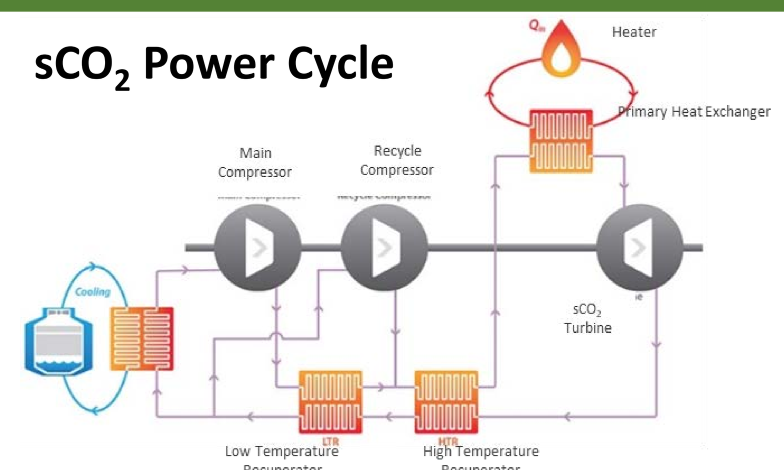
Manufacturing Compact Heat Exchangers for Supercritical CO_2 Power Cycles

Transient-Liquid-Phase Bonding of Ni-Alloys

Ö.N. Doğan, K.A. Rozman, M. Kapoor, R.P. Oleksak, J.A. Hawk, D.E. Alman
National Energy Technology Laboratory

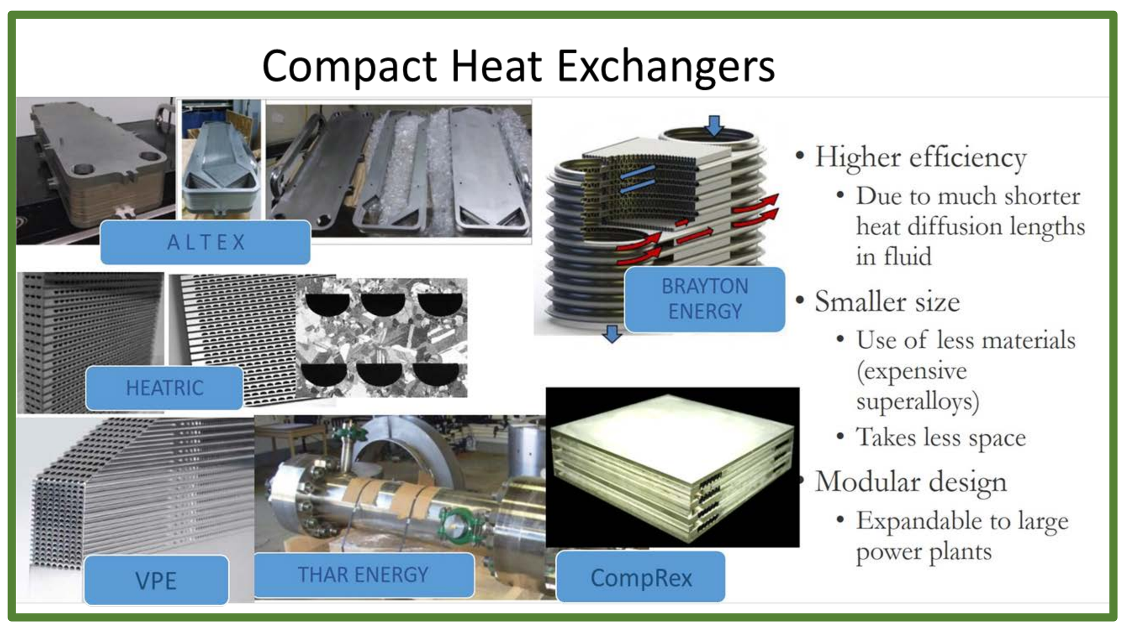
INTRODUCTION

sCO_2 Power Cycle



The use of supercritical CO_2 (sCO_2) as a working fluid in power generation results in higher thermodynamic efficiencies compared to steam cycles. This high efficiency is due primarily to the use of **compact heat exchangers**, which enhance heat transfer between the high- and low-temperature working fluid.

