Advanced Method of Joining RAFM/ODS Steels for Fusion Reactors

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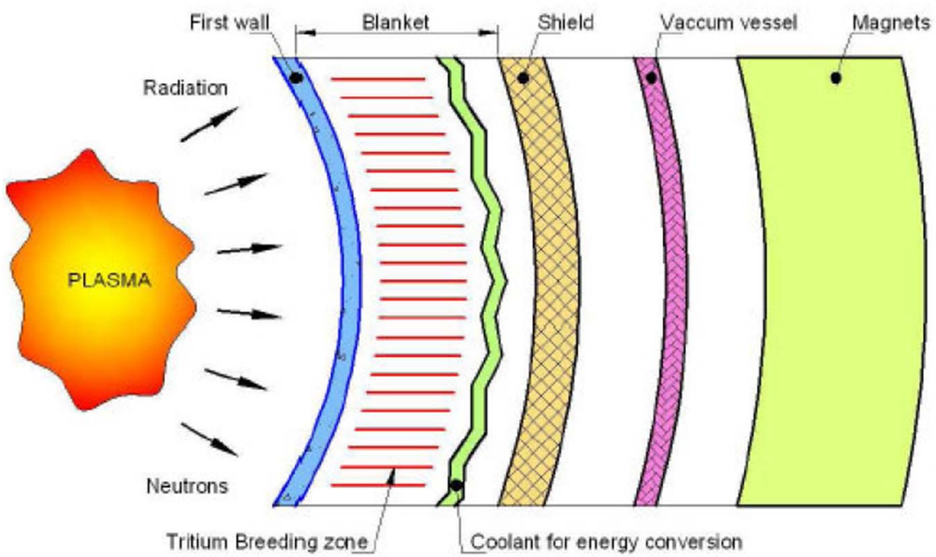
Structural Materials for Fusion Reactors



Schematic View of the Arrangement of Materials
Journal of Physics: Conference Series **208** (2010) 012001.

Issue: Long-Term Exposure to a Hostile Environment

- high temperatures
- reactive chemicals
- high stresses
- intense damaging radiation

Materials (to be developed for the Tokamaks)

- steels for the first wall and other structural parts
- copper alloys for the heat sink
- beryllium for facing the plasma

F82H (7.46% Cr, 1.96% W, 0.21% Mn, 0.15% V, 0.10% Si, 0.09% C, 0.023% Ta, bal. Fe, wt.%)
EUROFER97 (8.9% Cr, 1.1% W, 0.47% Mn, 0.2% V, 0.14% Ta, 0.11% C, bal. Fe, wt.%)

Low Activation Elements

- C, Si, Ti, Fe, Cr, V

High Activation Elements

- Al, Ni, Ag, Co, Nb

Candidate for Structural Materials

RAFM (reduced activation ferritic/martensitic) steels

- e.g. F82H, EUROFER97
- temperature window = 350~550°C

ODS (oxide dispersion strengthened) ferritic steels

- temperatures up to 800°C

Methods of Joining/Welding

Challenges

- The metals and joints must withstand intense radiation, neutron damage, etc.
- Martensitic steels become brittle upon conventional welding and need a variety of heat treatments to restore properties.
- The conventional (or even laser gas assisted processes) create molten metal which effectively destroys the oxides in ODS steels.
- Copper-beryllium joining

Need for Advanced Joining Methods

- Should handle large and complex geometry
- Non-conventional (non-fusion) type of joining/welding technique
- Retaining the original metal characteristics after joining

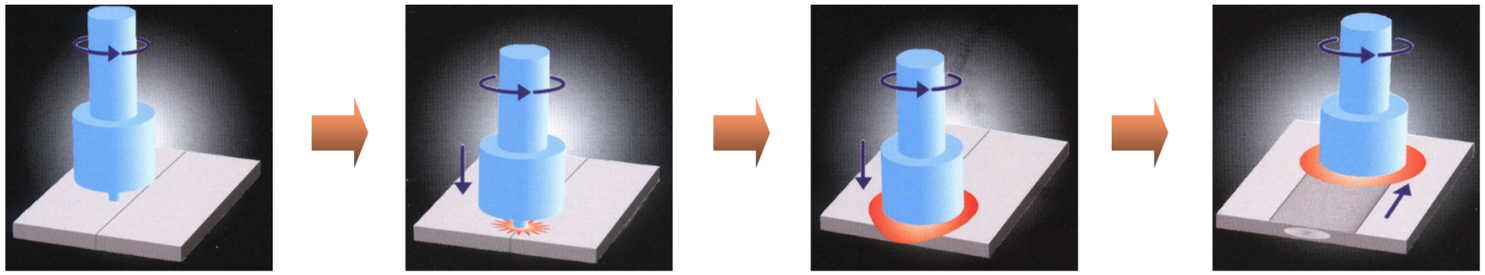
Electron Beam Welding (EBW)

