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Development of a High Strength Be/CuCrZr Joining Process for ITER Applications

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Overview

The design of the ITER First Wall includes the use of **S-65C** beryllium (Be) armor tiles as the plasma facing material joined to a **CuCrZr (C18150)** heat sink alloy, which in turn is bonded to a **316L** stainless steel support structure. Hot Isostatic Pressing (HIP), which allows for the simultaneous application of temperature and pressure, has been identified as the principal bonding process for all three materials. HIP bonding will occur in 2 steps; The initial bonding step will join the Cu alloy to the stainless steel backing structure at temperatures near 1000C. This will be followed by a second, lower temperature step to join the Be to the Cu alloy.

Parameters for these diffusion bonding processes are constrained by the mechanical property requirements of the precipitation hardenable copper alloy. In particular, cooling of the Cu-SS structure after bonding must occur in such a way as to render the copper alloy in nearly its fully solutionized condition. Further, the maximum allowable temperature for Be-CuCrZr bonding is limited by the overaging characteristics of the copper alloy. For all practical purposes, the upper temperature limit for HIP bonding is on the order of 600 ºC or less.

In order to prevent the formation of deleterious phases, barrier films are typically employed to prevent Be/Cu interdiffusion. We further report on the efficacy of titanium and various application techniques (physical vapor deposition and e-beam evaporation) as such a barrier film. Lastly, the effect of relatively thick copper films acting as strain accommodating compliant layers (and their application techniques) is described.

We report here the results of a study investigating the quality of HIP bonded Be-CuCrZr joints processed at temperatures at or below 580 ºC where the principal measure of bond integrity is a modified ASTM A263 shear test (similar to DIN 50162).

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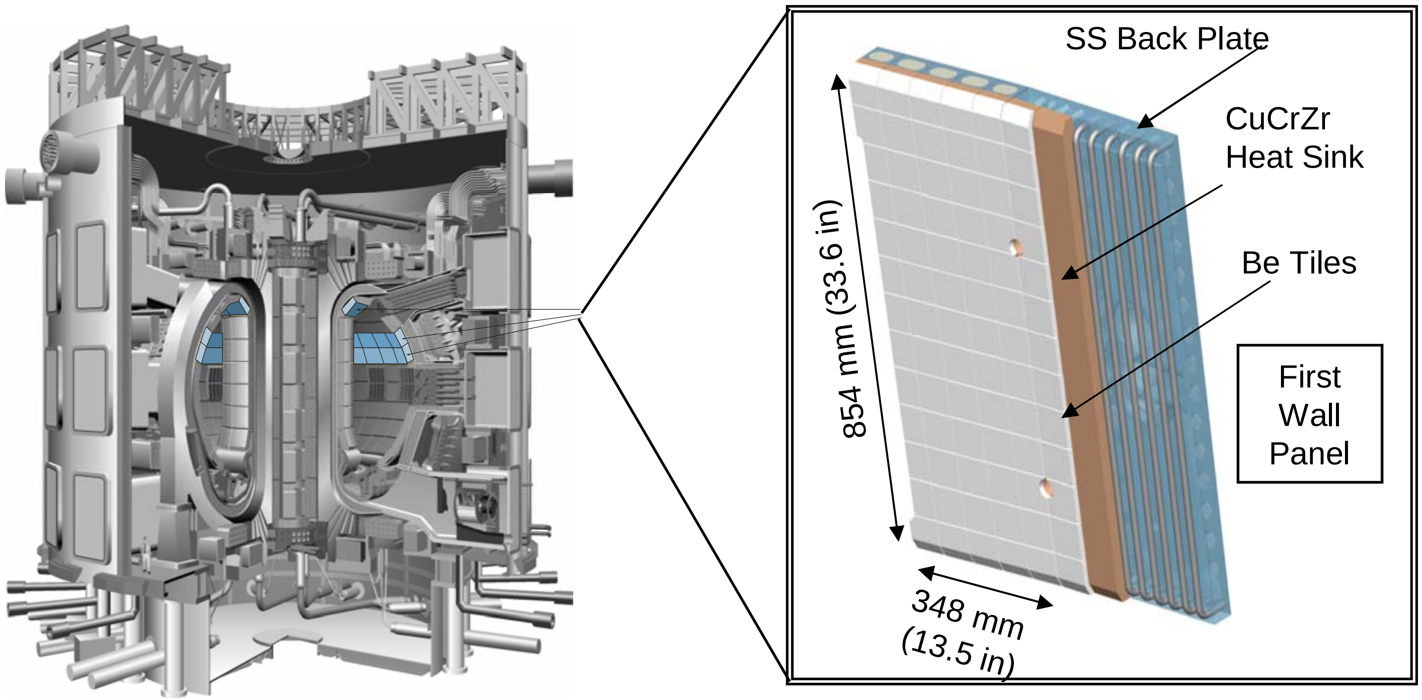
First Wall Panel



