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Brazing explosively bonded Nb-Cu to Alumina Ceramic

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Outline – brazing explosively bonded Nb/Cu

- Overview: Why this material set?
  - Switch processing methods:

    current, development, future
- Nb- Al_2O_3 material properties
- Brazing experiments
  - Overview, processing, testing results
- Conclusions & path forward

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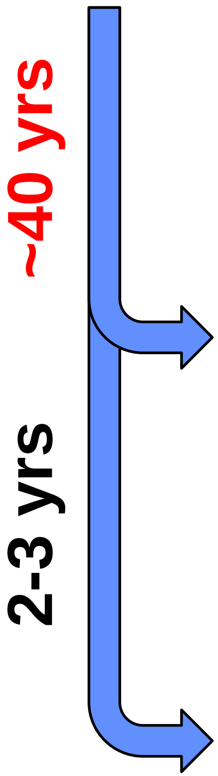
Why the interest?
Switch processing methods

Why the interest?



Currently used switch production process:

Braze, Ni/Sn-Pb plate, Reflow solder, Test. ($$$)

Development switch process:

Braze, Rebraze, Solder Dip, Test ($$)

Future switch process:

Braze, Solder Dip, Test ($)

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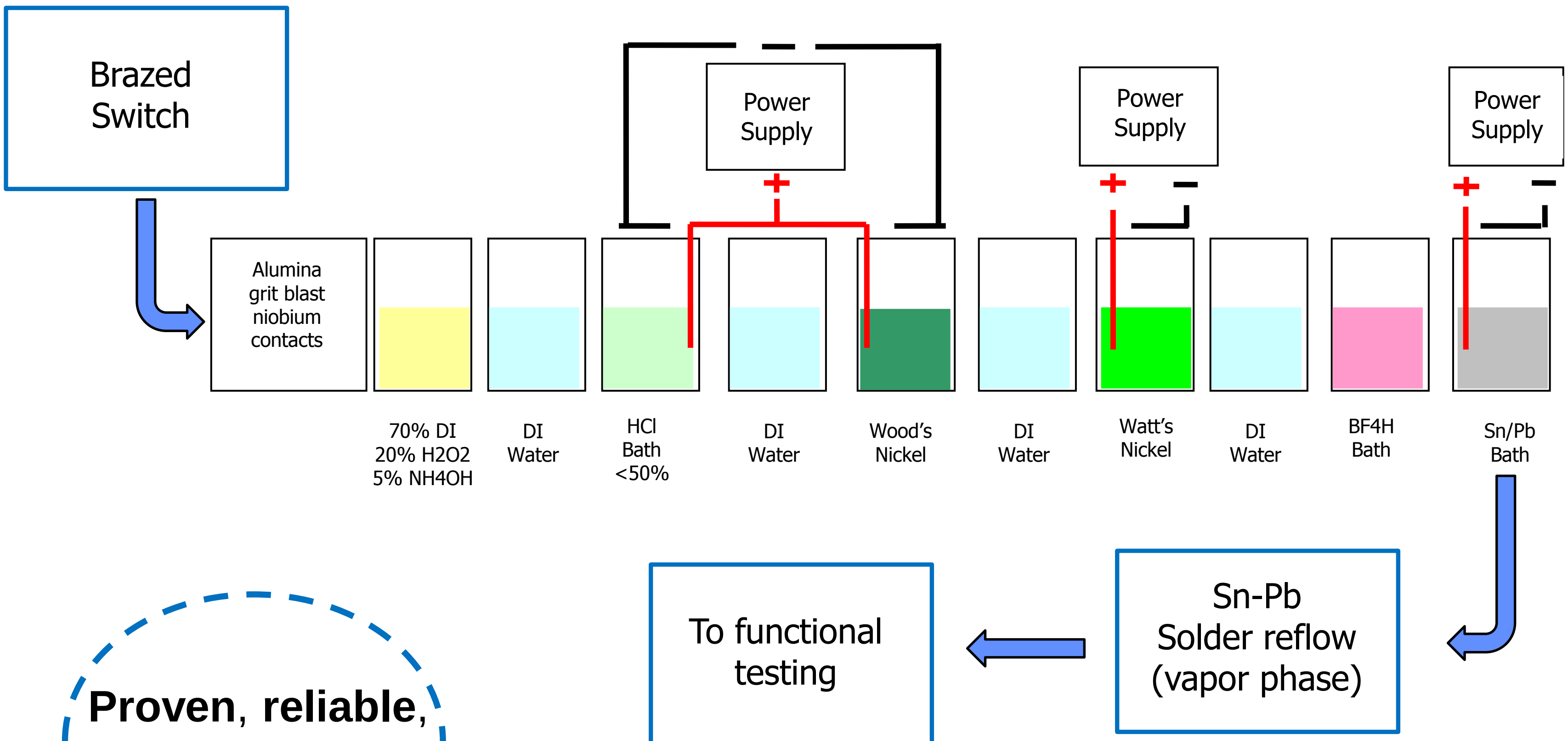
Current production post-braze processing



Proven, **reliable**, difficult & costly process

Development - step-brazing & solder dipping copper contacts

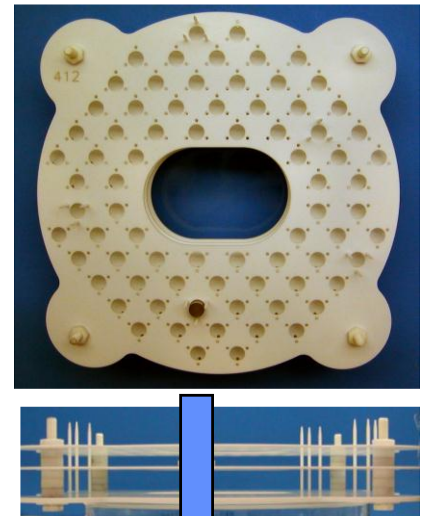
Refixture and furnace step-braze copper switch contacts

76 position laser-machined Al_2O_3 fixture

Brazed Switch

+

→



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Rebrazed Switch

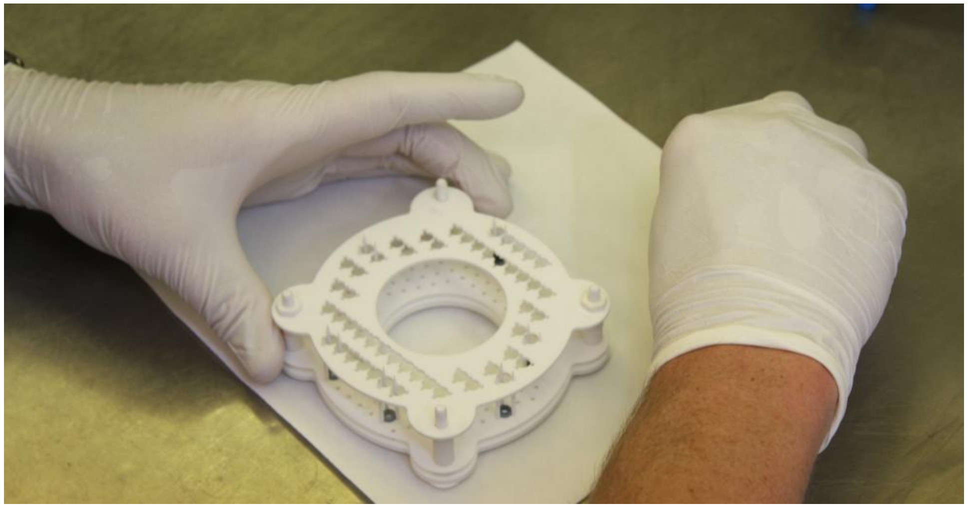
←

Solder Dip (SAC-305)

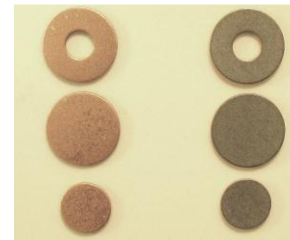
←

To functional testing

Future production: solder dipping explosively bonded Nb-Cu contacts



One fixturing step, one braze process



Explosively bonded Nb-Cu contacts

Solder Dip
(SAC-305)

To functional testing

Successfully demonstrated Q3 2011!!

