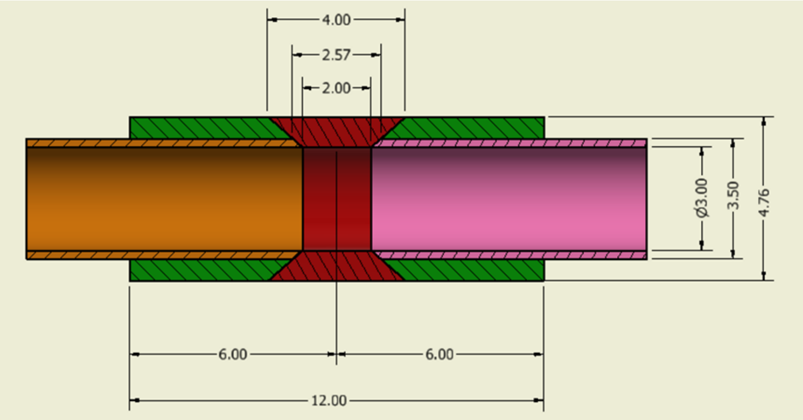
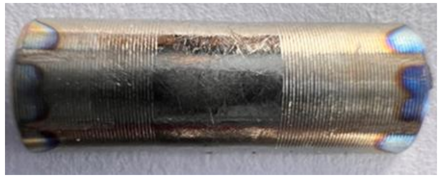
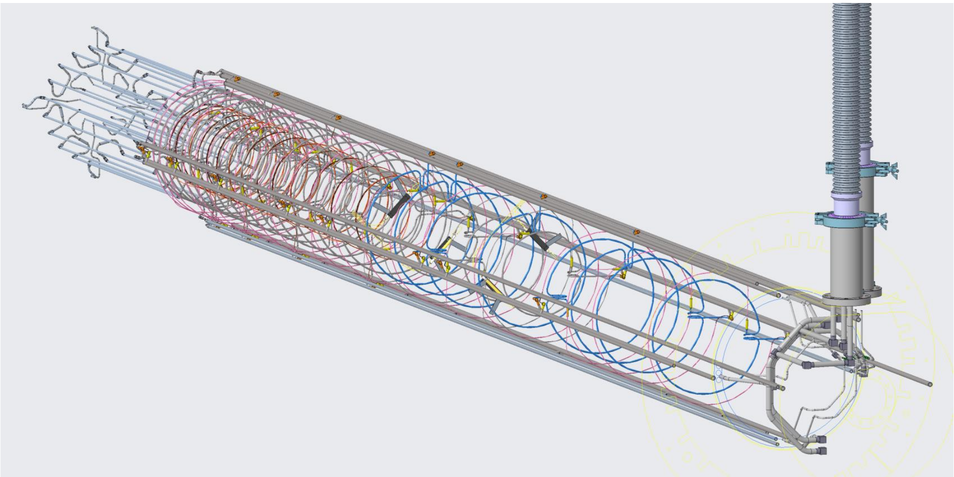
Thin-Wall Titanium Cooling Tubes for the ATLAS Inner Tracker: Sleeve Weld Design, Development & Qualification







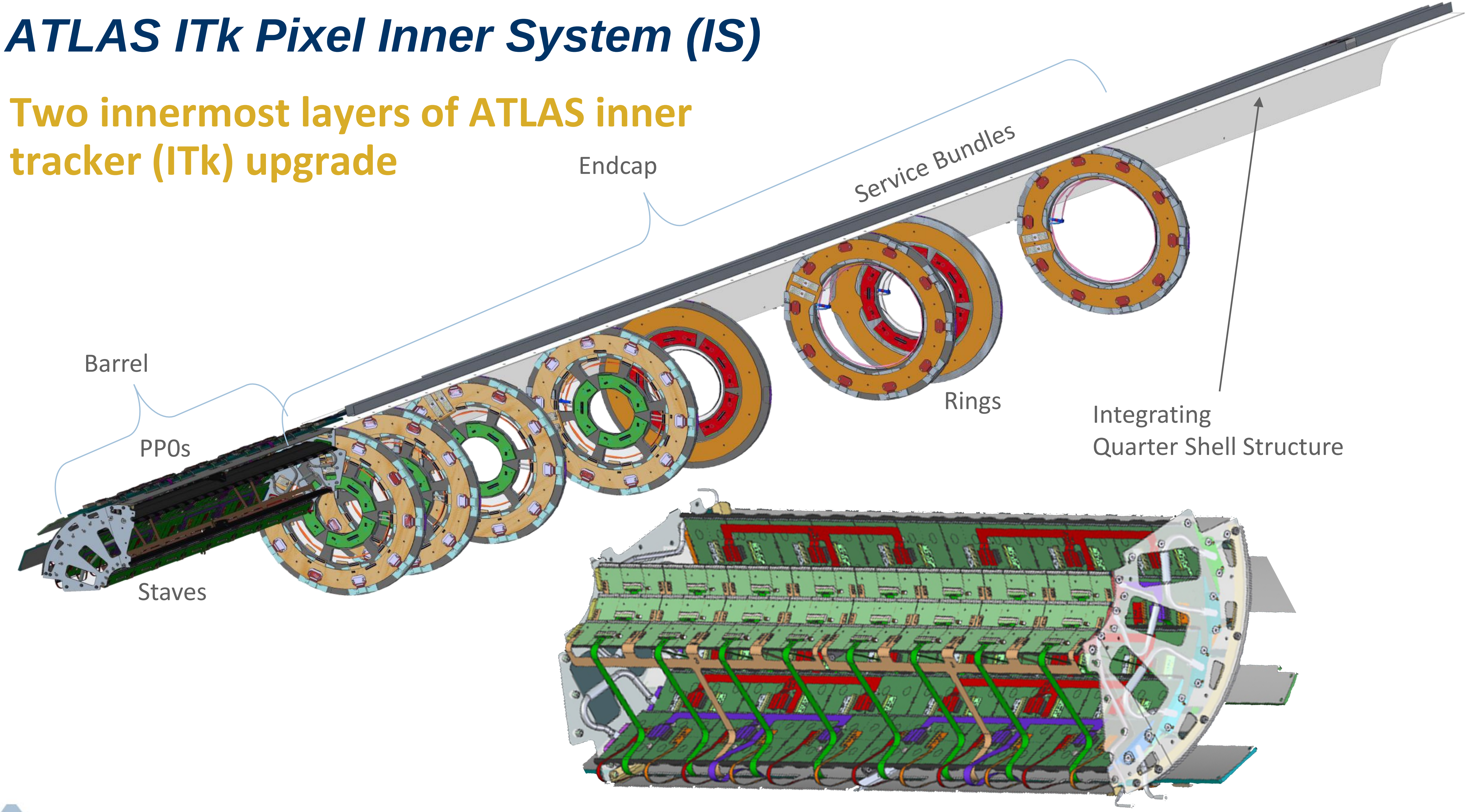
Christine McLean, **Jerin Pappachan**, James Proudfoot, and Allen Zhao

Forum on Tracking Detector Mechanics

May 30, 2024

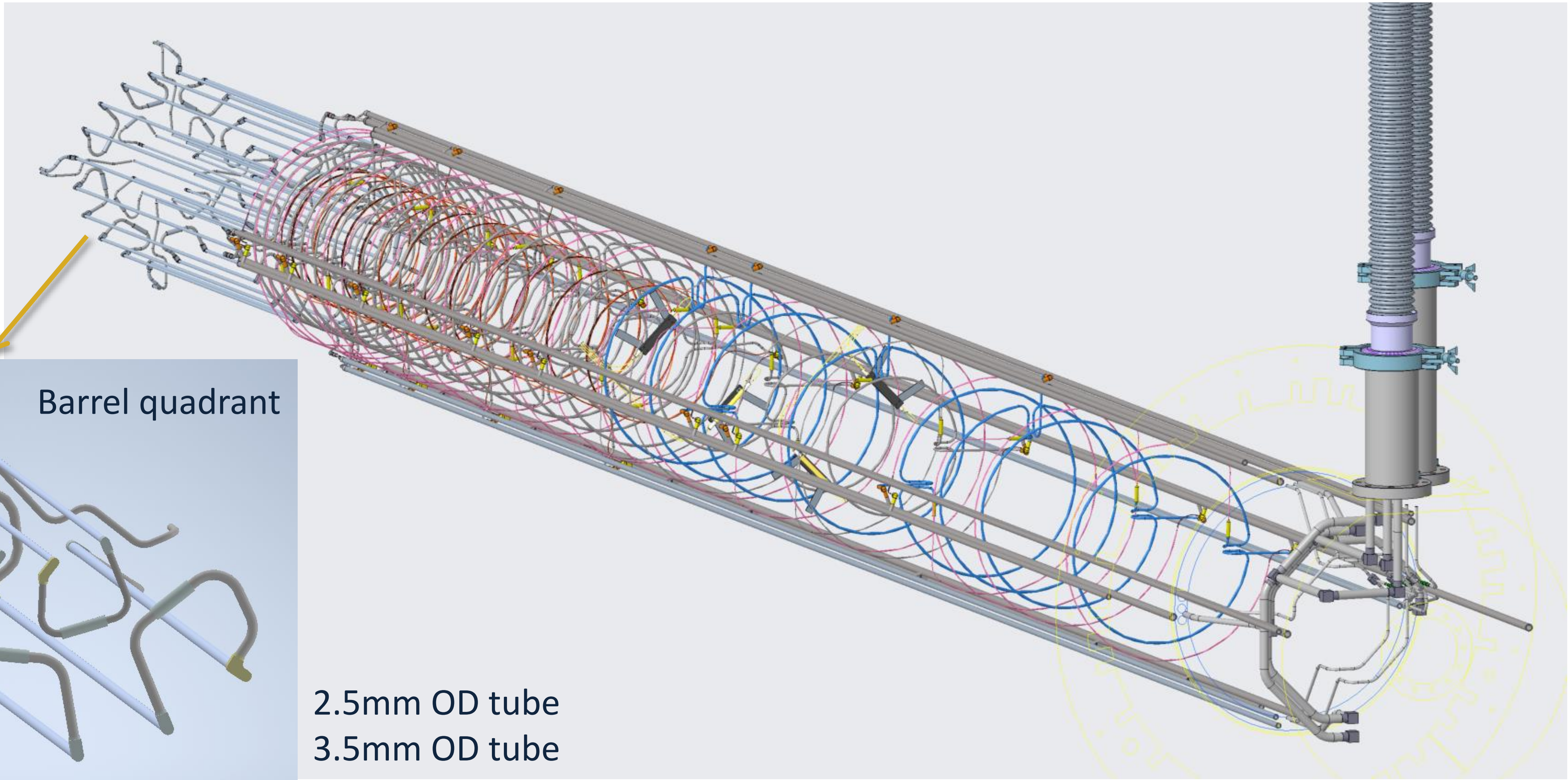
ATLAS ITk Pixel Inner System (IS)

