Welding of ZrB_2-Based Ultra-High Temperature Ceramics

Cheol-Woon (CW) Kim
MO-SCI Corporation, Rolla, MO

Derek King, W.G. Fahrenholtz, and G.E. Hilmas
Missouri University of Science and Technology, Rolla, MO

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  - Old welding system at MO-SCI for filler studies
  - Current progress
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Plasma Arc Welding of Ultra-High Temperature Ceramics

D.S. King[1], G.E. Hilmas[1], W.G. Fahrenholtz[1], C.W. Kim[2]

[1] Missouri University of Science and Technology, Rolla, MO

[2] MO-SCI Corporation, Rolla, MO

STTR Phase II

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Project Overview

Research Goal: Develop an inert environment plasma arc welding (PAW) system and utilize it for fusion joining of ultra-high temperature ceramics

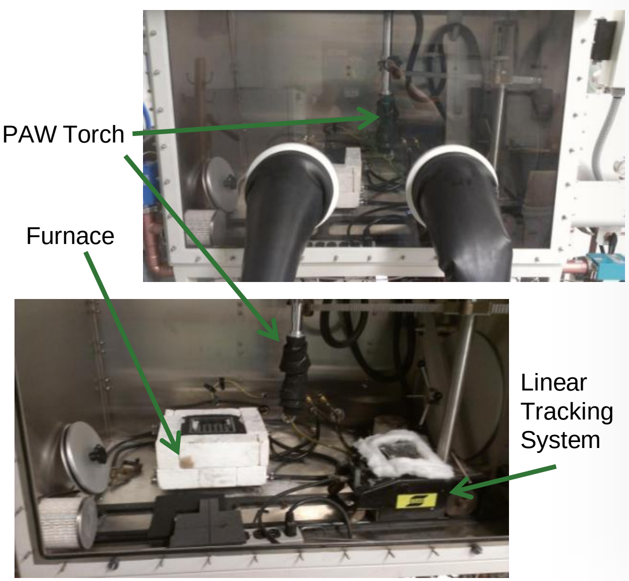
Current Status: Zirconium diboride (ZrB_2) has been successfully fusion bonded through PAW in an inert environment.

Research Challenges and Solutions

Oxidation

Problem: In an oxidizing environments, such as air, ZrB_2 will oxidize. During welding, oxidation can induce porosity in the melt fusion zone.

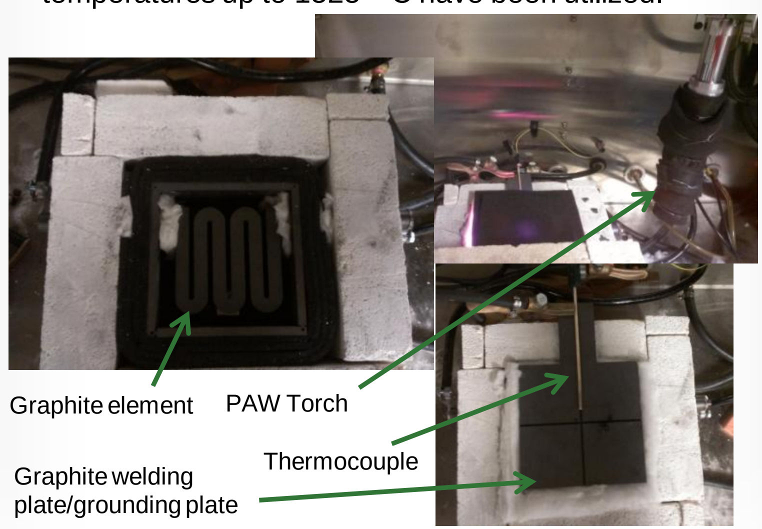
Solution: A glove box was modified with appropriate feed-through to act as an environmental chamber for arc welding of ZrB_2.



Thermal Shock

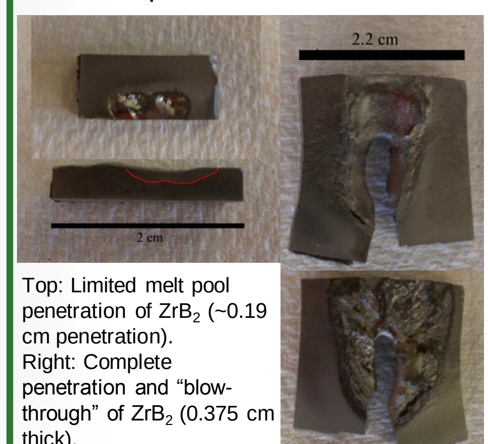
Problem: Metals have the ability to relieve thermal stress during welding due to their high fracture toughness and thermal conductivity values. ZrB_2 has a relatively low fracture toughness compared to metals, making it susceptible to thermal shock (ΔT_c=400° C). Welding can thermal shock ZrB_2 due to rapid heating when striking an arc.

Solution: A graphite element furnace is used to pre-heat ZrB_2 specimens for arc welding. Pre-heat temperatures up to 1525° C have been utilized.