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Summary Table: three methods of switch fabrication

Switch fabrication method	Pros	Cons
Standard (Ni/Sn-Pb plate, reflow)	• 1-step brazing process • Proven method • Works well	• Expensive • Time-consuming • Complex plating process
2-Step braze method	• Eliminates plating/reflow • Compatible with Pb-free solder-dipping processes • Works well.	• Refixturing required • 2-step brazing process • Additional parts • Additional risk
Braze using explosively bonded Nb-Cu	• 1-step brazing process • Compatible with Pb-free solder-dipping processes • Same part count as standard method.	• **Unproven method** • **CTE mismatch in bonded material** • **Unknown Nb-Cu bond interlayer strength** • **?**

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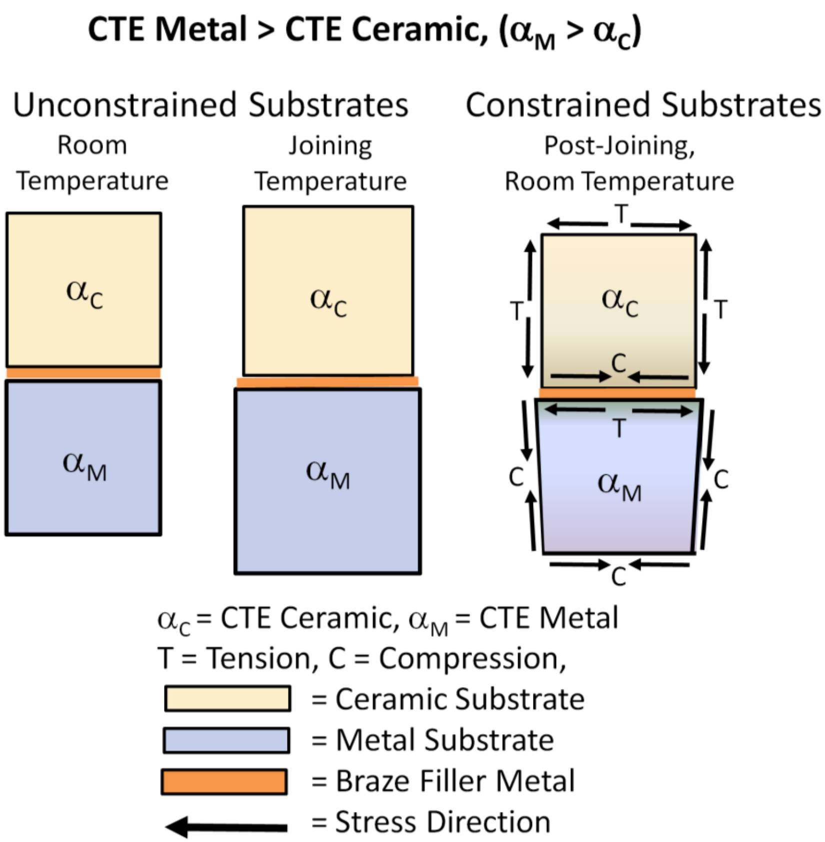
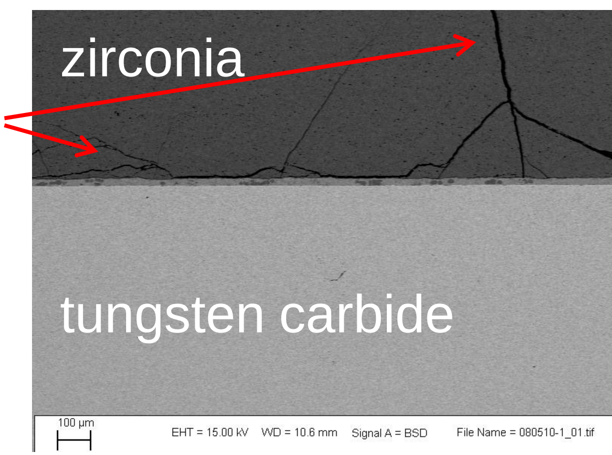
Resultant stresses due to CTE mismatch



Resultant stresses when brazing dissimilar materials

Sometimes the metal deforms

Sometimes the nonmetal fails



Selected substrate and braze filler metal material properties

Material	Coefficient of Thermal Expansion (linear, 20-1000°C, *10^{-6}/°C)	Ultimate Tensile Strength / Elongation at Break	Compressive Strength
94% Al_2O_3	**7.4**	138 MPa (20 ksi)	1931 MPa (280 ksi)
Sapphire	**6.7**	400 MPa (58 ksi)	2930 MPa (425 ksi)
Niobium (commercially pure)	**8.4**	300 MPa (43.5 ksi)/30%	----
Kovar	11.3	517 MPa (75 ksi)/30%	----
Copper	**25**	210 MPa (31 ksi)/60%	----
BAu-3 (Nicoro™)	17.8	427 MPa (62 ksi)/28%	----
Nicoro™+2%Ti	17.8 (est.)	427 MPa (62 ksi)/28% (est.)	----

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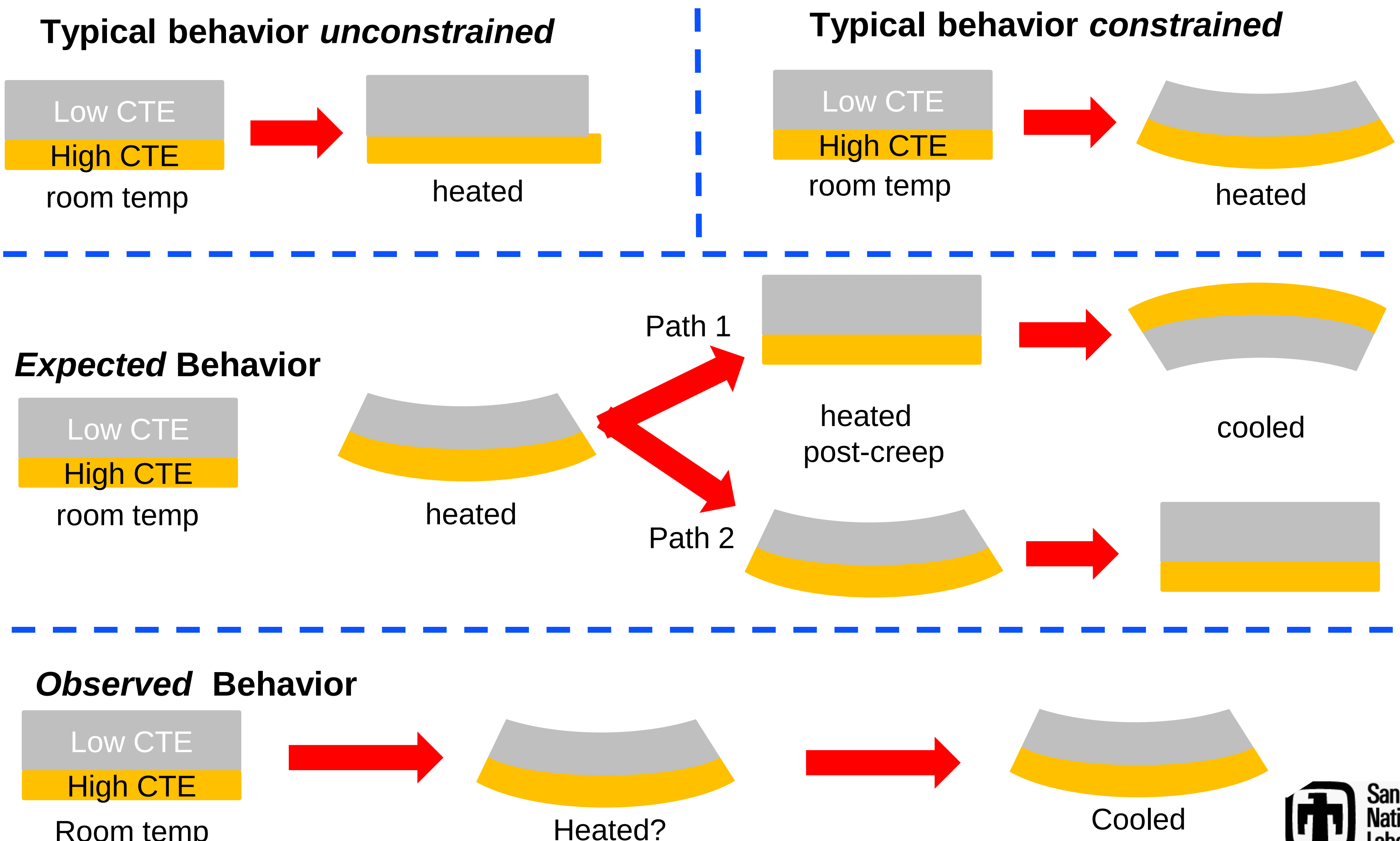
Bi-metallic strip behavior