- Well established technology
- Expensive and complicated equipment
- Need vacuum processing

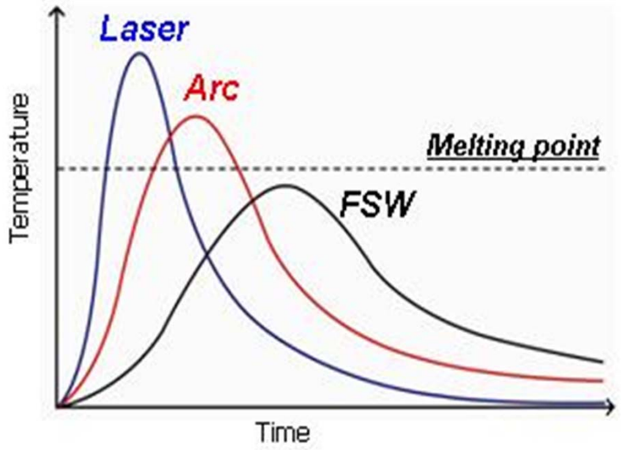
Friction Stir Welding (FSW)

- Developed over the last twenty years
- Growing rapidly in high volume applications for joining aluminum and its alloys

Friction Stir Welding (FSW)



1. Rotating tool prior to penetration
2. Contact of the tool pin, creating heat
3. Shoulder contact, expanding hot zone
4. Part moves under the tool, creating FSW nugget



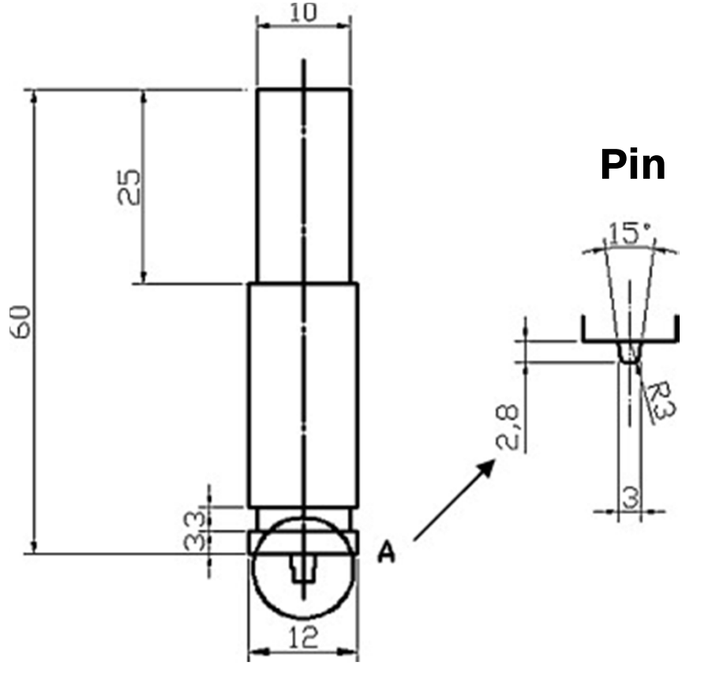
Principle of FSW

1. A rotating tool containing a pin and a shoulder is plunged into the joint between two work pieces, generating heat by friction
2. Once the heat is built up to the desired level, the tool is translated along the joint
3. Plasticized (but not melted) base material passes around the tool, where it is consolidated due to force applied by the shoulder of the tool.

Features of FSW

- ❖ Solid-state joining process
- ❖ Problems associated with cooling from the liquid-phase joining methods are avoided.
- ❖ Current industrial applications are limited to aluminum and low melting-temperature alloys.
- ❖ Tool materials must be stronger and thermally/chemically more stable than the joining materials.

FSW Tool Materials



Example of FSW Tool and Pin
J. of Mater. Proc. Tech. **210** (2010) 1667–1672.