Two innermost layers of ATLAS inner tracker (ITk) upgrade

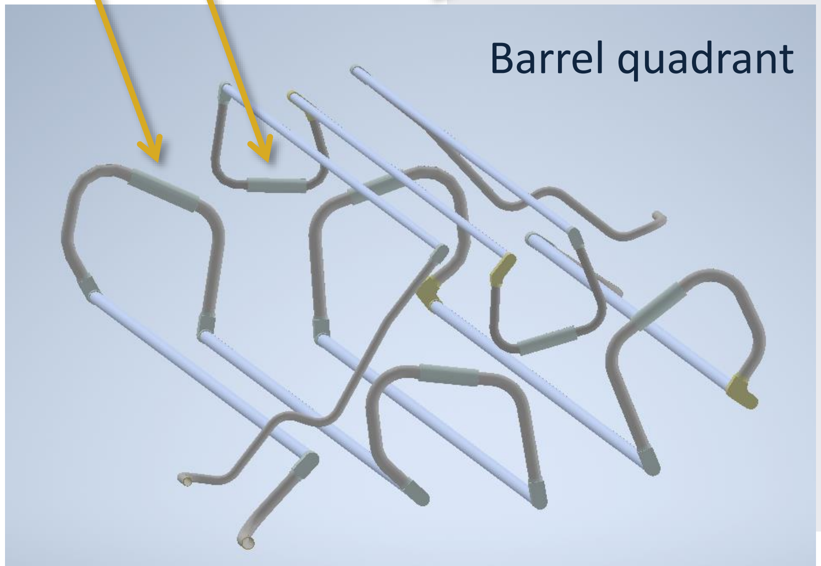


ATLAS ITk Pixel IS Cooling

Space is tight, tube thickness < 0.25 mm – requires thin-wall titanium welding

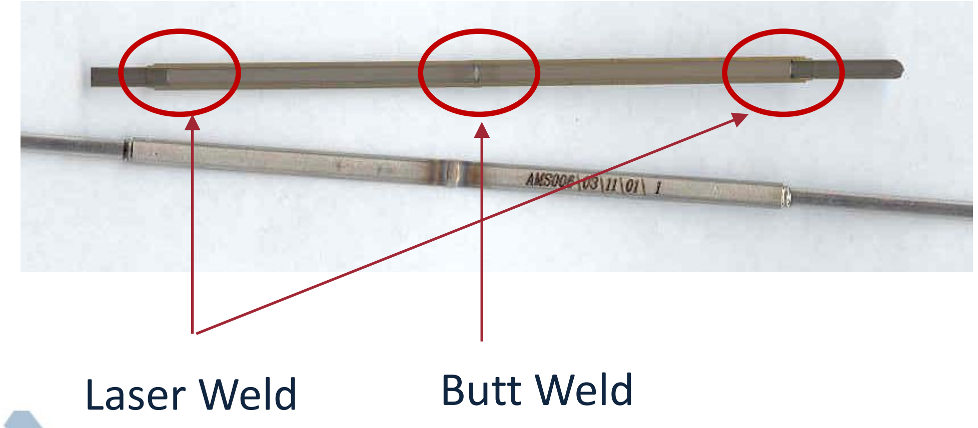


Sleeve welds



Background

- **Robust butt weld on thin wall tube with < 0.25mm thickness is proven to be practically impossible.** Yet thin wall tube weld is needed for many cases
- Bart Verlaat had designed a method for thin wall welding applied to LHCb-Velo
  - Thin wall tubes in straight length were laser welded to a thick wall tube weld connector
  - After bending and assembly the sections were welded together with orbital welding.

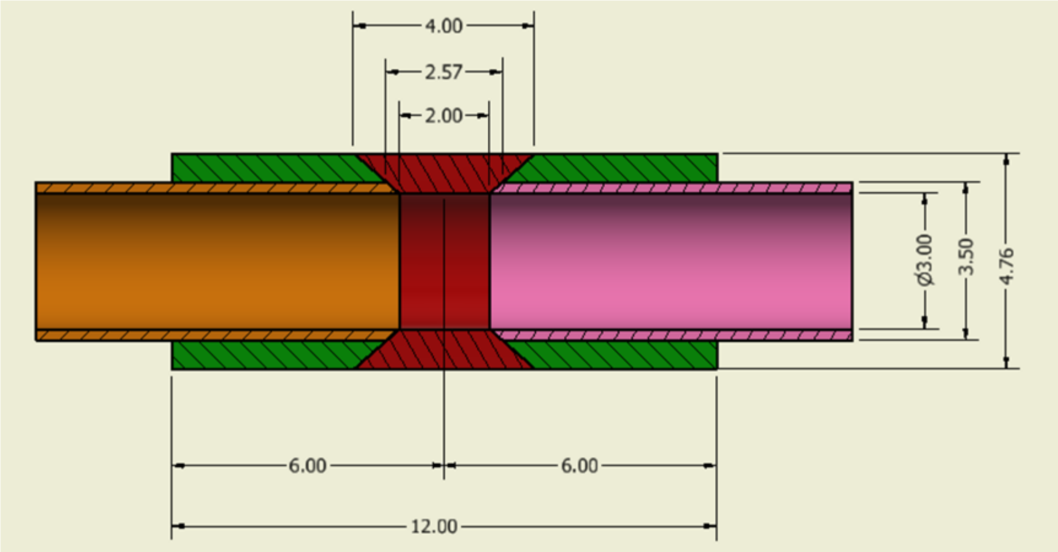


- Sheffield University design
  - Weld sleeve fitting with O ring groove for testing
    - Weld at edge of sleeve
  - only 0.2mm with total thickness < 0.5mm

- Our philosophy is to add material locally to the weld zone
- Total material thickness similar to industry weld thickness, therefore, achieve industry weld robustness

Sleeve Weld Design - Sleeve Thickness & OD

- Thickness of sleeve
  - Larger or equal to the tube thickness
  - Sleeve strength to resist the clamping force of micro-weld
    - Swagelok micro-weld using laser cut spring to clamp the tube
    - Sleeve thickness > 0.4 mm to resist the spring force without significant deformation
  - Minimum total thickness >= 0.7mm for good weld operation
    - Industry standard weld with extremely high reliability
    - few porosity issues and very robust
- Sleeve OD
  - If possible, choose sleeve OD with available Swagelok weld head fixture size
    - Possible choice 4.76 mm (3/16 inches) sleeve OD for 3.5mm tube
  - OD should be as popular as possible for easy procurement of sleeve and pressure testing fitting
- Overall choose 4.76mm OD sleeve, with a wall thickness of 0.63mm, giving a combined thickness 0.88mm

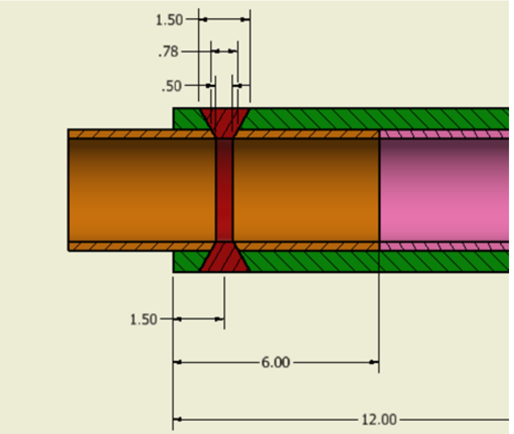


Case Study: OD 3.50/ID 3.00 mm

Swagelok series 4 micro weld head fixture

Sleeve Welding Design – Weld Strength Calculation

- Weld Failure modes
  - Fracture on bare tube
  - Fracture interfacial surface
  - Fracture HAZ on tube
- Designing for strength of weld joint
  - Sleeve tensile strength > tube tensile strength
    - Sleeve cross-sectional area is 15% larger than the tube cross sectional area
  - Shear strength at weld interface > tube tensile strength
    - Calculate the minimum required weld width for each weld size
    - For tube thickness 0.25mm (3.5mm OD), weld width at the interface >= 0.389 mm
- Distance between weld center to the edge of sleeve
  - Minimum distance of 1.0 mm if weld OD width is > 1 mm
  - This distance is important for qualification