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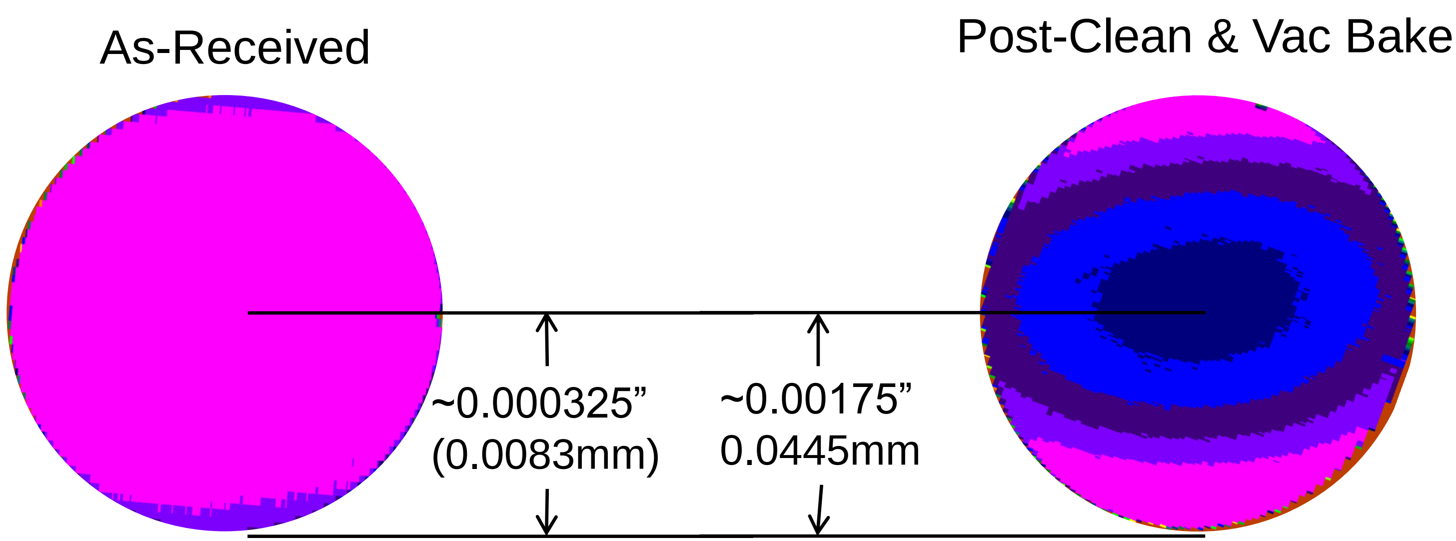
Measured warp:
7.92mm diameter Nb disc #A1



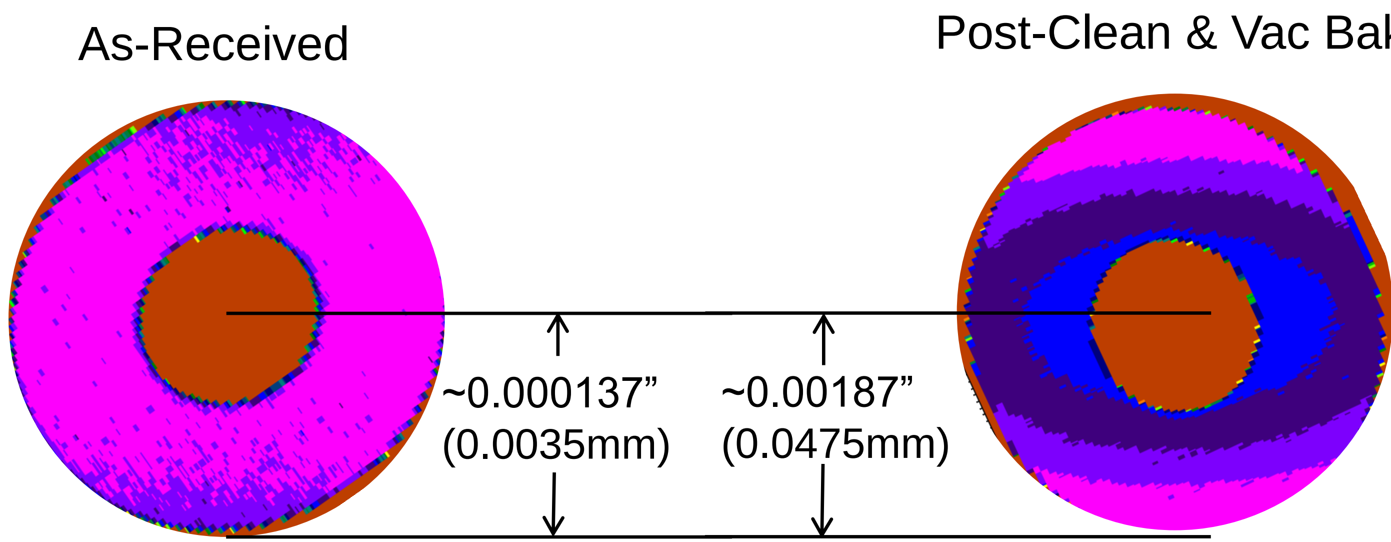
Scale Z-Axis (As-Received)

Z-Minimum	-5000.00 µin		Z-Maximum	200.00 µin
Range 01 fr.	-5000.00 µin		Range 09 to	-2400.00 µin
Range 02 to	-4675.00 µin		Range 10 to	-2075.00 µin
Range 03 to	-4350.00 µin		Range 11 to	-1750.00 µin
Range 04 to	-4025.00 µin		Range 12 to	-1425.00 µin
Range 05 to	-3700.00 µin		Range 13 to	-1100.00 µin
Range 06 to	-3375.00 µin		Range 14 to	-775.00 µin
Range 07 to	-3050.00 µin		Range 15 to	-450.00 µin
Range 08 to	-2725.00 µin		Range 16 fr.	-125.00 µin

Scale Z-Axis (Post-Clean & Vac Bake)

Z-Minimum	-5000.00 µin		Z-Maximum	2000.00 µin
Range 01 fr.	-5000.00 µin		Range 09 to	-1500.00 µin
Range 02 to	-4562.50 µin		Range 10 to	-1062.50 µin
Range 03 to	-4125.00 µin		Range 11 to	-625.00 µin
Range 04 to	-3687.50 µin		Range 12 to	-187.50 µin
Range 05 to	-3250.00 µin		Range 13 to	250.00 µin
Range 06 to	-2812.50 µin		Range 14 to	687.50 µin
Range 07 to	-2375.00 µin		Range 15 to	1125.00 µin
Range 08 to	-1937.50 µin		Range 16 fr.	1562.50 µin