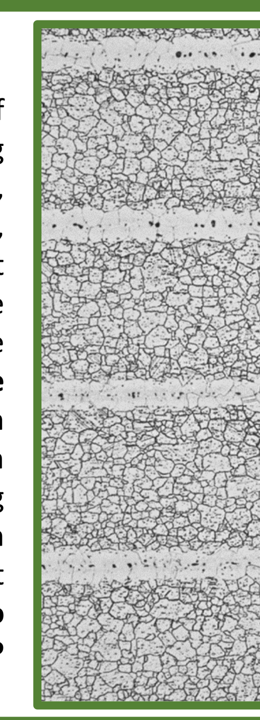
Compact Heat Exchangers



- Higher efficiency
  - Due to much shorter heat diffusion lengths in fluid
- Smaller size
  - Use of less materials (expensive superalloys)
  - Takes less space
- Modular design
  - Expandable to large power plants

Joining High-Temperature Alloys

For the compact heat exchangers, availability of materials determine the maximum operating temperatures, thus cycle efficiency. Currently, formable Ni-alloys such as Alloys 230, 625, 617, 740H, and 282 are the only option for heat exchangers operating above 700°C at high pressure differentials (>20 MPa). These alloys provide necessary **creep strength** and **high-temperature oxidation resistance** as well as high **ductility** to form thin sheet. Joining methods such as diffusion bonding and transient-liquid-phase (TLP) bonding are the most robust approaches for joining thin layers of sCO_2 compact heat exchangers with tight dimensional tolerances. **Goal of this work is to demonstrate the bondability of Alloy 230 using TLP bonding technique.**



Transient-Liquid-Phase Bonding

TLP bonding uses a coating on the joining surfaces, which acts as an interlayer between the joining surfaces and has a lower melting point than the two surfaces which are being joined. This lower melting point is achieved by adding an element which acts as a melting point depressant (MPD), such as B or P for joining Ni-base alloys. On heating up to the bonding temperature, the interlayer liquefies and the MPD diffuses into the base metal, lowering its melting point and resulting in the expansion of the liquid zone into the base alloy. Over time, this liquid zone homogenizes at the bonding temperature. As the diffusion of MPD into the base alloy continues, the liquid zone begins to isothermally solidify forming a monolithic microstructure between the two surfaces to be joined.

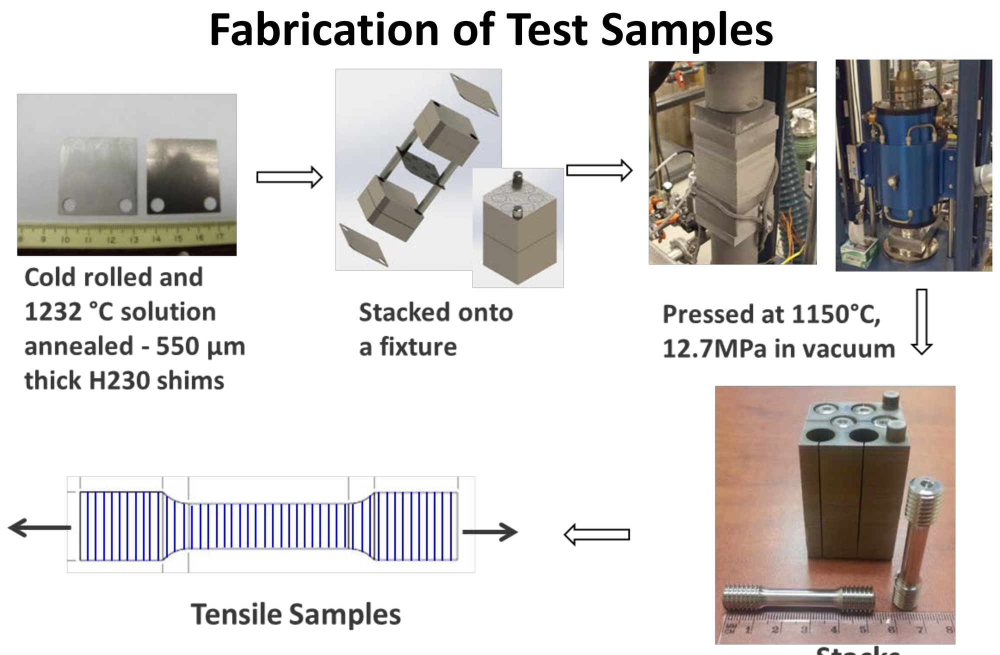
There is a knowledge gap on utilization of TLP bonding for high-temperature Ni alloys. This investigation intends to help narrowing that gap.