Current Progress

- Arc welding of ZrB_2 has been performed under inert environments at elevated temperatures.
  - Linear tracker controls weld speed
  - Weld sequencer controls current ramps and welding current
- Penetration of melt pool can be varied from slight penetration to full penetration.



Top: Limited melt pool penetration of ZrB_2 (~0.19 cm penetration).
Right: Complete penetration and "blow-through" of ZrB_2 (0.375 cm thick).

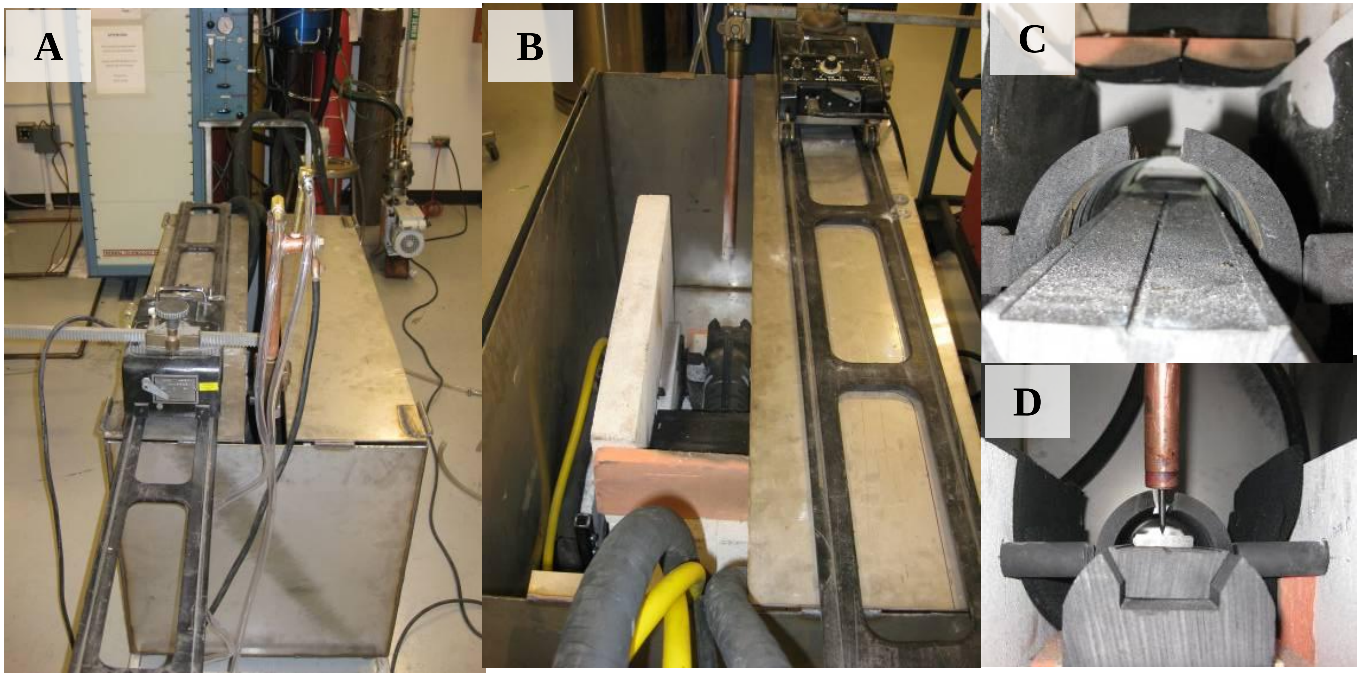
Background: Joining Methods and Needs

Increasing Temperature

- Common joining methods
  - Polymers and cements
  - Glassy interlayers
    Oxide and bulk metallic glass
  - Brazes
    Non reactive alloys
    Reactive
  - SHS joining
  - Mechanical fixtures
  - Diffusion Bonding
  - Plasma deposition
  - Fusion welding
    E-beam, GTAW, plasma arc

- Considerations for TPS joining methods
  - Oxidation of joint and structure
  - Elevated temperature properties
  - CTE of parts
  - Manufacturability

Phase I: Preheating and Welding Setup

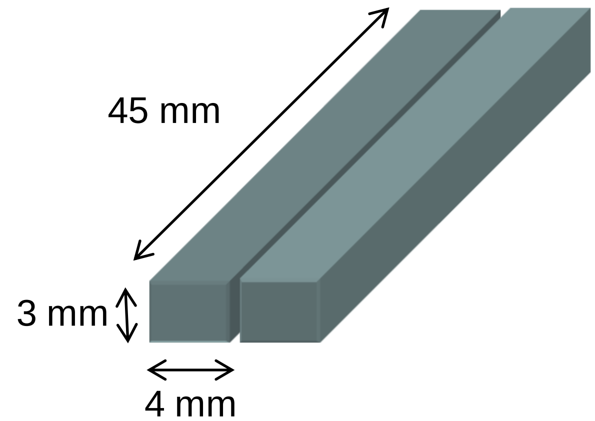


- **Welding chamber (A)**
  - **304 SS with graphite welding table**
  - **Split lid to contain Ar gas**
- **Preheating chamber (C)**
  - **5 mm x up to 205 mm long specimens**
  - **Preheat up to 1700°C**
- **Linear tracker (A & B)**
  - **Moves water cooled copper stinger**
  - **2 to 250 cm/min**
- **Water cooled copper welding stinger (D)**
  - **Holds 6.35 mm tungsten electrode**