Measured warp:
7.92mm OD x 3.10mm ID Nb washer #B2



Scale Z-Axis (As-Received)

Z-Minimum	-2000.00 µin	Z-Maximum	200.00 µin
Range 01 fr.	-2000.00 µin	Range 09 to	-900.00 µin
Range 02 to	-1862.50 µin	Range 10 to	-762.50 µin
Range 03 to	-1725.00 µin	Range 11 to	-625.00 µin
Range 04 to	-1587.50 µin	Range 12 to	-487.50 µin
Range 05 to	-1450.00 µin	Range 13 to	-350.00 µin
Range 06 to	-1312.50 µin	Range 14 to	-212.50 µin
Range 07 to	-1175.00 µin	Range 15 to	-75.00 µin
Range 08 to	-1037.50 µin	Range 16 fr.	62.50 µin

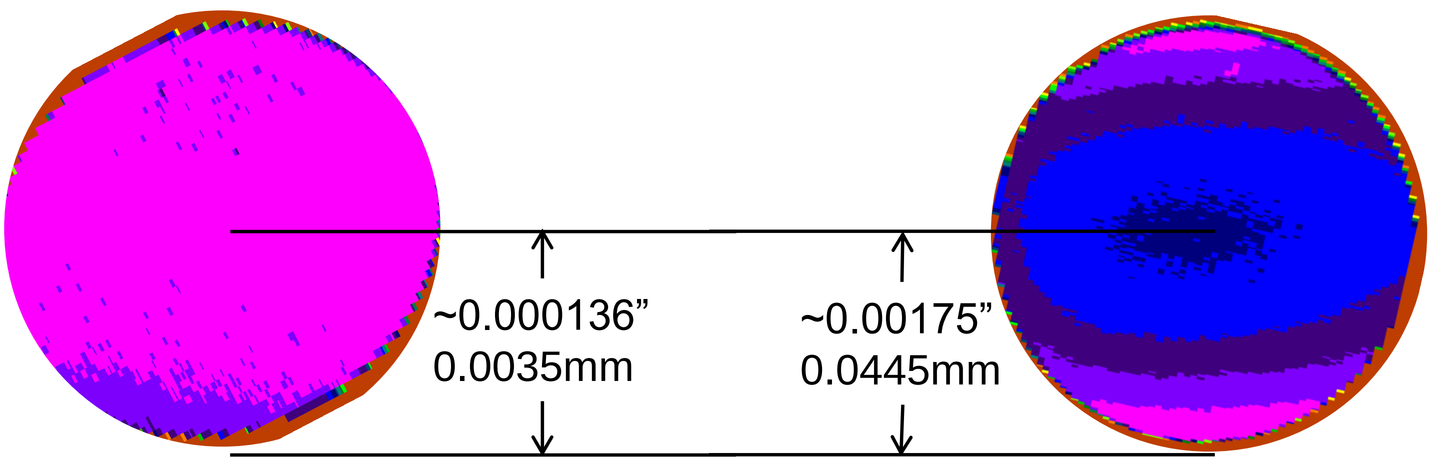
Scale Z-Axis (Post-Clean & Vac Bake)

Z-Minimum	-8000.00 µin	Z-Maximum	2000.00 µin
Range 01 fr.	-8000.00 µin	Range 09 to	-3000.00 µin
Range 02 to	-7375.00 µin	Range 10 to	-2375.00 µin
Range 03 to	-6750.00 µin	Range 11 to	-1750.00 µin
Range 04 to	-6125.00 µin	Range 12 to	-1125.00 µin
Range 05 to	-5500.00 µin	Range 13 to	-500.00 µin
Range 06 to	-4875.00 µin	Range 14 to	125.00 µin
Range 07 to	-4250.00 µin	Range 15 to	750.00 µin
Range 08 to	-3625.00 µin	Range 16 fr.	1375.00 µin

Measured warp:
5.44mm diameter Nb disc – #C4

As-Received

Post-Clean & Vac Bake



Scale Z-Axis (As-Received)

Z-Minimum	-2000.00 µin		Z-Maximum	180.00 µin	
Range 01 fr.	-2000.00 µin	red	Range 09 to	-910.00 µin	dark green
Range 02 to	-1863.75 µin	dark orange	Range 10 to	-773.75 µin	teal
Range 03 to	-1727.50 µin	orange	Range 11 to	-637.50 µin	dark blue
Range 04 to	-1591.25 µin	yellow	Range 12 to	-501.25 µin	navy
Range 05 to	-1455.00 µin	yellow-green	Range 13 to	-365.00 µin	blue
Range 06 to	-1318.75 µin	green	Range 14 to	-228.75 µin	indigo
Range 07 to	-1182.50 µin	green	Range 15 to	-92.50 µin	violet
Range 08 to	-1046.25 µin	dark green	Range 16 fr.	43.75 µin	magenta

Scale Z-Axis (Post-Clean & Vac Bake)

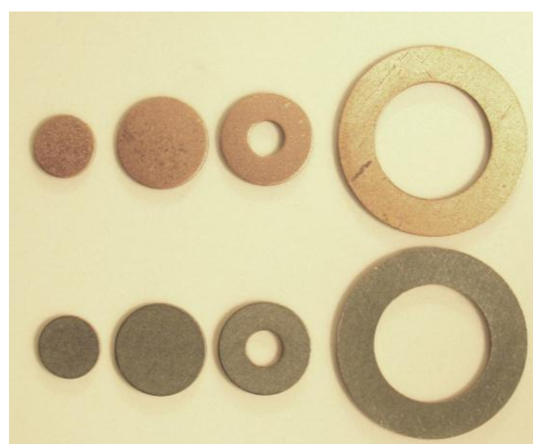
Z-Minimum	-5000.00 µin		Z-Maximum	2000.00 µin	
Range 01 fr.	-5000.00 µin	red	Range 09 to	-1500.00 µin	dark green
Range 02 to	-4562.50 µin	dark orange	Range 10 to	-1062.50 µin	teal
Range 03 to	-4125.00 µin	orange	Range 11 to	-625.00 µin	dark blue
Range 04 to	-3687.50 µin	yellow	Range 12 to	-187.50 µin	navy
Range 05 to	-3250.00 µin	yellow-green	Range 13 to	250.00 µin	blue
Range 06 to	-2812.50 µin	green	Range 14 to	687.50 µin	indigo
Range 07 to	-2375.00 µin	green	Range 15 to	1125.00 µin	violet
Range 08 to	-1937.50 µin	dark green	Range 16 fr.	1562.50 µin	magenta

Thermal-cycled Nb-Cu substrate behavior

Item	OD	Pre-bake flatness	Post-bake flatness	Average difference	Std. Dev
Small contact (disc)	5.44 mm 0.214”	0.010 mm 0.0004”	0.046 mm 0.0018“	**0.036 mm 0.0014“**	0.010 mm 0.0004”
Medium contact (washer)	7.92 mm 0.312”	0.020 mm 0.0008”	0.056 mm 0.0022”	**0.036 mm 0.0014”**	0.015 mm 0.0006”
Medium contact (disc)	7.92 mm 0.312”	0.015 mm 0.0006”	0.043 mm 0.0017”	**0.028 mm 0.0011”**	0.013 mm 0.0005”
Tensile button interlayer (washer)	15.88 mm 0.625”	N/A	N/A	**~0.25 mm 0.010”**	N/A

Braze joint area comparison:

Switch contacts to tensile button interlayers



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Active-brazing explosively bonded Nb-Cu to alumina

