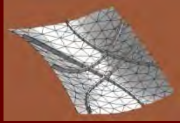

Residual Stresses in Panels Manufactured Using EBF3 Process

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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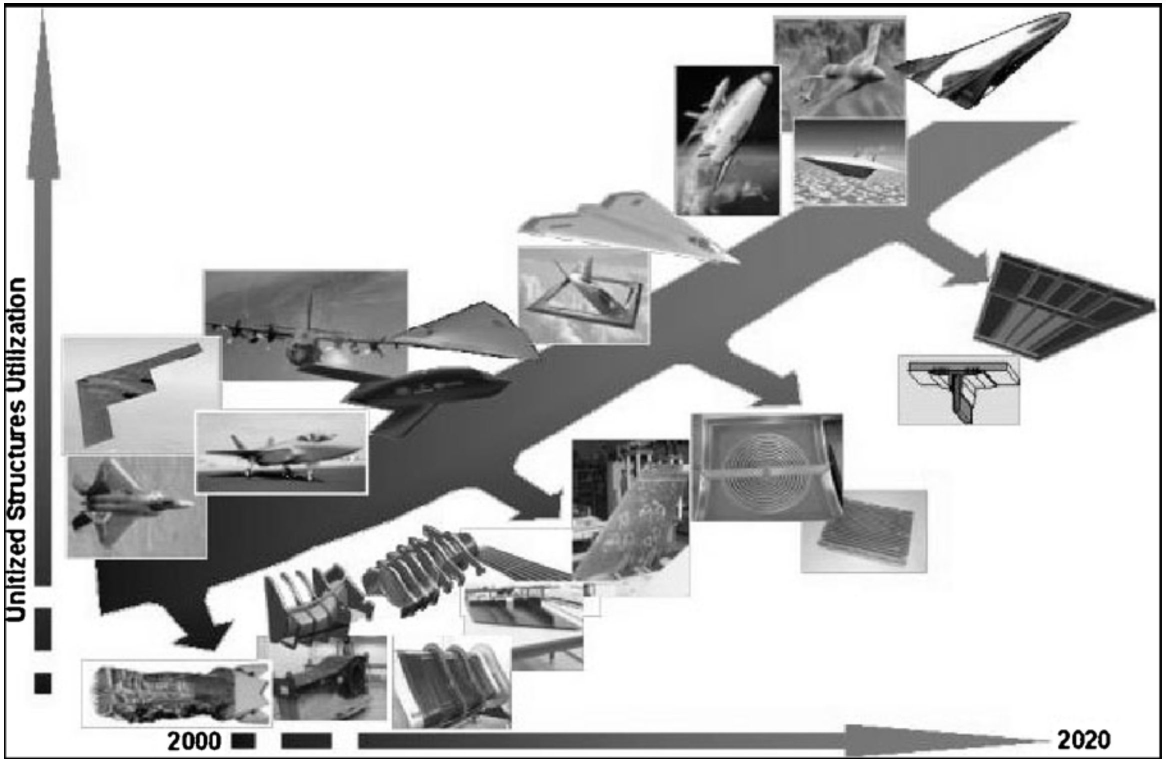
LOCKHEED MARTIN

Outline

- **Introduction**
- **EBF3 Manufacturing Process**
  - EBF3 Process
  - Objective
  - Residual Stresses
- **Problem Description**
  - Model Description
  - Governing Equations
  - Material Properties
  - Boundary Conditions
- **Results**