First wall panel consists of **S65C Be** armor tiles joined to a **CuCrZr** heat sink alloy/**316L** stainless steel back plate structure

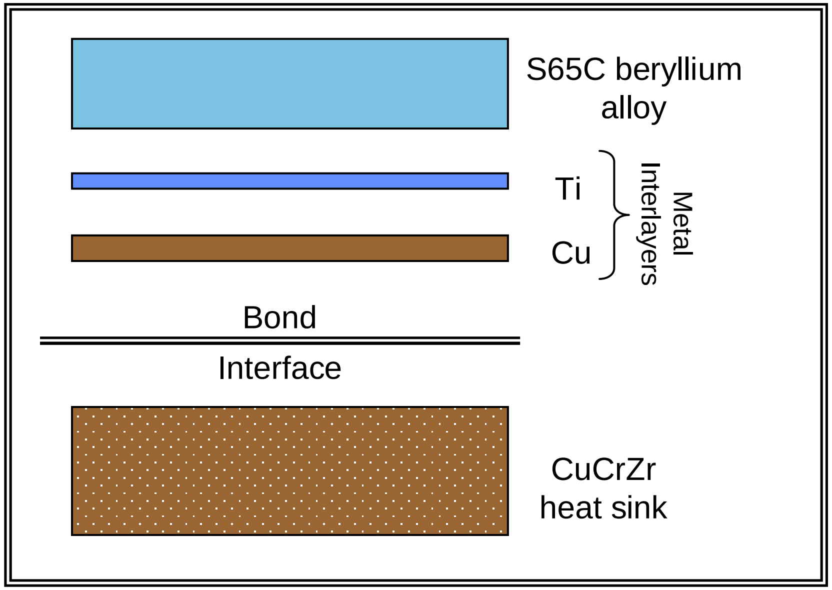
Joining of both the Cu-alloy/SS back plate and Be/Cu alloy is accomplished via Hot Isostatic Pressing (HIP)

Be substrates (5 cm dia. x 5 mm thick disks) are prepared by either grit abrasion or lapping to assess the effect of surface roughness. These mechanically prepared surfaces are then chemically cleaned.

Copper alloy substrates (5 cm dia. x 12.7 mm thick disks) are mechanically lapped and chemically polished to remove native oxides.

Interlayer metallizations are applied to the prepared Be surfaces by either sputter deposition or e-beam evaporation PVD processes. Titanium is applied to act as a diffusion barrier between Be and Cu suppressing the formation of brittle Be/Cu intermetallics. Thick Cu metallization is applied as a mechanical compliance layer to help accommodated thermal stresses. In some instances, free standing foils of copper are used in place of thick (25μm) Cu metallization films.

