Stiffener height 19.9 mm


Test #14

- Cylinder forming blank
- Stiffener height 11 mm

Evaluation of Material Flow Into Grooves

Straight Stiffener from Test #8

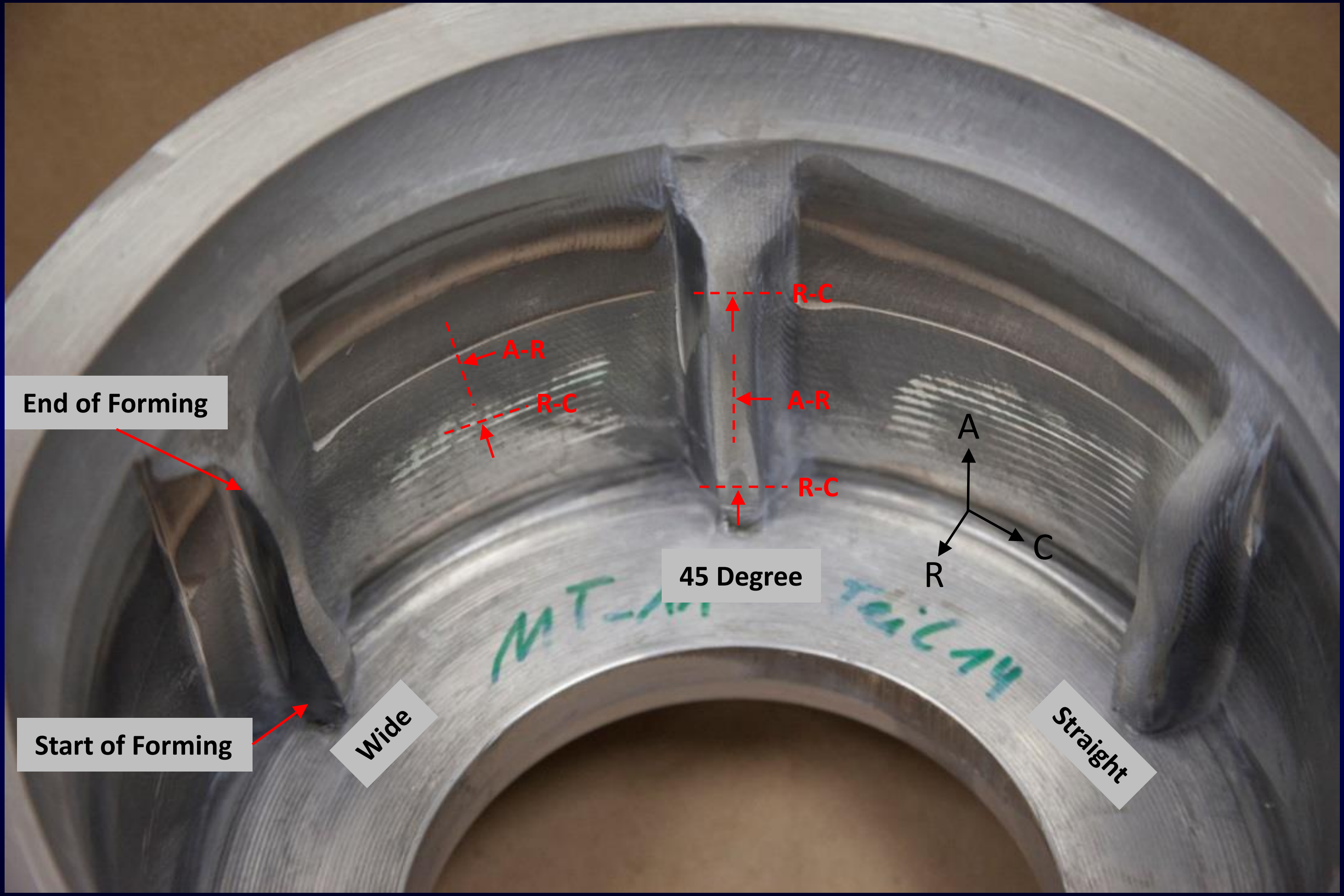
- Flow lines and cracking at start of forming
- Evidence that material reached bottom of groove