Joining Materials (Melting Point)	FSW Tool Materials
Aluminum/alloys (~650°C)	Alloy Steels
Copper/alloys (~1100°C)	Alloy Steels, W-alloys
Carbon Steels (~1400°C)	Tungsten Carbide (WC)
Alloy Steels (~1400°C)	PCBN*
Titanium/alloys (~1700°C)	N/A

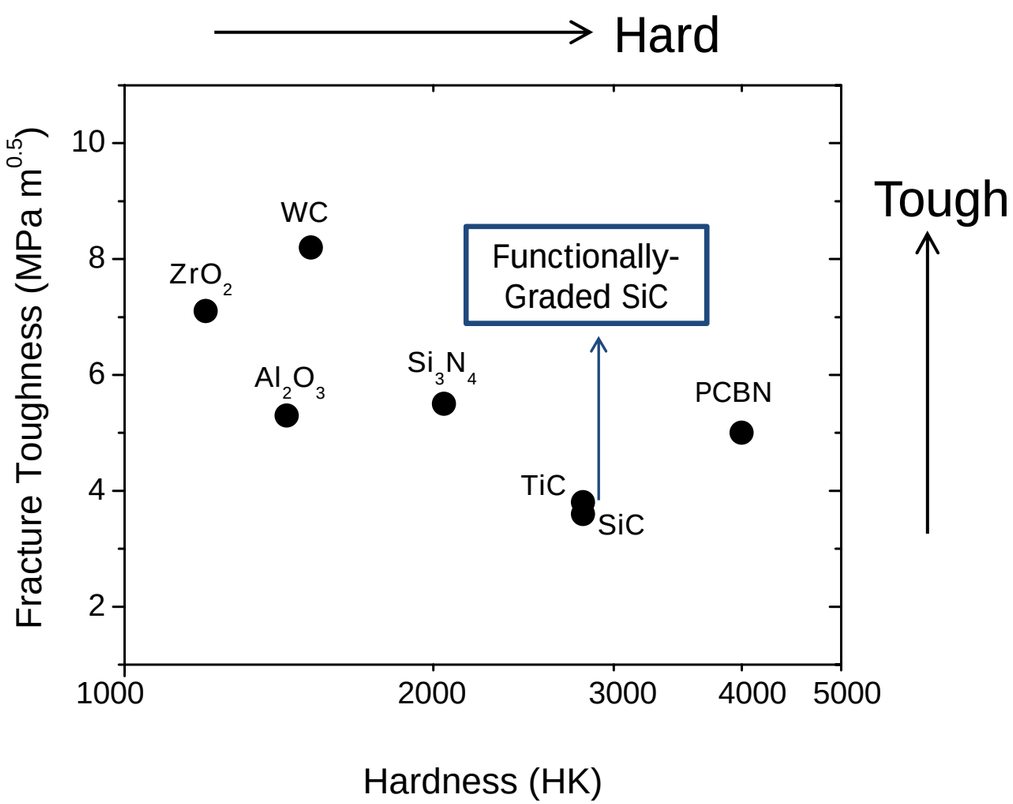
* PCBN = polycrystalline cubic boron nitride

- ❑ Wear of tools is not an issues in FSW of Al alloys.
- ❑ Wear of tools is a serious problem in FSW of steels and Ti alloys.
- ❑ No systematic studies have been reported.

Tool (Pin) Material for FSW of Alloy Steels

- ✓ Must have sufficiently high hardness and fracture toughness.
- ✓ Must be thermally and chemically stable.
- ✓ Ceramic materials are ideal.

Ceramic Tool (Pin) Material for FSW



PCBN (polycrystalline cubic boron nitride)

- ❖ Excellent hardness (next to diamond)
- ❖ Not enough fracture toughness
- ❖ Very expensive (~$10,000/pin)

WC (tungsten carbide)

- ❖ High fracture toughness
- ❖ Poor hardness (wear)

SiC (silicon carbide)

- ❖ High hardness
- ❖ Low fracture toughness

FG-SiC (functionally-graded silicon carbide)

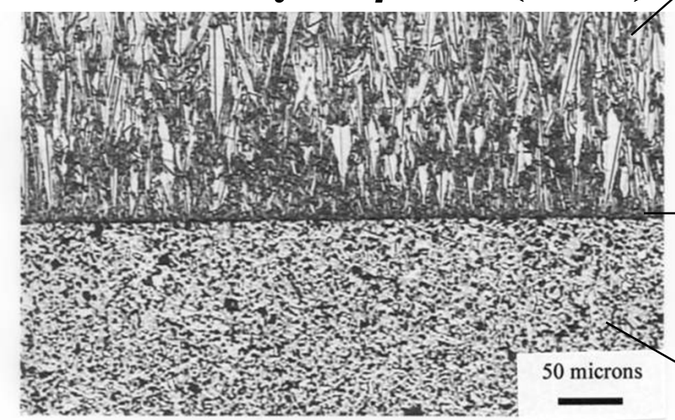
- ❖ High hardness
- ❖ Enhanced fracture toughness

Fracture toughness can be significantly enhanced by engineered microstructure.