APPROACH

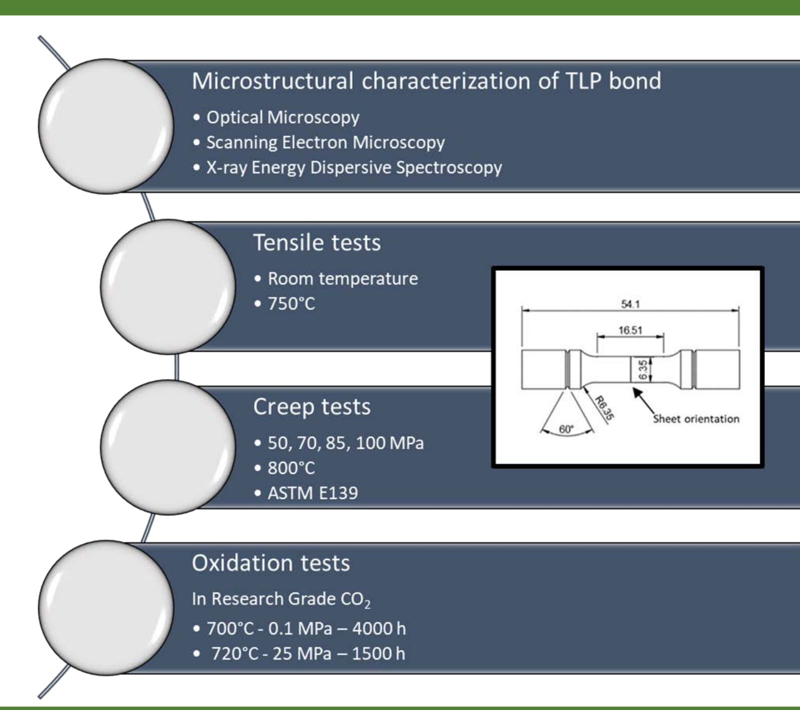
Alloy 230 was selected for this study for its superior resistance to grain growth at joining temperatures in addition to its creep and oxidation resistance. It is a solid solution strengthened Ni alloy with nominally 22Cr-14W-5Co-2Mo-3Fe (in weight %). Solution-treated Alloy 230 was received as a sheet with approximately 550 µm thickness.