Evaluation of Material Flow Into Grooves

45 Degree Stiffener from Test #8

- Flow lines and cracking at start of forming
- Evidence that material reached bottom of groove

Al-Li 2195 Integrally Stiffened Cylinders from 2014 Campaign - Analysis Plan



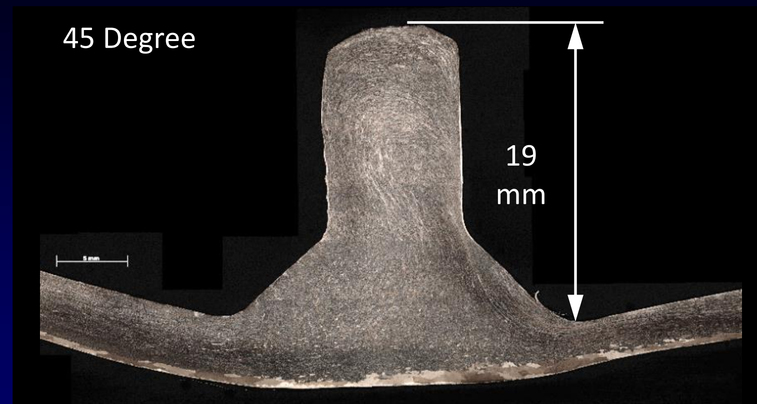
Comparison of Material Flow Into Grooves

Material Flow Pattern in Stiffeners Varies with Entry Angle of Stiffener Grooves

IML

Direction of material flow during forming

Direction of material flow about circumference during forming



OML

R

C

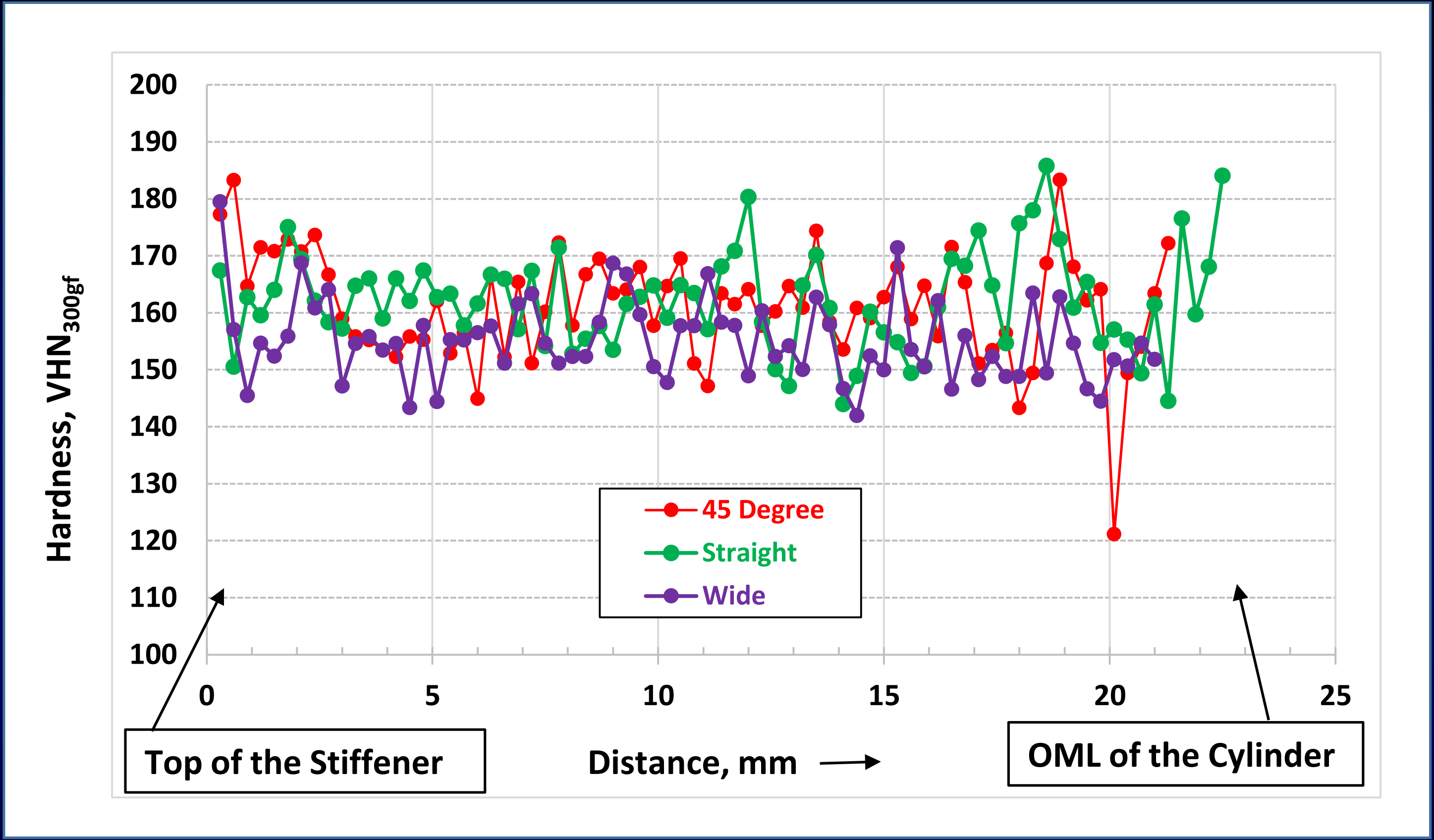
- Complex flow into grooves
- Greater fill in straight groove
- Grain flow similar in 45 degree and wide openings
- Wall thickness varies about cylinder circumference

