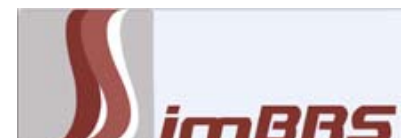




Combustion Joining for Composite Fabrication

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Report Documentation Page			Form Approved OMB No. 0704-0188		
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1. REPORT DATE 25 OCT 2009		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Combustion Joining for Composite Fabrication			5a. CONTRACT NUMBER W56 HZV-08-C-0236 (SimBRS)		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Paul McGinn; Ya-Cheng Lin; Alex Mukasya			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Dept. of Chemical & Biomolecular Engr. University of Notre Dame			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000, USA			10. SPONSOR/MONITOR'S ACRONYM(S) TACOM/TARDEC/RDECOM		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 20288		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 22	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Acknowledgements:

Jeremiah White

Funding: Honeywell
 Indiana 21st Century Fund
 US Army -Tardec

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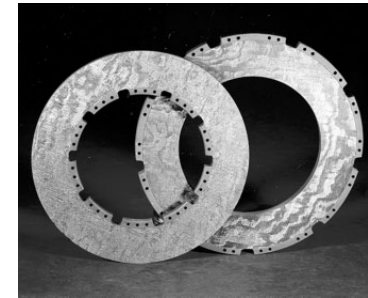
Joining Using Heterogeneous Combustion Systems

- 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

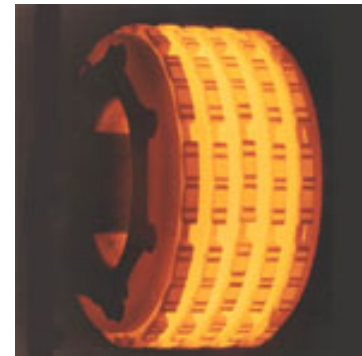
- Refurbishing of components
 - e.g., carbon brakes (Honeywell Aerospace)
 - Carbon-carbon (C-C) composites have low density, high strength-to-weight ratio, and withstand high temperatures
- Development of functionally graded materials
 - e.g., composite armor

- 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



C-C brakes

A380 -rejected take off test

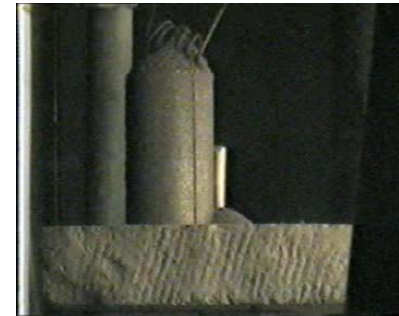
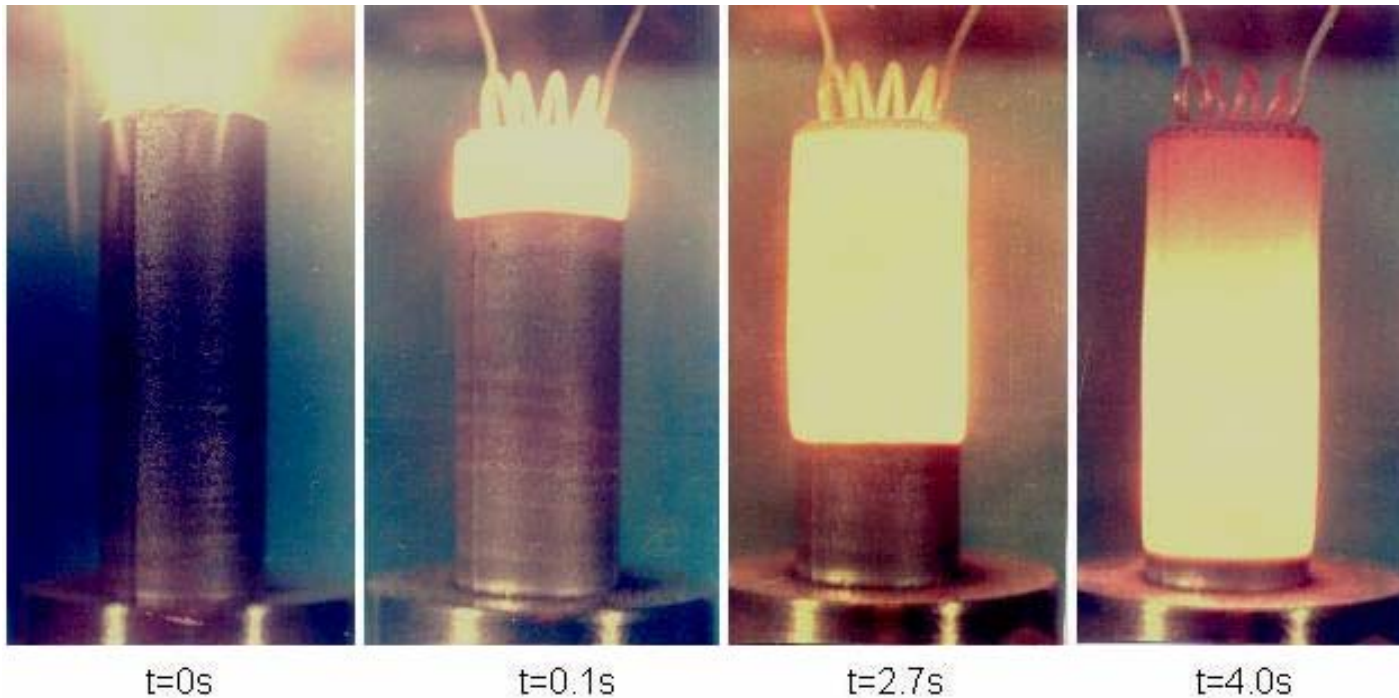