Full Penetration Lap Joint

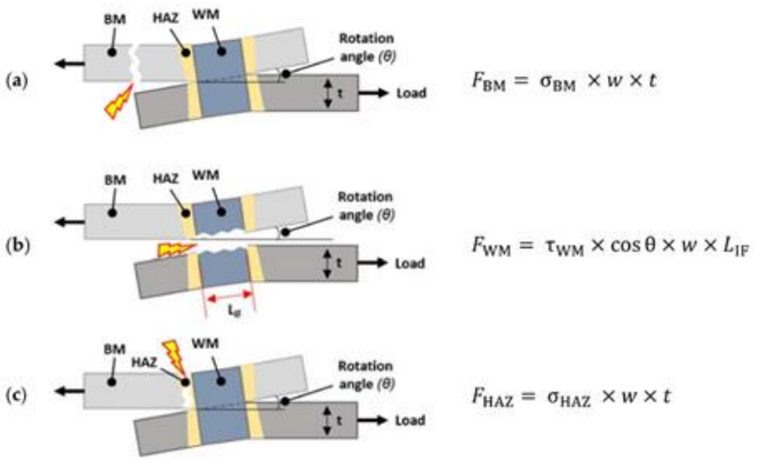


Figure 5. Classification of failure mode and effective force to fracture depending on ruptured location at (a) base metal, (b) interfacial surface, and (c) heat-affected zone.

Tensile–Shear Fracture Behavior Prediction of High-Strength Steel Laser Overlap Welds, Kang M et.al,, Metals 2018, 8(5), 365

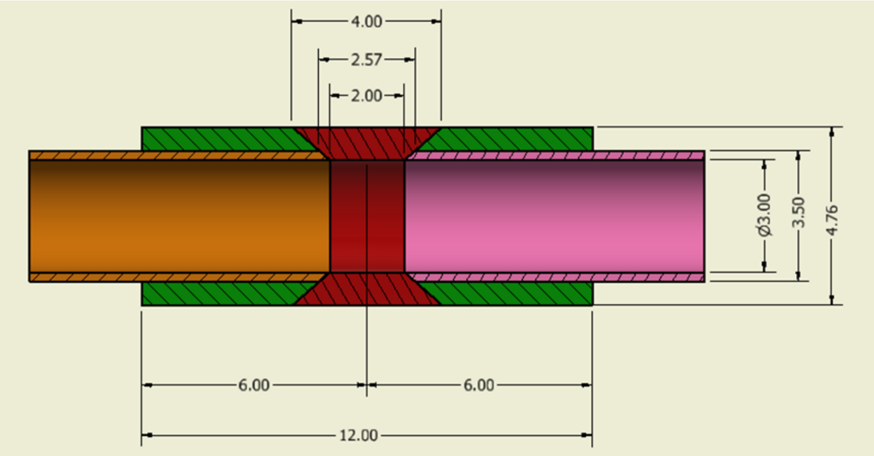
https://metalitec.zriha.com/eng/raw-materials/titanium-grade-2

$\sigma := 420\text{MPa}$	Titanium Grade 2 ultimate tensile strength
$\tau := 270\text{MPa}$	Titanium Grade 2 shear strength
$t := 0.25\text{mm}$	Tube thickness
$OD_{tube} := 3.5\text{mm}$	
$F1 := \sigma \cdot \pi OD_{tube} \cdot t$	Tensile force on tube
$F2 := \tau \cdot \pi \cdot OD_{tube} \cdot L_{interface}$	Shear on weld at interface
$F2 > F1$	Shear should be larger than tensile on tube
$L_{interface} := \frac{\sigma}{\tau} \cdot t = 0.389\text{mm}$	Minimal required weld width @ interface

Weld Design – Weld Geometry

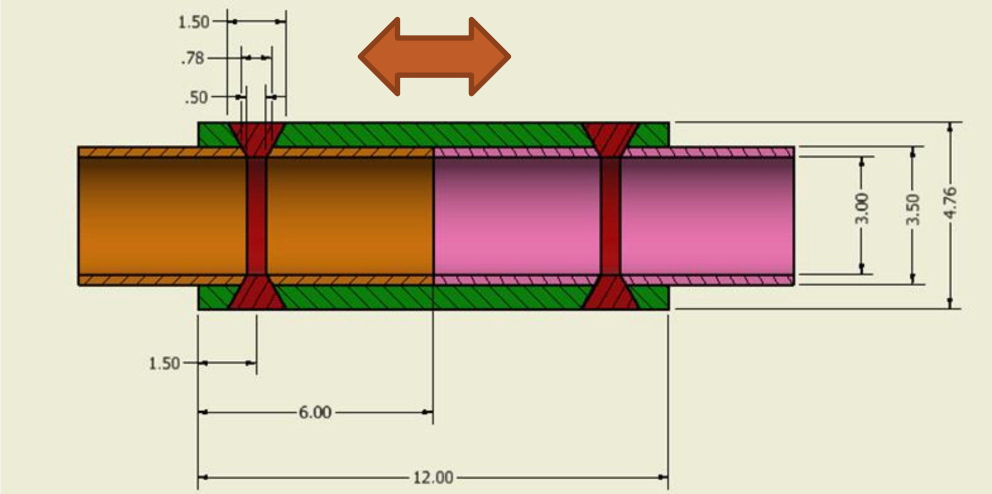
Sleeve Butt Weld

- Pro
  - Only needs 12mm space to weld
  - Robust design and similar to industry standard butt weld
- Con
  - High weld power causes large HAZ, higher temp
  - Sleeve is 12mm long
  - Complex alignment procedure
  - Not ideal for backup welds



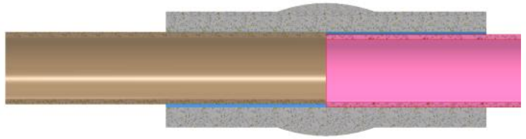
Sleeve Lap Weld

- Pro
  - Low weld power and heat generated during welding
  - Simple alignment procedure
  - Works well for backup weld
- Con
  - More complex fixture design

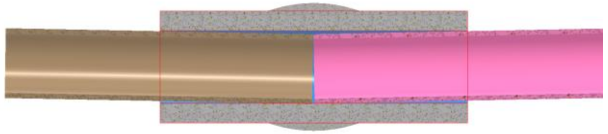


Gap Control Between Tube and Sleeve

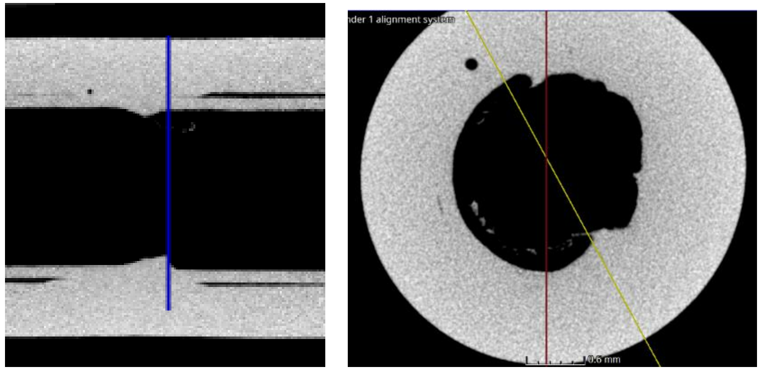
- The gap control is crucial for a good quality sleeve weld
  - Small gap makes the tube hard to insert into the sleeve and slide
  - Large gap will cause alignment issues
    - Tubes don't meet at the end (not butted together)
    - Possibility of blow through
    - Can cause large porosities in weld zone
- Ideal gap between sleeve ID and Tube OD is about 10-20 um
  - Tube OD measured at 3.500-3.506 mm
  - Ideal sleeve ID 3.516-3.526 mm
  - + 0.010mm is on the tight side
  - ID of sleeve is hard to measure to this precision, we use feel to estimate the tightness between tube and sleeve