Introduction: Increasing Use of Unitized Structures

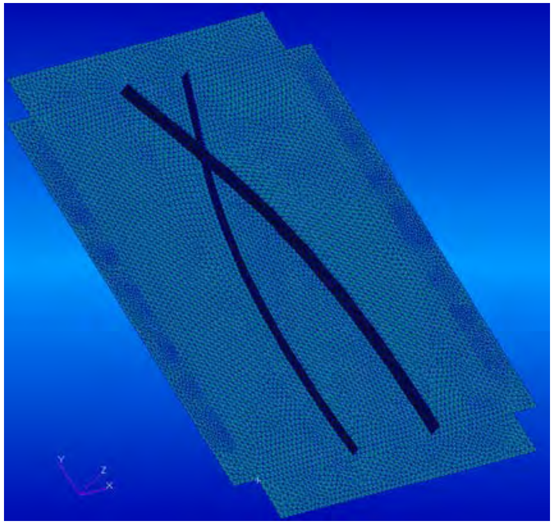


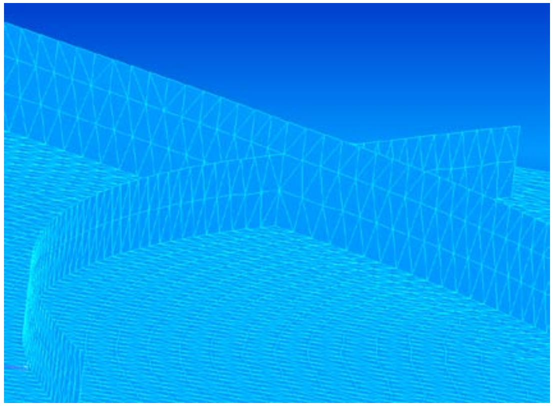
Renton et al. 2004

- **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
- **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

Introduction: EBF3 Process in Stiffened Panel

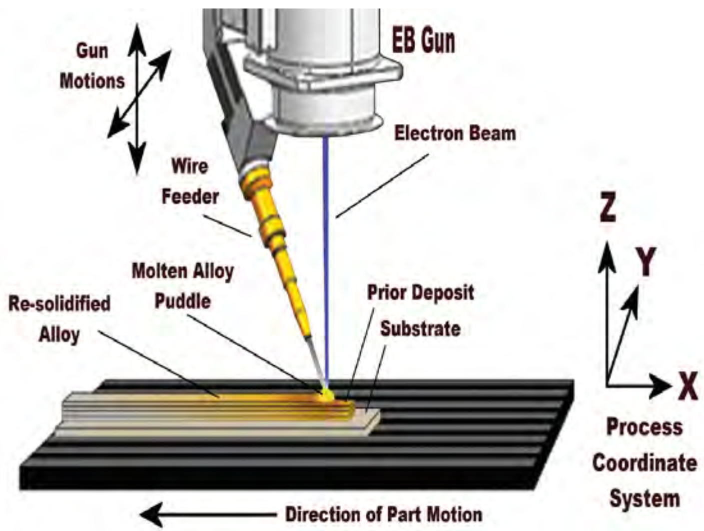
- Electron Beam Free Form Fabrication (EBF3) allow to easily manufacture complex shape structural parts.
- In aerospace designs, EBF3 can be used to fabricate panels with curvilinear stiffeners.
- Stiffeners with curvature, variable thickness and variable section shape can be manufactured using this 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.





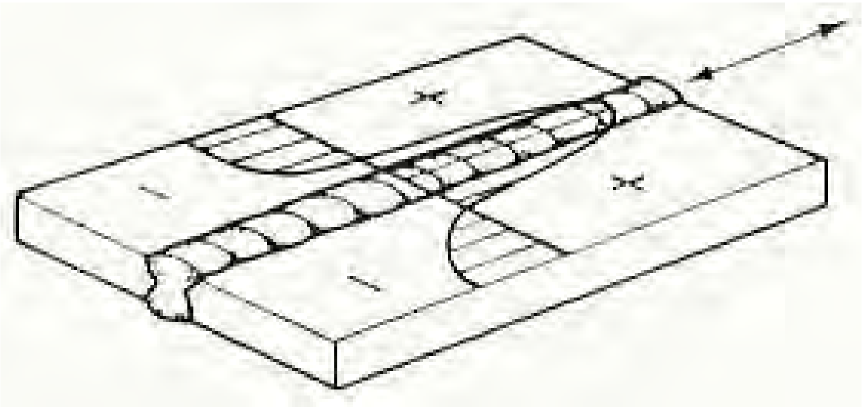
EBF3 Manufacturing Process

- A focused electron beam creates a molten pool on the metallic substrate.
- A metal wire is continuosly fed into the molten pool in layer-addictive 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 vaccum.

