Materials and Manufacturing Challenges for Compact Heat Exchangers for Supercritical CO_2 Power Systems

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U.S. DEPARTMENT OF ENERGY

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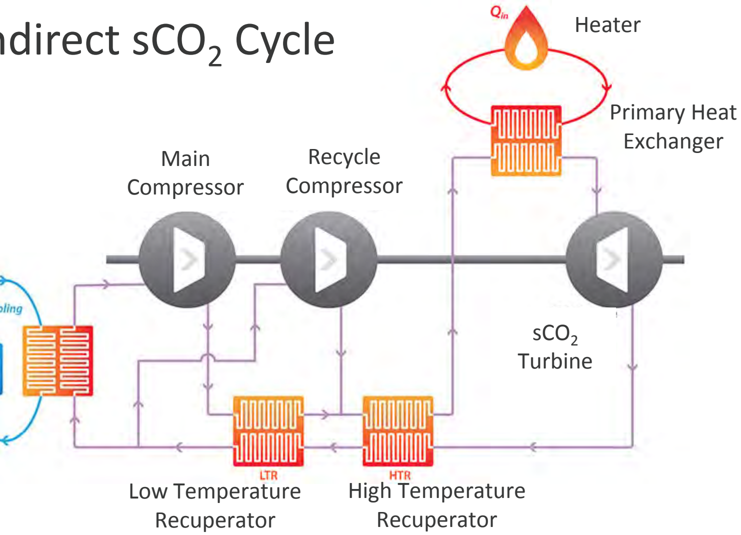
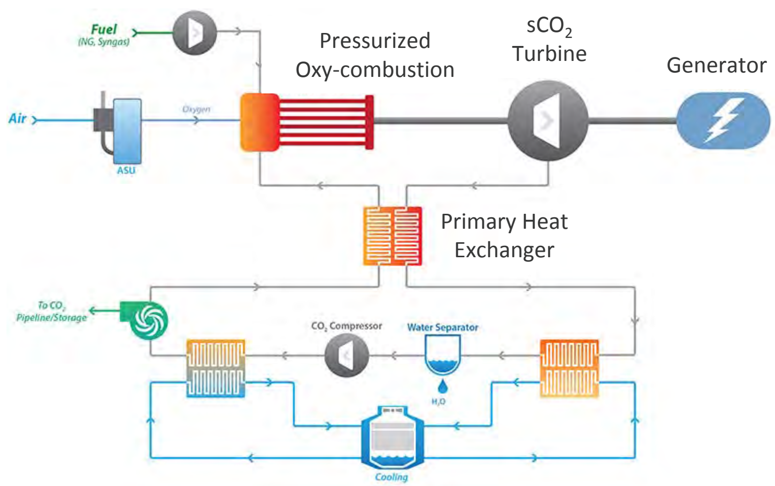
upercritical CO_2 Power Cycles

ndirect sCO_2 Cycle



Direct sCO_2 Cycle



Cycle/Component		Inlet		Outlet	
		T (C)	P (MPa)	T (C)	P (MPa)
Indirect	Heater	450-535	1-10	650-750	1-10
	Turbine	650-750	20-30	550-650	8-10
	HX	550-650	8-10	100-200	8-10
Direct	Combustor	750	20-30	1150	20-30
	Turbine	1150	20-30	800	3-8
	HX	800	3-8	100	3-8

Essentially pure CO_2

CO_2 with combustion products including O_2, H_2O and SO_2

ompact Heat Exchangers

Iigher efficiency

- Due to much shorter heat diffusion lengths in fluid

maller size

- Use of less materials (expensive superalloys)
- Takes less space

Iodular design

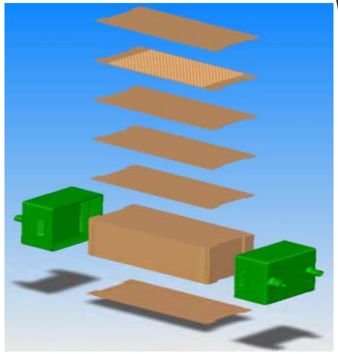
- Expandable to large power plants

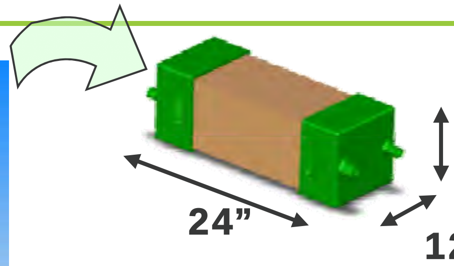
ypical Compact HX Fabrication rocess

Pattern microscale flow paths into laminae using a variety of methods
- Chemical etching
- Micromachining
- Laser cutting
- EDM

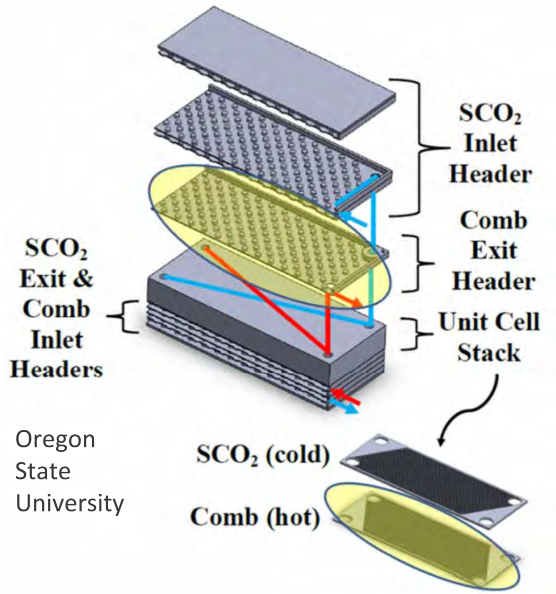
Bond these laminae using a variety of methods
- Diffusion bonding
- Transient liquid phase (TLP) bonding
- Laser welding
- Brazing

r sCO_2 cycles, diffusion bonding and TLP bonding considered to be the most robust approaches





*W. Ehrfeld, V. Hessel, H. Löwe, Microreactors: New Technology for Modern Chemistry, Wiley-VCH, 2000.



Oregon State University

onding

- onding is considered the "weak link" in the abrication process
- harp edges in the architecture lead to ocations of high stress concentration in the nechanical design simulations
- Ve need information on
  - The parameters for bonding process (T, P, t) of materials
  - The strength of the bond
  - Corrosion behavior of bonded regions in sCO_2