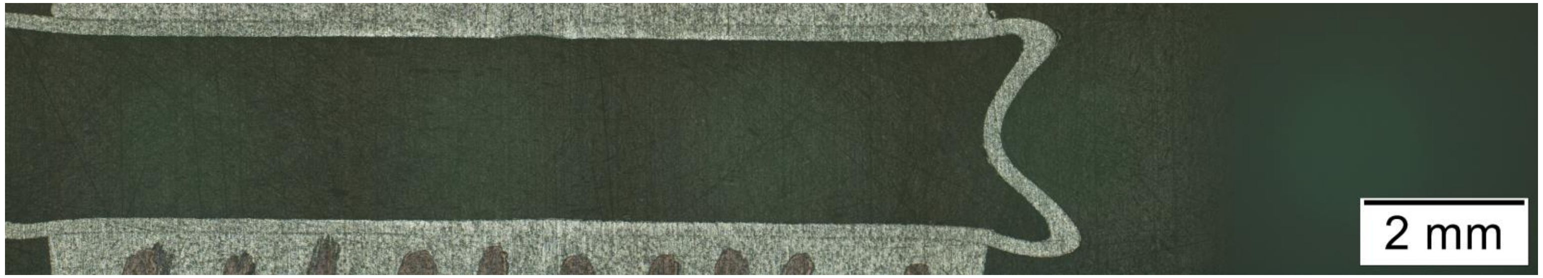
Offset 0.1mm



Angled 1 degree



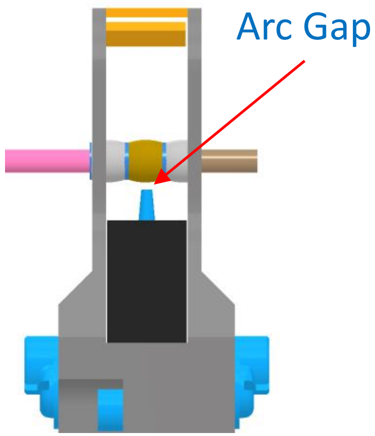
Loose ID tolerance

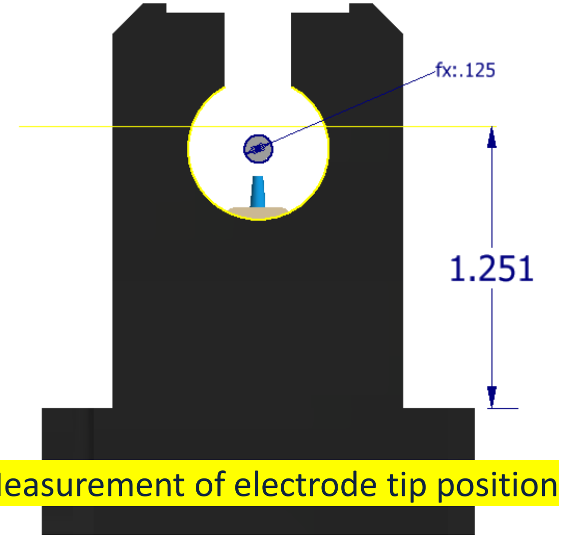


Cross section of butt-welded sleeve and tube – tight tolerance

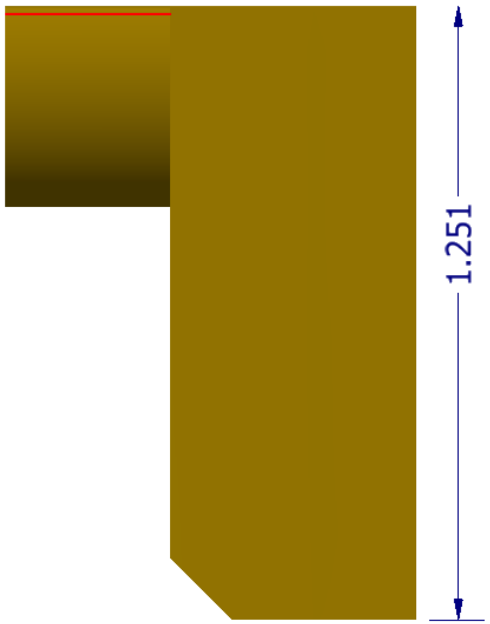
Weld Electrode and Arc Gap Setting

- Arc gap: Distance from the electrode to the OD of sleeve
- Impacts of arc gap
  - Large gap, arc will not initiate properly
  - Small gap, cause blow out
- Arc gap is set to the Swagelok recommended gap setting + 5 thousands.
  - Avoid/reduce the risk of damage to the weld head due to tip touching the tube
  - Avoid/reduce the risk of weld blow out
- Challenges: Swagelok arc gap setting procedure is not very precise and repeatable
- Solution: Designed an electrode gap setting gauge block
  - Sets the electrode with the desired arc gap for each weld type (2.5mm and 3.5mm)
    - Total length of gauge is distance from bottom reference point to OD of tube + arc gap = 1.251”
  - Gauge block is set into place, and we position the electrode until it touches the top of the gauge block

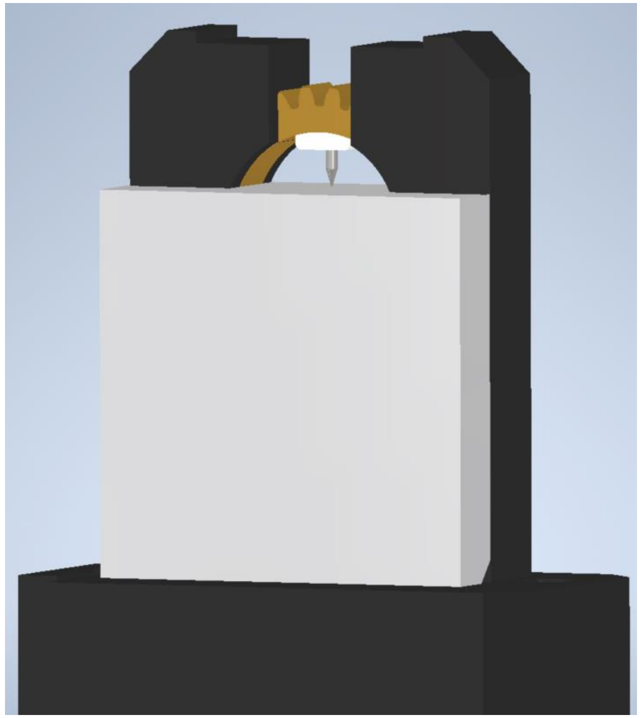




Measurement of electrode tip position

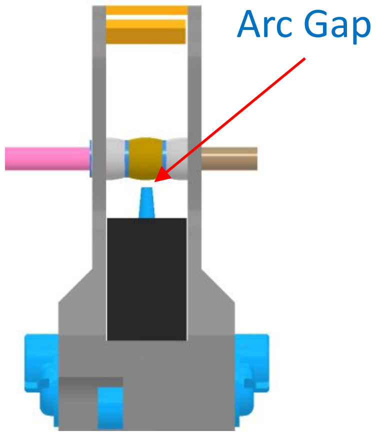


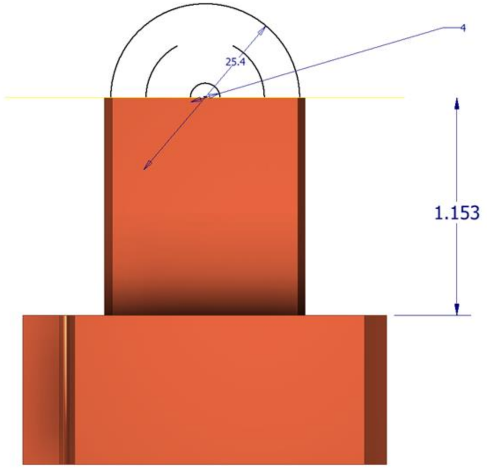
Arc gap setting block


Electrode set using arc gap set block

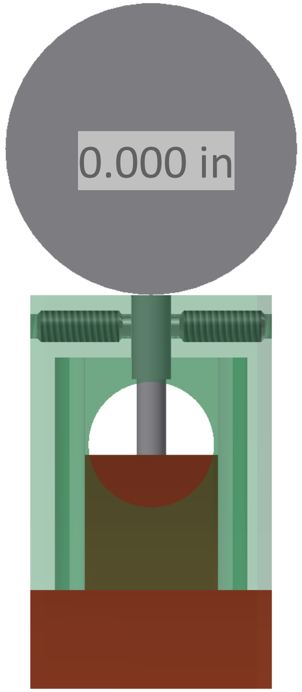
Weld Arc Gap Measurement

- Arc gap is very important for successful welding
- Challenges: Arc gap position may shift and no measurement tool
- Solution: Designed and fabricated an arc gap gauge to ensure that the arc gap is at the correct setting
  - Machined a block to define the zero position of arc gap for each weld tube (represents the OD of sleeve)
  - Set the dial indicator to zero using the zero block
  - Use the dial indicator to measure the position of the electrode tip
  - Measure the arc gap (distance from tube OD to electrode tip)
- When to use the gauge
  - Before the first weld in a day
  - Every 10 welds
  - After electrode replacement
  - Switch weld head or weld head fixture