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Joining C-Based Materials

- 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*

Self-Sustained High-Temperature Reactions



Characteristic Features:

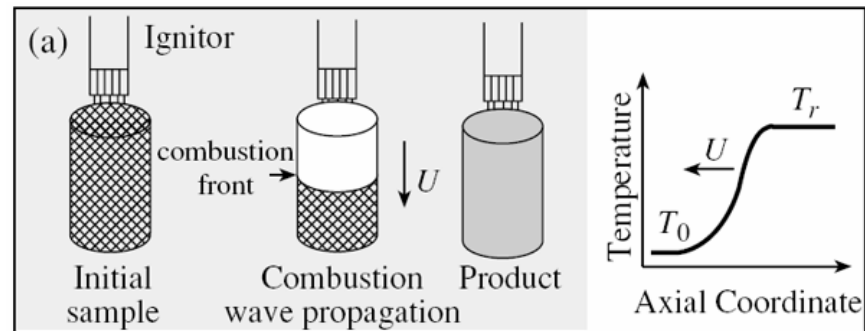
- High temperatures ($> 2000 \text{ K}$)
- High temperature gradients ($10^3\text{-}10^6 \text{ K/s}$)
- Short reaction times ($0.1\text{-}10 \text{ s}$)
- Low energy consumption
- Simple equipment

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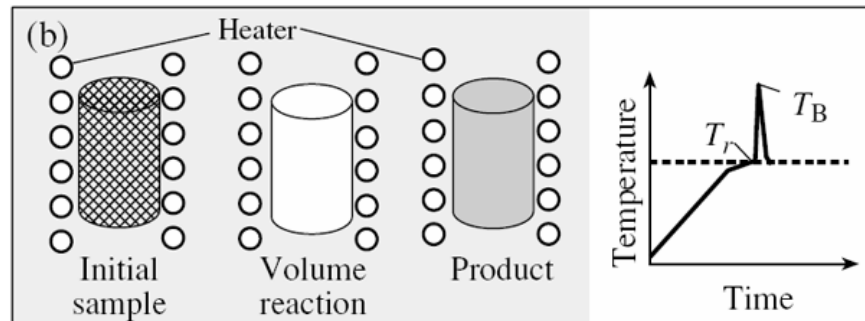
- Carbides, Borides, Nitrides
- Intermetallic Compounds
- Alloys
- Ceramics
- Functionally Graded Materials

Modes of Combustion Synthesis

Self-Propagating High-Temperature Synthesis (SHS)



Volume Combustion Synthesis (VCS)



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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