Be/CuCrZr HIP bonding scheme

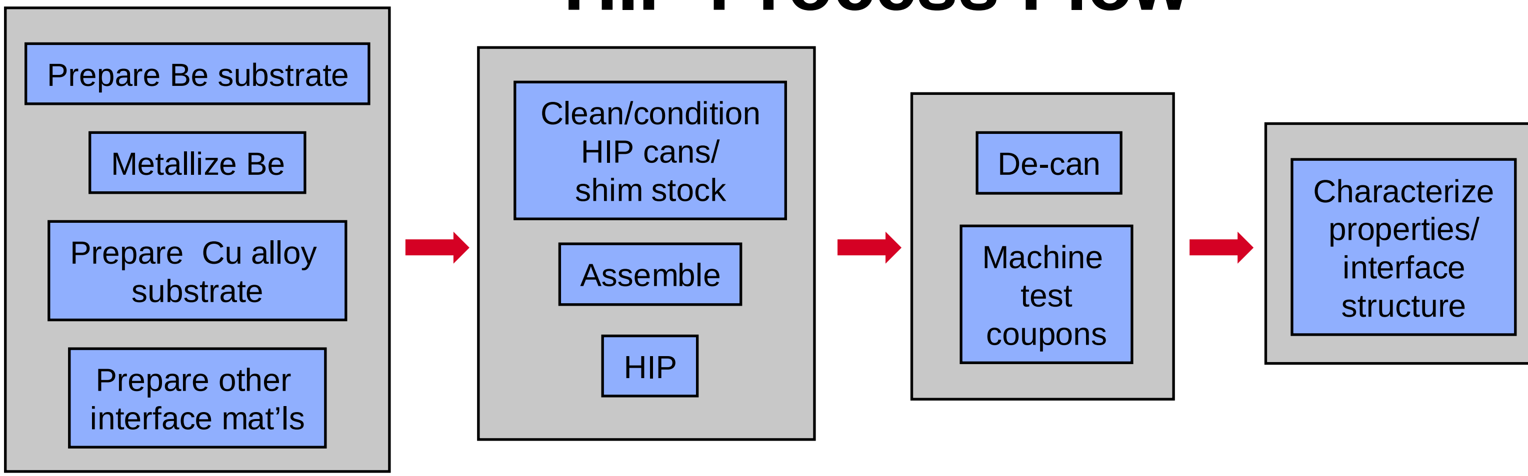


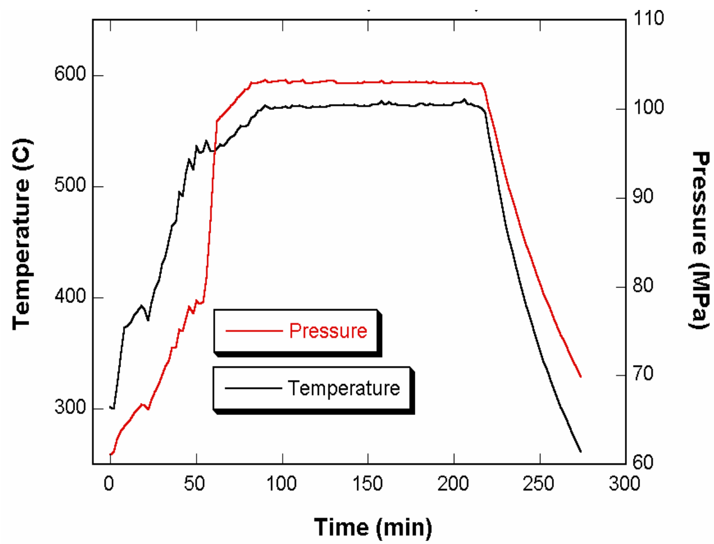
HIP processing conditions:

- Pressure: 100 MPa
- Time: 2 hr
- Temperature: 540C → 580 C

300 series SS HIP'ping containers and shim stock are hot caustic cleaned/passivated and vacuum baked prior to use. HIP containers are E-beam welded closed after being loaded with the metallized Be and Cu substrates.

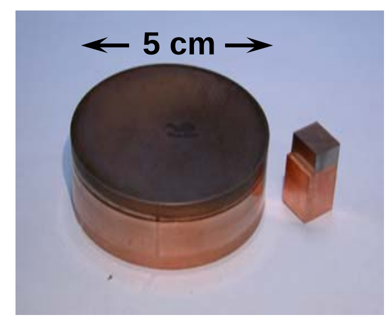
HIP Process Flow





Typical temperature/pressure traces for HIP bonding cycle

HIP'ped container



HIP bonded Be and Cu alloy disk along with shear specimen

Metallization/bonding schemes

Be Surface Prep.	Metallization Process	Diffusion Barrier	Compliant Layer	CuCrZr Surface Preparation	HIP Temp (C)
(ga)(s)[f]	Sputter Coat	2μm Ti[f]	25μm Cu[f]	Chem. Polish	580
(ga)(ns)	Sputter Coat	2μm Ti	25μm Cu	Chem. Polish	580
(ga)(s)	Sputter Coat	2μm Ti	3μm Cu-50μm Cu(f)	Chem. Polish	580
(ga)(s)[f]	Sputter Coat	2μm Ti[f]	25μm Cu[f]	Chem. Polish	560
(ga)(s)	Sputter Coat	2μm Ti	3μm Cu-50μm Cu(f)	Chem. Polish	560
(pl)(s)	Sputter Coat	2μm Ti	25μm Cu	Chem. Polish	560
(ga)(s)[f]	Sputter Coat	2μm Ti[f]	25μm Cu[f]	Chem. Polish	540
(pl)(s)	Sputter Coat	2μm Ti	25μm Cu	Chem. Polish	540