aterials

High-temperature strength
High-temperature oxidation resistance

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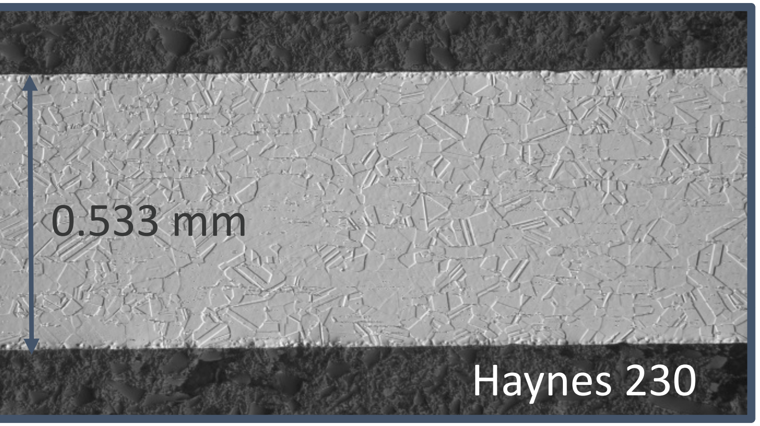
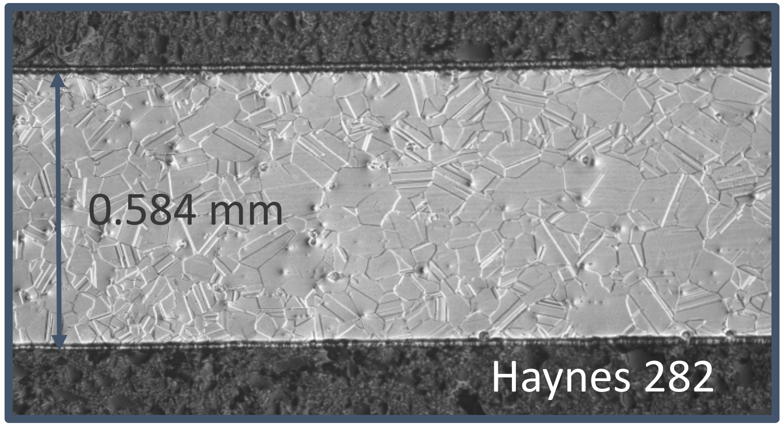
Nominal chemical composition (weight %) of materials used in this study (Haynes 230 and Haynes 282)												
	Ni	Cr	W	Ti	Mo	Fe	Co	Mn	Si	Al	C	B
	57	22	14	--	2	3*	5*	0.5	0.4	0.3	0.10	0.015*
	57	19.5	--	2.1	8.5	1.5*	10	0.3*	0.15*	1.5	0.06	0.005

* = maximum



Solid-solution strengthened
ld rolled and 1232 °C solution annealed sheet



Precipitation strengthened
1149 °C solution annealed sheet

Other materials consid
for this applicatio

Inconel 740H
Inconel 625
Inconel 617
347H Stainless stee
316 Stainless stee
304 Stainless stee
Grade 91 steel

iffusion Bonding vs. Transient Liquid hase (TLP) Bonding

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Diffusion Bonding

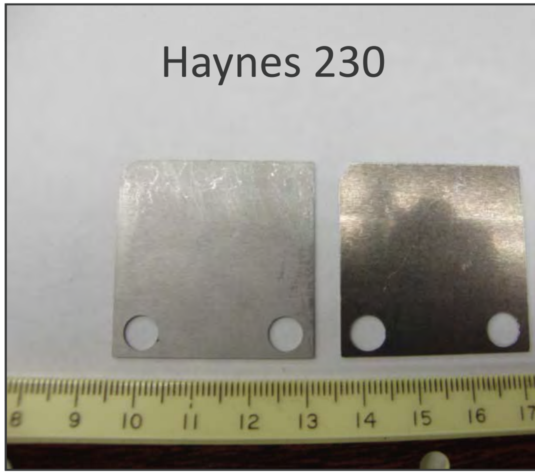
- Diffusion bonding is a solid tate process
- t requires applied high ressure at high temperature or a certain amount of time
- t involves diffusion of onstituent atoms and creep rocesses to close the voids resent due to roughness of he faying surfaces.

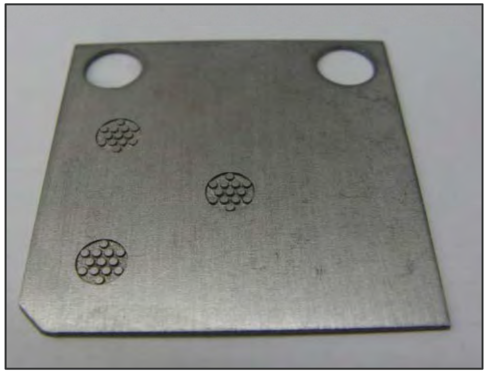
Transient Liquid Phase Bonding

- TLP involves both solid state and liquid state reactions
- It requires less pressure than diffusion bonding
- It requires a lower melting point interlayer
- It involves isothermal melting and solidification of interlayer

onding

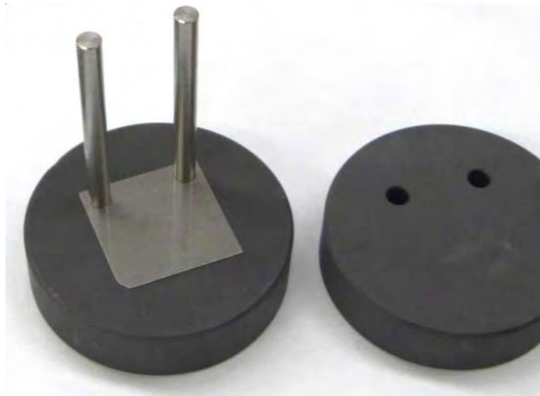
- heets were water-jet cut into shims
- 00 shims were bonded together in each stack
- ll shims were reverse current etched and cleaned vith acetone
- ome stacks used shims plated with electroless ickel, 2 - 4 μm thick
- ome shims contained pin-fin micro-features dentical to those used in a heat exchanger
- ll shims were thoroughly cleaned by hand and in an ltrasonic acetone bath for 15 minutes immediately efore bonding

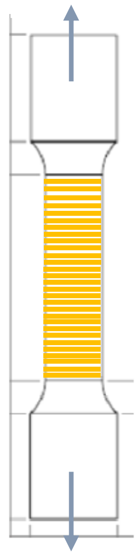




onding

- him stacks were held in a fixture during bonding nd pressure was applied only after the emperature ramped up to the desired value
- he hot press vacuum was maintained at pproximately 5 x 10^{-6} torr (0.0007 Pa)
- 150°C for 8 hours at 12.7 MPa
- fter bonding, each stack was machined to roduce 6 tensile specimens using wire EDM and CNC lathe
- 1282 without Ni plating did not bond well