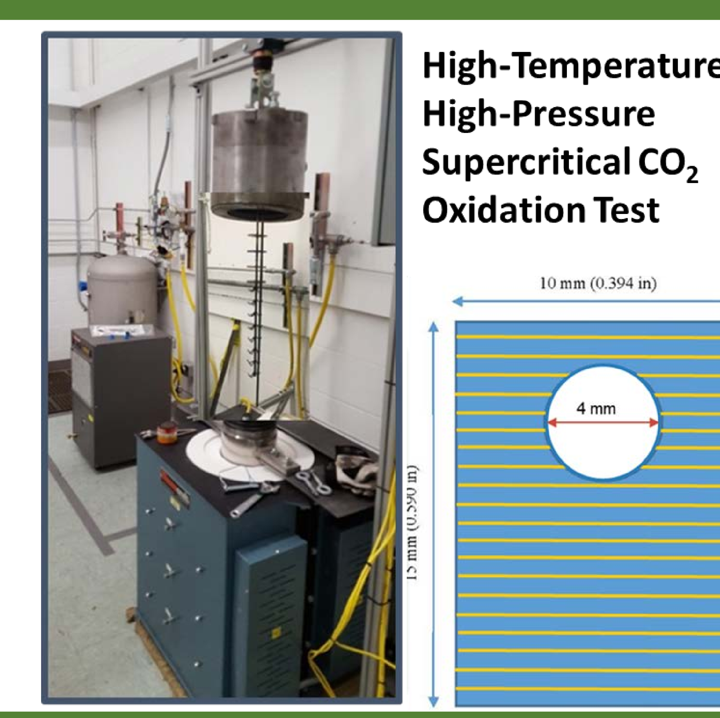
Two sets of Alloy 230 stacks were bonded (Set I and Set II). The square shims (2.25 in^2) were cut, cleaned, and plated (electroless) with a Ni-P alloy. The Ni-P plating alloy for Set I contained 12 mass percent P whereas that for Set II 6 mass percent.

Fabrication of Test Samples



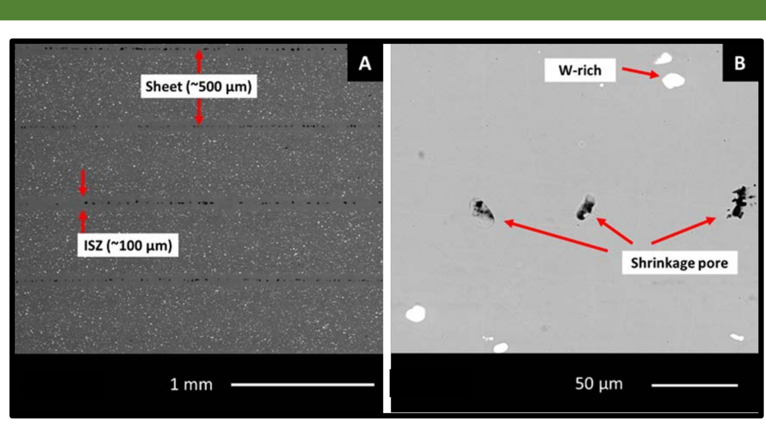
For both sets, the Alloy 230 sheets were bonded into stacks containing 100 shims. The stacks were bonded at 1150°C for 4 h (Set II) to 8 h (Set I) at 12.7 MPa pressure in a vacuum chamber. To mitigate the undesired effect of TLP bonding on the microstructure, a post-bonding heat treatment was applied to one stack of Set II. The treatment involved holding the bonded stacks for 1 hour at 1200°C followed by water quenching.