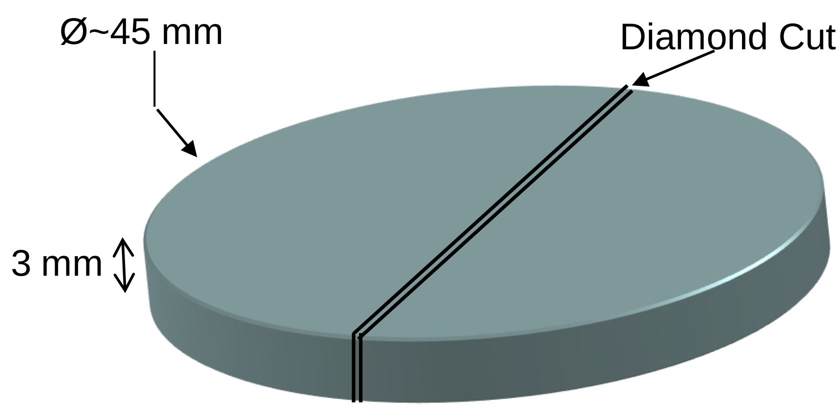
Phase I: Weld Specimens

- **Compositions**
  - **ZrB_2 + 20 vol% SiC (Z20S)**
  - **ZrB_2-SiC-B_4C (ZSB)**
- **Bars were cut and ground to size and then butt welded**
- **Disks were sectioned**
  - **Diamond saw**
  - **Cleaned and chamfered**
- **Welding methods**
  - **Gas tungsten arc welding (GTAW)**
  - **Plasma arc welding (PAW)**