Tensile Properties of Cylinder Wall from Test #8

	Tensile Properties of Al-Li Alloy 2195-T6			
Material	UTS (ksi)	YS (ksi)	elong. (%)	E (Msi)
ISC Test #8	68.6	60.6	6.0	10.6
Plate	68.6	54.4	17.3	11.1

- Tensile tests of cylinder wall for 2014 test #8
- Tensile UTS comparable to 2195-T6 plate
- Yield strength ~10% greater than 2195-T6 plate
- Elongation lower than 2195-T6 plate

Hardness Profile of Cylinder from Test #8



- Uniform hardness from top of stiffener to OML of cylinder wall
- Hardness comparable to cylinder from Test #20 from 2013 campaign

Test #8: Al-Li 2195-T6

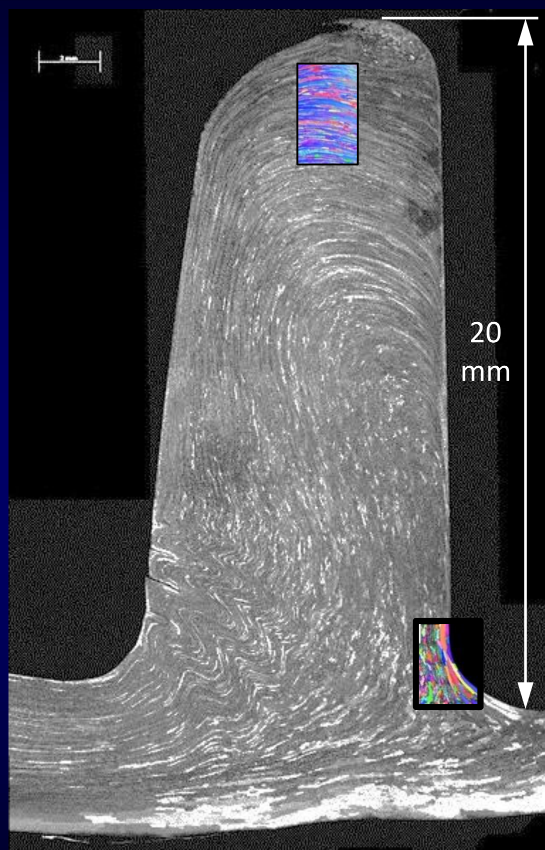
Comparison of Grain Size and Morphology in Stiffeners