Objective

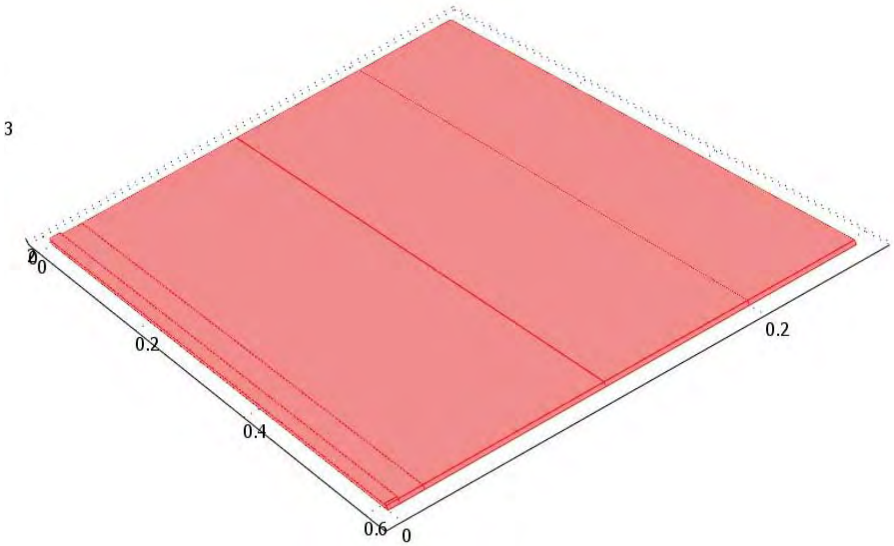


Theoretical longitudinal residual stresses in welded stiffened plates.

- **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.

- **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.

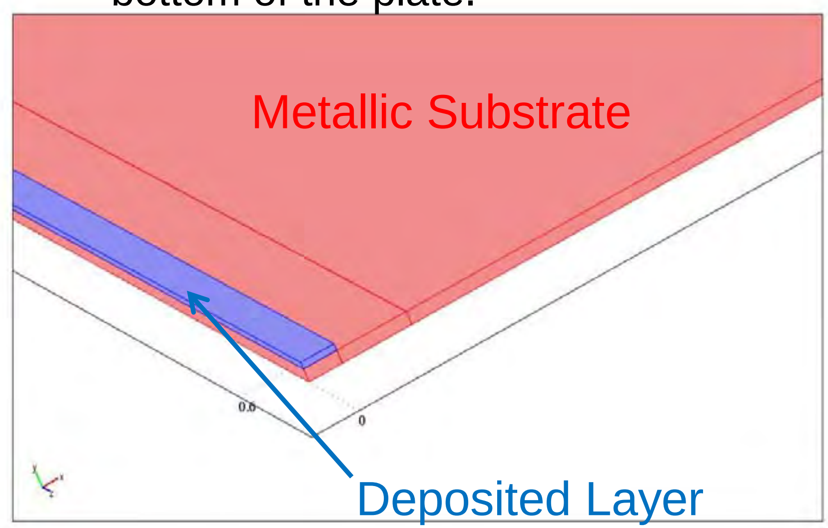
Model Description: Geometry



- Residual Stresses
  - Aluminum 2219 panel with a straight stiffener in the middle.
  - COMSOL: Coupling of Heat Transfer and Structural analyses using Elastic-Plastic Stress-Strain behavior.
  - 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.