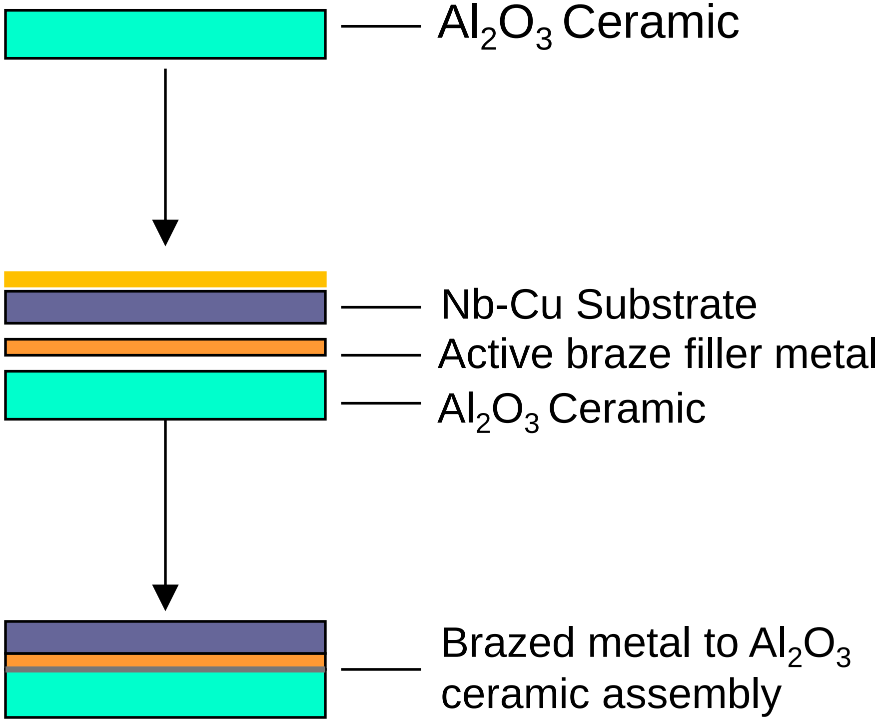
Advantages

- Ease of use
- Variety of filler metal schemes & temperature ranges
- No specialized metallization equipment or processes required
- Easily brazed using standard filler metals

Disadvantages

- Requires specialized equipment/atmosphere control
- Not usable with all joint designs
- Size constraints

Active filler-metal brazing



Proposed tensile button experiment

- **Fabricate ASTM-F19 tensile button assemblies using bare 94% and 96% alumina with explosively bonded niobium-copper interlayers.**
  - Alumina substrates air-fired @ 1575C-2 hours, Nb-Cu interlayers vac-baked @ 1060ºC-10 minutes, followed by 800ºC-2 hours, flattened.
  - Braze filler metal, Nicoro+2%Ti, BAu-3 (other filler metals in process)
- **Input variables:**
  - **Bare alumina composition (94%, 96%),** **surface finish varied from (28µin – 60µin)**
    - **Peak soak temp. (1025ºC or 1030ºC)**
    - **Peak soak time (1 or 2 minutes)**
  - **Control samples (metallized, Mo-Mn/Ni plated 94% alumina tensile buttons)**
    - **Peak soak temp. (1035ºC or 1055ºC)**
    - **Peak soak time (1 minute)**

- **Response variables: tensile strength & hermeticity**

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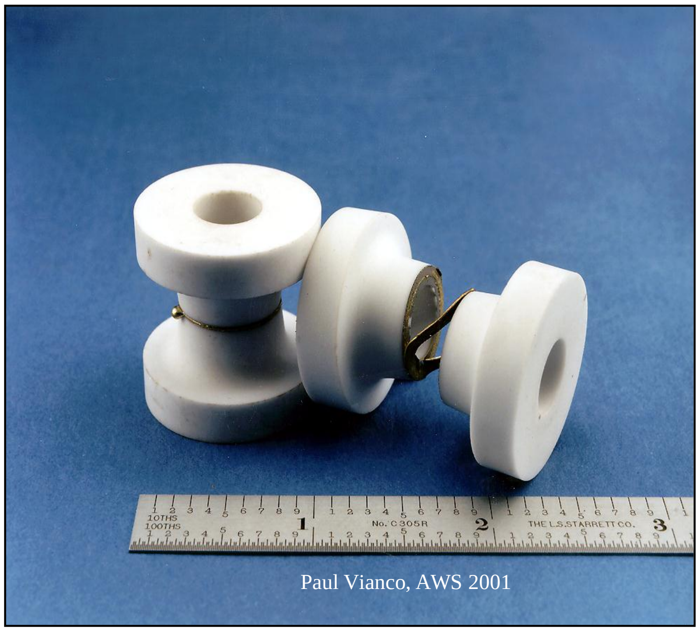
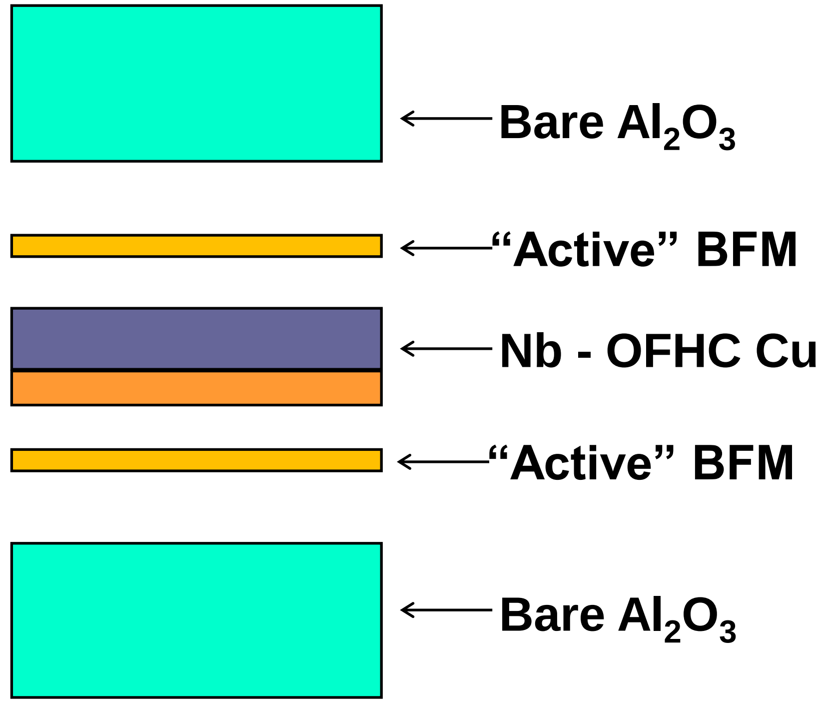
ASTM-F19 tensile button geometry


Paul Vianco, AWS 2001



Measured Responses

Tensile strength: MTS crosshead speed = 8.38E-03 mm/sec

Hermeticity : helium leak rates <5E-12 atm-cc/sec desired

Experiment drivers / goals

1. **Accommodate design changes in future products with no loss in hermeticity or joint tensile strength.**
2. **Use slightly lower active brazing process temperatures to minimize excess flow of braze filler metal sometimes observed using the current brazing profile.**

   T_ℓ Nicoro+2%Ti ~ 1020ºC, T_ℓ Nicoro ~ 1030ºC

Item	Existing	Proposed
Contact Material:	**Pure Niobium**	**Nb-Cu**
T_{PEAK}, Nicoro+2%Ti	**1035ºC – 1040ºC**	**1025ºC-1030ºC**
T_{PEAK}, Nicoro	**1060ºC**	**1035ºC-1055ºC**

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Experimental trials

- 36 tensile buttons were made in 6 separate brazing cycles.
  - 6 samples per condition.
  - Tensile strengths are the *average* of 6 samples.