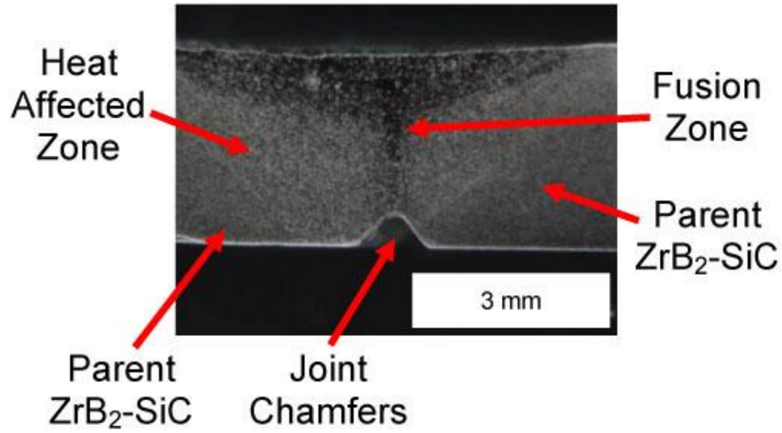
Butt Welded Bars



Butt Welded Discs

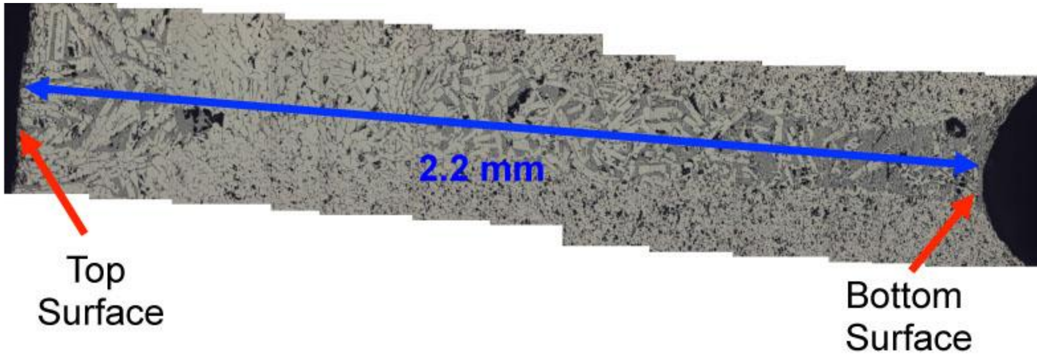


Phase I: GTAW Weld Pool Microstructure



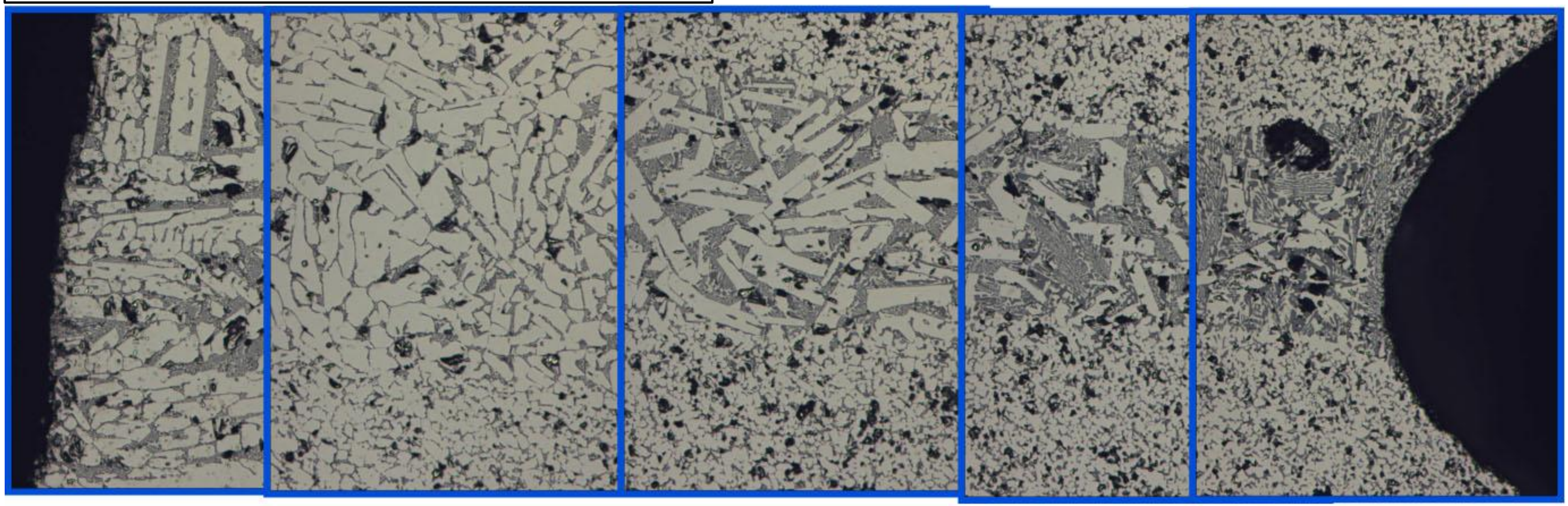
Welds have similar features to metal welds

- **Heat affected zone (HAZ)**
- **Fusion zone (FZ)**



Stitched SEM images of the weld show ZrB_2 (bright phase) and SiC (gray phase):

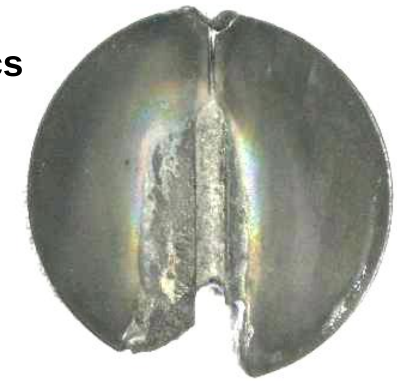
- **SiC appears to be partially depleted in HAZ**
- **Some porosity is visible**



Phase I: Summary of Results

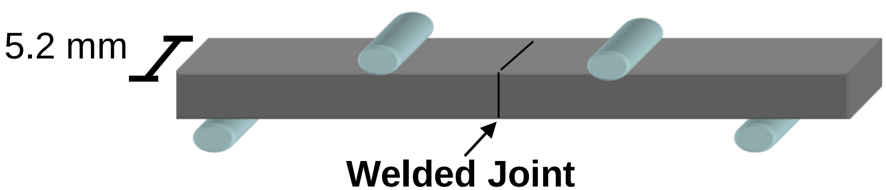

Z20S Ceramics

- **Thermal stresses can lead to cracking**
  - **Controlled by sample pre- & post-heating**

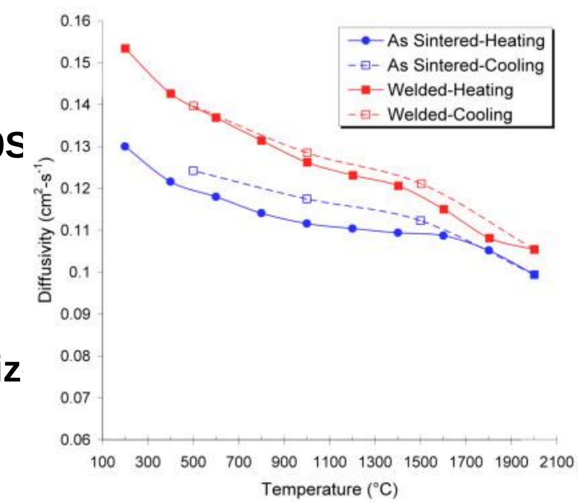
ZSB Ceramics

- **Full penetration welds, without thermal cracking, were achieved with the correct heating/welding conditions**



- **Mechanical properties of the welded joint are controlled by residual stresses and porosity**
  - **<200 MPa for joined specimens compared to ~800 MPa for Z20S**
  - **Void formation at the HAZ-parent material interface**