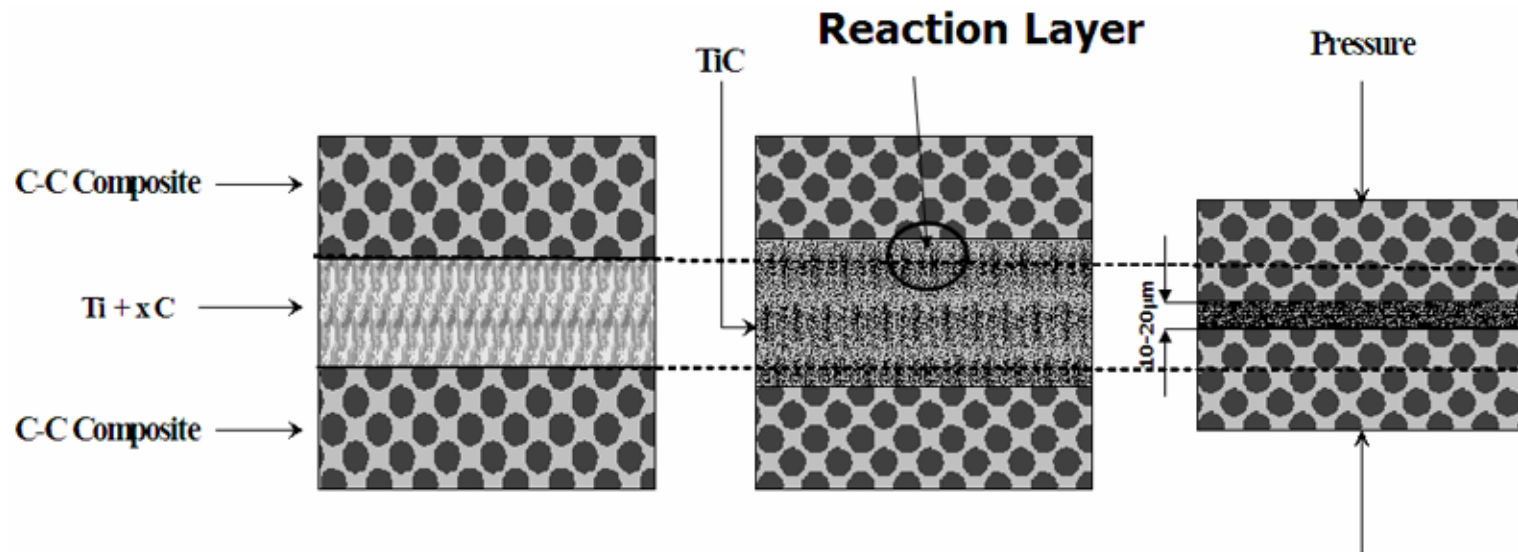
Reactive Resistance Joining

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

Preheat to the ignition temperature.

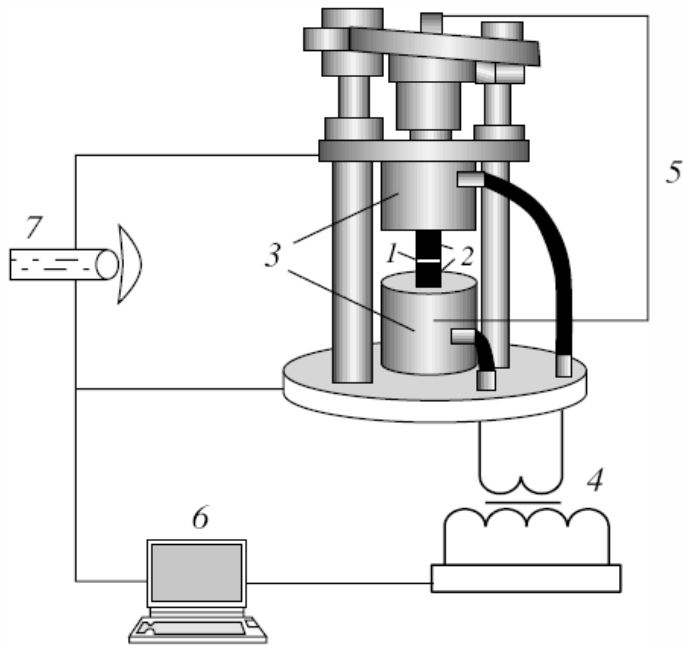
After initiation, a rapid (up to 10^4 K/s) high temperature (up to 3000 K) reaction occurs in a thin layer in the vicinity of the joint → leads to chemical interaction between the melt and disks to be joined.

A rapid press allows instant loading of the stack: enhancing the mechanical properties of the joint.



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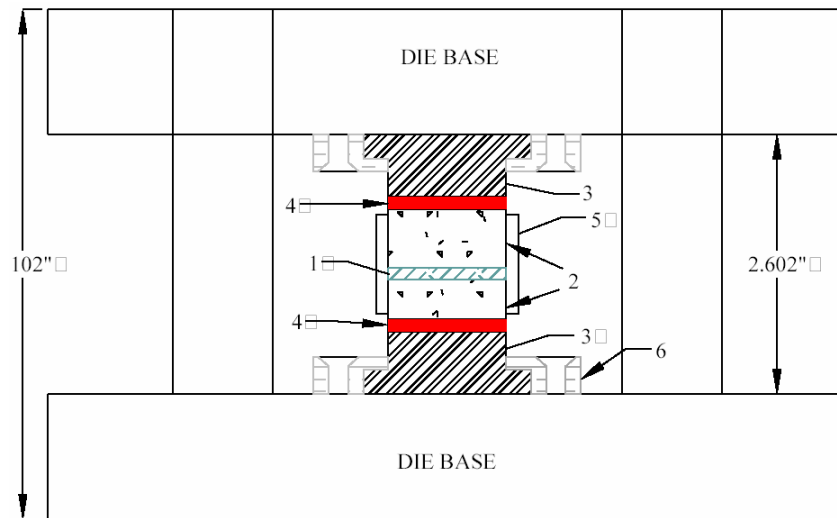
System for Rapid Joining of C-C Composites