- o Two-phase particulate composite (e.g. dispersion of TiC or TiB_2 into SiC matrix)
- o *In situ* toughening (e.g. large α-SiC platelets in a matrix of fine α-SiC grains)

Functionally-Graded SiC

Surface Layer: β-SiC (CVD)



Substrate: α-SiC+TiB_2(15%)

Surface Layer: *In situ* toughening
- Large SiC platelets in a matrix of fine SiC grains
- Using additives of Al, B, and C
- Increasing fracture toughness by "crack bridging"

Interface between Substrate and Surface Layer
- Thermal contraction mismatch
- High residual surface compression
- Enhanced Mechanical Properties

Substrate: Two-phase particulate composite
- Dispersion of TiC or TiB_2 into SiC matrix
- Thermal expansion: TiC or TiB_2 > SiC
- Debonding of the interface
- Increasing fracture toughness by "crack deflection"

(Ex.)

Ceramic	Fracture Toughness ($MPa \cdot m^{1/2}$)
α-SiC	2.41
CVD-β-SiC	2.98
SiC-30v% TiC	3.81
β-SiC coating on SiC-15 v% TiB_2	6.40

(This work was done at MSRI under the NSF Grant DMI-9800946)

Project Description and Work Plan

Contract No: W911QX-11-C-0014
Phase-I from June 2011 through March 2012

Goal

Develop a ceramic tool (pin) for FSW of alloy steels, specifically focusing on RAFM/ODS steels

Approach/Tasks of Phase-I

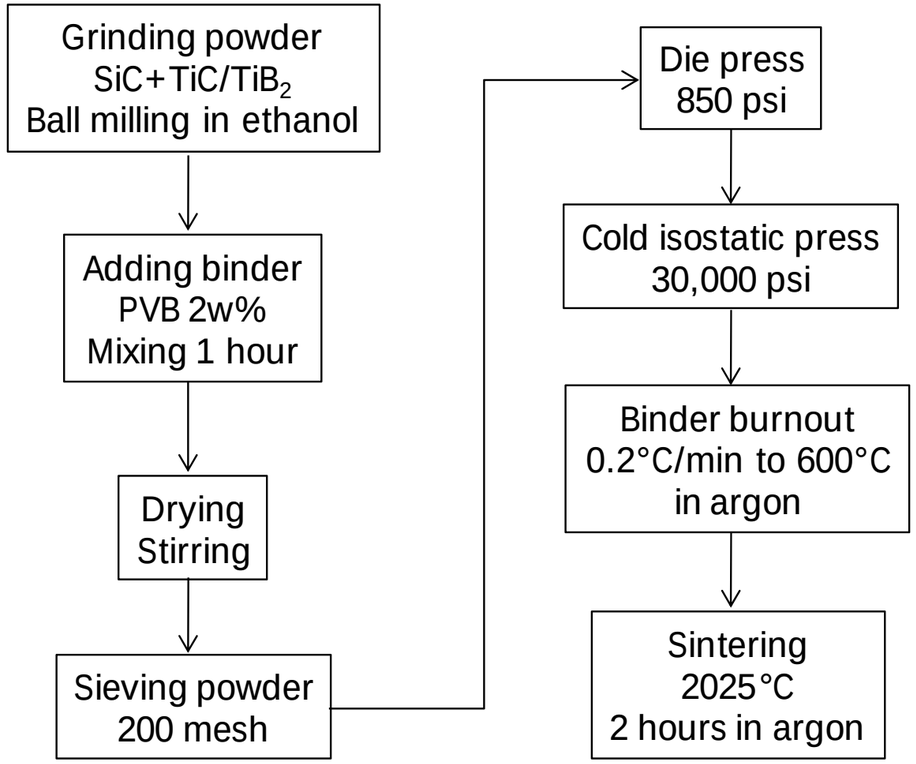
- ❑ Fabrication of functionally-graded silicon carbide tools
- ❑ Characterization of the tool material
- ❑ Demonstration testing of the fabricated tools

Fabrication Process

- ❑ Cold isostatic (CIP) pressing followed by CVD
- ❑ Co-sintering (cost-effective)

Collaboration

- ❑ University of Utah
- ❑ Welding Test Expert (e.g. EWI)
- ❑ FSW Tool Manufacturer



CIP Process for $SiC+TiC/TiB_2$ Substrate

Materials & Systems Research, Inc. (MSRI)

- Founded in 1990
- Currently 12 employees including 6 PhDs
- 10,000 sq. ft. research facility in Salt Lake City, Utah

MSRI's Major Areas of R&D

<u>Ceramic Materials & Processing</u>

- Structural ceramics
- Optical materials
- Beta-alumina (fast ion conductor)

<u>Energy</u>

- High-temperature electrolysis for H_2 production
- Batteries, fuel cells, thermoelectric converter
- Zirconia thermal storage
- Fusion reactors

<u>Sensors</u>

- High-temperature gas sensors
- High-temperature pressure & temperature sensors