<u>Panel Dimensions:</u>
610x510x2.54 mm

<u>Layer Dimensions:</u>
610x13x1.27 mm



Model Description: Governing Equations

Conduction Equation

$$\rho C_p \frac{\partial T}{\partial t} + \nabla.(-k \nabla T) = Q$$

Convection Boundary Condition

$$-\vec{n}.\vec{q} = q_0 + h(T - T_0)$$

Elastic-Plastic Stress-Strain relationship

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

$$\varepsilon_{th} = \alpha\left(T - T_{ref}\right)$$

Goldak Semi Ellipsoidal moving heat source

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

$$Q\left(x,\ y,\ z,\ t \ge t_{dep}\right) = 0$$

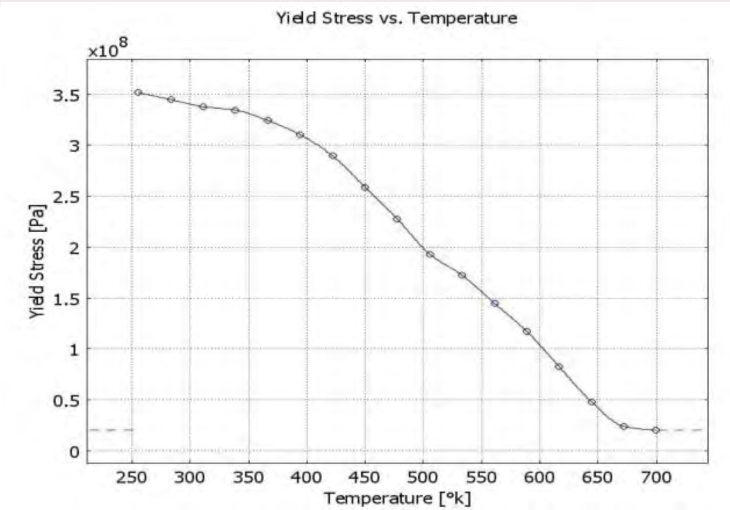
Model Description: Material Properties

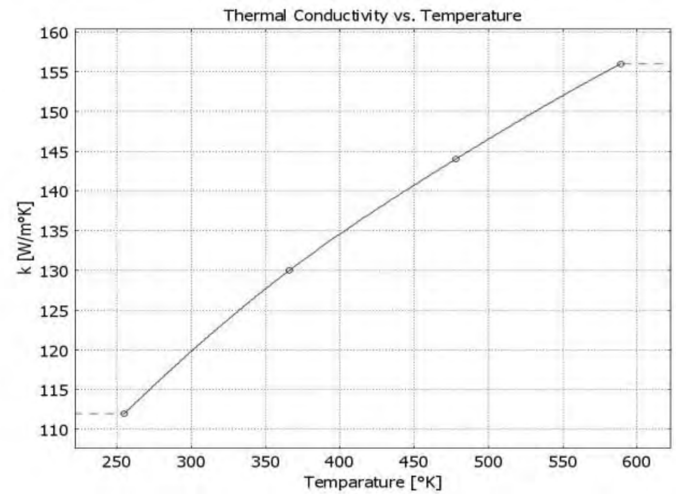
Aluminum 2219:

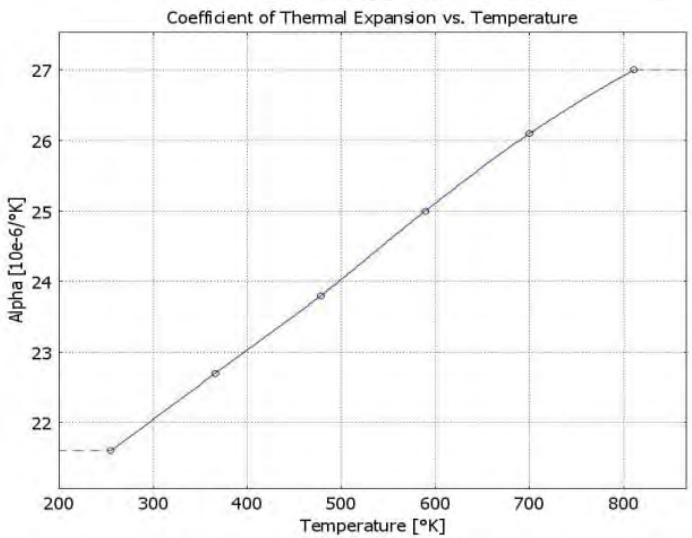
Relevant physical properties at room temperature