- **Thermal diffusivity increases after welding**
  - **0.13 cm^2/s at 200° C for Z20S**
  - **0.155 cm^2/s at after welding**
- **Welding alters ceramic**
  - **Larger grain siz**
  - **SiC polytype changes 6H to 3C**



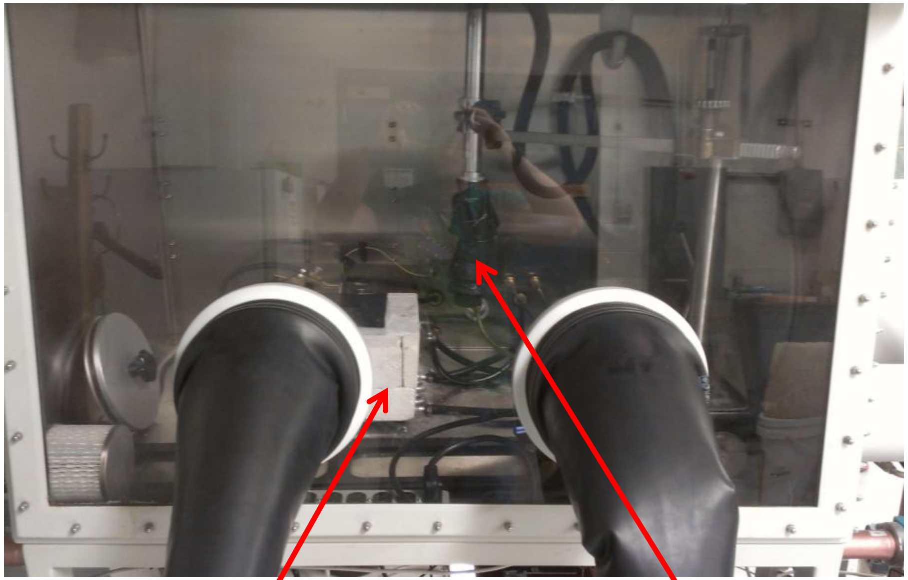
Phase II: Objectives

- Develop second generation ceramic welding unit for technology transfer from Missouri S&T to MO-SCI
- Develop novel strategies to remove fusion weld discontinuities in UHTCs
- Complete macrostructure and microstructure characterization of welded UHTCs
- Measure thermo-mechanical and thermo-physical behavior and relate microstructural and macrostructure features to specific material response including fracture resistance, thermal management, and oxidation behavior of UHTCs
- Test a series of welded structures in an inductively coupled plasma heater facility (Prof. Fletcher – Univ. of Vermont) to better understand if UHTC weldments can withstand the aggressive thermal and oxidative environment associated with hypersonic flight

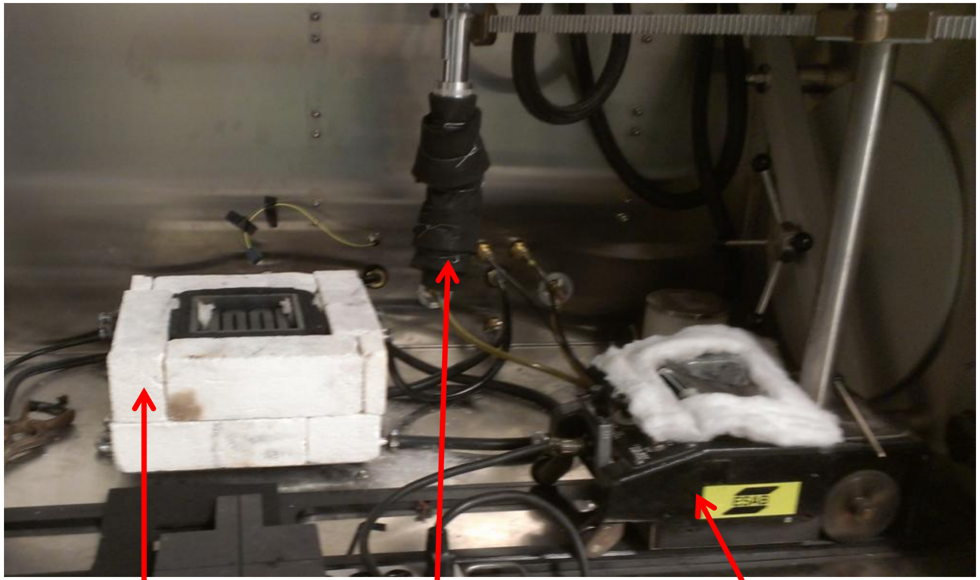
Phase II: Inert Environment Chamber

- **An M-Braun Glovebox was modified to hold the necessary tools for performing plasma-arc welding of UHTC's**
- **Chamber holds pre-heating furnace, PAW torch, and linear tracking system**