Zero block



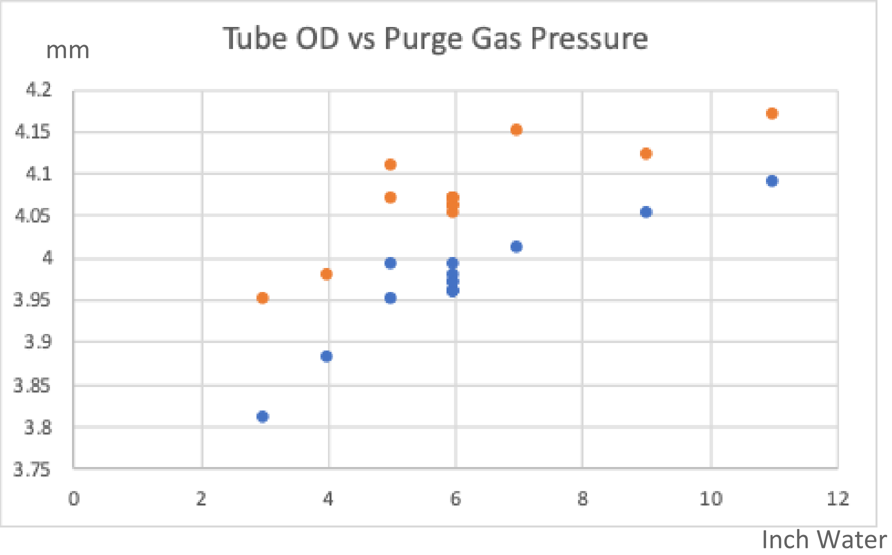
Set gauge to zero

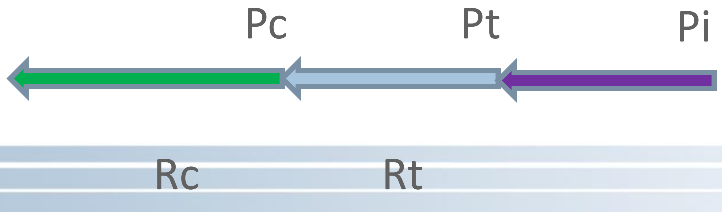
Arc gap measurement

Purge Gas

- Purge gas has three functions
  - Together with shield gas, isolate the weld zone from oxidation (coloration)
  - To support the liquid state weld puddle from sagging
    - Low purge gas pressure will cause OD concave
    - High purge gas pressure will cause OD convex, even blow out
  - Cooling during welding
- Set purge gas pressure by using a Tee section to measure pressure at weld zone before welding
- Use Poiseuille's law to determine the relationship between a control path and the weld zone using a Tee section. We then use this relationship to calculate what we need to set the control path at to get the ideal pressure at the weld zone without the Tee section when we weld.
  - Poiseuille's law: $Q = Pc * Rc = (Pt - Pc) * Rt$

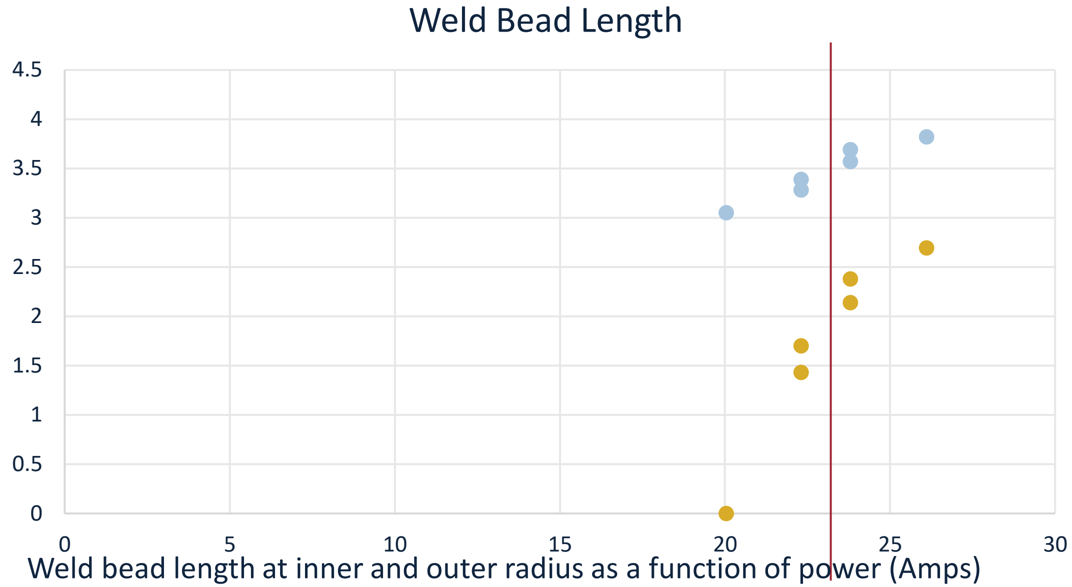
2.5mm OD tube + 4 mm sleeve

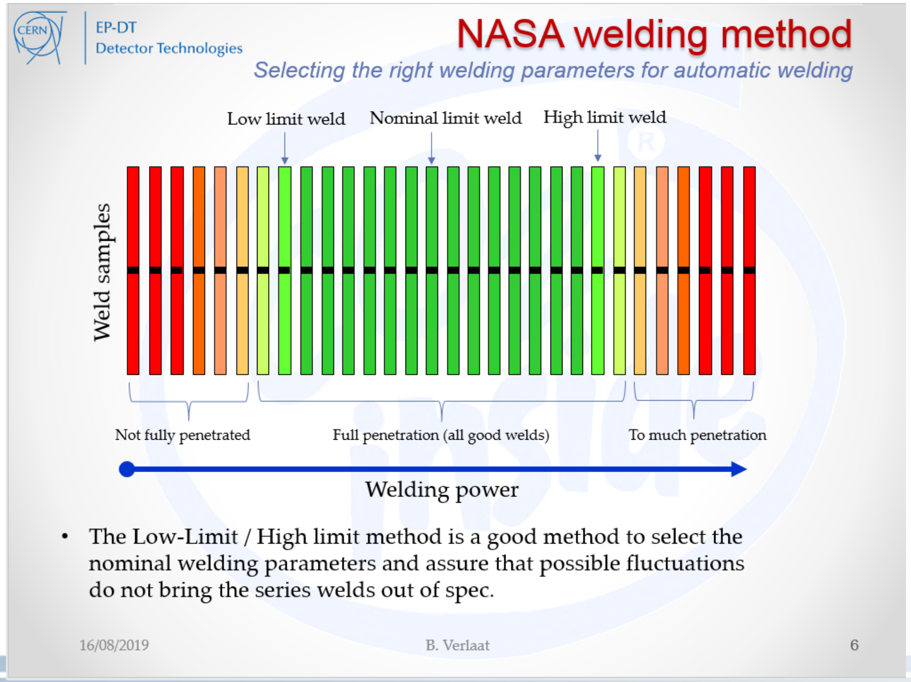




Welding Power Control

- Follow the NASA welding method for selecting the right welding parameters for orbital welding
  - Min Power is required to get full penetration of weld
  - 20 amp - NOT full penetration
  - 22 amp - Full penetration
  - 26 amp - max power, large weld seam, may risk damage to the weld fixture
  - Choose 22.9A as our base line

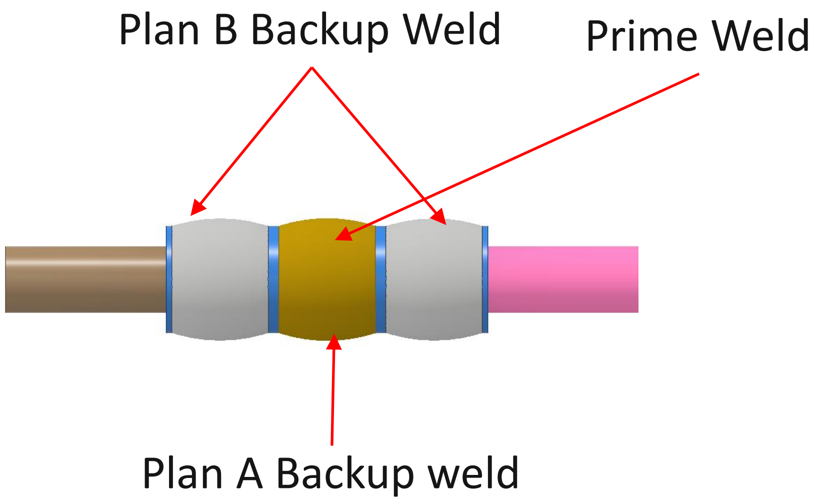


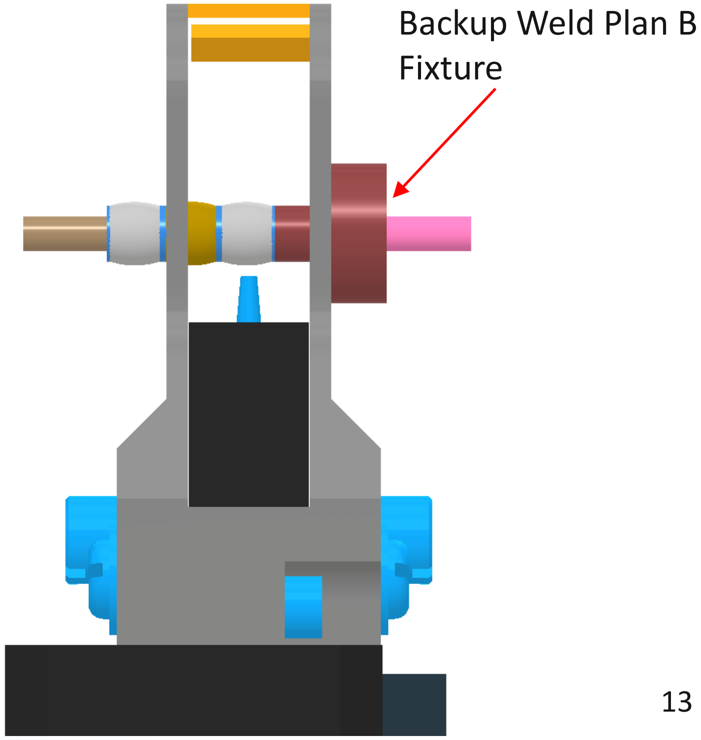


Parameter	1	2	3	4
High Amps, A	47.1	44.9	42.5	40.0
Low Amps, A	14.7	14.7	14.7	14.7
Weld Time, s	1.5	1.5	1.5	1.5
Ramp Time, s	0	0	0	0
Pulse Rate, Hz	8.0	8.0	8.0	8.0
High Amps Width, %	25	25	25	25
High Amps Speed, rpm	12.73	12.73	12.73	12.73
Low Amps Speed, rpm	12.73	15.16	12.73	12.73
Average Amps, A	22.9	22.4	21.8	19.221.2