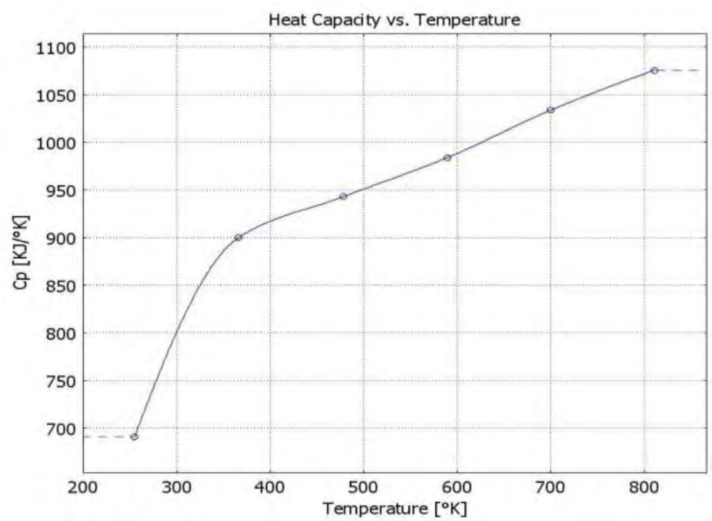
Density	ρ	2831 $kg.m^{-3}$
Young Modulus	E	72.4 GPa
Poisson's Ratio	v	0.33
Melting Temperature	T_f	816-917 °K
Convection Coefficient	h	500 $W.m^{-2}.°K^{-1}$
Reference Temperature	T_{ref}	293.15 °K
Yield Stress	σ_{yield}	375 MPa