iffusion Bonding of Alloy 230

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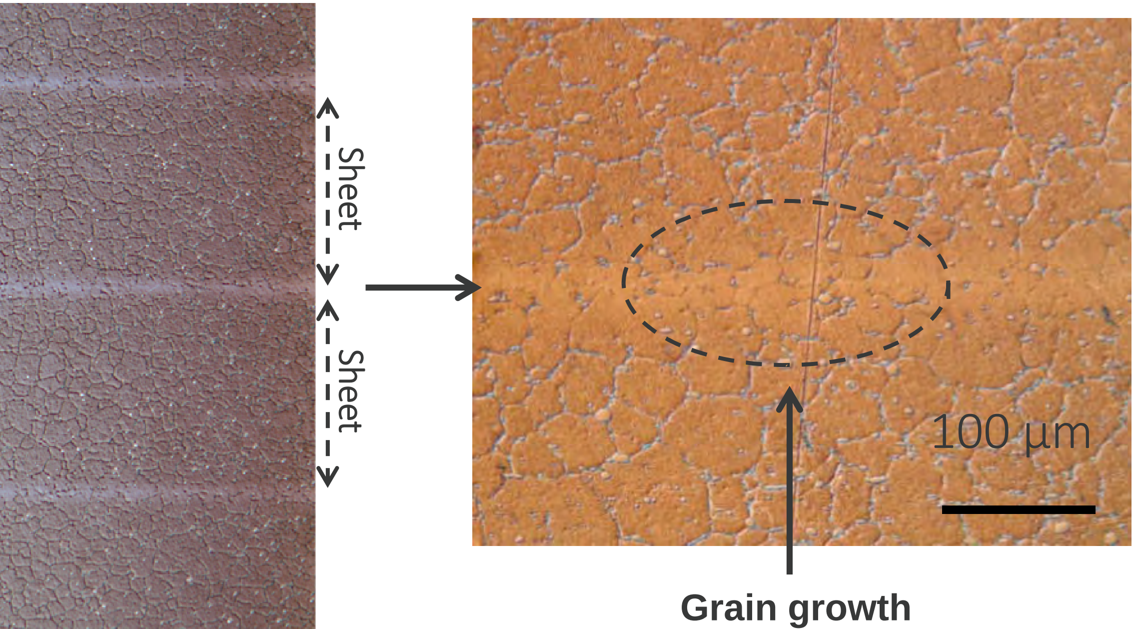
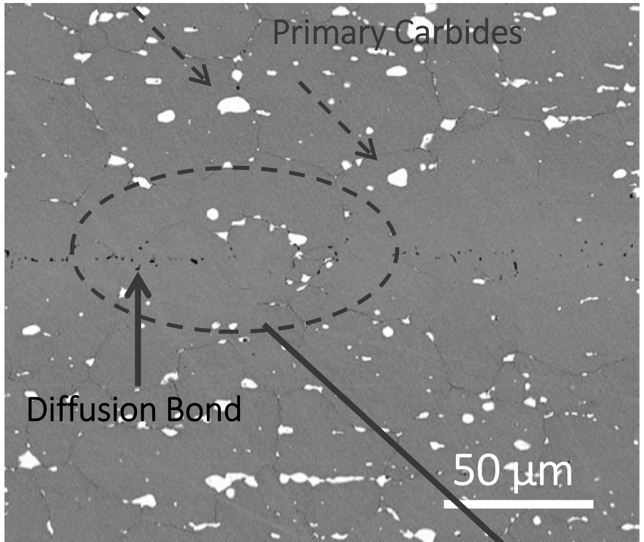
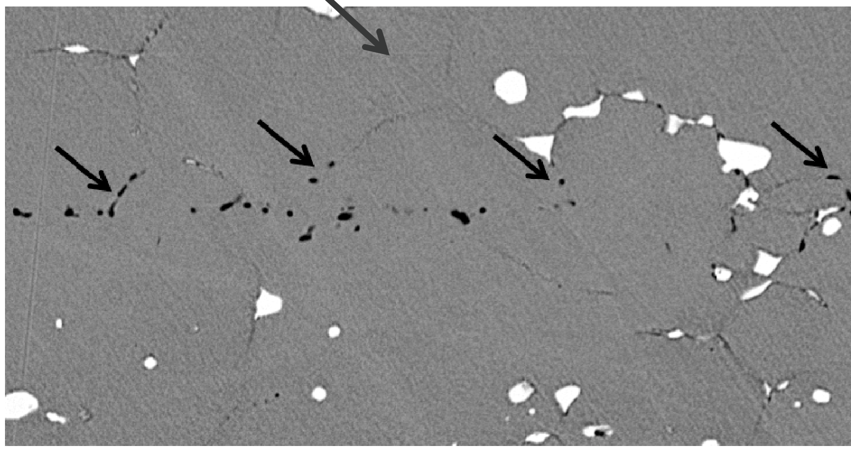
Microstructure





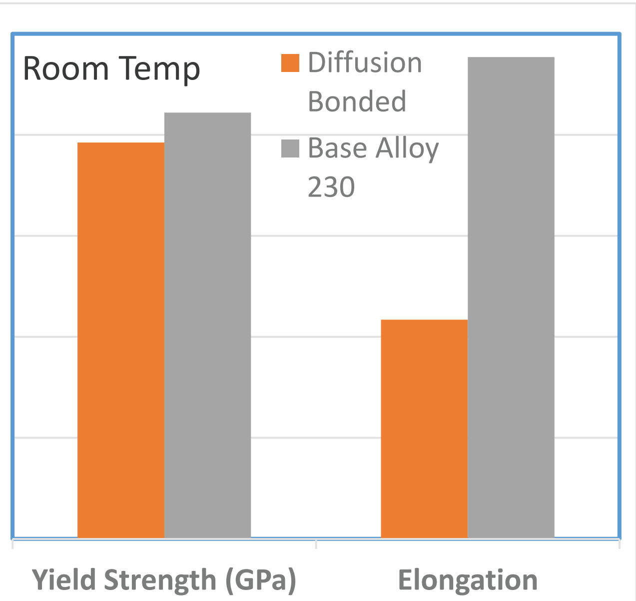


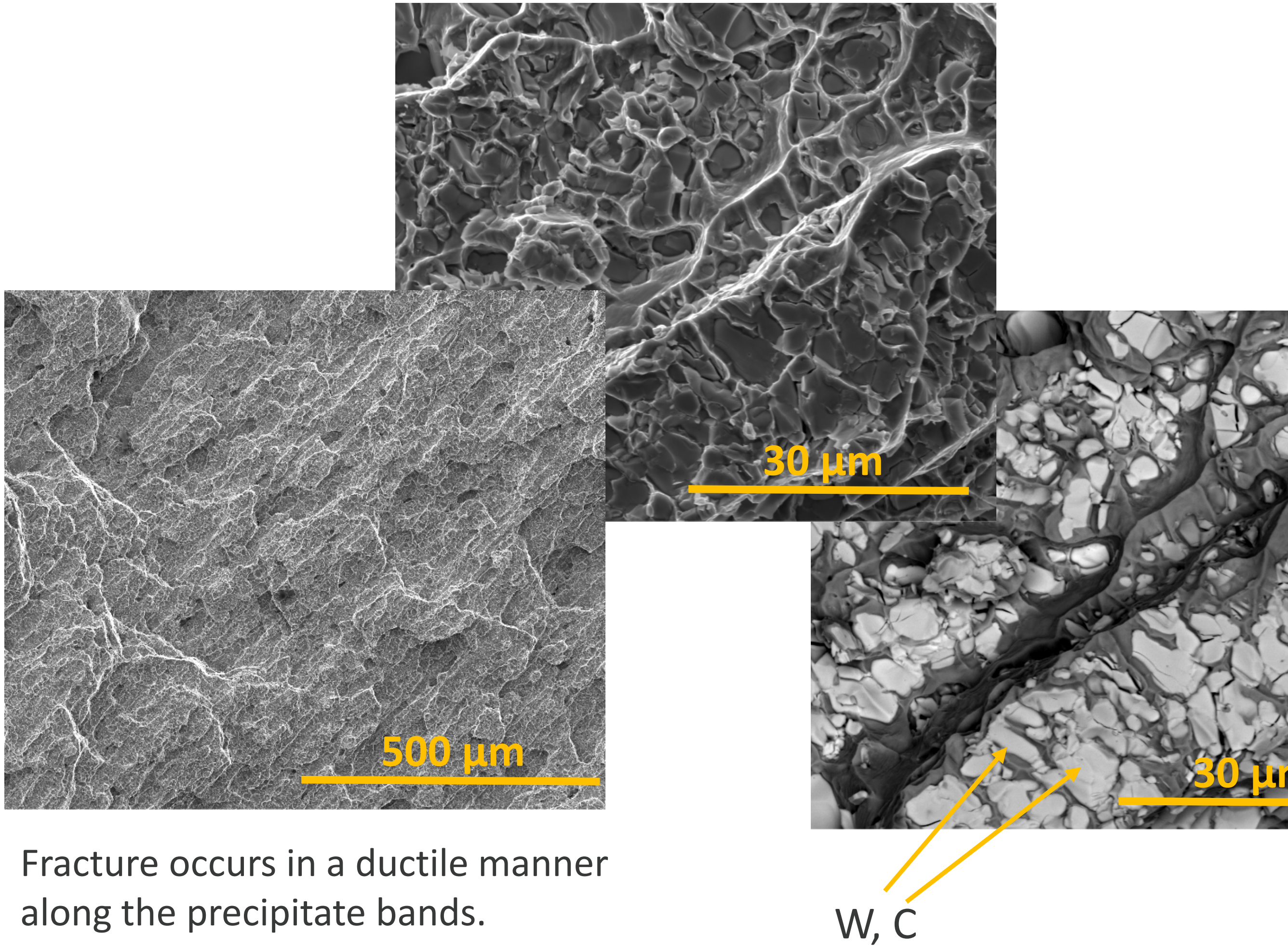
- Primary carbides form at higher temperature