Backup Weld Plan

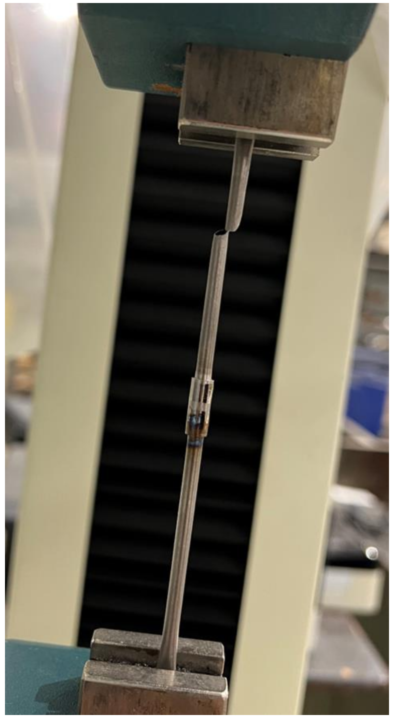
- Plan A – weld at the same location as the prime weld
  - Reweld same location up to 3 times with no visible changes or damage
  - Tested and repaired a previous leaking weld
    - Large gap between sleeve and tube
- Plan B – weld at both ends of the sleeve with the help of a fixture
  - Sleeve lap weld 3mm left and right of prime weld



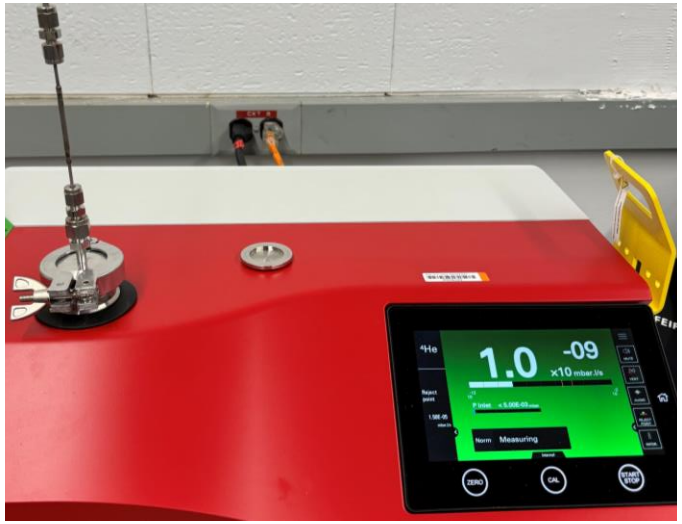


Weld QA/QC

- QA process
  - Cut and inspect inner weld seam
    - Inner weld bead length
  - Weld cross sectional microscopy inspections
    - Cross sectional image of weld penetration
  - Tensile testing
    - Validate weld strength
  - CERN Micro-CT scans
    - Porosity measurements



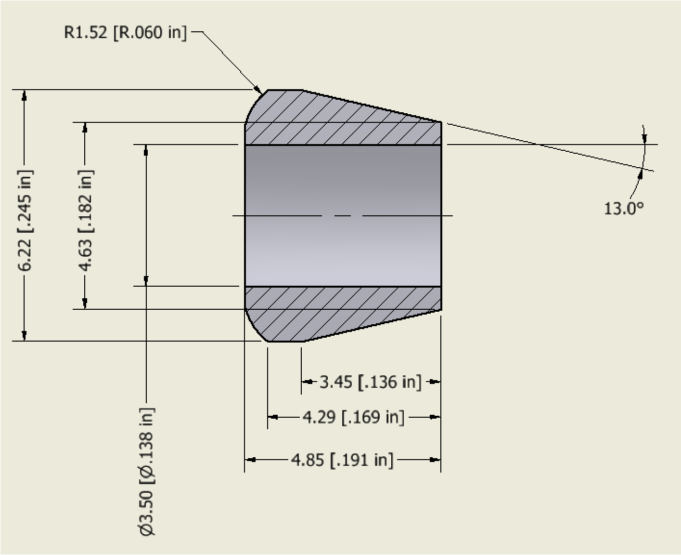
- QC process
  - Visual inspection and measurements
    - Weld uniformity
    - Weld OD range (max and min)
    - Weld width
    - Discoloration
  - Helium leak test
    - < 1.0 * 10^-9 mbar l/s
  - Pressure proof test at 162.5 bar



Temporary High Pressure Fittings for Thin Wall Tubing

- Motivation
  - Nondestructive fittings for high pressure testing of short length tubing
    - Straight section of less than 12mm was needed
  - Fitting should be easily removable
  - Better control of the tightening process
- Action
  - Combined a Swagelok fitting with a PEEK ferrule
  - Shorten the ferrule by 1.5mm, more material at end of ferrule (0.3mm -> 1mm) and takes most of the deformation and enlarges the compression zone so that the tube will deform far less
  - Hand tighten first, then 90-degree turn using wrench
    - Measured torque is about 0.75 NM for 45 degree
- Result
  - Reduced the minimum straight section needed for testing
    - Only 7.5 mm
  - Works at high pressure with no leak (2500 psi)
  - Tube is not crimped and easily removable

Swagelok fitting with PEEK ferrule



PEEK ferrule design

ASME IX Qualification Process

- ASME IX of Boiler and Pressure Vessel Code (BPVC)
  - A part of the ASME boiler pressure vessel code that contains the rules for qualifying welding procedures and welders.
- Procedures for welding to ASME code and QC
  - Material procurement to ASME or ASTM standard; allowable stress values assigned by ASME B31.3; verified by Argonne certified material receipt inspectors
  - Argonne processes will need to address WPS: calibration of the orbital welding device and settings. Procurement control of gases. Oversight of welding (third party oversight)
  - Certified visual inspection and qualified NDE (non-destructive examination) such as leak and or pressure testing of the final welds per ASME B31.3. Per ASME B31.3, 5% radiography would be required on circumferential butt welds using CERN Micro-CT scan. Micrography also be added to verify quality.
- Since the weld process is automatic, operators can be qualified by welding test specimens and qualifying to ASME IX welds

ATLAS ITk Pixel inner System Welding Procedure Specification

WPS Number: WPS-ANL-Pixel-2-Rev1

By: J. Papachan

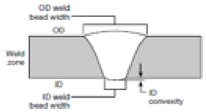
Title : Mechanical Engineer, EOF Division Argonne National Laboratory

Date: Nov 18, 2022

Supporting Procedure Qualification Record (PQR): PQR-ANL-Pixel-

Welding Process:
Gas Tungsten Arc Welding , automatic, Closed chamber.

QW-402 Joints



Pipe inserted into sleeve, centered <0.2mm

Weld bead width >1.5mm

Electrode position centered on joint <0.2mm

QW-403 Base Metal
ASME IX P number P51 welded to ASME IX P number P51

Tube is Titanium Grade 2 (ASME P51 – Titanium alloys)

Sleeve is Titanium Grade 2 (ASME P51 – Titanium alloys)

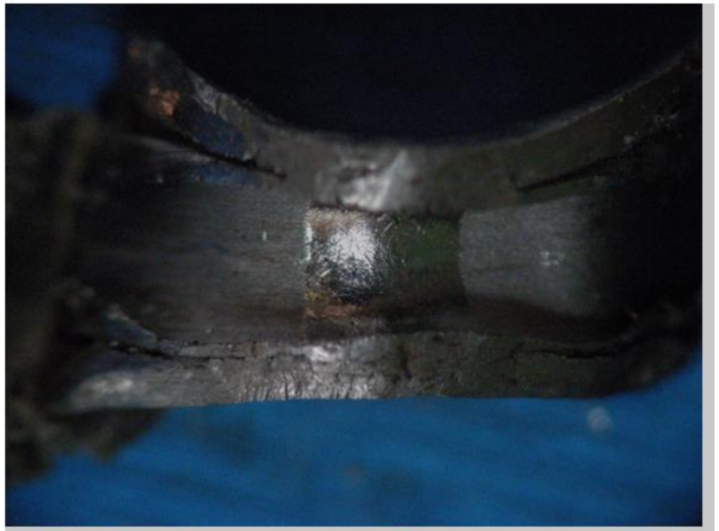
Thickness:

Tube (Nominal)	**Sleeve (Nominal)**
Titanium Grade 2	Titanium Grade 2
3.50 +0 / -0.05 mm	4.76 +/- 0.08mm
0.250 +/- 0.010 mm	0.63 +/- 0.065mm

ASME IX Qualification Process

- Weld samples are sent to an independent qualified (NACAP accredited) laboratory and evaluated.
- Received ASME certified test reports on **tensile** and **bend** tests.