Decreasing HIP Temperature

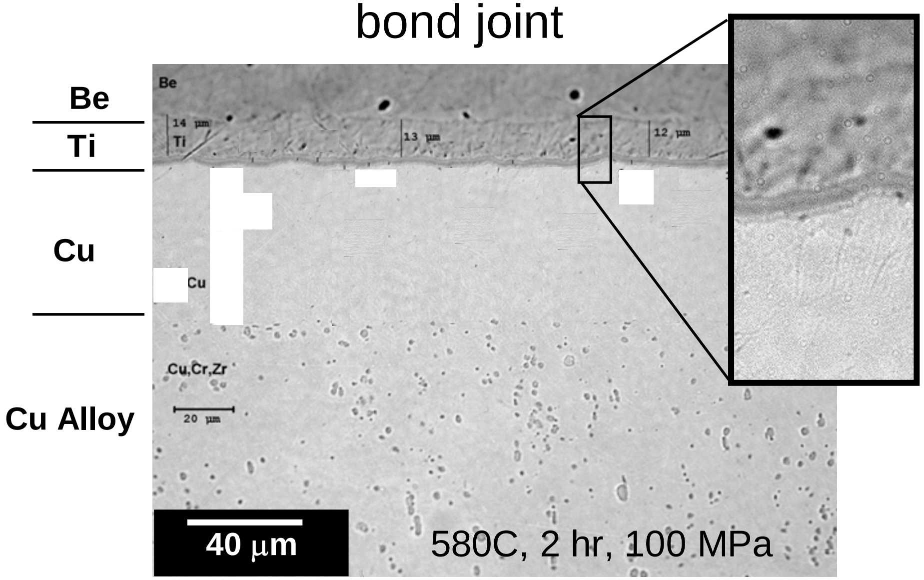
(ga)(ns)	E-beam Evap.	2μm Ti	3μm Cu-50μm Cu(f)	Chem. Polish	580
(pl)(ns)	E-beam Evap.	2μm Ti	3μm Cu-50μm Cu(f)	Chem. Polish	580
(ga)(ns)	E-beam Evap.	2μm Ti	3μm Cu-50μm Cu(f)	Chem. Polish	560
(pl)(ns)	E-beam Evap.	2μm Ti	3μm Cu-50μm Cu(f)	Chem. Polish	560
(ga)(ns)	E-beam Evap.	2μm Ti	3μm Cu-50μm Cu(f)	Chem. Polish	540
(pl)(ns)	E-beam Evap.	2μm Ti	3μm Cu-50μm Cu(f)	Chem. Polish	540

Decreasing HIP Temperature

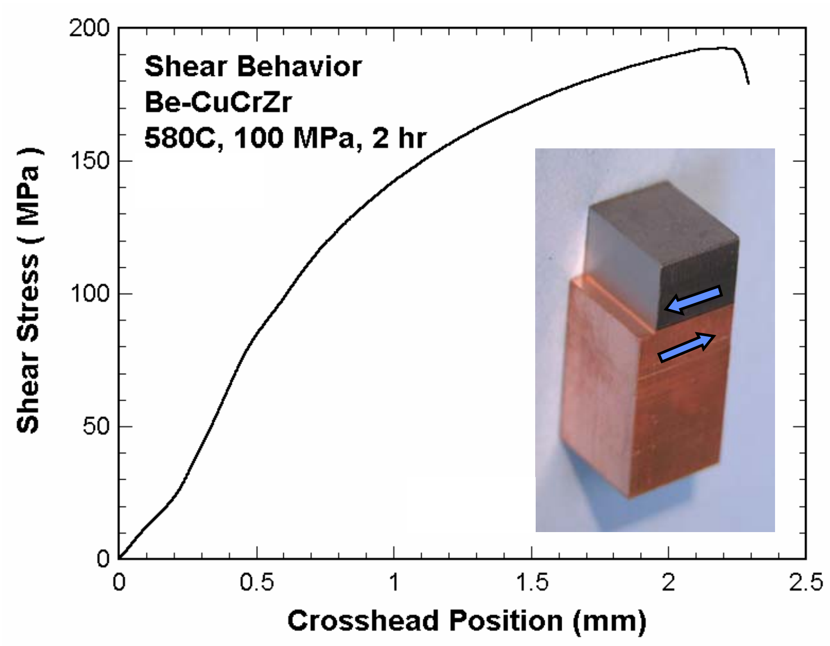
(ga): grit abraded, acid etched
(s): sputter clean
(*f*): "baseline" process
(ns): no sputter clean
(f): foil
(pl): lapped