⊗ Direction of material flow during forming

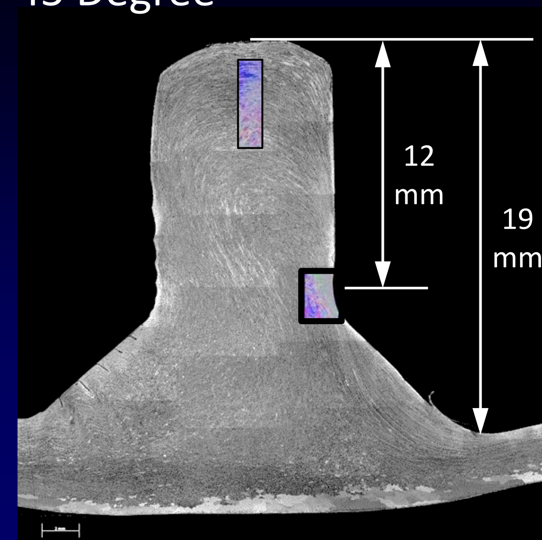
→ Direction of material flow about circumference during forming

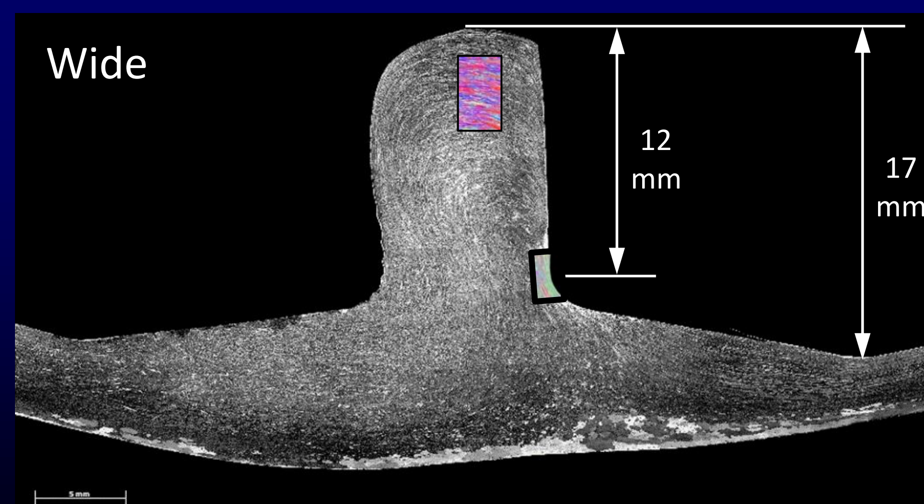
R ↑ → C

Straight



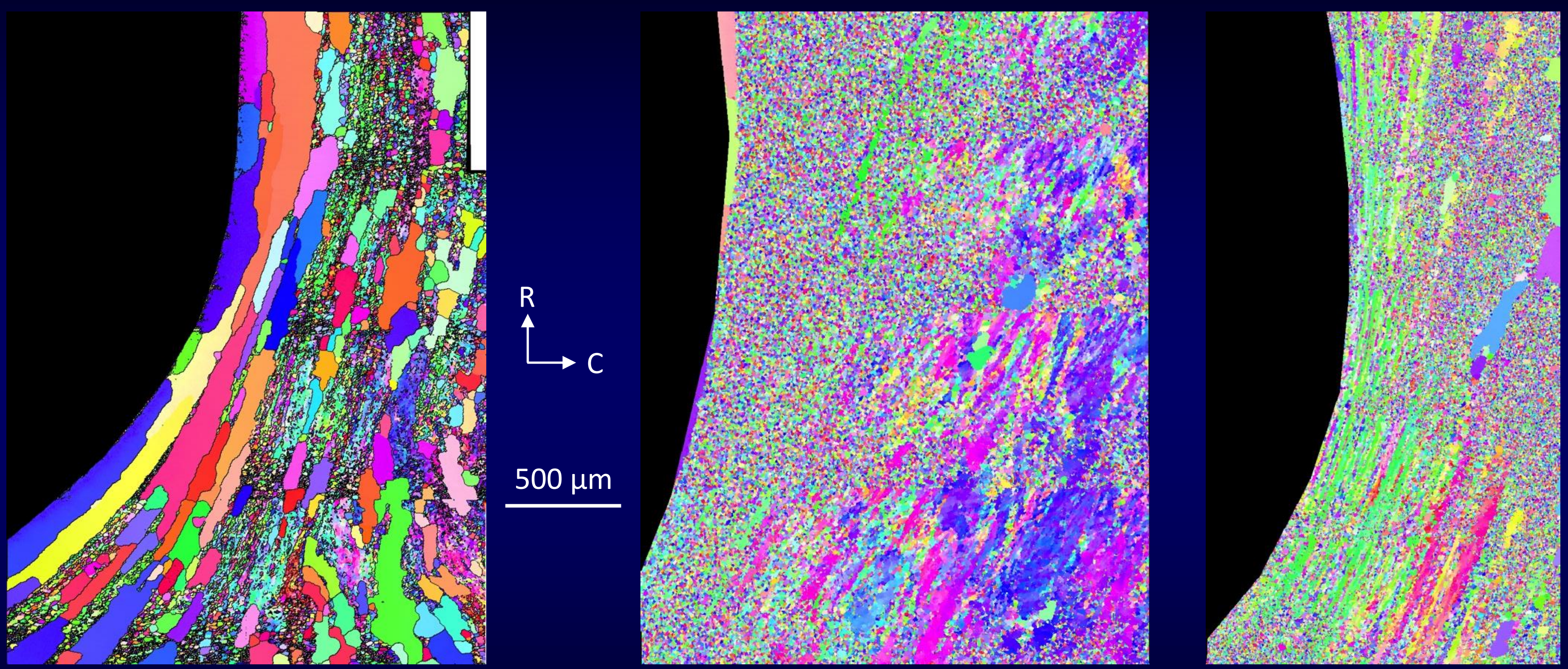