Above: Typical Tensile Test. Failure at the HAZ of the tube (right)



Above: Typical Root Bend

Above: Typical face bend test

ASME IX Qualification of Grade 2 Ti Tube welds for ATLAS Inner Pixel System: Cooling weld process

By: William Toter NWM Welding Engineer Sr. 2/6/2022

REF:

1. Welding procedure Specification: WPS-ANL-Pixel-1
2. Laboratory Test Report: T 121999
3. Welding procedure/Welder performance qualification: PQR-ANL-Pixel-1

Qualification testing was performed on weld samples produced in building 360 by Jerin Pappachchan.

The welds were produced by welding Gr2 Ti tubing to the requirements of welding procedure specification WPS-ANL-Pixel-1. Six sample welds were welded and sent to Element Materials Technology testing Laboratory for testing to the requirements of ASME IX.

Two complete welds were used to demonstrate Tensile Test performance per ASME section IX, and four welds were sectioned in half and used to demonstrate two face bend and two root bend tests.

The welds were visually inspected and tested per ASME IX. All tensile and bend tests pass the requirements of ASME IX for procedure qualification. A procedure qualification test record PQR-ANL-Pixel-1 was created to reflect the tests performed.

Tensile failures were ductile in the tube in the heat affected zone of the specimen.

Bends were examined a 20X and deemed acceptable.

The following are photographs of the samples after testing:

Orbital Weld Qualifications

- ATLAS ITk Pixel IS orbital welds fully ASME-IX qualified
- For TIG orbital welding, the qualifications that we have extends to additional welds of the same type up to two times the minimum qualified total thickness
  - Our 2.5mm and 3.5mm weld qualifications extend to multiple weld thickness types

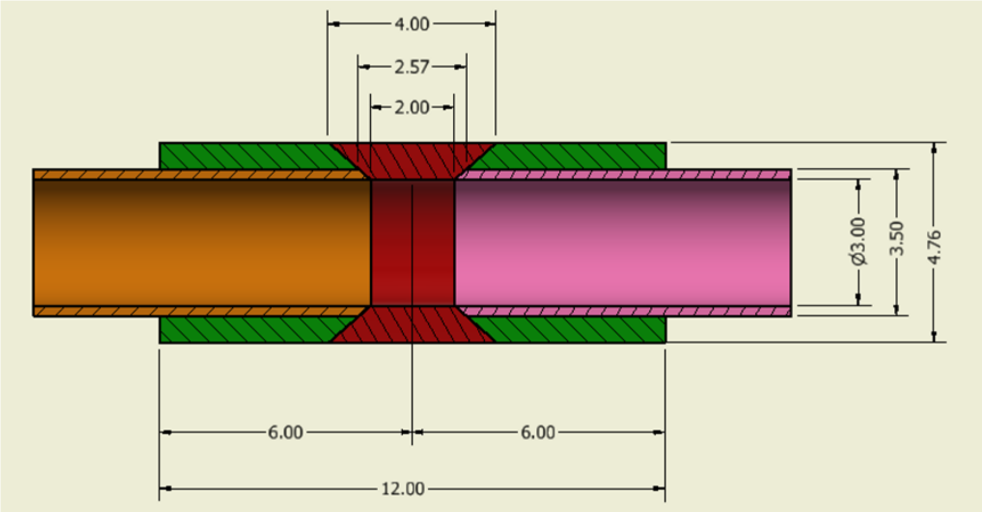
	Tube Size OD/ID	OD	ID	Tube Thickness	Total Thickness
	mm	mm	mm	mm	mm
	3.5/3.0	3.5	3.00	0.25	0.880
Evaporator	2.5/2.15	2.5	2.15	0.175	0.925

TI

	Tube Size OD/ID	OD	ID	Tube Thickness	Total Thickness
	mm	mm	mm	mm	mm
	3.5/3.0	3.5	3.00	0.25	0.880
Evaporator	2.5/2.15	2.5	2.15	0.175	0.925
	2.0/1.5	2	1.5	0.25	0.838
L1 Capillary	1.6/1.1	1.6	1.10	0.25	0.950

Summary and Conclusion

- We have developed a unique and robust solution to welding thin wall tubing by using a sleeve to add materially locally at the weld zone
  - Sleeve butt weld and sleeve lap weld
- We deem our sleeve weld is very robust and easy to work with once it is developed
- Designed and developed custom fittings required to connect welded assemblies to pressure testing and helium leak testing as part of the weld development
- All welds have been qualified to ASME IX and meets the pressure codes, giving us a high confidence on tube leak tightness
- **Sleeve weld design is potentially useful for many other experiments!**



Backup slides

Outline

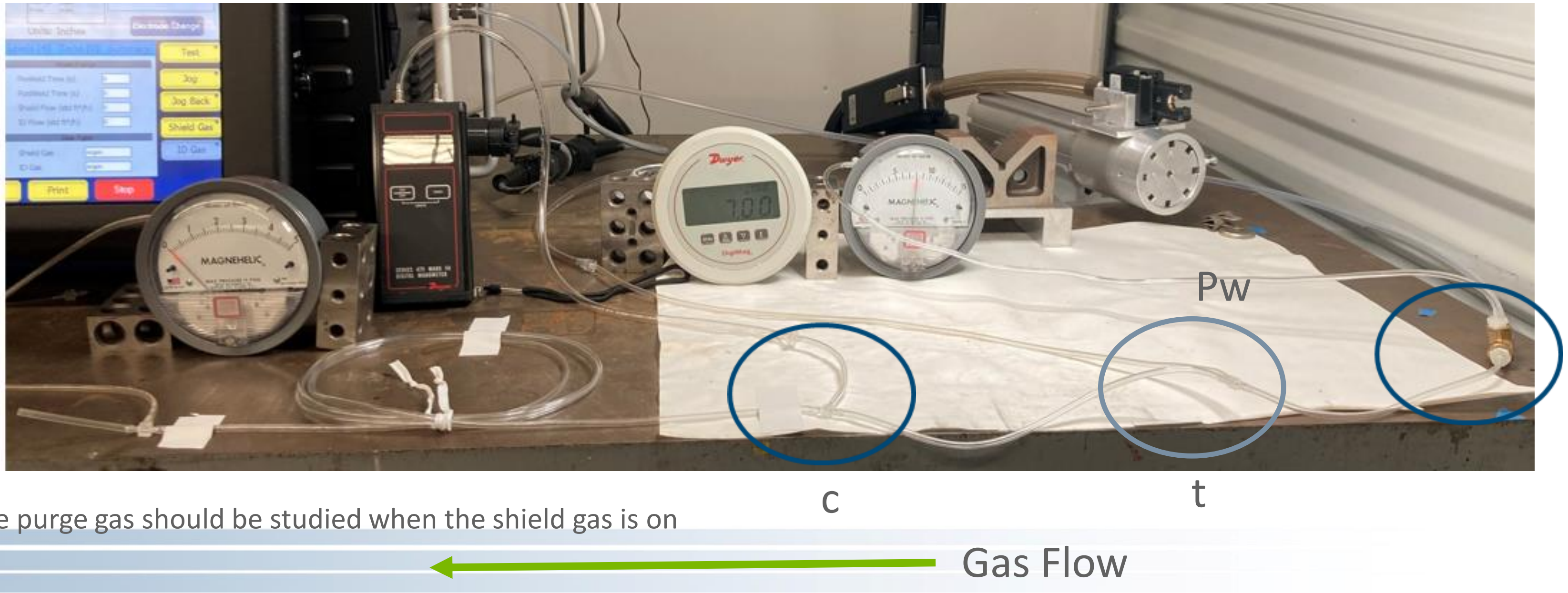
- Background
- Sleeve weld design
  - Design sleeve OD and thickness
  - Design weld interface width
  - Design weld shape
- Welding study and preparations
  - Gap control between tube and sleeve
  - Arc gap measurement and setting
  - Purge gas control
- Welding power study
- Back up welds
- Weld QA/QC process
- Custom high pressure fittings
- ASME IX Qualification