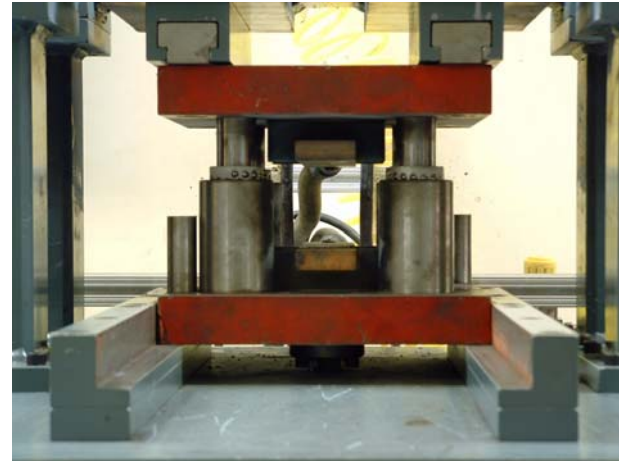
- **Max. Current: 950 A**
- **Max Voltage: 44 V**
- **Max Load: 35,000 N**
- **Press Response Time: 10 ms**

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Press Die Design and Construction



1 - Reaction Layer ; 2 - C-C Disks; 3 - Dielectric Layers ;
4- High Current Power Supply; 5 - Thermo Insulator; 6 - Retainer Ring;



Reaction zone is observable: can
measure temp.!