tched microstructure to observe grain growth through the bond line

iffusion Bonding of Alloy 230

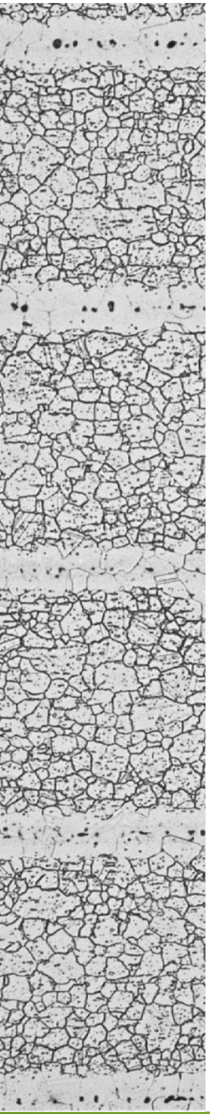
Mechanical Behavior



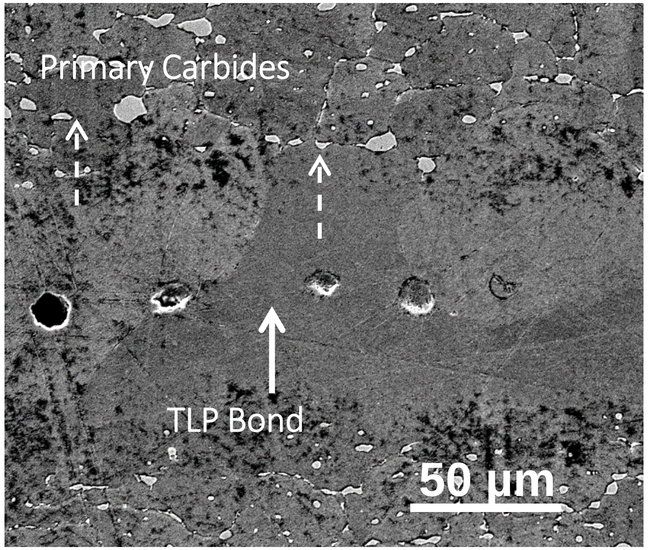


Fracture occurs in a ductile manner along the precipitate bands.

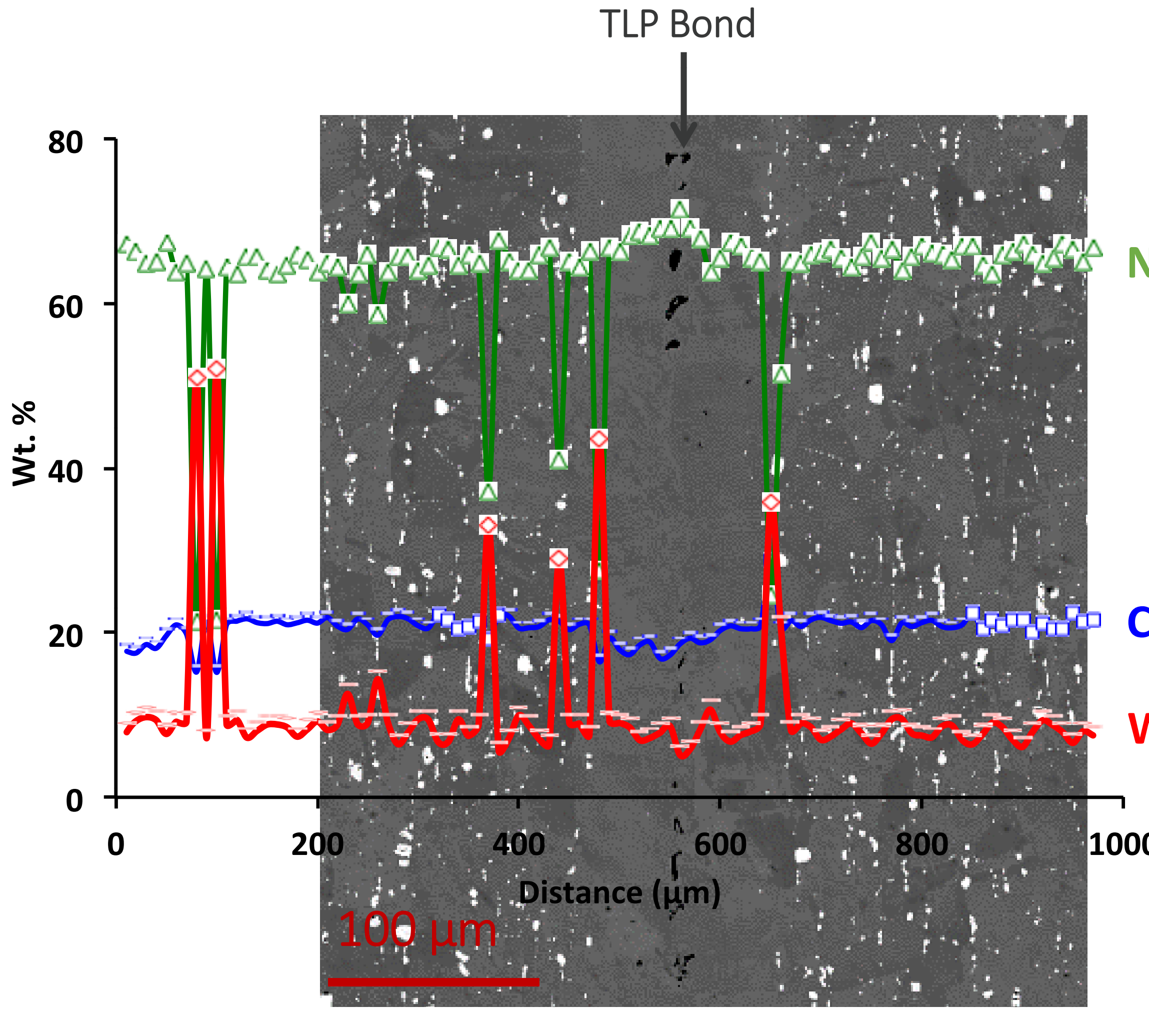
P Bonding of Alloy 230



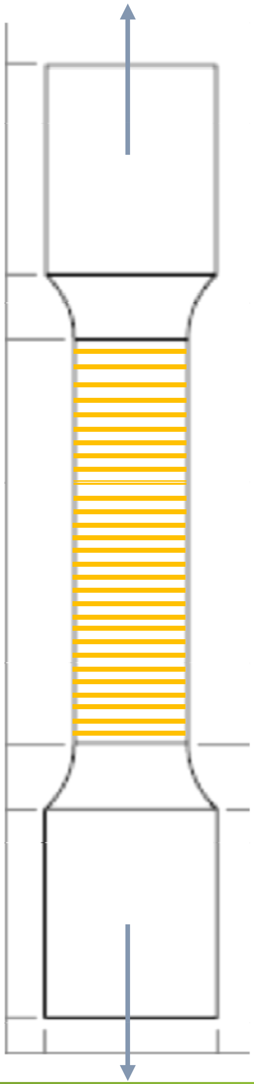
Microstructure



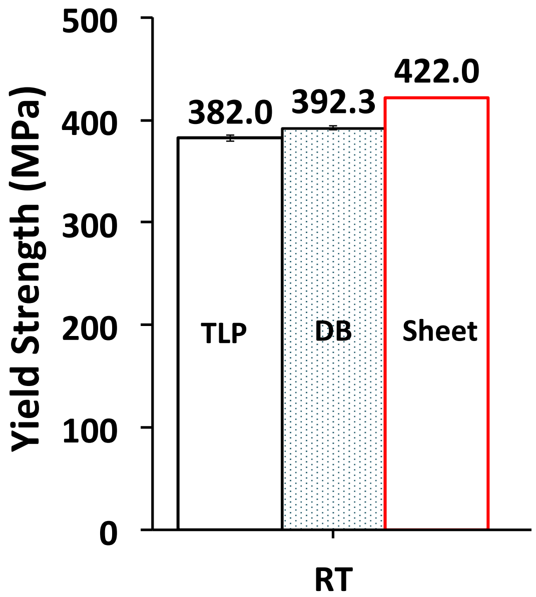
- Primary Carbides
- Increase in Ni, dip in Cr at the bond

