Advanced Analysis and Characterization of the UAM and VHPUAM Bonding Processes

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Outline

- Motivation
  - UAM Process
- Basic and Applied Research
  - Microstructural Characterization
  - Thermal Characterization
  - Mechanisms for Interfacial Bonding
- Potential Applications
- Summary and Conclusions
Ultrasonic Additive Manufacturing

- Uses solid-state ultrasonic metal welding (UMW) to create net-shape metal parts
- [http://www.solidica.com/systems.advanced.html](http://www.solidica.com/systems.advanced.html)

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Potential hybrid examples:

- Embedded Electronics
- Embedded Fiber Optics
- Armor Materials
- Complex Shapes

Thermal Management Parts

- What is the challenge?

Ref: K. Johnson, Solidica
K. Graff, EWI

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Challenge: Fundamental mechanism of joint formation is not clear

- What are the stages in the bond formation:
  - Plastic Strain and Strain Rate (can be $\sim 10^3$ to $10^5$/sec)
  - Peak Temperature
  - Heating and Cooling Rate

- At OSU we have started a systematic fundamental and applied research to address this need.
Experimental Parameters

- **Materials:**
  - 6061-H18 & 3003-H18
  - 1.5 kW Solidica formation™

- **UAM Process Parameters**
  - **Substrate Temperature:**
    - 300° F (~150° C);
  - **Frequency:** 20 kHz
  - **Tack Pass:**
    - 12 µm (ampl), 200-350 N
    - 60-140 ipm (25-59 mm/s)
  - **Weld Pass:**
    - 17-26 µm (ampl), 1150-1800 N;
    - 100 ipm (42 mm/s) (for 3003 only)
    - 25 - 35 ipm (20.6 to 14.8 mm/s) - 6061

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Anisotropic mechanical properties are observed in UAM Builds.

- Why do we observe such anisotropy?
Optical microscopy shows lack of bonding at interfacial regions

- Tensile failures correlate with these un-bonded regions
Linear void density distribution leads to scatter in transverse properties

- Macroscopically brittle (but) microscopically ductile failures
UAM processing leads to increase hardness of the 3003 alloy foils.

- Hardness mapping is in agreement with the observed increase in longitudinal strength.

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Fundamental question: How does the bonding occur during UAM?

We need multi-scale characterization techniques to understand the formation of joints.
Focused Ion Beam (FIB) Machining is used to extract the samples from localized regions.

- Both bonded and un-bonded regions are analyzed.
OIM analyses show recrystallized grains at the interface region.

- This is in agreement with data from ultrasonic metal welding research.

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Transmission electron microscopy shows complex microstructure distributions.

- Original deformation microstructure is still present in foil regions.
Non-bonded void regions show nano-structured Corundum oxide layers

- This phenomenon is related to the conditions during sonotrode interaction and subsequent thermal excursions.
Transmission electron microscopy confirms the recrystallization at the interface region (bottom)

Is this microstructural change consistent?
Recrystallization appears to be consistent (middle).

What about the top region?

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Extent of recrystallization and grain growth appears to be less significant (top).

What did we learn from these results?

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EWi - THE MATERIALS JOINING EXPERTS

(c)
Both bonded and un-bonded regions show microstructural evolution similar to localized hot-working.

- Is there a temperature increase at the interface regions?
Temperature measurements were made in different locations simultaneously.

- Measurements showed interesting behavior.

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All thermocouples (1-6) show simultaneous heating without any delay!

- Thermal diffusivity appears to be infinite! Why do we see such behavior?
Thermo-mechanical effects appear to be felt by all interfaces

- What is the role of temperature increase?

Ultrasonic Vibration Out of Plane

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Analyses using Zener-Holloman equation suggests a rapid thermo-mechanical process at the interface region.

$$d_{sub} = \left[ -0.60 + 0.08 \log(Z_h) \right]^{-1}$$

$$Z_h = \varepsilon \exp\left\{ \frac{18,772}{T_p} \right\}$$

- Key: Induce plastic deformation followed by recovery and recrystallization.
- Currently, we cannot measure both simultaneously!

Substrate Temperature = 423 K
What is the significance of these results for industrial application? Currently UAM process is limited to aluminum alloys.

How can we extend this to other high temperature alloys?
Very High Power Ultrasonic Additive Manufacturing

- Collaboration with EWI
- 11000 Cu
- Up to 9 kW
- Amplitude: 38µm
- Normal Force: 6700N
- Welding Speed 30mm/s

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Microscopy shows interfacial deformation & recrystallization

- Similar to UAM processed Al alloys
- In principle, can be extended to other alloys as long as we can increase the interface temperature locally.
- What do we need?
Future Directions: A Large VHPUAM machine will be commissioned in April 2010

- OSU has common-use agreement
- Embedding Targeted alloys/liquids/gases possible
- Very relevant to Y12 missions
Summary and Conclusions

- Near-net shaped hybrid materials can be fabricated using UAM and/or VHPUAM.
- Temperature increases at interfaces between tapes due to localized high-strain rate thermo-mechanical processing of asperities.
- Recrystallization and grain growth appears to be a requirement for joint formation.
- Future directions to adopt this process to high-temperature alloys are presented.