Focus is directed towards reducing HIP'ping temperature in order to increased margin on CuCrZr strength

Optical cross-section of
bond joint

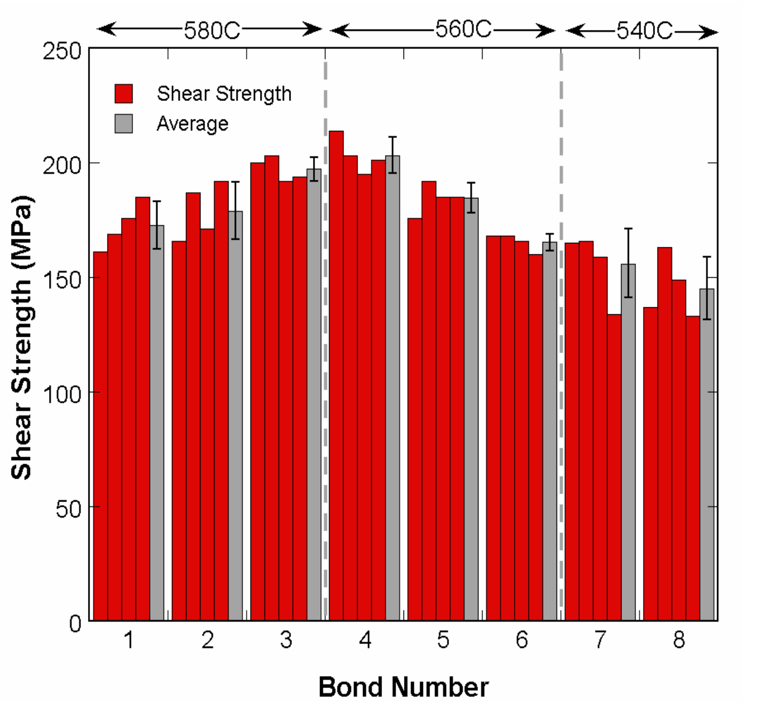


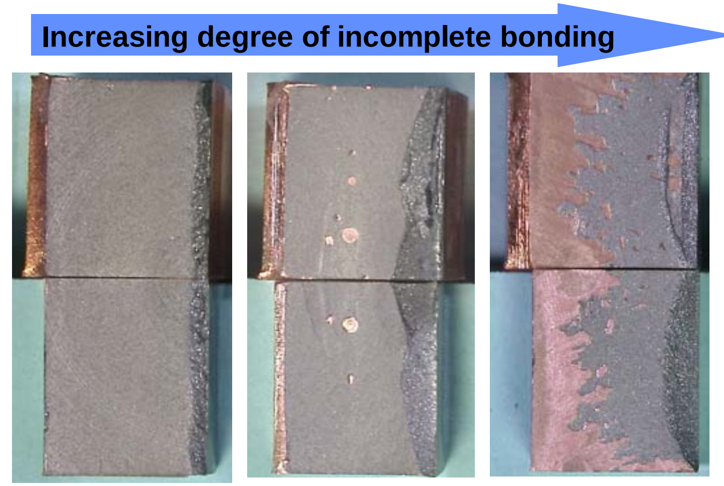
HIP processed bonds exhibit
no interface defects