45 Degree





Test #8: Al-Li 2195-T6
Comparison of Grain Size and Morphology in Stiffeners

Straight | 45 deg | Wide



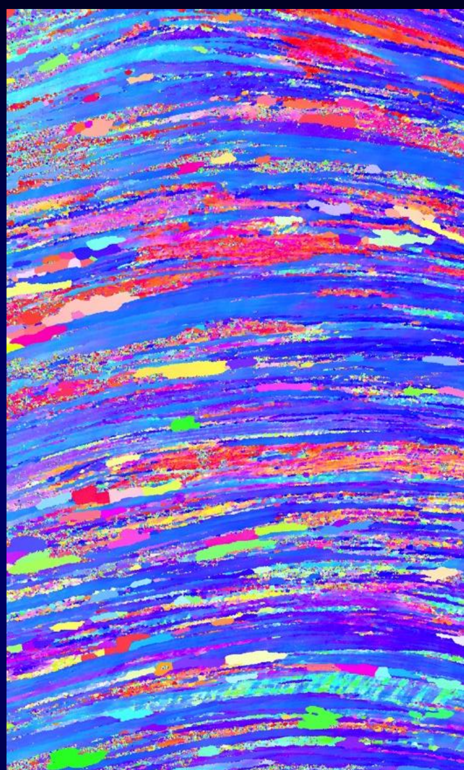
Mix of large recrystallized grains and finer equiaxed structure

