Residual Stresses in Panels
Manufactured Using EBF3 Process

J. Gaillard
(Masters Student, Microelectronics and Micromechanics Department,
ENSICAEN (Ecole National Superieure d'Ingénieurs de Caen))

Davide Locatelli
(Ph.D. Research Assistant, Engineering Science and Mechanics Department)

Sameer B. Mulani
(Post-Doctoral Research Associate)

Rakesh K. Kapania
(Mitchell Professor, Aerospace and Ocean Engineering Department)
Multidisciplinary Analysis and Design Center for
Advanced Vehicles
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0203

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Introduction: Increasing Use of Unitized Structures

- **Industrial Benefits of Unitized Structures**
  - Reduced Lead Time, Manufacturing Restrictions & Time to Tooling
  - Reduced Part Count & Wastage
  - Environmental Friendly
  - Curved Stiffeners and Plates
  - Functionally Graded & Multi-functionality
  - Manufacturing in Space
  - Easy Repairability

- **Design Impact on Aeronautics and Space Exploration**
  - Improve Buckling Performance
  - Modal Control
  - Sound Power Reduction and Higher Transmission Loss

- **Impact on NASA Goals**
  - Reduce Fuel Burn Rate
  - Reduce Field Length
  - Reduce NOX
  - Reduce Cabin Noise
Introduction: EBF3 Process in Stiffened Panel

- Electron Beam Free Form Fabrication (EBF3) allow to easily manufacture complex shape structural parts.
- In aerospace designs, EBF3 can be used to fabricate panels with curvilinear stiffeners.
- Stiffeners with curvature, variable thickness and variable section shape can be manufactured using this technology.
- Multiobjective optimization can be achieved for mass reduction, buckling factor, vibration modes, acoustic sound-power and damage tolerance constraints.
- Lighter, stiffer and safer structures can be designed and fabricated.
EBF3 Manufacturing Process

- A focused electron beam creates a molten pool on the metallic substrate.
- A metal wire is continuously fed into the molten pool in layer-additive fashion, while the beam is translated.
- The electron beam can be controlled and deflected very precisely.
- EBF3 can be used in low gravity environment.
- Deposition is in vacuum.
Objective

Residual Stresses

- Stresses which remain when all External Loads are null: Residual Stress.
- Stresses due to the Moving Heat Source.
- The differences of Temperature cause a Contraction of the Metal and constrain the panel.
- Residual stresses can compromise the Integrity of a Structure.
- COMSOL model to analyze the residual stresses of the first layer of deposition on a panel in Aluminum 2219.

Theoretical longitudinal residual stresses in welded stiffened plates.

Objective of the analysis

- Estimate the residual stresses resulting from the melting of the metallic substrate and the deposition of the new layer of material in the molten pool.
- Estimate eventual permanent deformations occurring in the plate and their dependence from the boundary conditions.
- Investigate the dependence of the maximum residual stress value from the deposition rate and the coefficient of convection value.
Model Description: Geometry

- Residual Stresses
  - Aluminum 2219 panel with a straight stiffener in the middle.
  - Use of a Moving Heat Source to simulate the deposition
  - No convection since EBF3 process occurs in vacuum chamber. A steel table is modeled as heat sink at the bottom of the plate.

Panel Dimensions: 610x510x2.54 mm
Layer Dimensions: 610x13x1.27 mm
Model Description: Governing Equations

Conduction Equation

\[ \rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q \]

Convection Boundary Condition

\[ -n \cdot \vec{q} = q_0 + h(T - T_0) \]

Elastic-Plastic Stress-Strain relationship

\[ \sigma = D \varepsilon_{el} + \sigma_0 = D \left( \varepsilon - \varepsilon_p - \varepsilon_{th} - \varepsilon_0 \right) + \sigma_0 \]

\[ \varepsilon_{th} = \alpha (T - T_{ref}) \]

Goldak Semi Ellipsoidal moving heat source

\[ Q(x, y, z, t \leq t_{dep}) = \frac{6\sqrt{3}q_0}{abc\pi \sqrt{\pi}} \exp \left( -\frac{3x^2}{a^2} - \frac{3y^2}{b^2} - \frac{3(z-\nu t)^2}{c^2} \right) \]

\[ Q(x, y, z, t \geq t_{dep}) = 0 \]
Model Description: Material Properties

Aluminum 2219:
Relevant physical properties at room temperature

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>2831 kg.m$^{-3}$</td>
</tr>
<tr>
<td>Young Modulus</td>
<td>$E$</td>
<td>72.4 GPa</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>$\nu$</td>
<td>0.33</td>
</tr>
<tr>
<td>Melting Temperature</td>
<td>$T_f$</td>
<td>816-917 °K</td>
</tr>
<tr>
<td>Convection Coefficient</td>
<td>$h$</td>
<td>500 W.m$^{-2}.°K^{-1}$</td>
</tr>
<tr>
<td>Reference Temperature</td>
<td>$T_{ref}$</td>
<td>293.15 °K</td>
</tr>
<tr>
<td>Yield Stress</td>
<td>$\sigma_{yield}$</td>
<td>375 MPa</td>
</tr>
</tbody>
</table>
Model Description: Material Properties

Data points are taken from Ref. 4 and then interpolated using the piecewise cubic method embedded in COMSOL Multiphysics.

[Graphs showing Yield Stress vs. Temperature, Thermal Conductivity vs. Temperature, Coefficient of Thermal Expansion vs. Temperature, and Heat Capacity vs. Temperature]
Model Description: Boundary Conditions

- Two kind of BC
- Heat transfer: vacuum chamber (convection on the bottom to simulate the conduction with the steel table)
- Elastic-Plastic Stress-strain:
- Avoid the Rigid Body motion
Results: Temperature Distribution

Results for the speed of 6.7 mm/s
Results: Von Mises Residual Stresses

Time=1500  Subdomain: von Mises stress Gauss point eval. [MPa]

Max: 553
Min: 0.0639

Time=1500  Slice: von Mises stress [MPa]

Max: 570
Min: 0.266
Comparison of Experimental Data (NASA) and Numerical COMSOL Results

<table>
<thead>
<tr>
<th>Speed in mm/sec</th>
<th>VM max in MPa</th>
<th>h in W.m(^{-2}).s(^{-1})</th>
<th>VM max in MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.7</td>
<td>310</td>
<td>500</td>
<td>360</td>
</tr>
<tr>
<td>10</td>
<td>350</td>
<td>1000</td>
<td>350</td>
</tr>
<tr>
<td>13.4</td>
<td>325</td>
<td>1500</td>
<td>325</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2000</td>
<td>305</td>
</tr>
</tbody>
</table>
Conclusion and Future Work

- Single Layer Deposition Residual Stresses Calculation Successful.
- Good Agreement with Welding Process Results.
- Residual Stresses depends on the Speed of Deposition and Convective Coefficient between Steel Table and Bottom of the Plate.
- High Residual Stresses but always under the yield strength of Aluminum 2219.
- Estimation of Convective Coefficient, $h$ for Steel Table.
- Account the Changes in the Microstructure.
- Analyze 10 layers of deposition (a full stiffener).
- Other Mechanical boundary conditions.
- Optimization of Deposition Speed and Residual Stresses.


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