Model Description: Material Properties



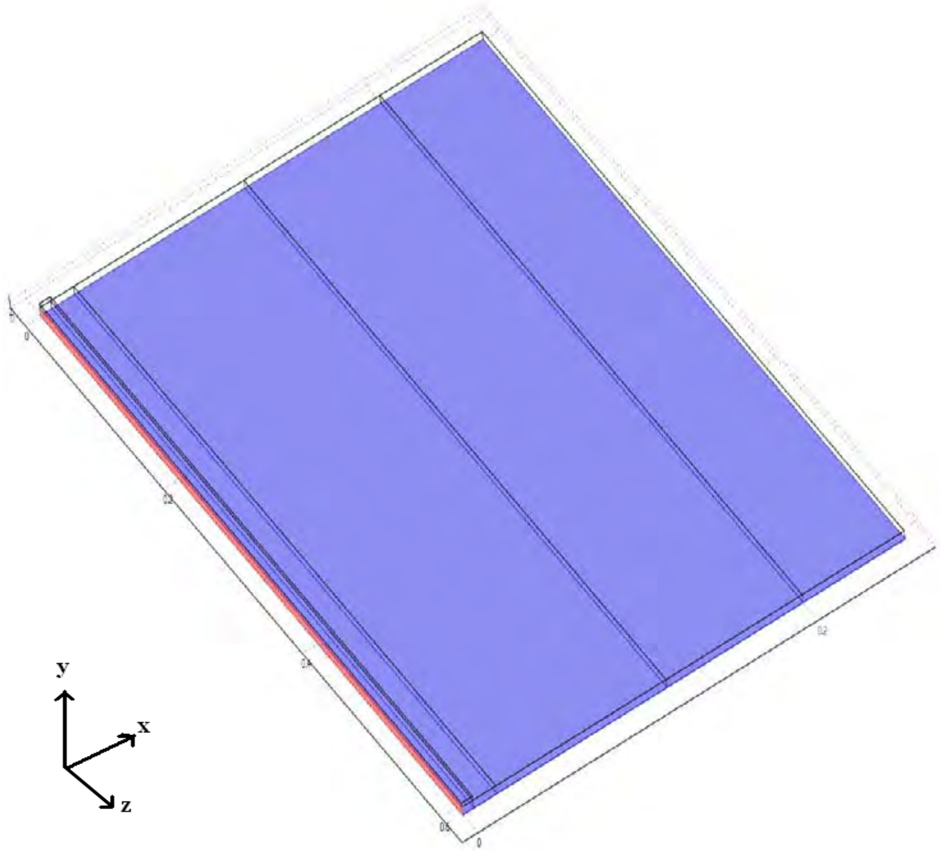






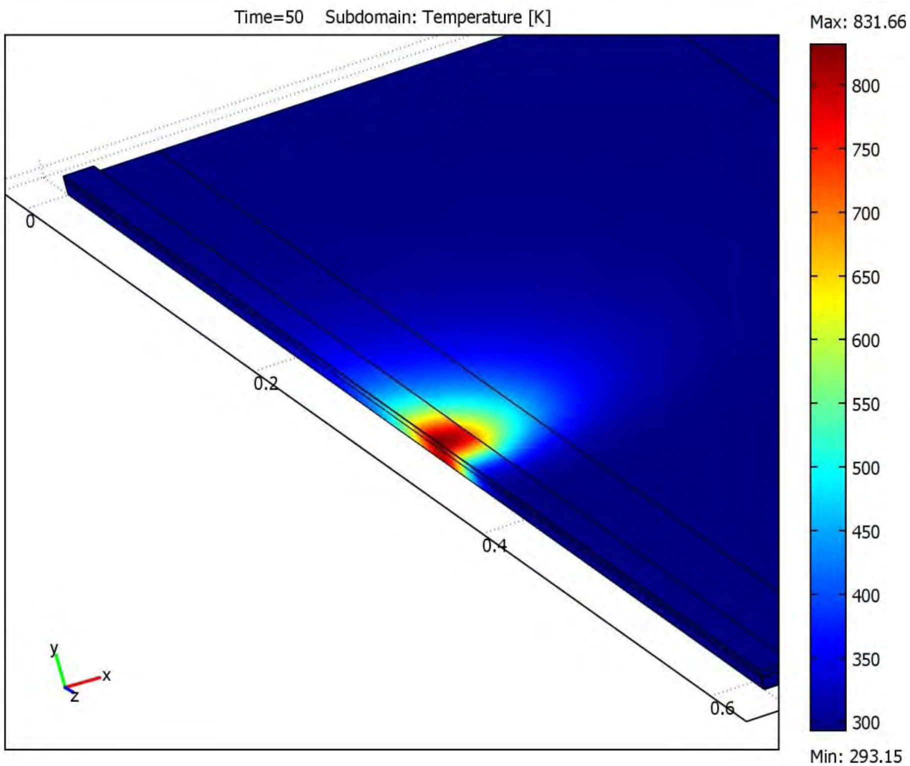
Data point are taken from Ref. 4 and than interpolated using the picewise cubic method embedded in COMSOL Multiphysics.