Shear strength is the principal measurement of bond quality

Shear strength summary- sputter deposition





CuCrZr Substrate

Be Substrate

#1
580C
173 MPa

#4
560C
203 MPa

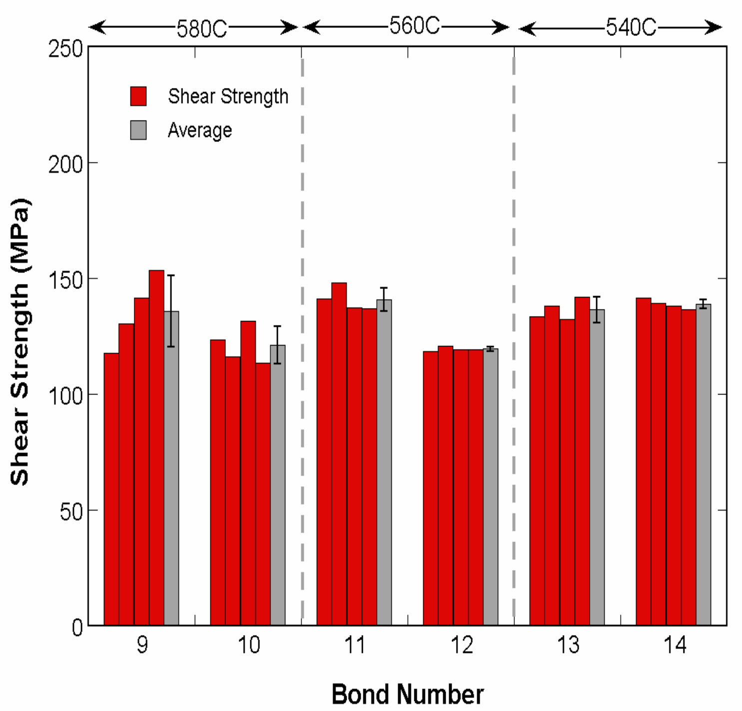
#7
540C
156 MPa

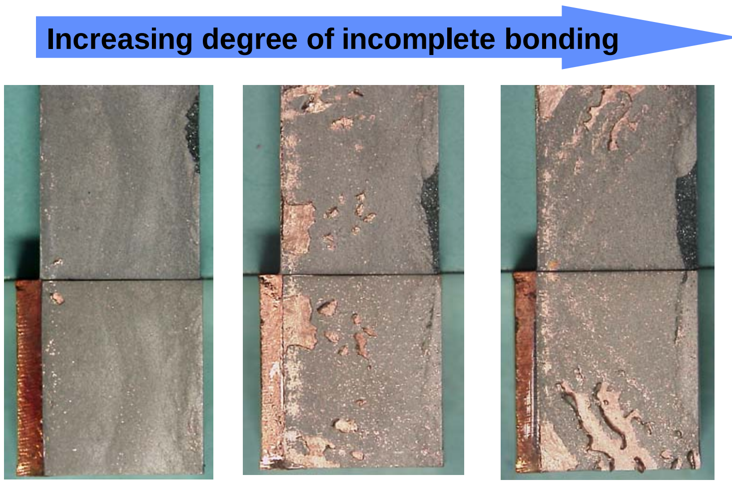
Bond #	Be Surface Prep.	Diffusion Barrier	Compliant Layer	HIP Temp (C)	Avg. .Shear Strength (MPa)
1	(ga)(s)^f	2μm Ti^f	25μm Cu^f	580	173
2	(ga)(ns)	2μm Ti	25μm Cu	580	179
3	(ga)(s)	2μm Ti	3μm Cu-50μm Cu(f)	580	197
4	(ga)(s)^f	2μm Ti^f	25μm Cu^f	560	203
5	(ga)(s)	2μm Ti	3μm Cu-50μm Cu(f)	560	185
6	(pl)(s)	2μm Ti	25μm Cu	560	165
7	(ga)(s)^f	2μm Ti^f	25μm Cu^f	540	156
8	(pl)(s)	2μm Ti	25μm Cu	540	145

High strength bonds with little sample-to-sample variation is observed for 580C and 560C HIP joints

Lowering the bonding temperature to 540C results in incomplete Cu-CuCrZr bonding and some reduction in strength