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Frames of a Joining Process



$t = 0.00 \text{ s}$



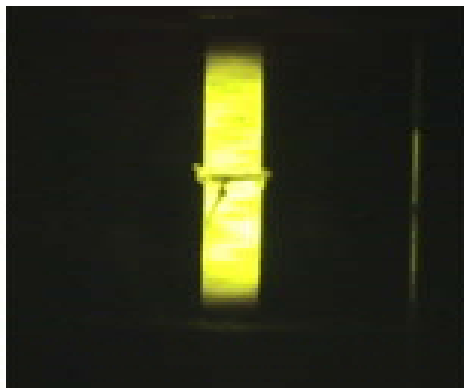
$t = 0.30 \text{ s}$



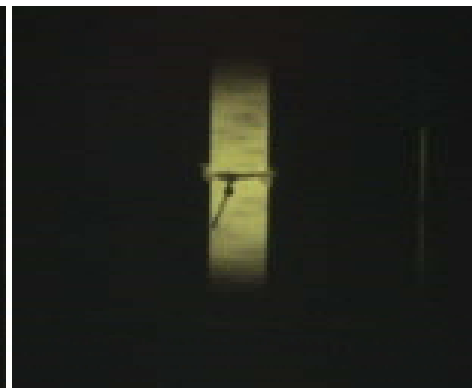
$t = 1.20 \text{ s}$



$t = 3.00 \text{ s}$



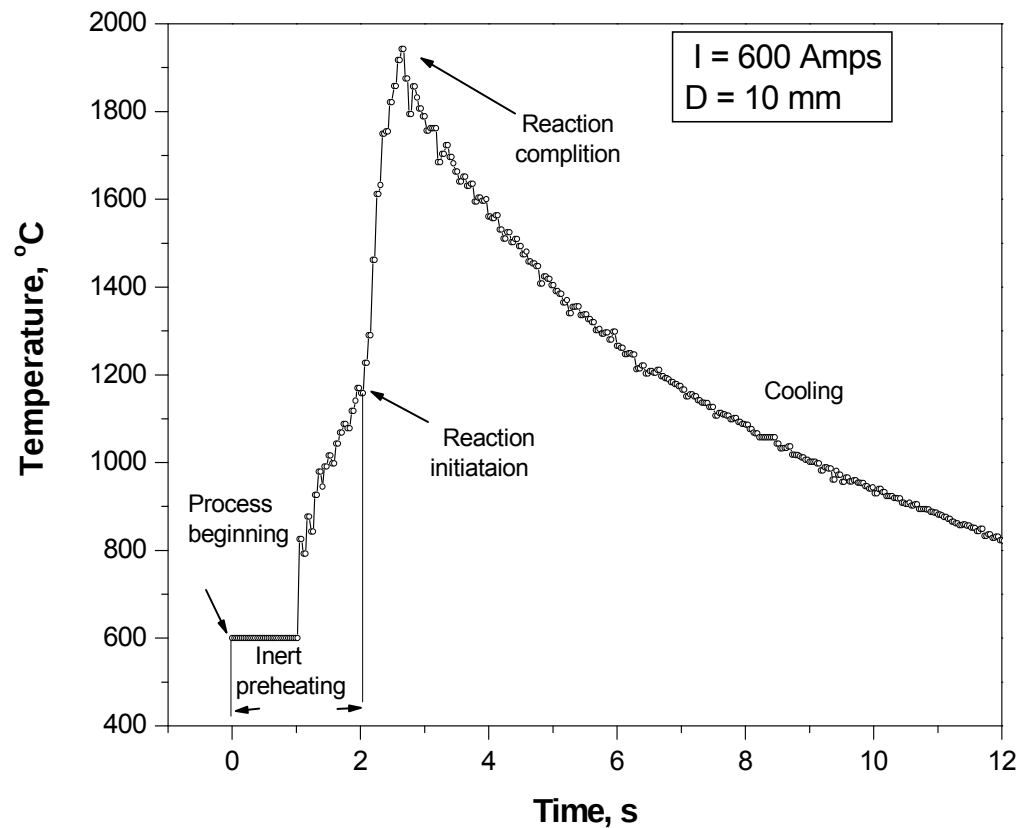
$t = 5.00 \text{ s}$



$t = 7.50 \text{ s}$

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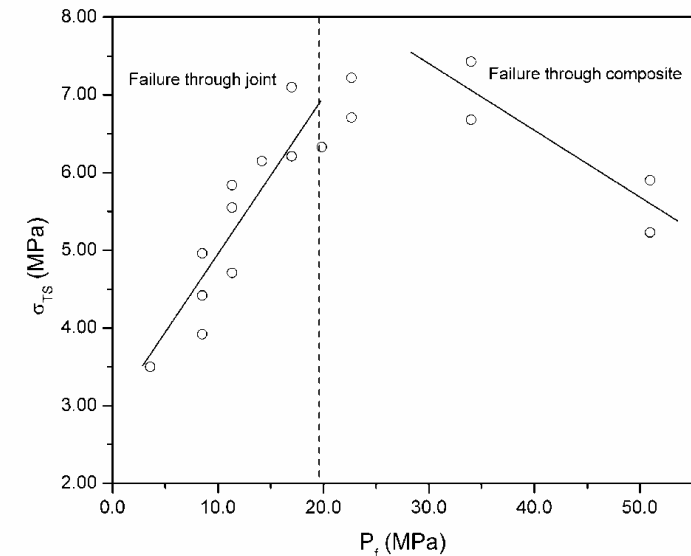
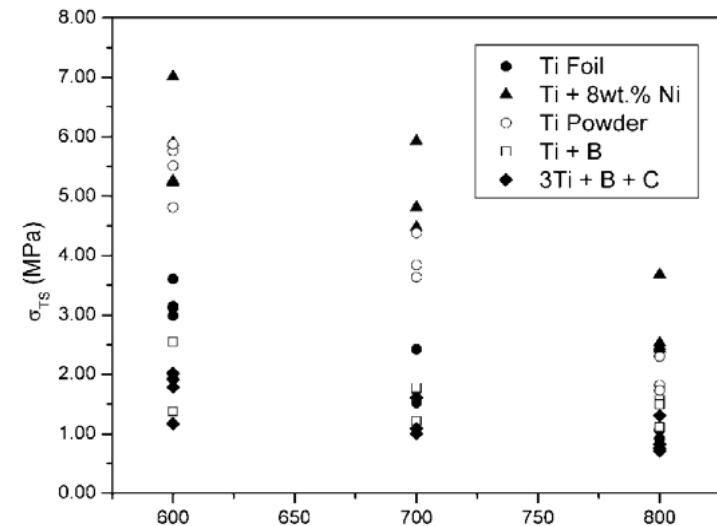
Typical Temperature Profile of Joining Process