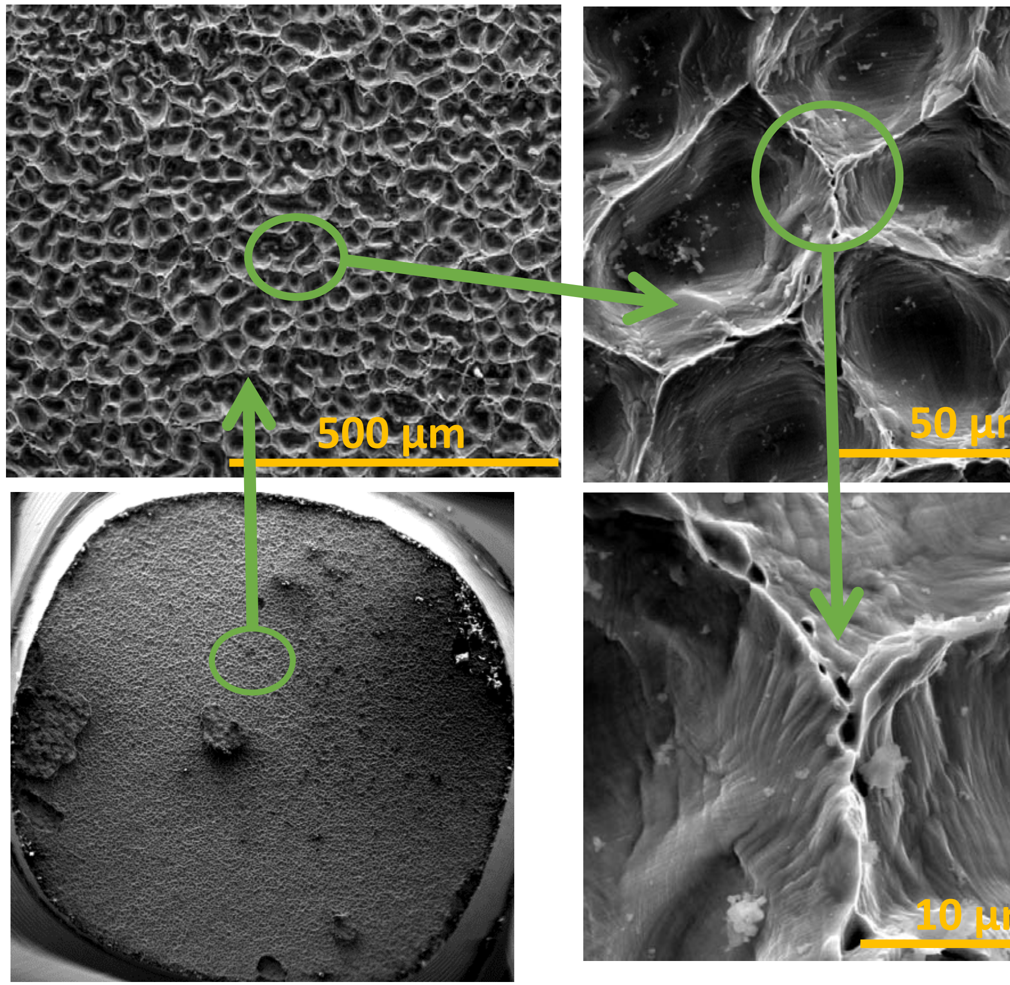


ond Strength – TLP Bonding of Alloy 230



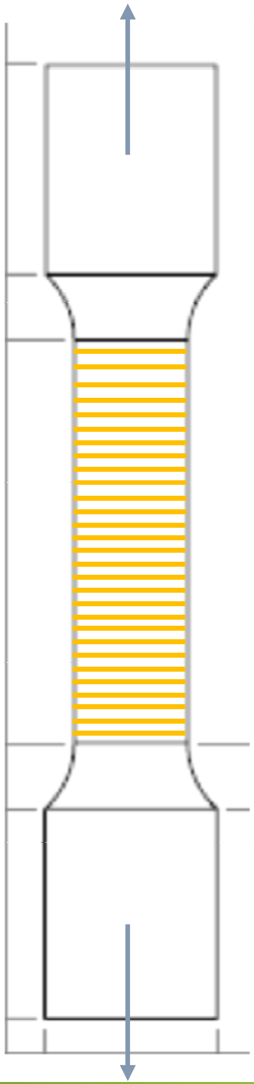
Room Temperature Strength



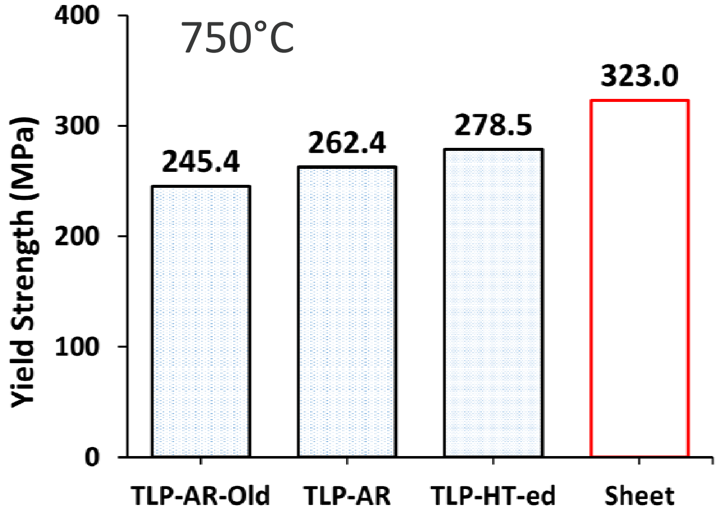


Fracture occurs in a ductile manner at the bonding layer.