Thin recrystallized layer along edge of stiffener
Much lower extent of recrystallization than straight groove geometry

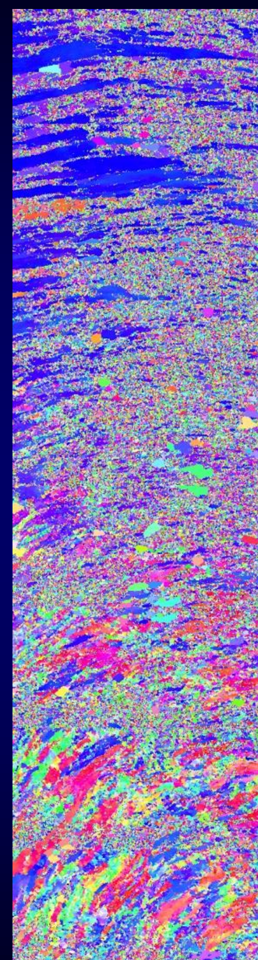
Test #8: Al-Li 2195-T6

Comparison of Grain Size and Morphology in Stiffeners

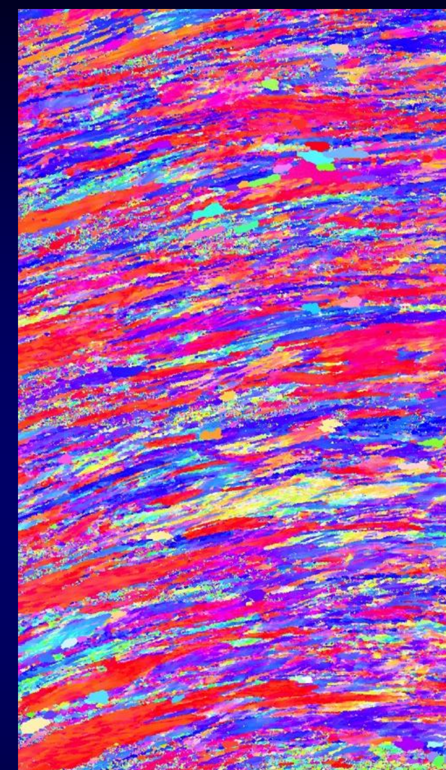
Straight



45 deg



Wide



R