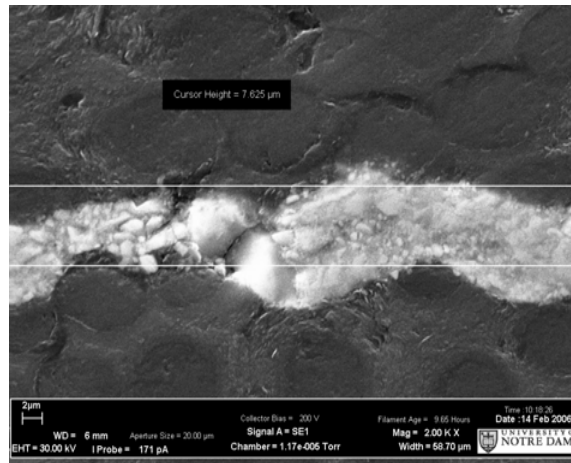
Joule preheating only up to T_{ig}

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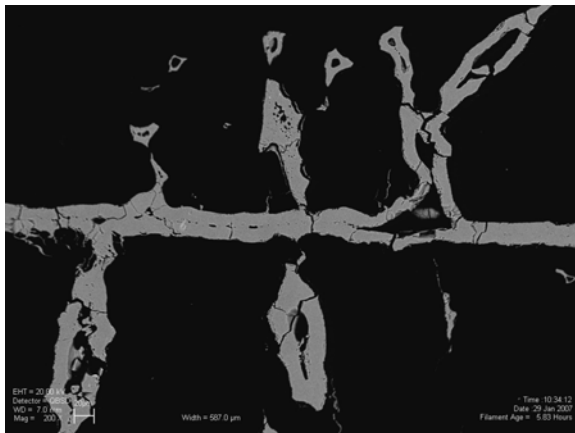
- **C-C composite highly reactive** – don't need carbon in joining layer (Ti foil, Ti powder, *Ti + 8wt% Ni*, Ti + B, 3Ti + B + C)
- Don't need highest current
- Applied pressure affects composite properties
- Final layer thickness independent of initial media thickness



Final join structure



final product layer independent of initial layer



Ti powder: $h_i = 3000 \mu\text{m}$



Ti foil: $h_i = 25 \mu\text{m}$

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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Al – SiC Composites

Up-Armored HumVee

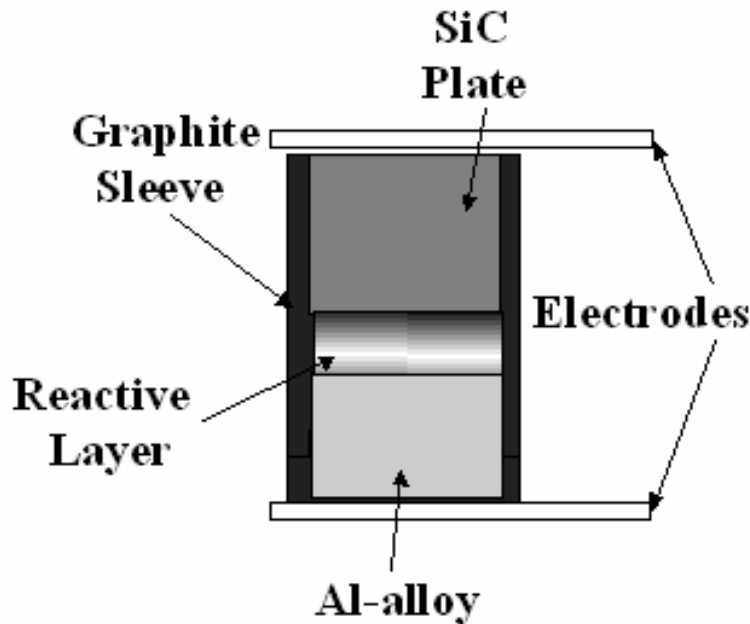


“The three-quarter-ton armor that gets plated onto the humvees, for example, limits its carrying ability and puts additional strain on the transmission, according to service officials...”