ond Strength – TLP Bonding of Alloy 230

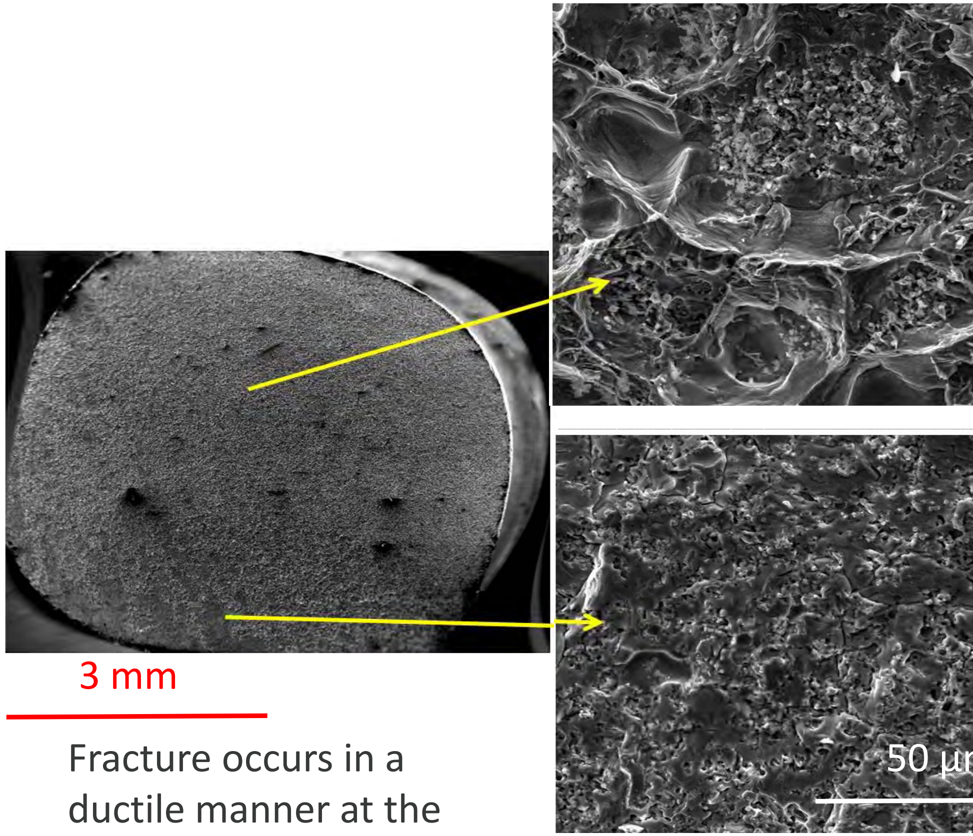


High-Temperature Strength



High Temperature Yield Strength

- **TLP-AR-Old = 76%**
- **TLP-AR = 81%**
- **TLP-HT-ed = 86%**



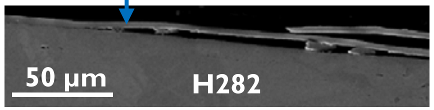
Fracture occurs in a ductile manner at the bonding layer and the sheet.

onding Defects

Challenges with TLP bonding of H282 – Surface oxides & Intermetallic formation

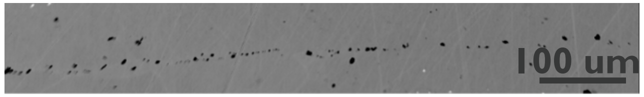
Surface Oxides

Ni-12P coating on the metal for TLP bonding



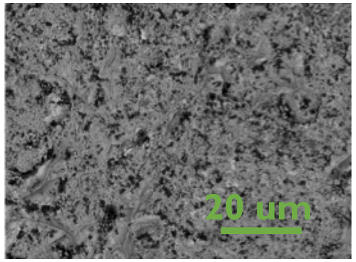
Coating does not adhere to the metal

Bondline after TLP bonding



AlO particles (dark) along the bondline

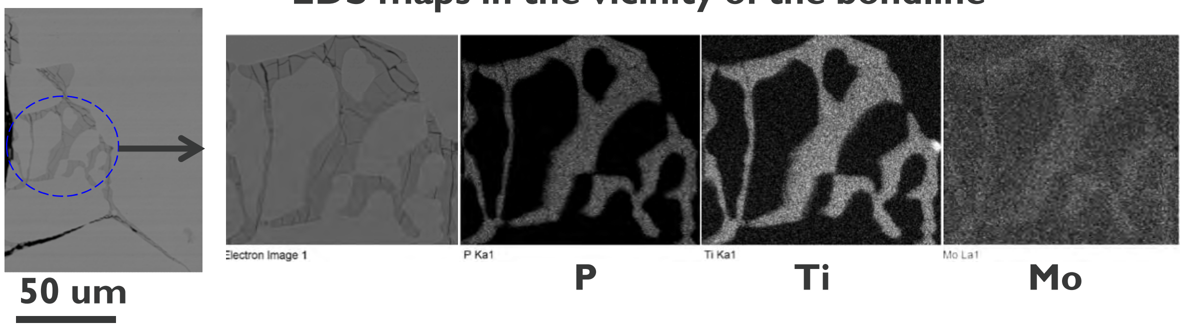
Fracture Surface



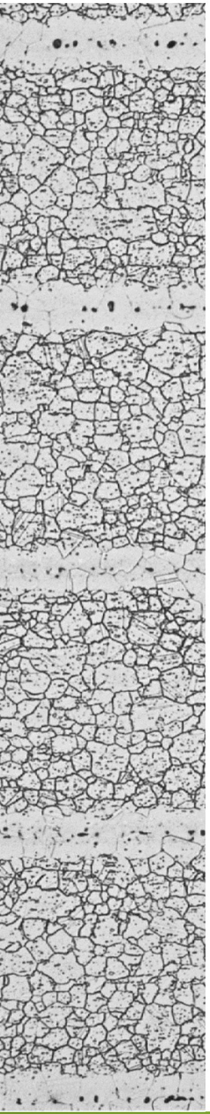
AlO particles (dark) on the fracture surface

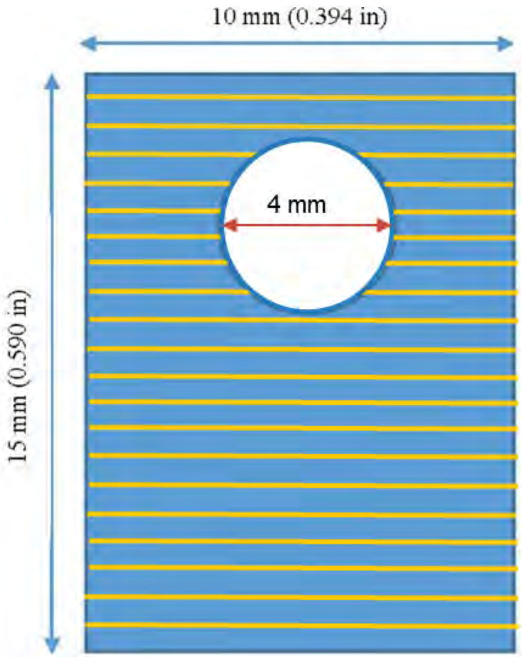
Intermetallic formation due to 12 wt. % P

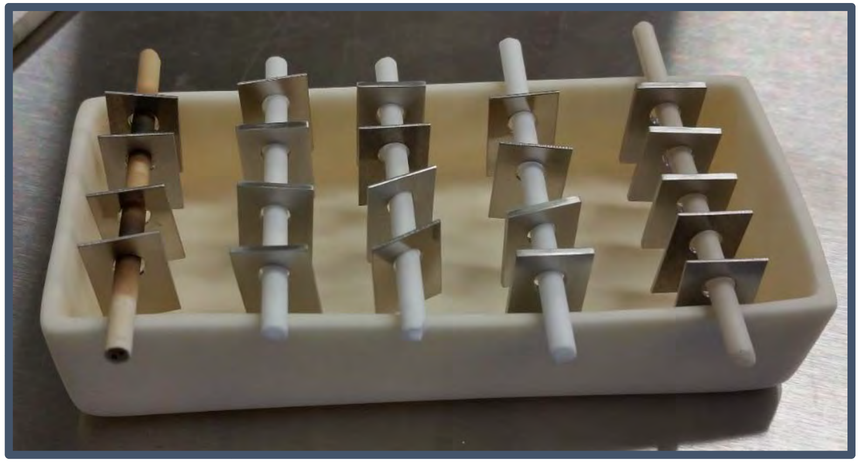
EDS maps in the vicinity of the bondline