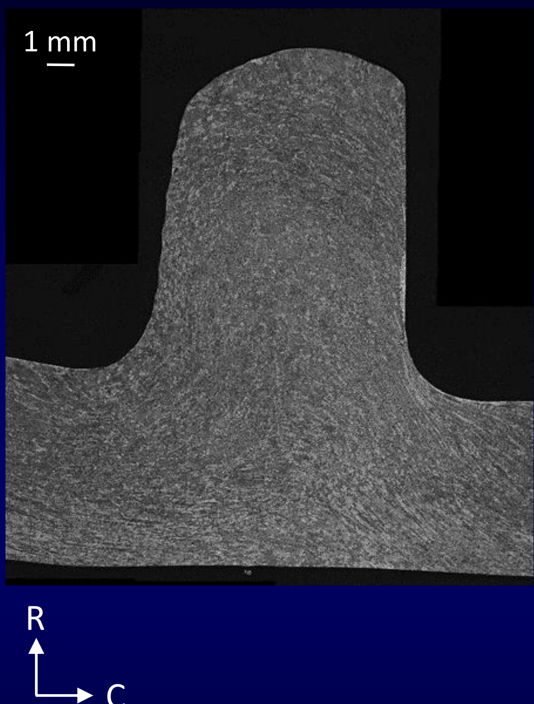
C

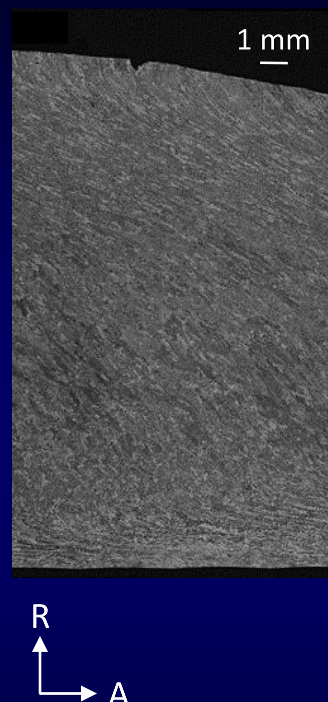
500 µm

- Mixture of elongated, Rx grains, deformed microstructure with isolated fine grain regions
- Stronger texture than 2013 cylinders

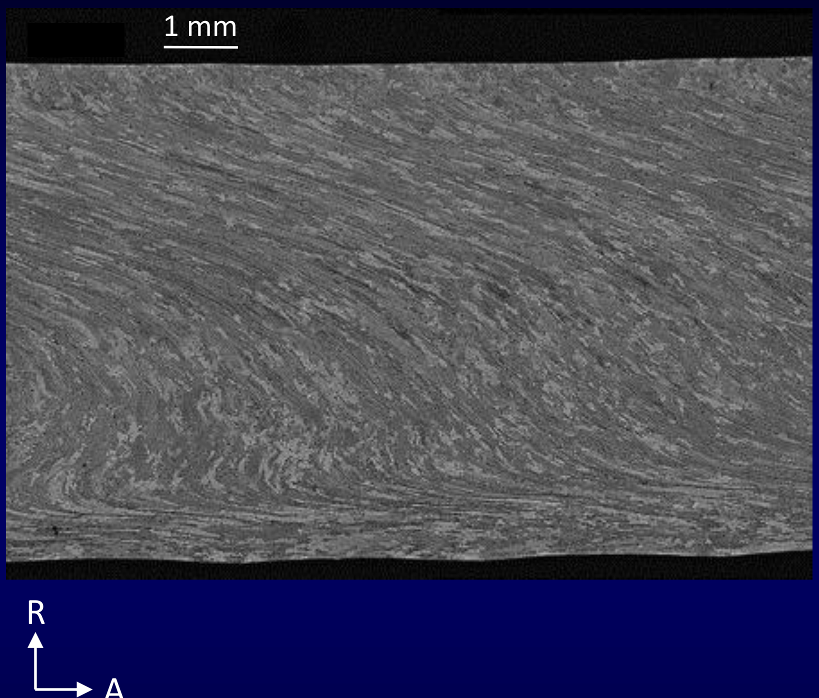
Comparison of Material Flow Into Grooves
Test #14 – Cylindrical Preform