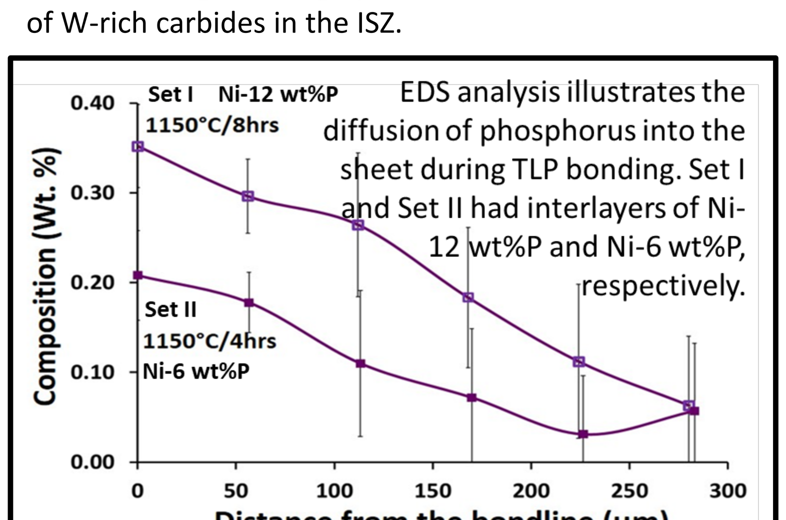


High-Temperature High-Pressure Supercritical CO_2 Oxidation Test

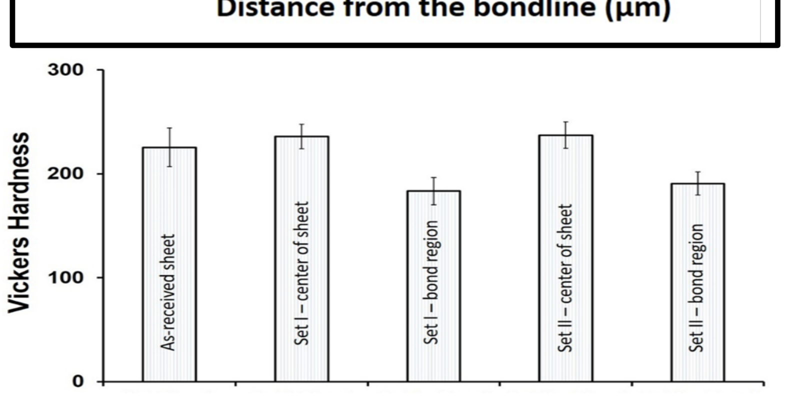
RESULTS

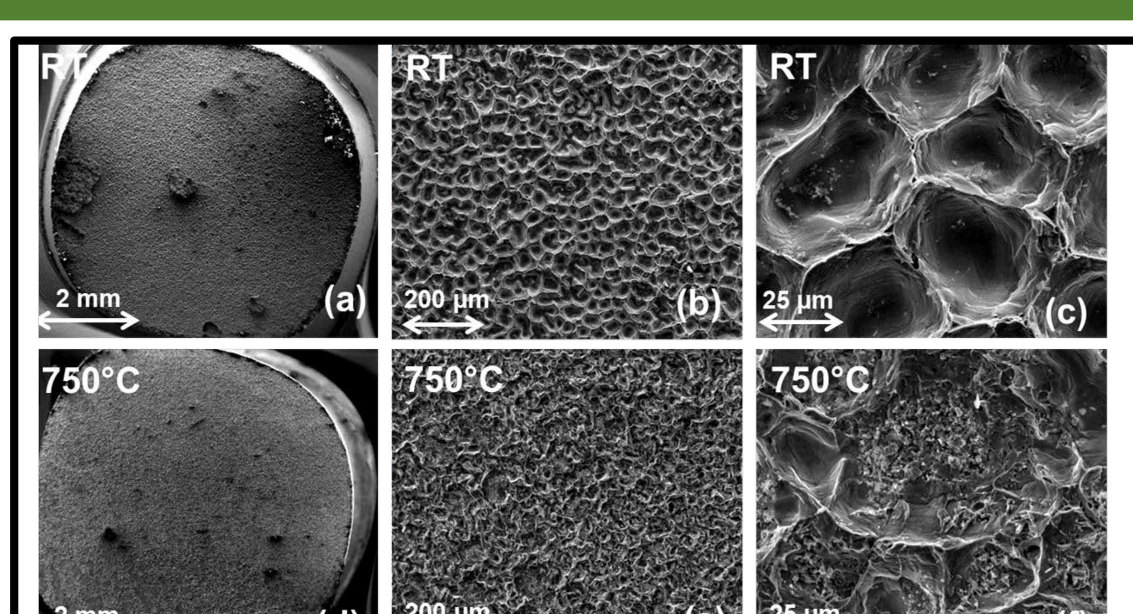


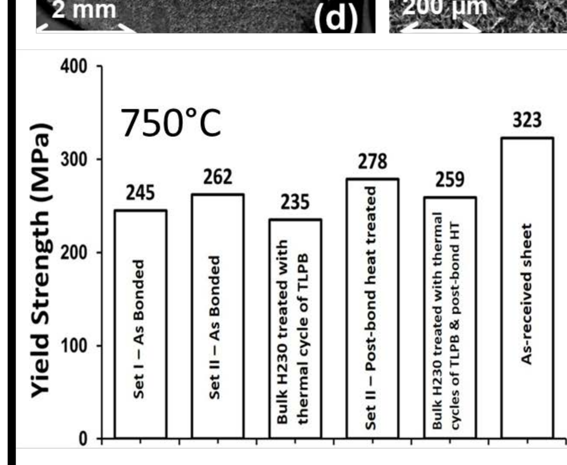
SEM back-scattered electron images showing a cross section of a TLP bonded H230 stack. In (A), three distinct regions are observed: (1) Joint centerline, (2) isothermally solidified zone (ISZ), and (3) base H230. In (B), a higher magnification image of the bondline and ISZ is showing shrinkage pores in the bondline and lack of W-rich carbides in the ISZ.



EDS analysis illustrates the diffusion of phosphorus into the sheet during TLP bonding. Set I and Set II had interlayers of Ni-12 wt%P and Ni-6 wt%P, respectively.