- All samples were made in a modified Brew furnace in UHV atmosphere, 1.3×10^{-3} Pa (1×10^{-6} Torr) at peak temperature. Braze joint preload was 47g/cm^2 (~300g/in^2)

- Brazing Cycle:
  - 15ºC/min to 975ºC, soak 10 minutes;
  - 10ºC/min to T_{PEAK}*, soak t_{PEAK}** minutes;
  - 25ºC/min to 975ºC, soak 0 minutes;
  - 15ºC/min to ambient.

* T_{PEAK} = 1025ºC, 1030ºC, 1035ºC or 1055ºC; **t_{PEAK} = 1 or 2 minutes

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Experimental trials – sample results

Ceramic Substrate	Peak Temp	Peak Time	Helium Leak Test Results (Ratio Passing*/Total)	Avg. Tensile Strength (psi)
94% alumina	1030ºC	2 min.	3 / 6	34.2 ± 24.5 Mpa (4732)
94% alumina	1025ºC	1 min.	0 / 6	18.7 ± 9.8 MPa (2717)
96% alumina	1030ºC	2 min.	4 / 6	28.2 ± 18.7 MPa (4088)
96% alumina	1025ºC	1 min.	2 / 6	27.6 ± 10.4 MPa (4000)
95% alumina metallized	1055ºC	1 min.	6 / 6	61.7 ± 20.8 MPa (8947)
95% alumina metallized	1035ºC	1 min.	2 / 6	42.3 ± 19.8 MPa (6135)

*Passing = leak rates ≤5.0E-012 atm-cc/sec or NDL.

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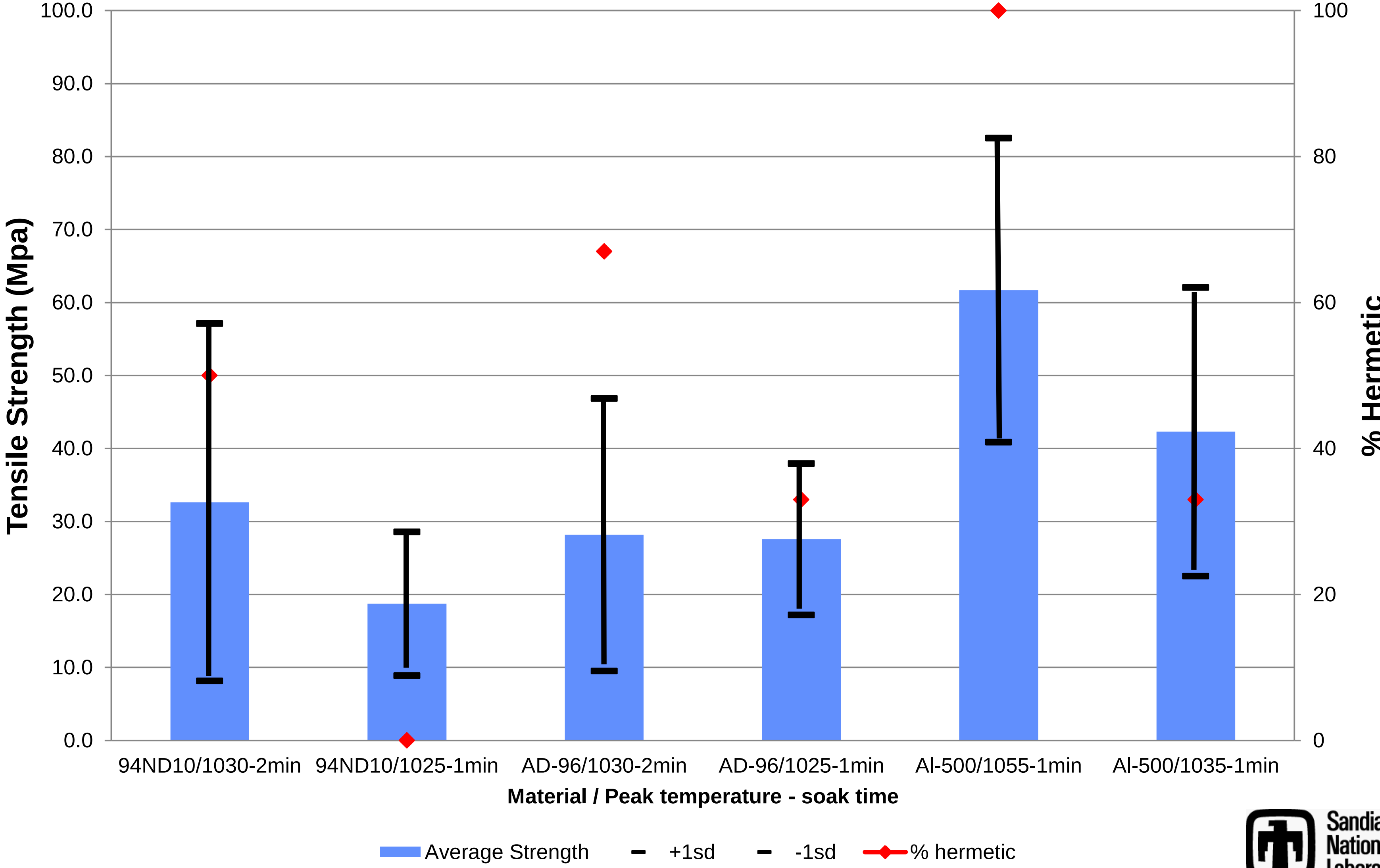
Brazed Tensile Strength
ASTM-F19 Tensile Buttons with explosively bonded Nb-Cu interlayers