xidation of Bonded Regions







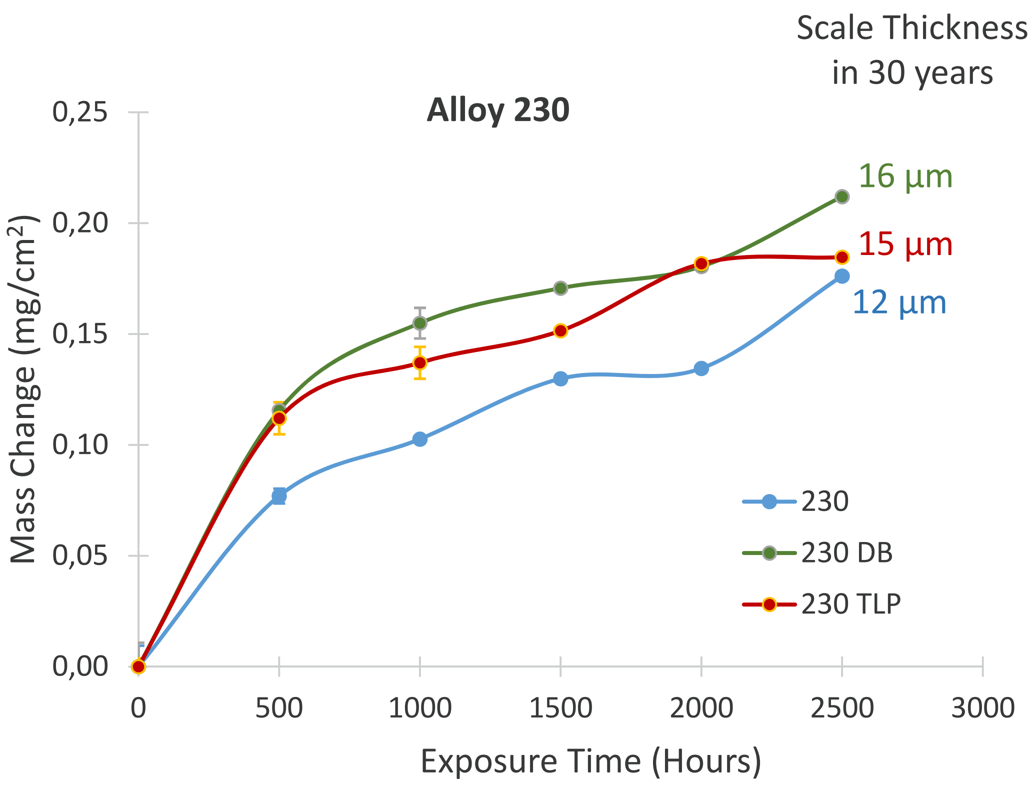
Gas: 1 bar CO_2 (99.999% purity)
Gas flow rate: 0.032 kg/h
Temperature: 700°C
Duration: 2500 h
24 h purging with CO_2 before heating