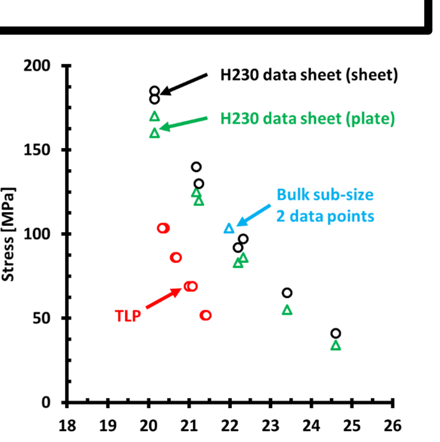


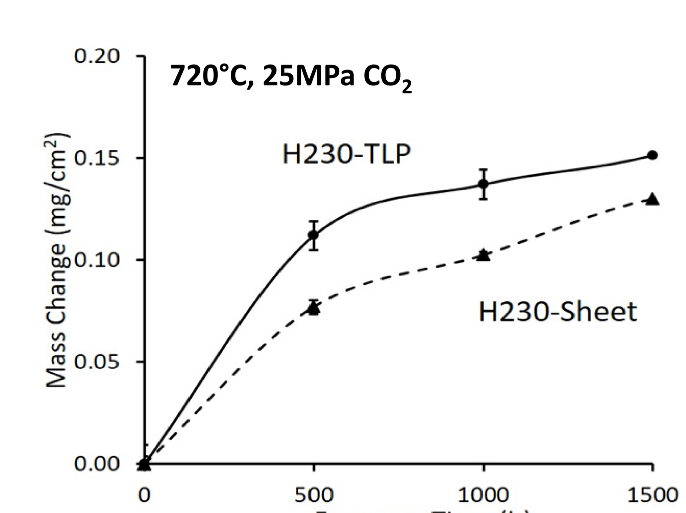


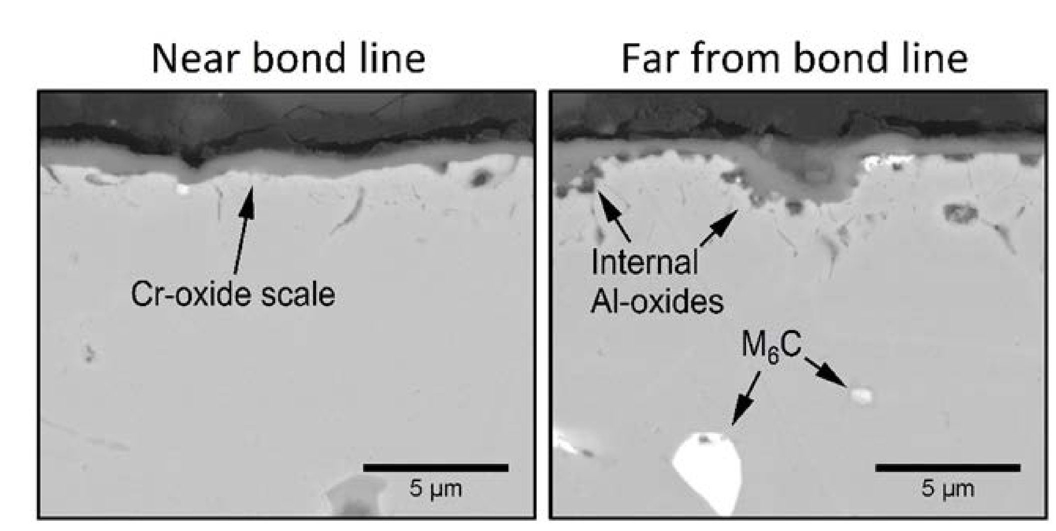


At both room temperature and 750°C, TLP bond strength was comparable to the bulk material. In all cases, tensile specimens failed in the ISZ. Although the failure was ductile in the microstructure level, the elongation measured was low (~1%). This was because the strain was localized in the thin layer of ISZ and was not transferred to the base metal. There was no second phases observed on the fracture surfaces.

Creep tested TLP specimens demonstrated 7-11% reduction in LMP compared to the bulk 230. Three specimens were tested at 85 MPa with LMP averaging 23338 with standard deviation of 18.4. Such a small standard deviation of LMP suggests good reproducibility of the TLP bond. Rupture elongation for these three specimens averaged 2.3%, with a standard deviation of 0.24 percentage points, also showing good reproducibility in the TLP bond.







The Alloy 230 monolithic coupons (H230-Sheet) showed mass gains which were less than that of the TLP bonded coupons (H230-TLP). The mass for both bonded and monolithic Alloy 230 increases fast during the first 500 h of exposure and slower during the rest of the exposure. Cross-section examination of the exposed TLP bonded coupons using back-scattered electron (BSE) imaging revealed a thin oxide scale on all of the coupons (Fig. 7). The scale was approximately 1-2 µm thick. A thicker scale was observed above carbide particles near the sample surface. No significant thickness variation was observed between the scale on the bond and the scale on the sheet.

SUMMARY AND ON-GOING WORK