Glovebox with front panel



Glovebox without front panel



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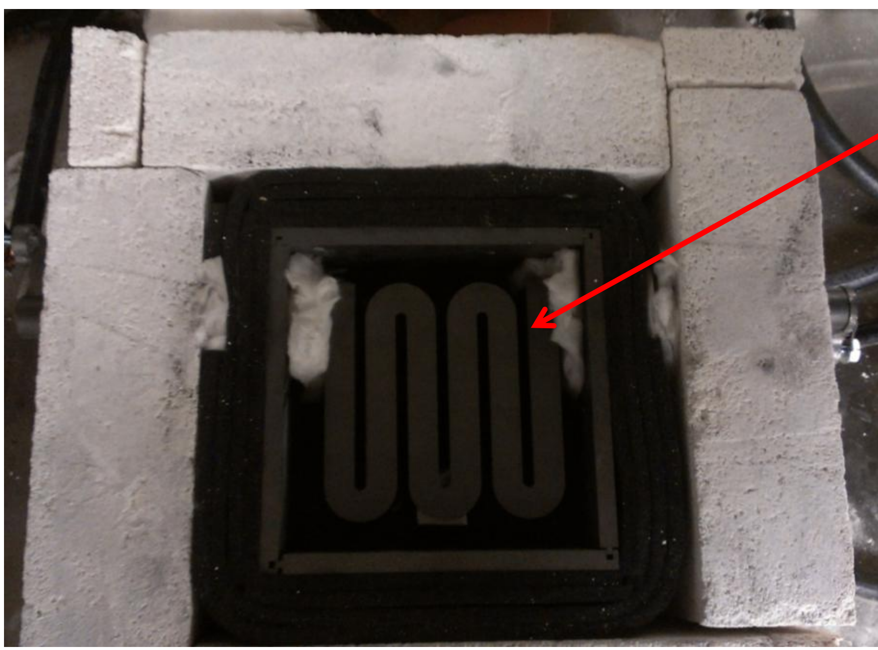
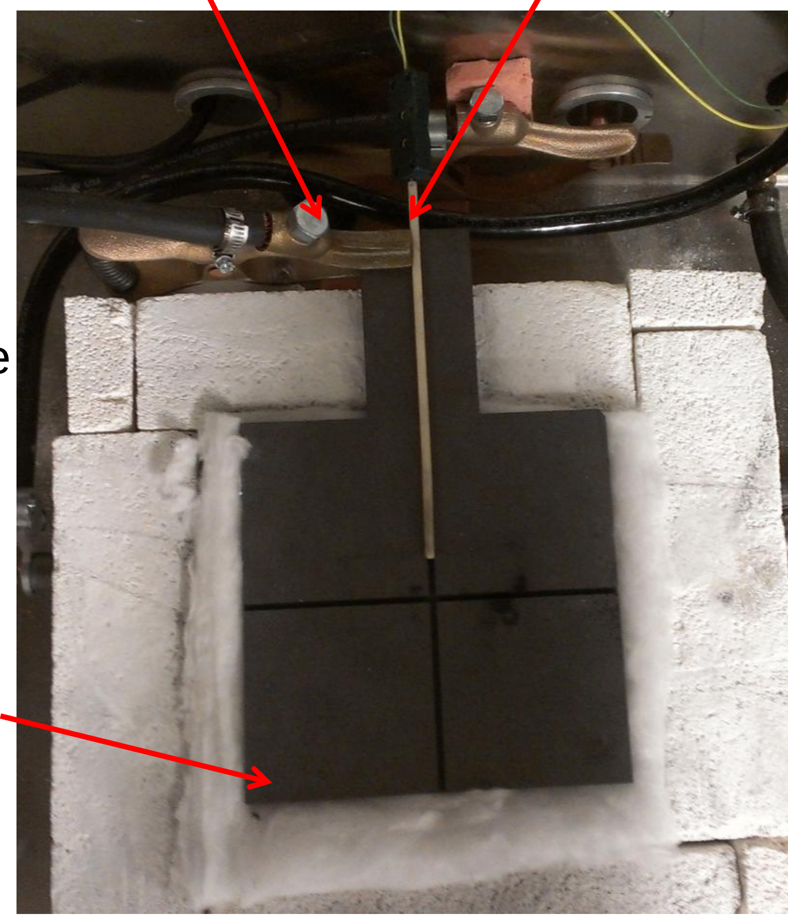
Phase II: Pre-heating Furnace

- **Graphite element furnace**
  - **Pre-heat temperatures of 1550°C**
  - **4x4" hot zone**
  - **Controlled ramp up and cool down**
  - **Graphite lid for welding ground**



Graphite element



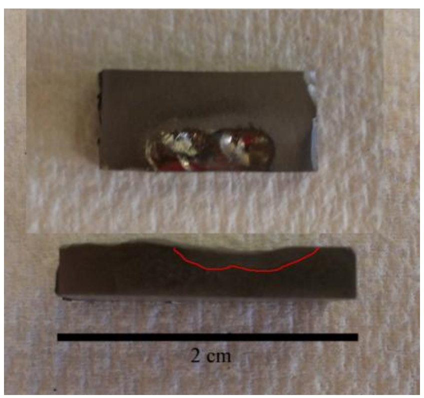
Type B thermocouple

Welding ground

Graphite welding plate

Phase II: Welding of ZrB_2

- ZrB_2 base was pre-heated to 1450°C or higher
- Varying penetration achieved
- High thermal stresses due to high melting point of ZrB_2
  - >3000°C
  - Cracking and warping have been observed