Stiffener





Cylinder Wall



- More uniform flow lines than in cylinder formed from tapered plate blank

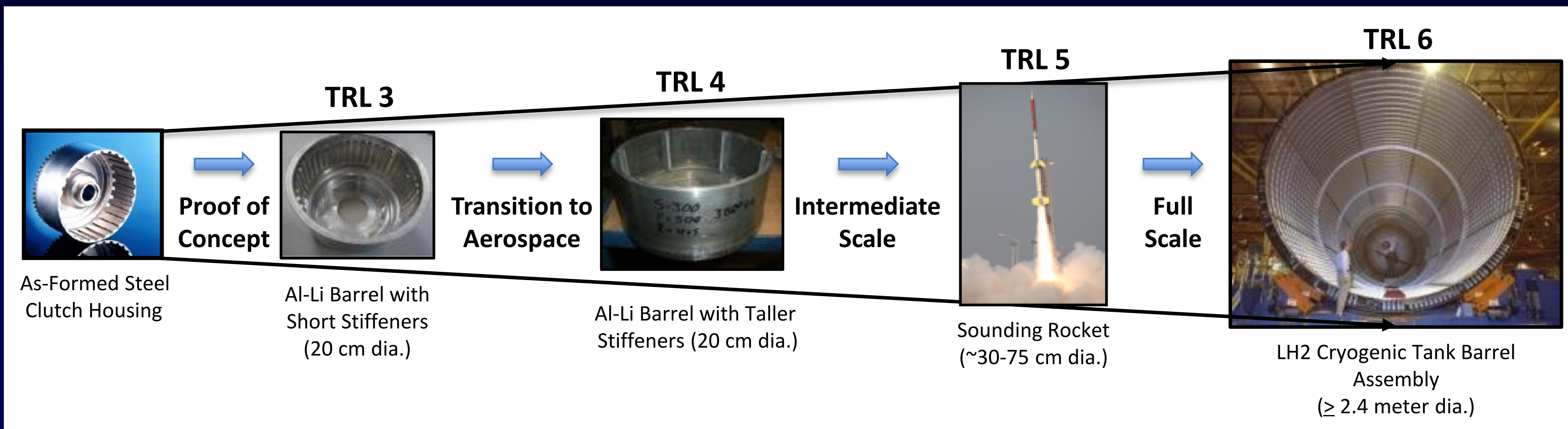
Integrally Stiffened Cylinder (ISC) Process Development – Summary and Future Plans

- Process Development
  - Optimize process parameters for cryogenic tank scale stiffener geometries
  - Continue analysis of formed integrally stiffened cylinders
    - Evaluate effect of forming parameters
    - Tensile test of stiffeners and cylinder wall
    - Examine microstructural evolution

- Scale up
  - Identify intermediate scale structural applications that are within the currently available manufacturing capability
    - Identify configuration for Sounding Rocket application
  - Develop strategy for larger scale manufacturing
    - Launch vehicle applications
    - Construction of manufacturing capability

- Project support
  - Continue to advocate for support from NASA and commercial launch providers
  - Identify more opportunities for partnerships

Technology Maturation of Integrally Stiffened Cylinder (ISC) Process

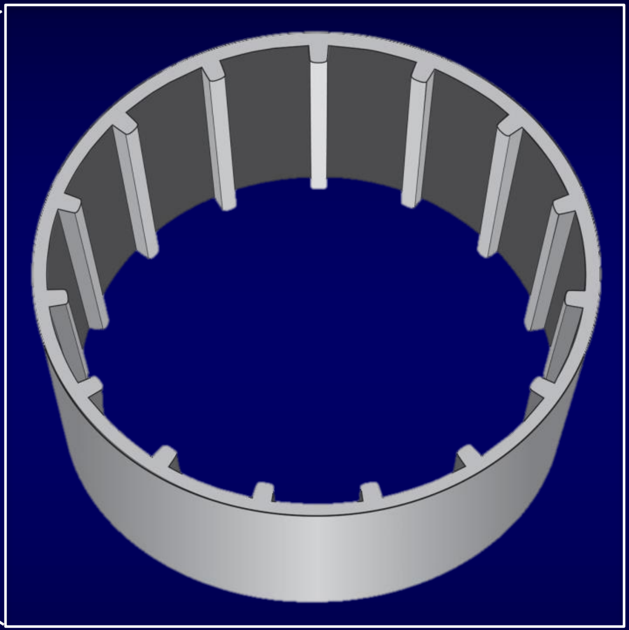


- Intermediate scale-up for Sounding Rocket demonstration
- Long term goal to pursue large-scale cryogenic tank structures

Integrally Stiffened Cylinder (ISC) Process Development

- Extension and scale-up of the ISC process is being pursued.
- Subscale cylinders produced are first of a kind with regard to stiffener height.

20 cm dia.



First forming of Al-Li alloy 2195;
First forming of 12 mm tall stiffeners

2012 - 2014

Scale-up to 30-75 cm diameter with 25 mm tall stiffeners

2015 - 2016

Scale-up of the ISC process will enable Sounding Rocket flight test consideration

2017 - 2018