- Although TLP bonded Alloy 230 showed yield strength comparable to the bulk Alloy 230 alloy, plastic strain localization in the bond region (ISZ) caused low tensile and creep elongation. This is shown to be a major challenge with the TLP bonding of Alloy 230.
- The strain localization was caused by slightly lower yield strength of the bond region originating from the lack of second phases. Carbon content of the ISZ (which was in equilibrium with the C content of the sheet matrix) was too low to precipitate new carbides.
- High-temperature oxidation behavior of TLP-bonded Alloy 230 was not significantly different from that of Alloy 230 sheet.
- Currently, NETL is working on improving the tensile elongation of joined Alloy 230. Diffusion bonding with and without Ni interlayer is being investigated in collaboration with Oregon State University. In addition, NETL is investigating diffusion bonding of another high-temperature Ni superalloy, IN 740H, in collaboration with Vacuum Process Engineering, Inc.

ACKNOWLEDGEMENTS

This work was performed in support of the U.S. Department of Energy's Fossil Energy Crosscutting Technology Research Program, Briggs White, NETL Technology Manager, Regis Conrad DOE-FE HQ Program Manager. The Research was executed through the NETL Research and Innovation Center's Advanced Alloy Development Field Work Proposal. Research performed by Leidos Research Support Team staff was conducted under the RSS contract 89243318CFE000003.

REFERENCES

1. Transient-Liquid-Phase Bonding of H230 Ni-Based Alloy Using Ni-P Interlayer: Microstructure and Mechanical Properties, M. Kapoor, Ö.N. Doğan, C.S. Carney, R.V. Saranam, P. McNeff, B.K. Paul, *Met. Mat. Trans. A* 48 (2017) 3343-3356.

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

2019 Crosscutting Annual Review Meeting
Pittsburgh, Pennsylvania April 9-11, 2019