Process-Property Relationships in Ultrasonic Additive Manufacturing of Lightweight Structures

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Talk Overview

• Ultrasonic Additive Manufacturing- UAM
• Bond Formation in UAM
• Welder Energy and Parameters
• Effect of Build Compliance on Effective Weld Power
• Power Compensation
• UAM Process Modeling
• Concluding Remarks
Ultrasonic Additive Manufacturing - UAM

- **Recent technology** that combines:
  - Ultrasonic metal welding
  - Additive manufacturing
  - CNC machining center

- **Low temperature** process:
  - Interface near \( \frac{1}{2} T_{\text{melt}} \)
  - Measureable temp near 100 °C for Al 6061-H18 [1]

- **Enabling** technology for dissimilar metal joining and low temperature applications

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Base plate: milling for flatness
UAM Applications and Strengths

Automotive

Aerospace

Efficient Cooling and Embedded Sensing

Multi-Material Joints and Reinforcement

Solid-State Actuation

Embedded Temperature Sensitive Sensors and Electronics

Complex Internal Cooling

Light-Weighting with Dissimilar Materials and Metals

Smart Materials Integration

PVDF in Al

Fiber Optic Cable

SS tube

Carbon Fiber

NiTi

Al

Cu

Ti

Al

NiTi

Al

http://jwst.nasa.gov/

www.dolphin.fr
Bond Formation in UAM

- Recent **advancements** in delivered **power** and **down force** have remedied interface voids, i.e. gapless structures [2]
- Weld microstructure is composed of **recrystallized** small (~1 micron) **equiaxed grains** within narrow region of weld interface (~ 20 micron) [3-4]
- The **degree of recrystallization** is foretelling of the **shear strain** at the interface due to dynamic recrystallization being a function of (i) strain and (iii) temperature [5]

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Welder Energy and UAM Parameters

- Controllable Parameters:
  - Vibration amplitude, $\delta$ (µm, % of max)
  - Normal force (N)
  - Sonotrode travel speed, $V_t$ (in/min)
  - Baseplate temperature (°F)

- Fixed Parameters:
  - Vibration frequency (~20 kHz)
  - Sonotrode roughness (~7 or 14 micron $R_a$) and material (tool steel)
  - Tape thickness (~0.006”)

- Typical weld power for Al 6061-H18 is near 2-3 kW
- Typical weld power for as rolled 4130 steel is near 5-7 kW

$$E_{\text{weld}} = \int P \cdot dt = \frac{1}{V_t} \int F \cdot \omega \cdot \delta \cdot dx$$
Effect of Build Compliance on Effective Weld Power

• **Build compliance** refers to the mechanical deformation of the part when subjected to shear force during the UAM process – compliance increases with part height [6]

• Build compliance leads to a decrease in plastic deformation, i.e., a decrease in effective weld power

• **Power compensation** achieved by increasing weld amplitude manually

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• **Does power compensation lead to stronger welds?**

• **Approach:**
  - Measured weld power for compensated and uncompensated stack builds
  - **Push-pin** testing to evaluate bond strength
  - **Focused Ion Beam (FIB)** imaging used to analyze interface microstructure
**Power Compensation: Push-Pin Testing**

- **Comparative test**
- Used to evaluate UAM interfacial **bond strength**
- Successfully used in recent Al 6061-H18 weld study [7].

![Graphic showing comparative test results]

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Power Compensation: Weld Microstructure

- Enhanced interface recrystallization with power compensation
### Power Compensation: Energy Balance

\[ E_{surf} + E_{plastic} = E_{bulk} + E_{recryst} + E_{thermal} \]

- **Energy balance** can be utilized to analyze bonding process
- \( E_{plastic} \) measured remotely via transducer power consumption (\( E_{weld} \))
- \( E_{recryst} \) measured via quantity of new small grains at interface \[^8\]
- Stronger welds achieved with larger \( E_{recryst} \) due to **Hall-Petch** relationship \[^8\]
- First time **weld microstructure** has been correlated with energy input

UAM Process Modeling: LTI Model

**Inputs**
- Electric current: $i$
- Shear force: $F_s$

**Linear System**
- Welding Assembly

**Outputs**
- Voltage: $V$
- Weld velocity: $j\omega\delta$

**LTI Model**
\[
\begin{bmatrix}
{j\omega\delta}
\end{bmatrix} = \begin{bmatrix}
H_{em} & H_e^* \\
H_m^* & H_{me}^*
\end{bmatrix}
\begin{bmatrix}
i \\
F_s
\end{bmatrix}
\]

**Lumped System: Welder Characterization**

**Lumped System: Welder Operation**

- **Electroacoustics theory** [9-12]

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UAM Process Modeling: Characterization

- Shear force: High frequency modal hammer
- Weld velocity: Laser vibrometer
- Voltage and current: Linear amplifier
- Frequency response functions: Quattro analyzer
- Boundary conditions: In UAM machine
UAM Process Modeling: Model Fit

- Good agreement with measured and closed form FRFs
- Fit procedure found in literature \cite{9}
LTI model assumption valid?

- Yes, welder dynamics are pseudo-stable during operation
- Measurements support model assumptions
UAM Process Modeling: Shear Force and Efficiency

Shear Force Estimation

\[
i = \frac{P}{i_{ref}} = \frac{P}{P_{ref}} \quad F_S = \frac{H_{em}i - j\omega\delta}{H_m^*}
\]

Efficiency

\[
e = \frac{j\omega\delta * F_S}{P}
\]

Power Control Law

\[
\Delta P = \frac{1}{2\Psi_t} \Delta F_S
\]

- **Shear force** near 2000 N, which is similar to de Vries \(^{[13]}\).
- **Welder efficiency near 82%**, which is near ultrasonic metal welding estimates \(^{[14]}\) and below piezoelectric transducer efficiency \(^{[15]}\).
- Upward frequency shift from UAM build stiffening system.


Conclusion

- UAM enables fabrication of unique materials and products
- Weld power/energy correlation with bond quality
- Weld power as an in-situ process variable
- LTI model which uses shear force as a system input
- In-situ measurements of welder