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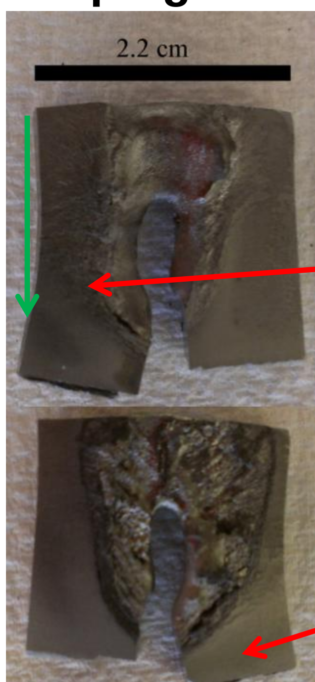
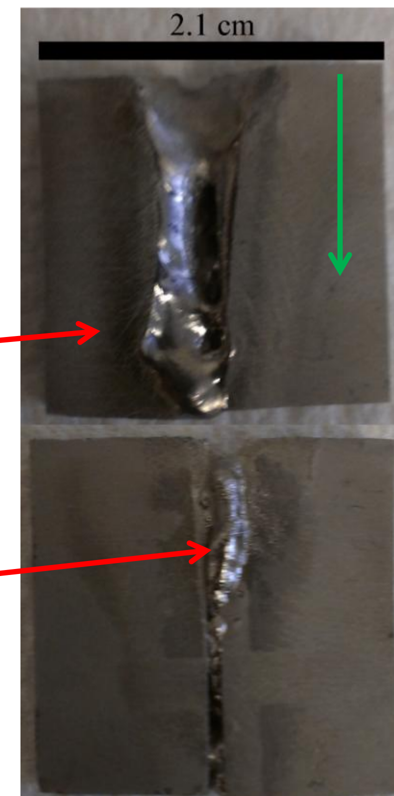


Weld direction indicated by green arrows

Cracking along weld due to high thermal stresses

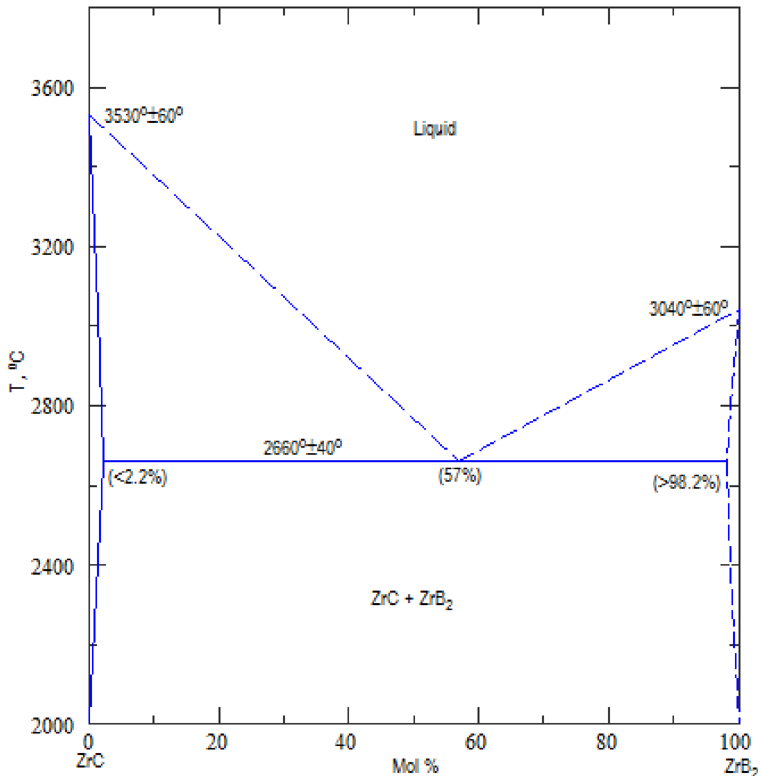
Full penetration of joint

Thermal warping of ZrB_2



Phase II: Diboride-Carbide Eutectics

- Diboride-Carbide eutectics have lower melting temperatures than the pure diboride
- Decreases thermal gradient
- Possible compositions
  - ZrB_2-ZrC, T_M=2660°C
  - TiB_2-TiC, T_M=2520°C
  - ZrB_2-SiC, T_M=2270°C
  - TiB_2-SiC, T_M=2190°C



Phase II: Reactive Filler Production

- Candidate fillers:

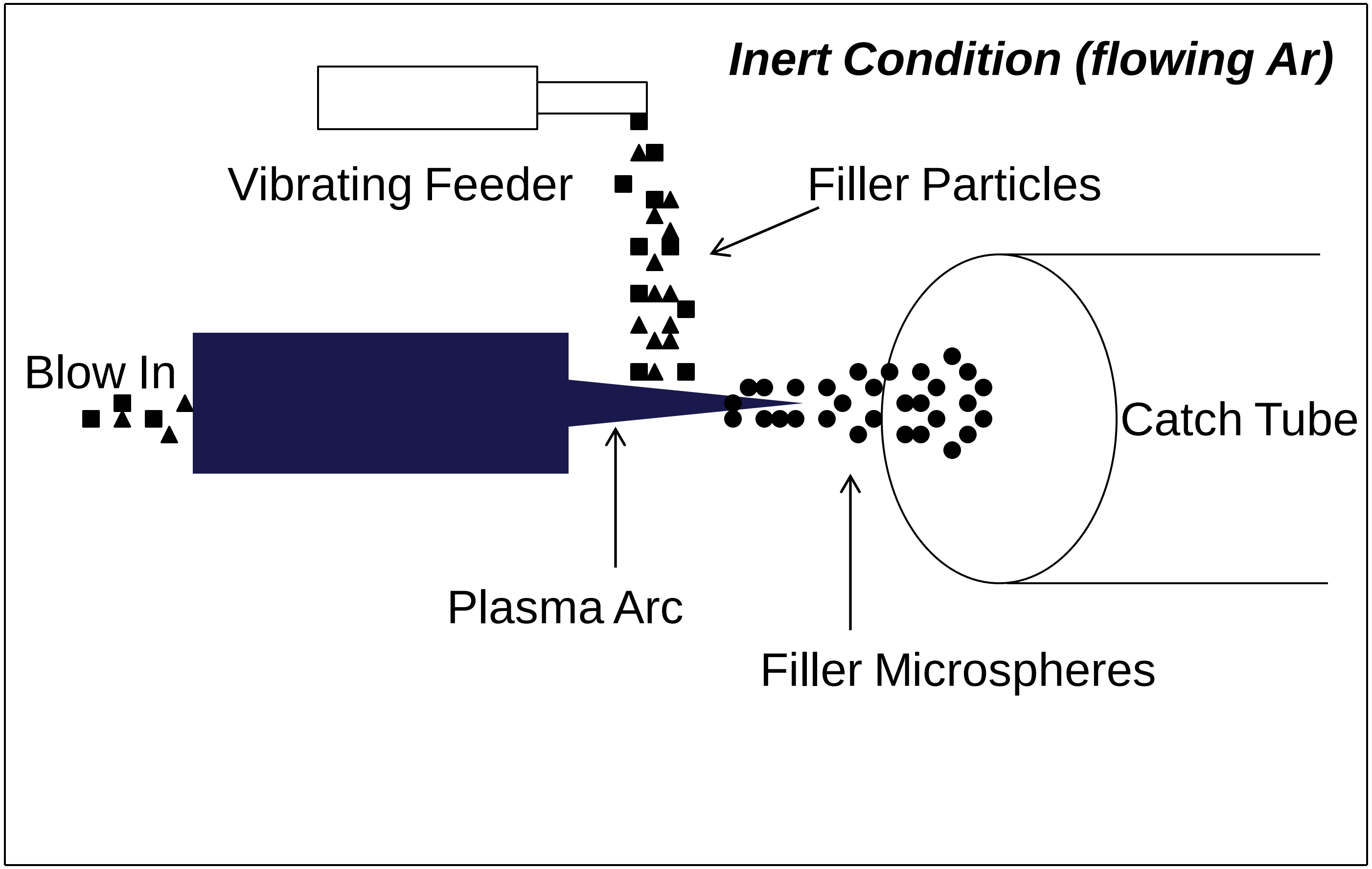
  Reactive: High purity SiB_6, ZrC, Zr → ZrB_2-20 v/o SiC

  Excess reactive: Mg- or Zr-alloys → MgO or ZrO_2 precipitates (i.e., deoxidize)

- Form: microspheres → easy to apply through the PAW system
- Size: <75 microns
- Plasma arc "Spheridization" using "old welding system"

Phase II: Reactive Filler Production-cont.

- **Ultra high temperature (>3000°C) spheridization system**



Summary

- **Phase I (Completed)**
  - **ZrB_2-based ceramics up to 3 mm thick were joined by fusion welding**
  - **Joint microstructures varied through the part**
  - **Joint strengths (<200 Mpa) were lower than the parent materials (800 MPa), likely due to void formation**
  - **Thermal conductivity of joints was higher than parent material**
- **Phase II (In progress)**
  - **Second generation ceramic welding unit designed and built at MS&T**
  - **Welding technology being transferred from MS&T to MO-SCI**
  - **MS&T welding ZrB_2-based UHTCs with efforts focused on eliminating porosity in the welds and obtaining full weld penetration**
  - **MO-SCI developing technologies for filler materials to add to the PAW systems at both MS&T and MO-SCI**