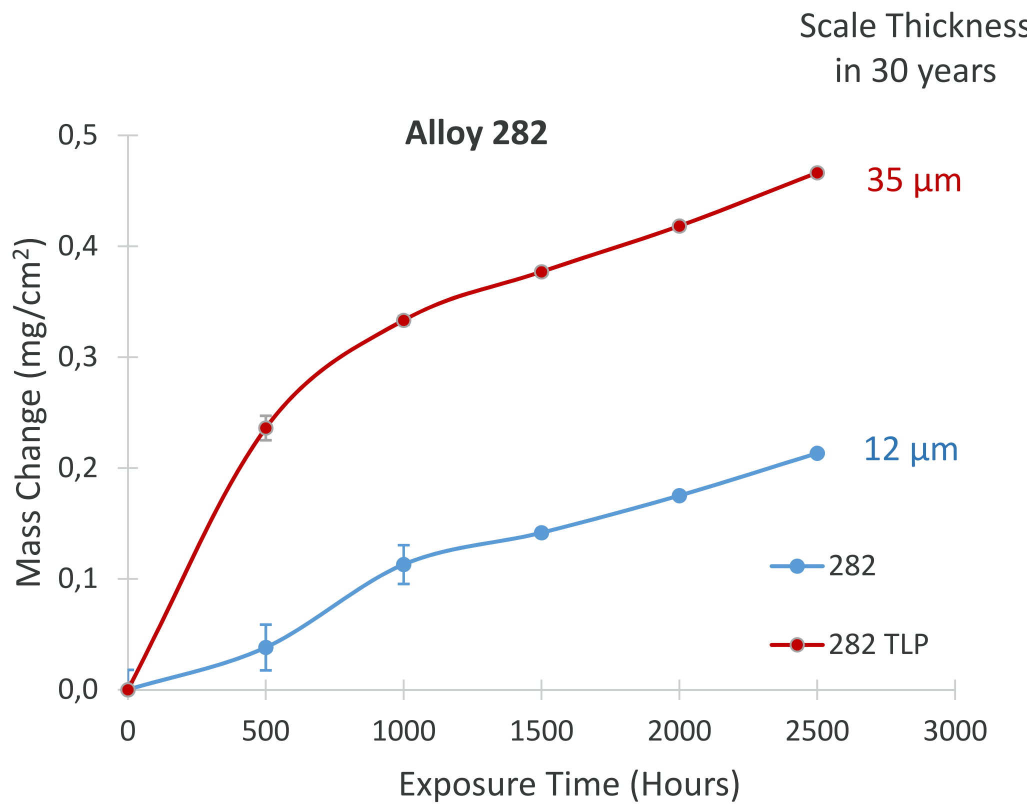
Characterizatio

Mass Change
XRD
SEM

xidation of Bonded Regions

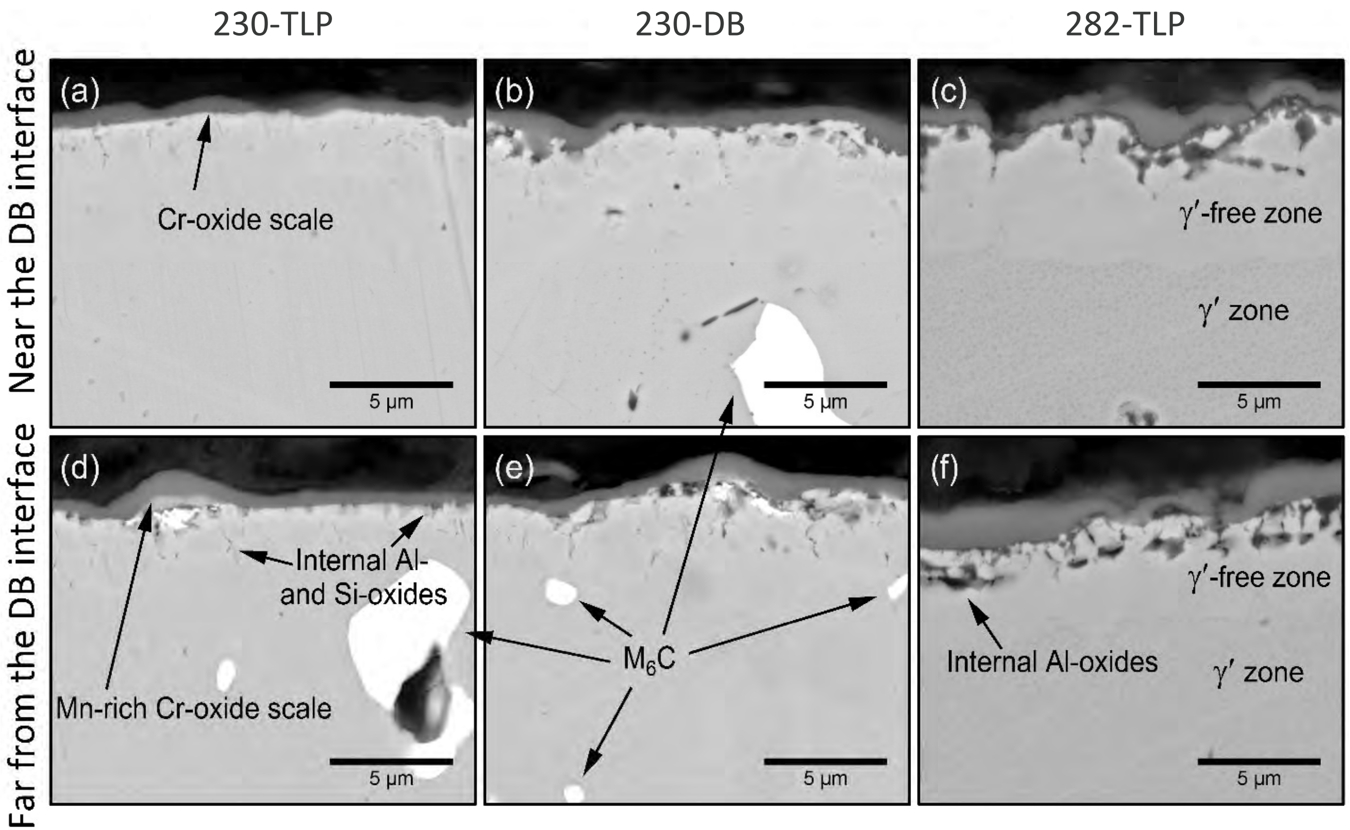
bar CO_2 at 700°C





xidation of Bonded Regions

bar CO_2 at 700°C



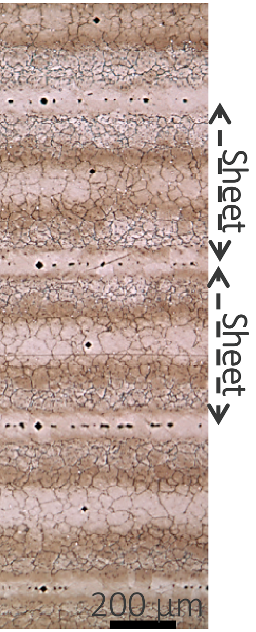
No significant difference between bond regions and away from bond regions

More internal oxidation in H282, resulting from higher Al and Ti levels

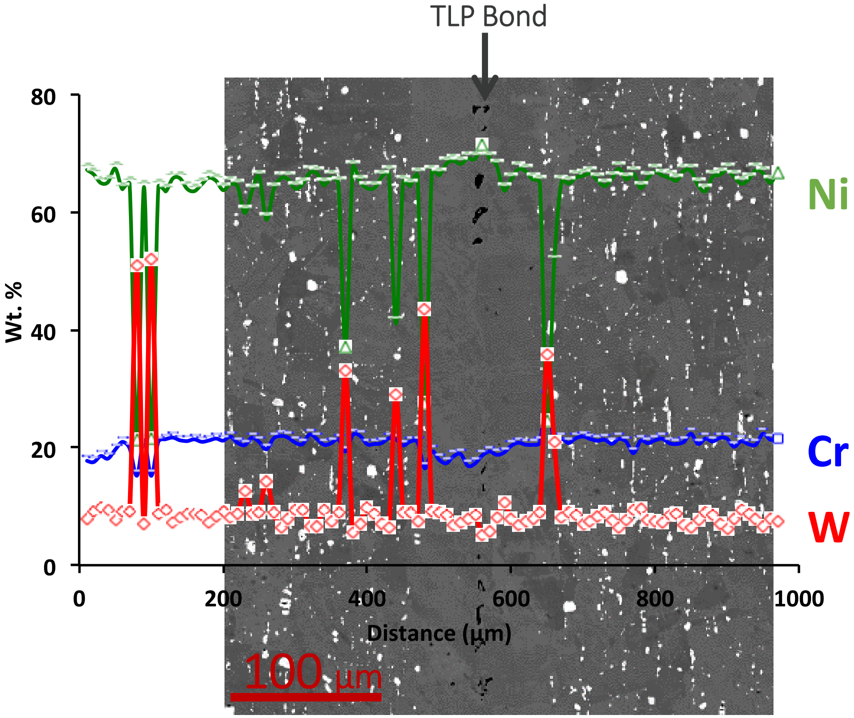
γ′ loss in H282 below the internal oxidation layer

Back-Scattered Electron Images

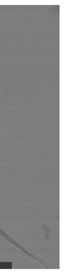
ummary



ids at bondline

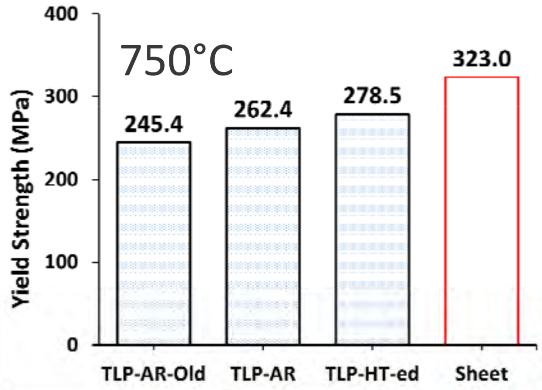


Composition of TLP bonded regions were similar to the base material



Intermetallic formation

m



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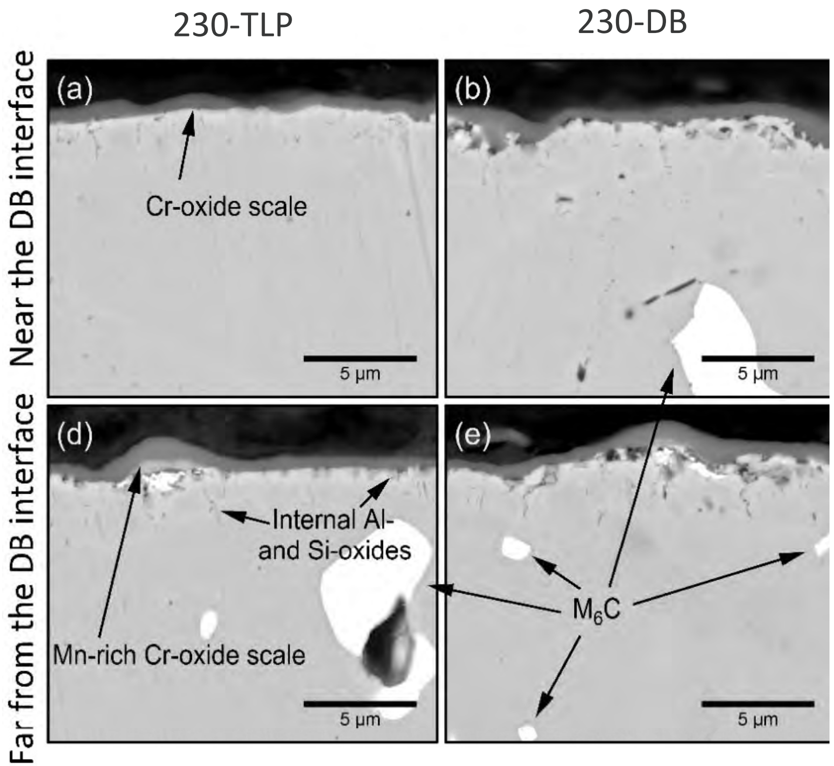
Both DB and TLP bonded stacks exhibited good strength at high and room temperature



No signific difference oxidation behavior i CO_2 at 700 between b regions an away from bond regio