★ 120 MPa



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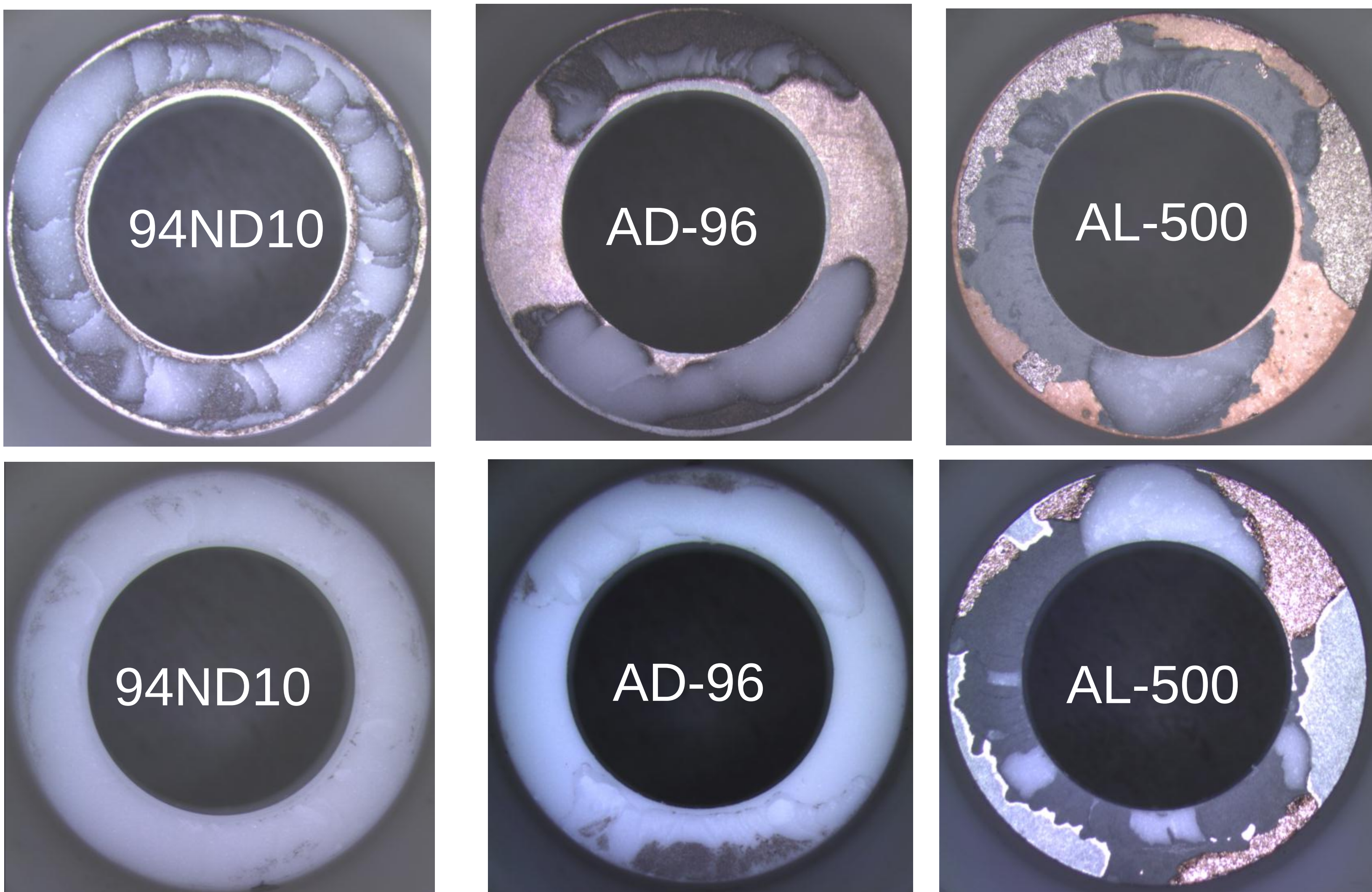
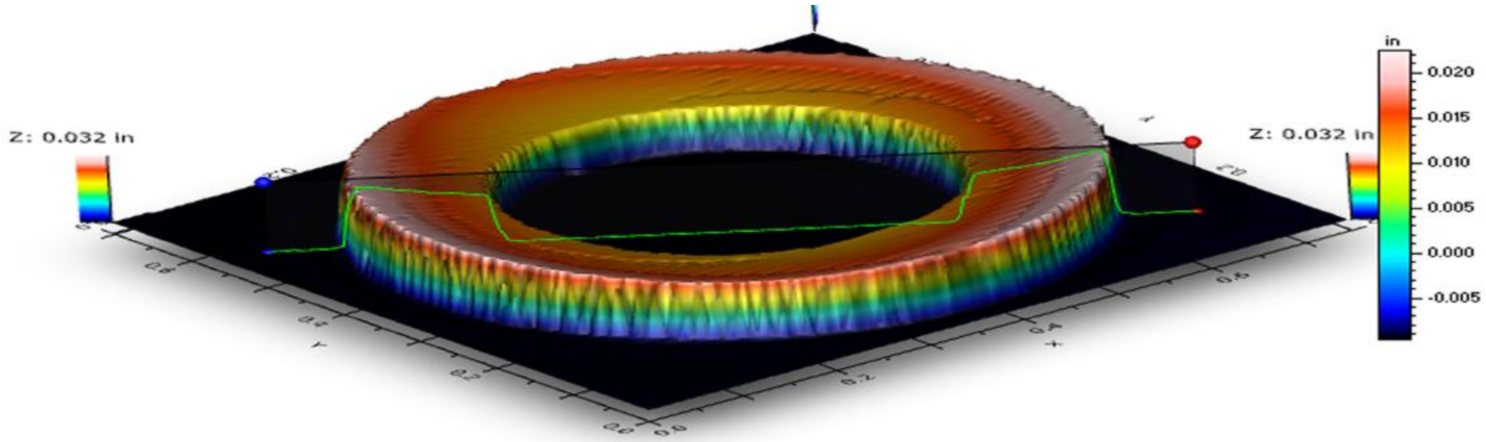
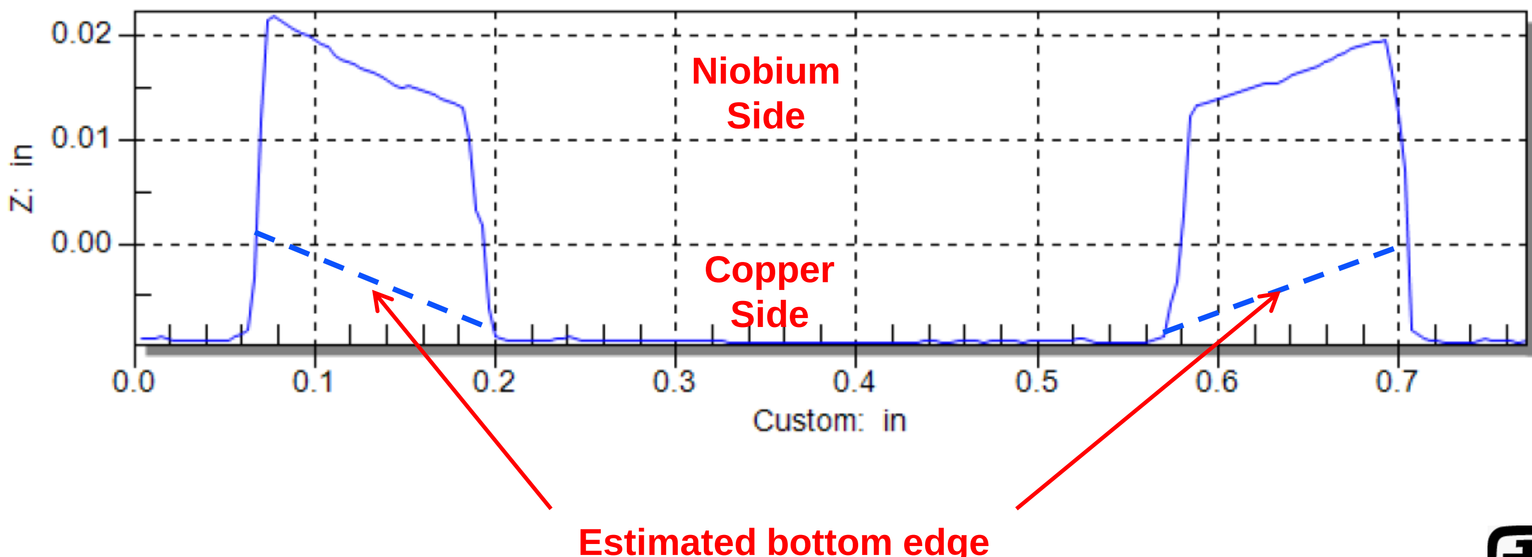
Observed brazed joint failures



Measured Nb-Cu interlayer flatness following thermal cycle





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Proposed "cupping" mechanism

Niobium & Copper Selected Material Properties

	Niobium, Cold- worked	Niobium, Annealed	Copper, Cold-worked	Copper, Annealed
UTS (MPa/ksi) [1] = 1000°C, [2] = 600°C	600 / 87.0	300 / 43.5 90-120 / 13-17[1]	344 / 49.9	210 / 30.5 10 / 1.5[2]
CTE , linear 0-1000°C (in/in-°C)	8.5	8.5	24.8	24.8
Melting Pt. (°C)	2468	2468	1084	1084
Anneal Temp* (°C) *1/2 – 1/3 Abs mp (K)	1100 - 1550	1100 - 1550	400 - 630	400 - 630