Purge Gas control

Use p law to measure the resistance of T section and use

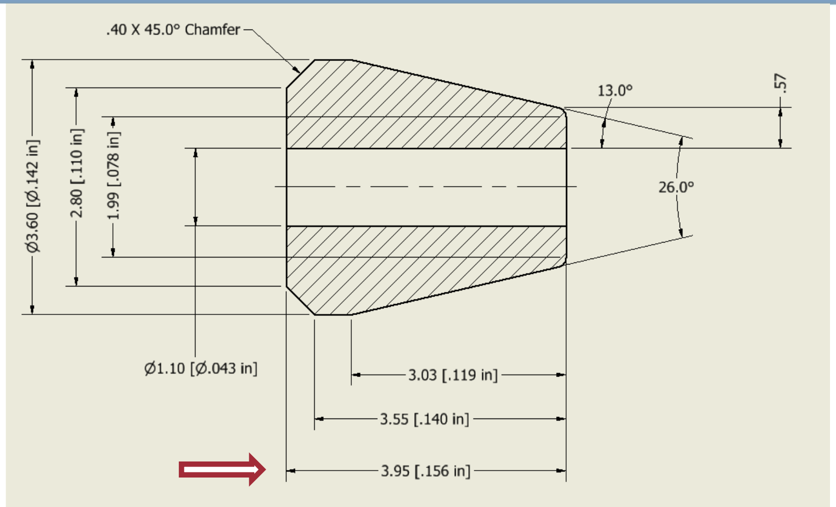
1. Setup Pc=7.8, measure Pw, Pi with T on
2. Take off T, measure Pw, Pi, Pc
3. Calculate Rt =(Pw-Pc)/Pc
4. Calculate Pw'=Pc + Pc*Rt
5. Set Pw=8.2, calculate Pc, then set pressure at control to this number

Purge Gas Measurement & Control		
P-ControlWithTee	7.88	7.74
P-WeldzoneWithTeeT	8.36	10.81
P-InletWithoutTee	17.73	
P-InletwithTee		19.83
R-WithTee (Calculated)	0.061	0.397
P-Weldzone(Target)	8.2	8.2
P-ControlCalculated(Target)	7.7	5.9

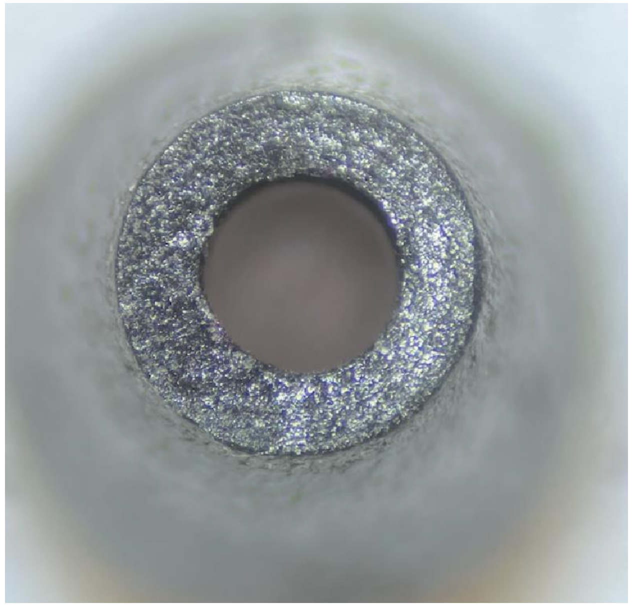


The purge gas should be studied when the shield gas is on

1/16 Swagelok Fitting + 1/16 PEEK Ferrule 1.1mm OD Capillary Fitting



- Original 1/16 Valco ferrule design is too long to fit in 1/16 Swagelok fitting
  - The nut is not be able to engage the thread
  - Reduce the length 0.75mm
- Hand tight first, then 90 degree turn
  - Torque at hand tight 5.1 cNm (0.051 Nm)
  - Torque at 45 degree 15 cNm
  - Torque at 90 degree 35 cNm
- Max pull force at 45 degree is 25 vs 3.5 lbf
- Hold high pressure 163 Bar 2450 PSI
  - More sensitive to defect on ferrule and tube surface
  - Make sure no burs inside the ferrule, tube is clean and in good shape
- Still work well with Valco fitting
- We have made 22 of them and ready to ship to UMASS and Capillary calibration facility



Qualification Timeline

- Tube sleeve weld design & talk to Weld engineer to start qualification process – 1 week
- Preparation for Welding Study - 2 weeks
  - Gap control between tube and sleeve
  - Arc gap measurement and setting
  - Purge gas setting
- Welding study – 2 weeks
  - Stage 1: weld study using tube with same OD of sleeve and ID of tube
  - Stage 2: weld study of low/high limit power using sleeve
  - Stage 3: choose target power and its lower and higher setting and study robustness
  - Stage 4: fabricate 7 samples for ASME IX qualification
- ASME IX Qualification Process – 4 weeks
  - Send samples to external test lab for tensile & bend testing and analyze result
  - Weld engineer at Argonne will give out ASME IX qualification paperwork

Procedure Qualification Record (PQR)

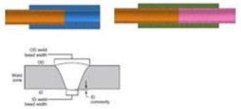
ASME BPVC.IX-2019

(19)

FORM QW-483 SUGGESTED FORMAT FOR PROCEDURE QUALIFICATION RECORDS (PQR)
(See QW-200.2, Section IX, ASME Boiler and Pressure Vessel Code)
Record Actual Variables Used to Weld Test Coupon

Organization Name Argonne National Laboratory
Procedure Qualification Record No. PQR-ANL-XXXX Date 10/16/2023
WPS No. WPS-ANL-Pixel-2-Rev1
Welding Process(es) Gas Tungsten Arc Welding
Types (Manual, Automatic, Semi-Automatic) Automatic

JOINTS (QW-402)



Pipe inserted into sleeve, centered <0.2mm
Weld bead width >1.5mm
Electrode position centered on joint <0.2mm

Groove Design of Test Coupon
(For combination qualifications, the deposited weld metal thickness shall be recorded for each filler metal and process used.)

BASE METALS (QW-403)
Material Spec. Titanium alloys
Type or Grade, or UNS Number Grade 2
P-No. 51 Group No. ____ to P-No. ____ Group No. ____
Thickness of Test Coupon 0.25 mm (Tube) 0.63mm (Sleeve)
Diameter of Test Coupon 3.5 mm (Tube) 4.76 mm (Sleeve)
Maximum Pass Thickness
Other

POSTWELD HEAT TREATMENT (QW-407)
Temperature NA
Time
Other There shall be no post weld heat treatment

GAS (QW-408)

	Gas(es)	Percent Composition (Mixture)	Flow Rate
Shielding	Argon	99.9%	7.08 l/min
Trailing			
Backing	Argon	99.9%	1.89-2.36 l/min
Other			

FILLER METALS (QW-404)

	1	2
SFA Specification	NA	NA
AWS Classification		
Filler Metal F-No.		
Weld Metal Analysis A-No.		
Size of Filler Metal		
Filler Metal Product Form		
Supplemental Filler Metal		
Electrode Flux Classification		
Flux Type		
Flux Trade Name		
Weld Metal Thickness		
Other	There is no filler metal used in this PQR	

ELECTRICAL CHARACTERISTICS (QW-409)
Current Direct
Polarity Straight polarity (electrode Negative)
Amps. 20 Volts
Waveform Control
Power or Energy
Arc Time
Weld Bead Length 3.6 mm
Tungsten Electrode Size 0.040 inches in diameter (CWS-C.040-0405-P)
Mode of Metal Transfer for GMAW (FCAW)
Heat Input
Other

POSITION (QW-405)
Position(s) 5G
Weld Progression (Uphill, Downhill)
Other

TECHNIQUE (QW-410)
Travel Speed 7 inches/min
String or Weave Bead String
Oscillation 8 Hz (Pulse rate)
Multipass or Single Pass (Per Side) Multipass
Single or Multiple Electrodes Single Electrode
Other

PREHEAT (QW-406)
Preheat Temperature No Preheat
Interpass Temperature
Other 15-25 degree C is therequired temp range for welding

(07/17)

FORM OW-483 (Back)

Tensile Test (QW-150)

PQR-ANL-XXXX

Specimen No.	Width	Thickness	Area	Ultimate Total Load	Ultimate Unit Stress, (psi or MPa)	Type of Failure and Location
001-Cross Weld	0.1385 dia.	0.0095 thick	0.0038	251 lbs	66,200 psi	Ductile base metal HAZ
002- Cross Weld	0.1385 dia	0.0095 thick	0.0038	255 lbs	67,000 psi	Ductile base metal HAZ

Guided-Bend Tests (QW-160)

Type and Figure No.	Result
003 face bend	Satisfactory
004 face bend	Satisfactory
005 root bend	Satisfactory
006 root bend	Satisfactory

Toughness Tests (QW-170)

Specimen No.	Notch Location	Specimen Size	Test Temperature	Toughness Values ft-lb or J	% Shear	Mils (in.) or mm	Drop Weight Break (Y/N)

Comments: Visual Inspection 6 specimens acceptable

Fillet-Weld Test (QW-180)

Result - Satisfactory: Yes ________ No ________ Penetration into Parent Metal: Yes________No_____

Macro test : N/a

Other Tests

Type of test:

Deposit Anaylsis
Other________

Welder's Name: Jerin Pappachan ________ Clock No. 302004________
Tests Conducted by: Element Materials Technology ________Laboratory Test No.: T 300200-01

We certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of Section IX of the ASME Boiler and Pressure Vessel Code. Organization: Argonne National Lab LLC

Date: 10/16/2023 By: William F Toter Welding Engineer Sr.

Detail of record of tests are illustrative only and may be modified to conform to the type and number of tests required by the Code.)

(07/19)