Combustion Joining for Composite Fabrication

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Joining Using Heterogeneous Combustion Systems

• Thermite Reactions
  – Used mostly to produce steels and copper alloys
  – Common example: Joining railway tracks

• High-Temperature Synthesis Reactions (Combustion Synthesis)
  – Similar and dissimilar materials
  – Refractory alloys, intermetallics, ceramics, etc.
Motivation

• Refurbishing of components
e.g., carbon brakes (Honeywell Aerospace)
  – Carbon-carbon (C-C) composites have low
density, high strength-to-weight ratio, and
withstand high temperatures

• Development of functionally graded
  materials
e.g., composite armor
• Honeywell Corp (South Bend, IN)
• Currently build aircraft brake disks from carbon fibers
• use a long (~ 100 day) CVD process to densify
• Brake wear/oxidation with every landing

A380 -rejected take off test
Joining C-Based Materials

• Difficult task
  – Carbon cannot be welded ($T_{mp} \sim 3800$ K)
  – Little or no wetting with conventional braze or solder compositions

• Mechanical or adhesive means – limited application

• Solid-state bonding takes a long time at high temperatures

• Chemical joining in liquid state – attainable with combustion reactions

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Self-Sustained High-Temperature Reactions

Characteristic Features:
- High temperatures (> 2000 K)
- High temperature gradients (10^3-10^6 K/s)
- Short reaction times (0.1-10 s)
- Low energy consumption
- Simple equipment

Example:
\[ \text{Ti} + \text{C} \rightarrow \text{TiC} + 230 \text{ kJ/mol} \]
\[ T_{ad} = 3200 \text{ °C} \]

- Carbides, Borides, Nitrides
- Intermetallic Compounds
- Alloys
- Ceramics
- Functionally Graded Materials
Modes of Combustion Synthesis

Self-Propagating High-Temperature Synthesis (SHS)

Volume Combustion Synthesis (VCS)
Initiation Methods

• SHS Joining
  – Advantages: No additional energy to propagate reaction
  – Disadvantage: Finite rate of reaction

• VCS Joining
  – Advantages: Uniform combustion and distribution of temperature
  – Disadvantage: Relatively slow process
VCS Joining

- Relatively slow preheating (up to $10^2$ K/min)
  - Solid state reactions could impact final composition/gradients
  - Limiting case: reactive sintering
- Materials to be joined also heated to $T_{ig}$ (not just the reactive media)
- For most systems, $T_{ig} \sim T_{mp}$ of least refractory component (eutectic temperature)
  - Could be difficult to reach for refractory reagents
Reactive Resistance Joining

Place a thin layer of desired reaction composition between two disks of the material to be welded.

Preheat to the ignition temperature.

After initiation, a rapid (up to $10^4$ K/s) high temperature (up to 3000 K) reaction occurs in a thin layer in the vicinity of the joint → leads to chemical interaction between the melt and disks to be joined.

A rapid press allows instant loading of the stack: enhancing the mechanical properties of the joint.
System for Rapid Joining of C-C Composites

- Max. Current: 950 A
- Max Voltage: 44 V
- Max Load: 35,000 N
- Press Response Time: 10 ms
Press Die Design and Construction

Reaction zone is observable: can measure temp.!
Frames of a Joining Process

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Typical Temperature Profile of Joining Process

I = 600 Amps
D = 10 mm

Joule preheating only up to $T_{ig}$

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• C-C composite highly reactive – don’t need carbon in joining layer (Ti foil, Ti powder, Ti + 8wt% Ni, Ti + B, 3Ti + B + C)

• Don’t need highest current

• Applied pressure affects composite properties

• Final layer thickness independent of initial media thickness

TS of samples joined w/ Ti+8 wt% Ni
Final join structure

**Final product layer independent of initial layer**

- Ti powder: $h_i = 3000 \, \mu m$
- Ti foil: $h_i = 25 \, \mu m$

characteristic squeezing rate is much higher than the characteristic diffusion time of C into Ti, the thickness of the final joining layer is essentially independent of $h_o$.  

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“The three-quarter-ton armor that gets plated onto the humvees, for example, limits its carrying ability and puts additional strain on the transmission, according to service officials... “

http://www.defensetech.org/archives/001349.html
Conductivity of stack too low; pass current through graphite to preheat

Sample Configuration

Disks of SiC / reaction layer / Al 5083 alloy

Reaction layer = Ti; Ti+C, Ti-Al gradient

Thermo calcs: Ti + SiC → TiC, TiSi_{x}, possible reaction temperature > Al_{mp}, close to Ti_{mp}, < SiC_{mp} (3100K).

This design does not allow for compaction during reaction

different die design now being used

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(i) Reaction starts at melting point of Al (~ 932K).
(ii) Ti layer reacts with Al-alloy, elevating temperature (~2000K) in the boundary layer
2mm Ti+C rxn disk

Ti confined to region ~3 μm wide near interface
Summary

• Combustion Joining of refractory materials has great potential for low cost, rapid fabrication of composites, esp. for some materials that are difficult or impossible to join using more conventional techniques:

• Rapid combustion reactions provide a unique set of conditions for synthesizing functionally graded layers:
  – short reaction times (~1–10 s) allow the desired functionally graded material structure to be maintained

• Demonstrated the concept for joining of SiC-Al-alloy using a combustion-based approach

• Need to determine optimum reaction layer composition and heat-treatment conditions to form various phases:
  - Ti$_3$SiC$_2$ (ductile), Si(Al)CO, TiC-SiC-Al

• New press set-up /die design implemented to produce optimized materials for sub-scale ballistic tests