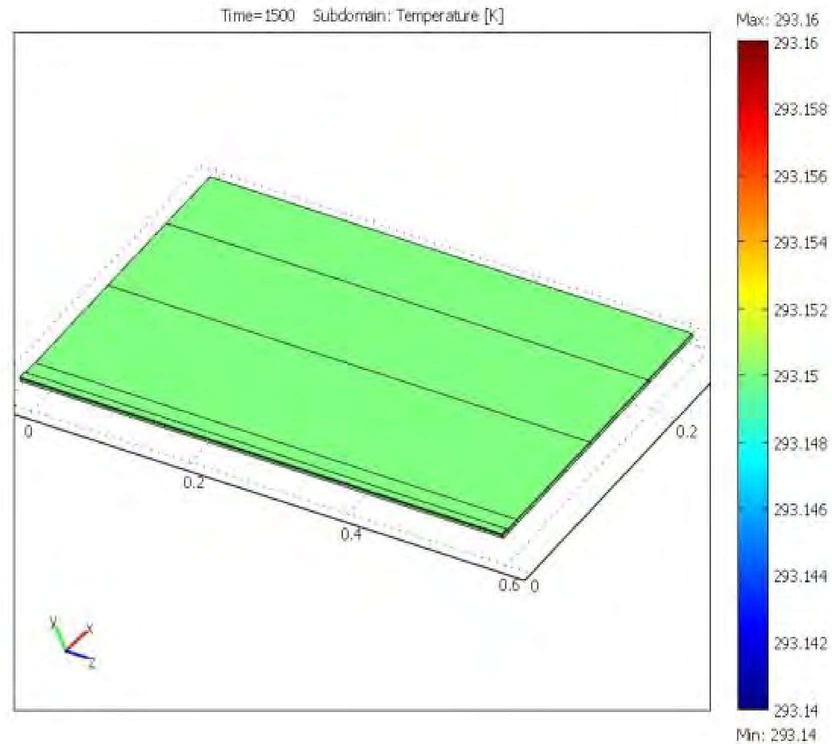
Model Description: Boundary Conditions



- 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

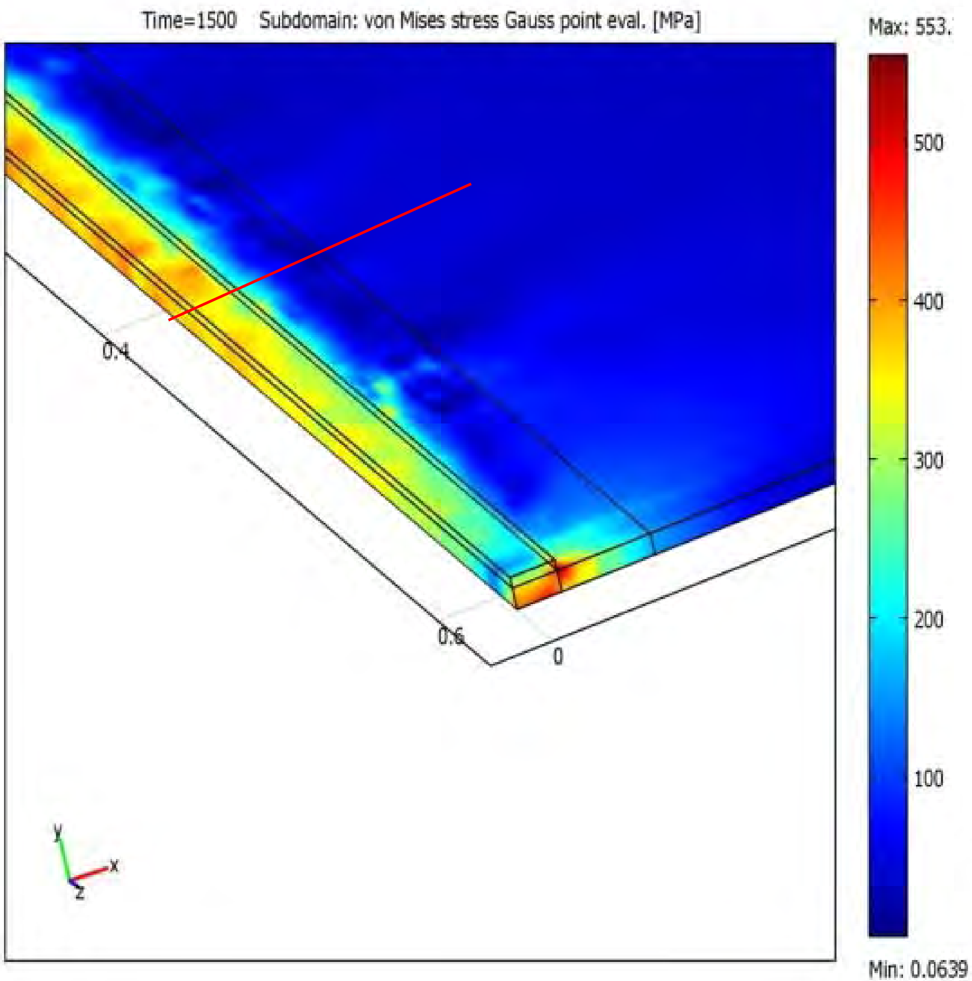
Results: Temperature Distribution

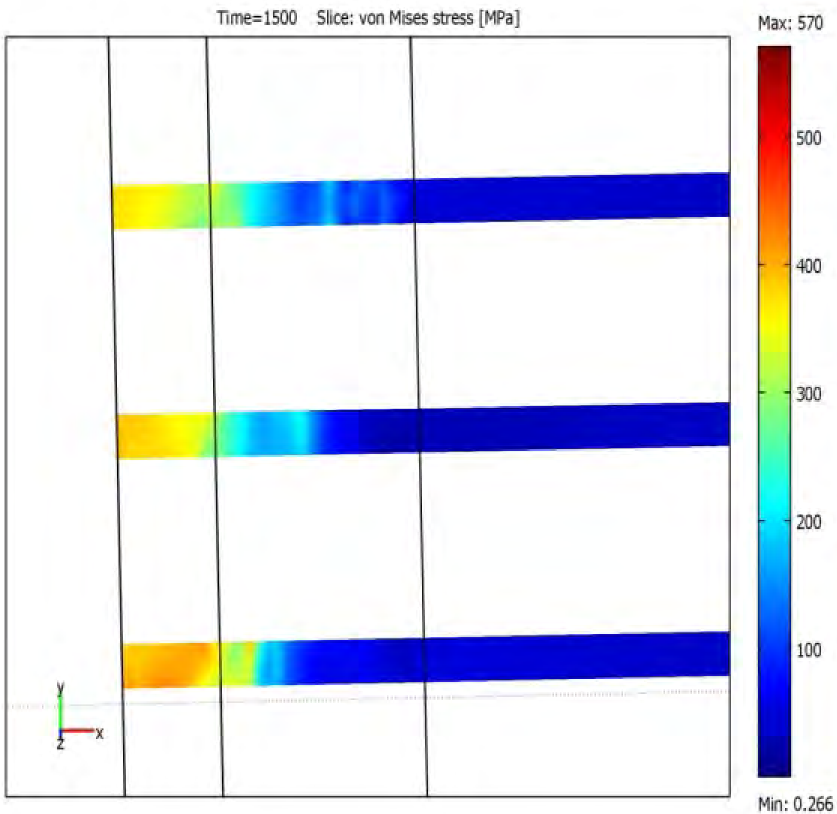




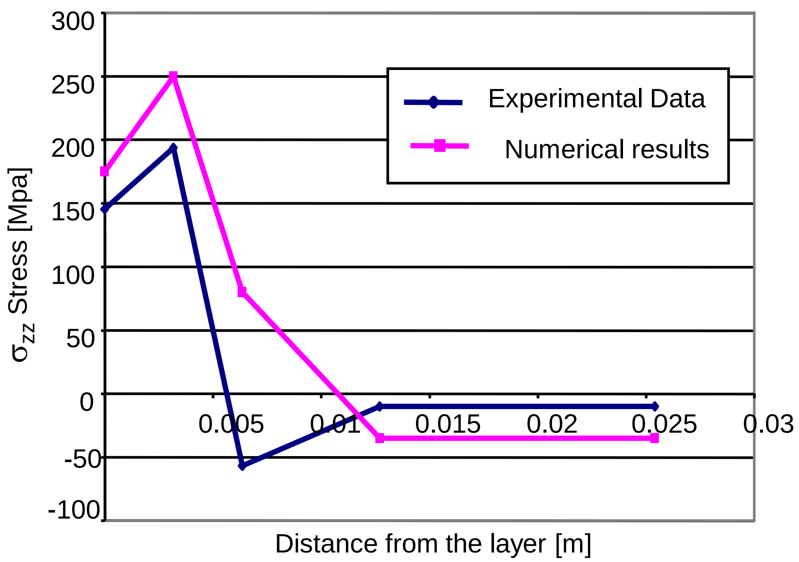
Results for the speed of 6.7 mm/s

Results: Von Mises Residual Stresses





Results



Comparison of Experimental Data (NASA) and Numerical COMSOL Results

Speed in mm/sec	VM max in MPa
6.7	310
10	350
13.4	325

h in $W.m^{-2}.s^{-1}$	VM max in MPa
500	360
1000	350
1500	325
2000	305

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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