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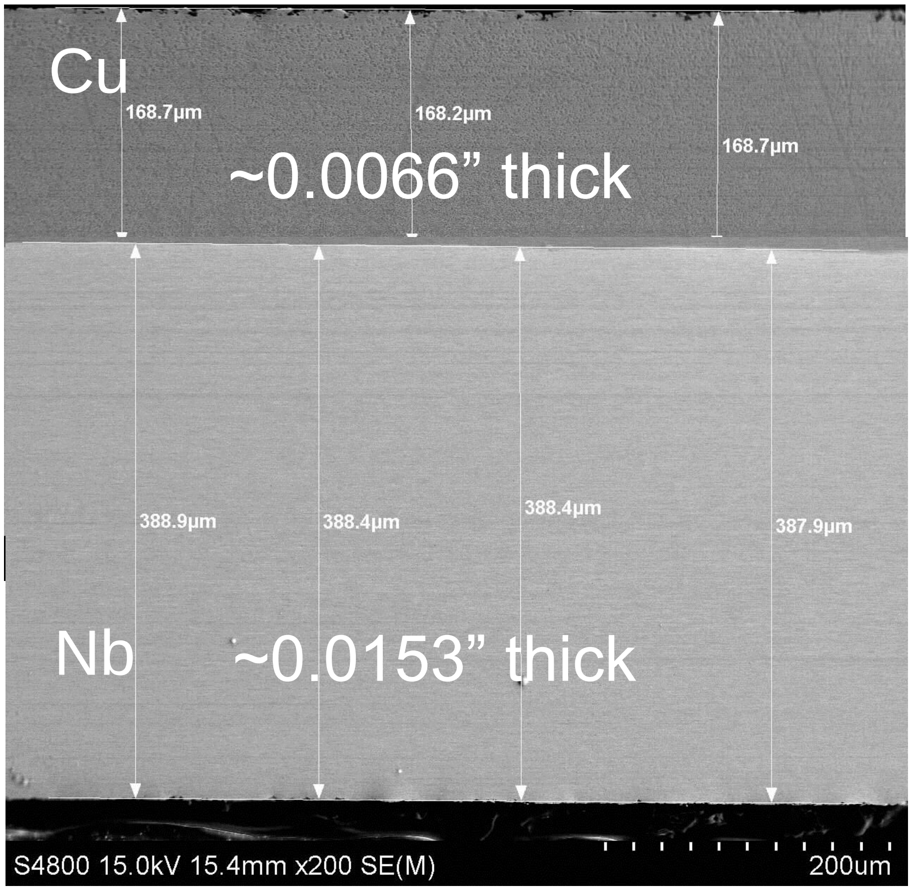
Cupping mechanism - continued



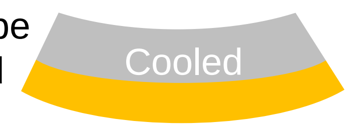
Cold-worked (high stress) Nb-Cu substrate at room temperature

1060ºC-10 minutes,
800ºC – 180 minutes

Nb warps as some internal stresses are relieved.

The much weaker Cu yields to the thicker, stronger Nb material.

Though under compression, Nb remains too strong to be deformed by the annealed Cu...cup shape remains.



Experimental trials (round 2) – additional joint preload sample results

Ceramic Substrate	Peak Temp	Peak Time	Joint Preload (g/in²)	Helium Leak Test Results (Ratio Passing*/Total)	Tensile Strength (psi)
96% alumina	1055º C	2 min.	101 g/cm² (653)	0/1	34.2 Mpa (4961)
96% alumina	1055º C	2 min.	188 g/cm² (1212)	1/1	85.8 MPa (12447)
96% alumina	1050º C	2 min.	275 g/cm² (1771)	1/1	52.3 MPa (7581)
96% alumina	1055º C	2 min.	361 g/cm² (2329)	1/1	117.1 MPa (16989) Expected with this material set

*Passing = leak rates ≤5.0E-012 atm-cc/sec or NDL.

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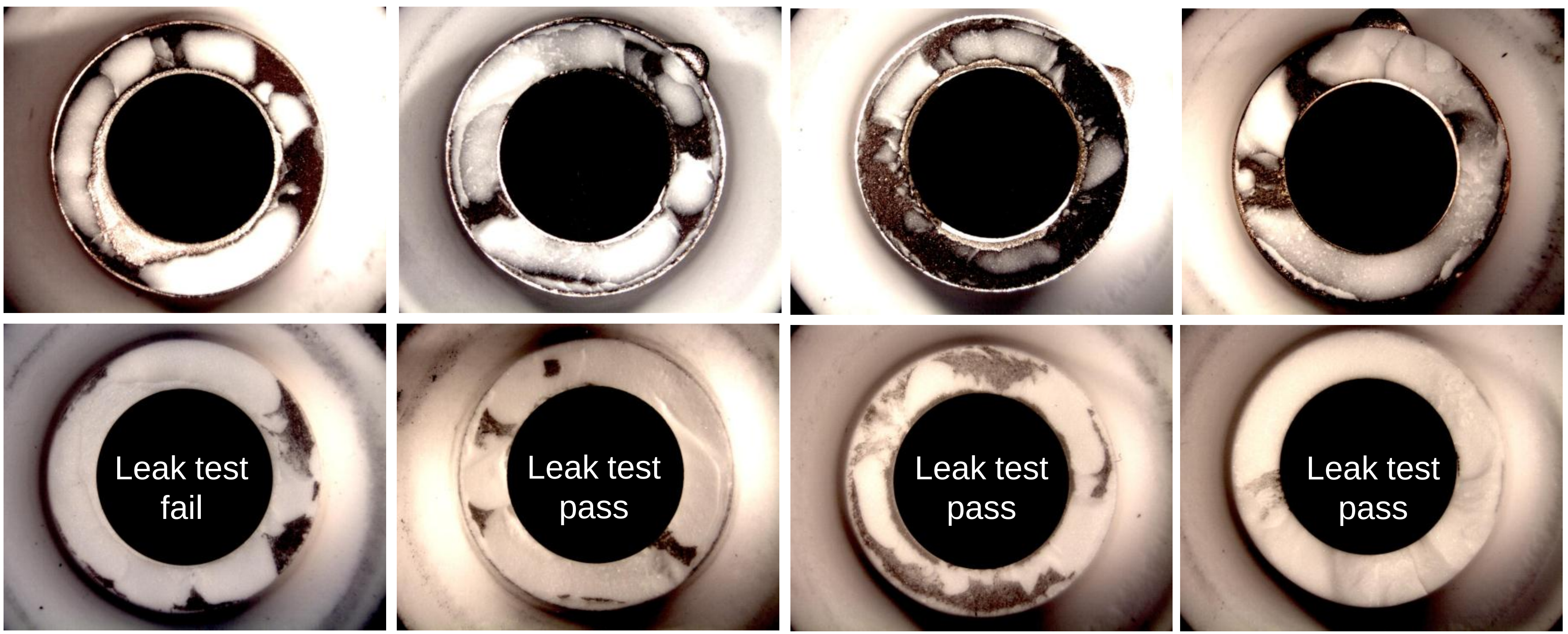
Increased joint preload failure images

Increasing joint preload = increased tensile strength

AD-96	AD-96	AD-96	AD-96
101 g/cm^2	188 g/cm^2	275 g/cm^2	361 g/cm^2
34.2 Mpa / 4961psi	85.8 Mpa / 12447 psi	52.3 Mpa / 7581 psi	117.1 Mpa / 16989 psi



Conclusion & path forward

Conclusion

Residual stress in the explosively bonded Nb-Cu substrates is relieved during heating cycle resulting in excessive warp.

Additional joint preload to increase effective joint area greatly increases sample tensile strength.

Mass required to completely “flatten” substrates not practical for brazing manufacturing process.

Fully functional switches have been brazed/solder-dipped (SAC- 305) using the smaller bonded substrates.

Path forward

Investigate alternative manufacturing methods

- Diffusion-bonding
- Cold-spraying
- Rolling/forming operation modifications

Perform additional characterization of braze joints.

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Acknowledgements

- **Tom Crenshaw –** Mechanical properties testing
- **Randy Herrick –** SEM analysis
- **David Saiz –** OGP & measurements
- **Lynna Esquibel** – Measurements

(All Sandia National Laboratories, NM)

The End

Thank you!

Questions?