Shear strength summary- E-beam evaporation





#9
580C
136 MPa

#11
560C
141 MPa

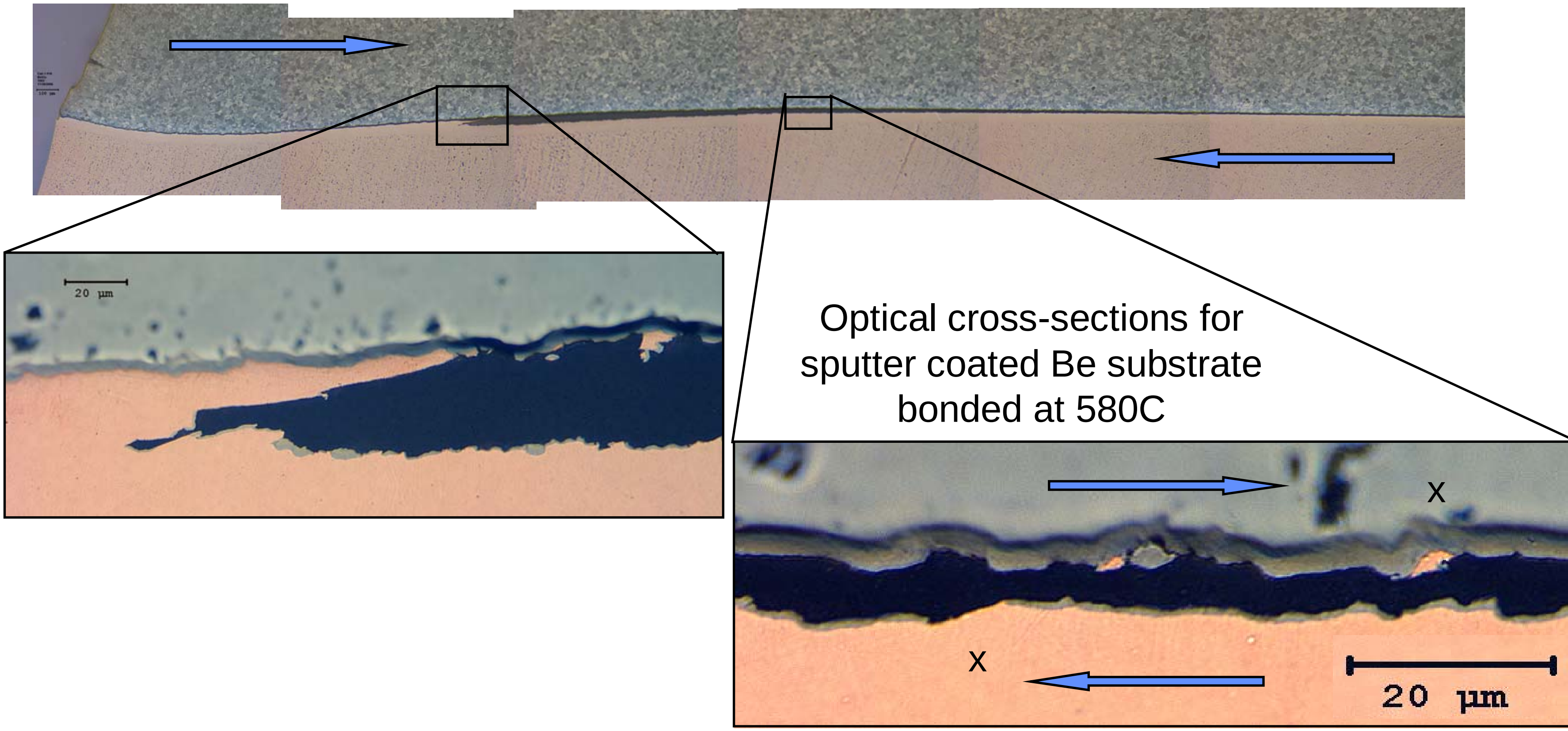
#13
540C
136 MPa

Metallization via e-beam evaporation results in lower bond strength at all HIP processing temperatures

Incomplete Cu-CuCrZr bonding is observed at the lower joining temperatures

Bond #	Be Surface Prep.	Diffusion Barrier	Compliant Layer	HIP Temp (C)	Avg. Shear Strength (MPa)
9	(ga)(ns)	2μm Ti	3μm Cu-50μm Cu(f)	580	136
10	(pl)(ns)	2μm Ti	3μm Cu-50μm Cu(f)	580	121
11	(ga)(ns)	2μm Ti	3μm Cu-50μm Cu(f)	560	141
12	(pl)(ns)	2μm Ti	3μm Cu-50μm Cu(f)	560	120
13	(ga)(ns)	2μm Ti	3μm Cu-50μm Cu(f)	540	136
14	(pl)(ns)	2μm Ti	3μm Cu-50μm Cu(f)	540	140