<http://www.defensetech.org/archives/001349.html>

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Sample Configuration



Disks of SiC / reaction layer / Al 5083 alloy

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

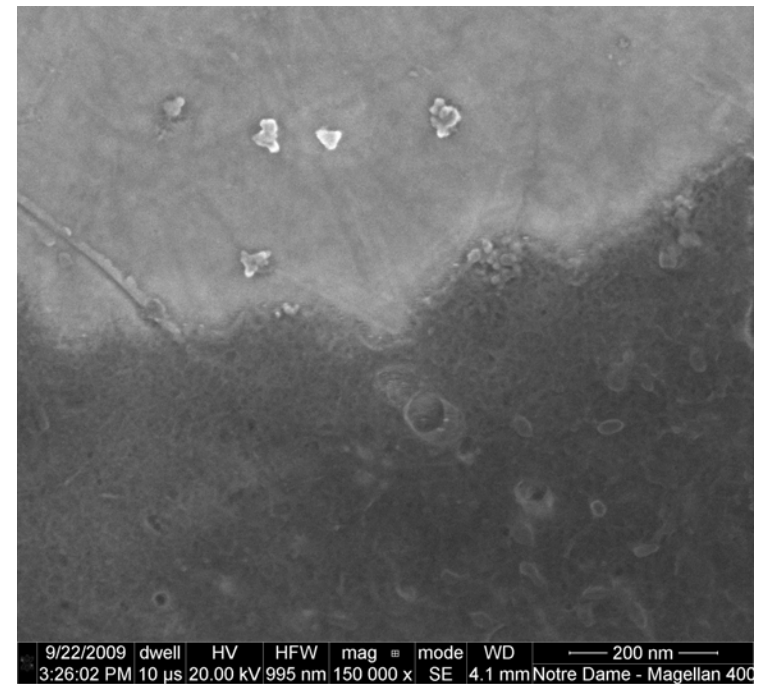
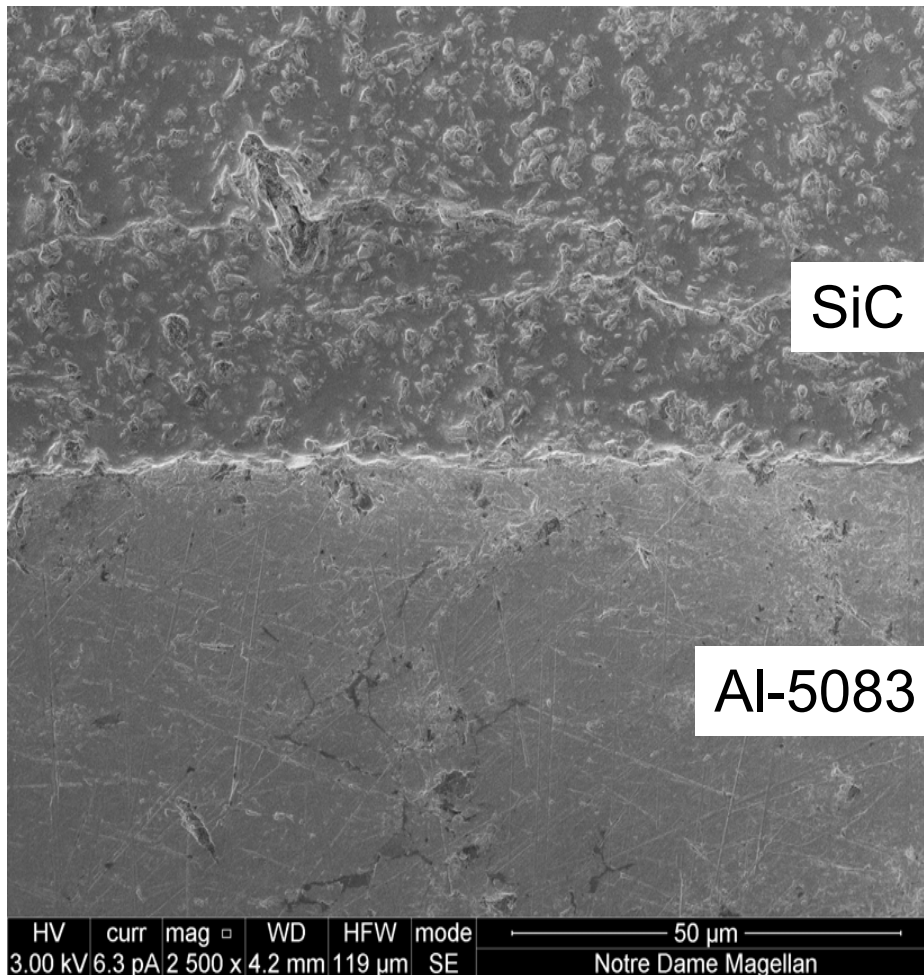
Thermo calcs: $\text{Ti} + \text{SiC} \rightarrow \text{TiC}, \text{TiSi}_x$, possible

reaction temperature $> \text{Al}_{\text{mp}}$, close to Ti_{mp} ,
 $< \text{SiC}_{\text{mp}}$ (3100K).