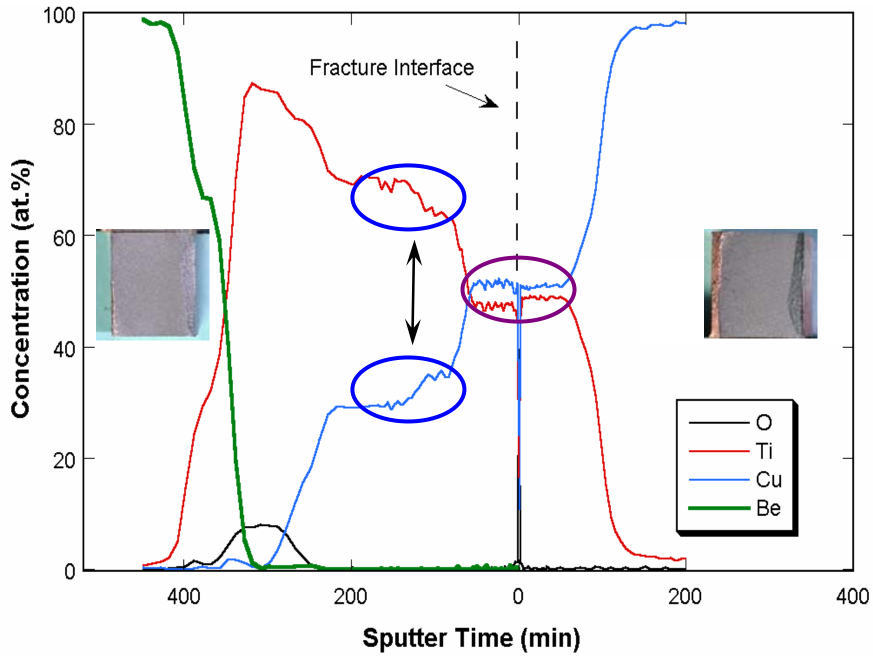
Interrupted shear test

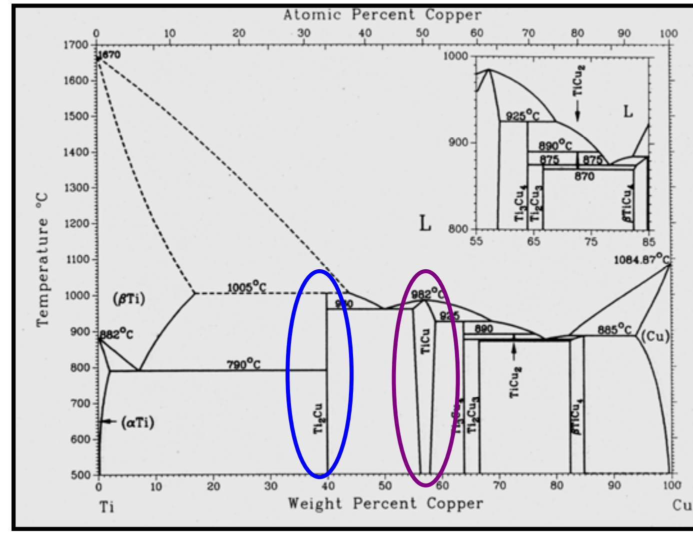


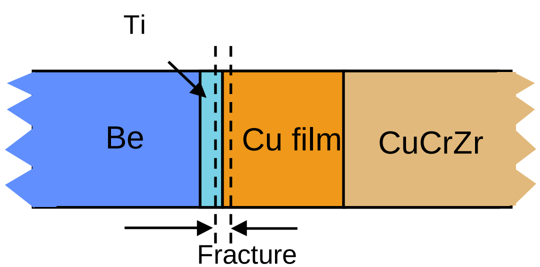
Thick Cu metallization is an effective compliance layer, allowing the joint to accommodated substantial deformation prior to failure

Fiducial marks ("x") indicate the relative shear offset within the internal crack

Auger depth profiling of fracture surface







Ti metallization suppresses the formation of Be/Cu intermetallic while forming Ti/Cu intemetallics

Intermetallic regions most well defined for 580C HIP bonds

For 580C and 560C bonds, fracture is coincident with 50 at% Cu-50 at.% Ti

Plateaus in Cu-Ti depth profiles correspond to specific intermetallic compounds identifiable in the Ti/Cu phase diagram:

Ti_3Cu (η–phase), TiCu (ζ-phase)

Summary

- HIP bonding schemes are yielding high quality bond joints
  - High strength
  - Small scatter
- Thin Ti metallizations are effective in acting as a diffusion barrier between Be and Cu
- Cu interlayers successfully accommodate interface strains
- Failure is in the Ti/Cu or Ti/Be intermetallic formed during the HIP cycle
- Maximum bonding strength is observed for 580C and 560C HIP bonding runs
- E-beam evaporation yields lower overall bond strength for comparable metallization and HIP bonding conditions