Conductivity of stack too low;
pass current through **graphite**
to preheat

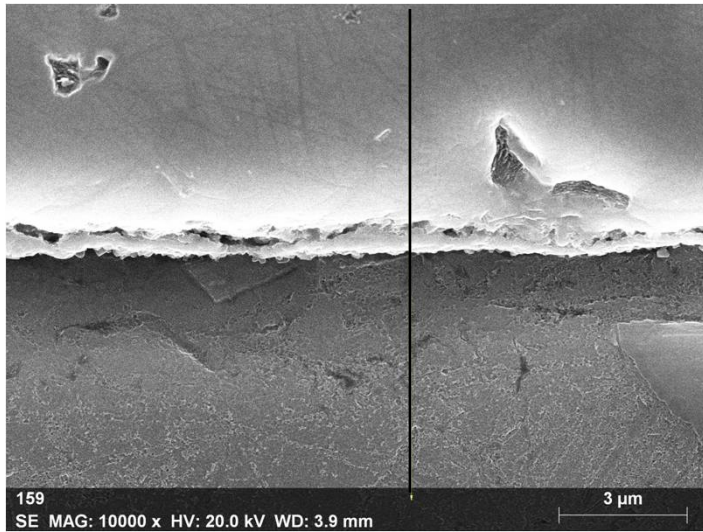
This design does not allow for compaction during reaction
different die design now being used

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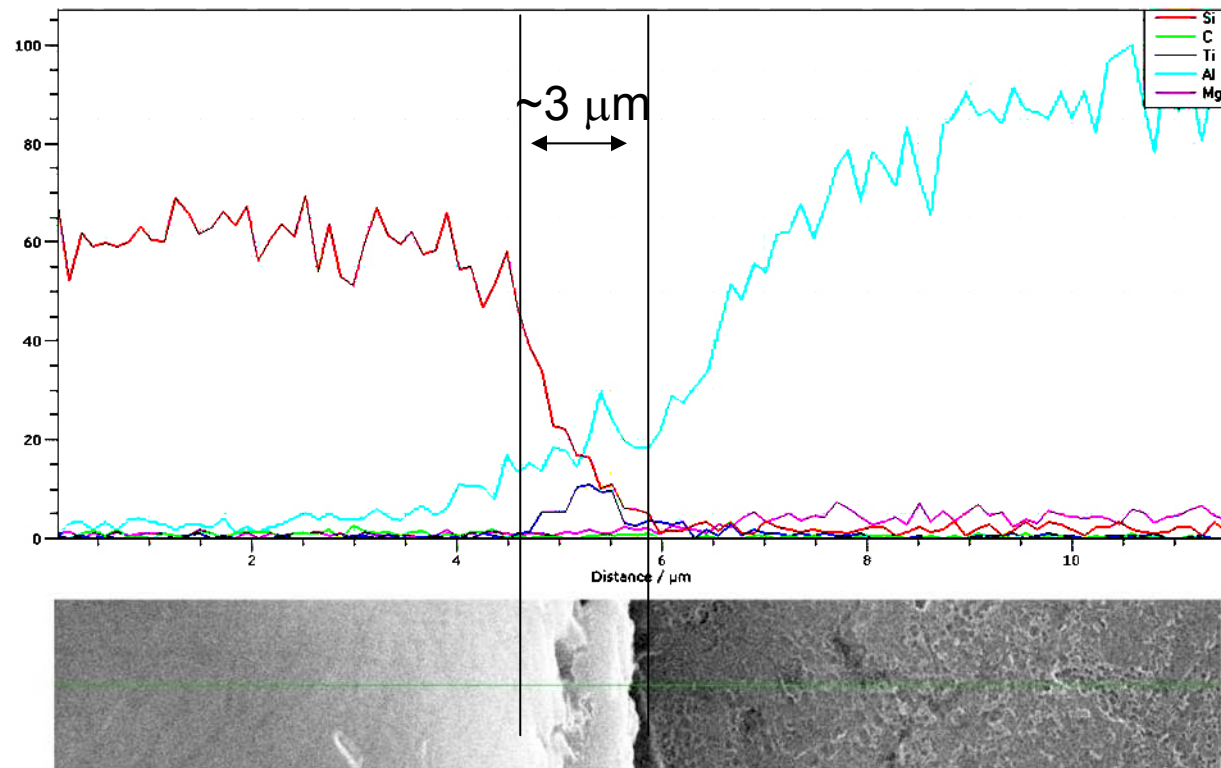
- (i) Reaction starts at melting point of Al (~ 932K).
- (ii) Ti layer reacts with Al-alloy, elevating temperature (~2000K) in the boundary layer

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2mm Ti+C rxn disk

Ti confined to region $\sim 3\ \mu\text{m}$ wide near interface



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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 ($\sim 1\text{--}10$ 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_3SiC_2 (ductile), Si(Al)CO , TiC-SiC-Al
- New press set-up /die design implemented to produce optimized materials for sub-scale ballistic tests

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