Distortion and Residual Stress Control in Integrally Stiffened Structure Produced by Direct Metal Deposition

Shih-Yung Lin, Ph.D., Lockheed Martin Mission Service
Eric Hoffman, Marcia Domack, NASA Langley Research Center, Hampton VA

AeroMat 2007
June 27, 2007
Outline

• **Background and Objectives**
• DMD Process – Electron Beam Freeform Fabrication (EBF$^3$)
• Analytical and Experimental Approaches
• Results
• Summary and Future Plans
Integrally Stiffened Structure for Aerospace Applications

Features:
- Tailored stiffener arrays
- Near-net-shape fabrication
- Multi-functional novel designs

Benefits:
- Reduced cost, weight, part count, assembly time
- Enhanced structural performance

Fabrication:
- Machining
- Direct Metal Deposition
- Joining Methods
Objectives

- Use FEA results to guide development of Direct Metal Deposition (DMD) fabrication process for aerospace structures
- Develop experimental methods to control distortion and residual stresses in integral structure produced by DMD
- Understand the effects of geometry, boundary conditions, and processing parameters on distortion and residual stresses in integral structures produced by DMD
Outline

- Background and Objectives
- **DMD Process – Electron Beam Freeform Fabrication (EBF³)**
- Analytical and Experimental Approaches
- Results
- Summary and Future Plans
Electron Beam Free Form Fabrication (EBF$^3$)

- Direct metal deposition process
- Focused electron beam to create a molten pool on a metallic substrate
- Metallic wire fed into molten pool created by electron beam
- Substrate translated with respect to the electron beam to build up 3-D parts layer by layer
- Metallic parts build directly from CAD files without molds or tooling
EBF³ System

Computer Control System

42 kW EB Gun

Vacuum Chamber

Dual Wire Feeders

Tilt/Rotate Positioner

Website:  http://ebf3.larc.nasa.gov
Fabrication of Single-Blade Stiffened Panel Using EBF$^3$ Deposition Process

Fabrication Arrangement

- Electron Beam
- Wire Feed Nozzle
- Blade Stiffener
- Clamps

Completed Panel

- Blade Stiffener
- Build Plate

Build Plate
- Al 2219-T8
- 0.190 in. thick

Wire
- Al 2319

Panel Distortion
- Transverse (across width)
- Axial (lengthwise) curvature
Outline

• Background and Objectives
• DMD Process – Electron Beam Freeform Fabrication (EBF³)
• Analytical and Experimental Approaches
• Results
• Summary and Future Plans
Finite Element Approach

- PATRAN and NASTRAN FEA software
  - 2-D plain strain model
- Transient thermal analysis
  - To determine temperature profiles at any instance
- Thermal-mechanical analysis, nonlinear
  - To determine mechanical strain, stress, and distortion based on temperature change and boundary conditions
  - Elastic / perfect plastic material, temperature dependent
- Repeat transient thermal and thermal-mechanical analysis for each deposited layer
- Mechanical analysis, linear
  - To determine the effects of clamp release
Finite Element Approach – cont.

- All intrinsic processing parameters held constant:
  - wire feed speed, voltage, beam current, translation speed

- Experimental data used to supplement boundary conditions
  - melt pool depth and width
  - temperature profile
  - residual stresses and distortion

- Single-variable parametric study
  - Number of build deposit layers
  - Clamp position / clearance
  - Plate thickness
  - Machined build lands
  - Elastic/plastic pre-strain
  - Selective pre-heating / cooling / insulation
Material: Aluminum 2219-T81 base plate and 2319 Al weld wire

Deposition Temperature = 1200°F (latent heat fusion ignored; melt pool size increased)

Room Temperature = 70°F

Yield Stress = 50 ksi (temperature dependent)

Young’s Modulus = 10.5 Msi (temperature dependent)

Poisson’s Ratio = 0.33

CTE = 12.4E-6 in/in/°F
Experimental Approach

- All intrinsic processing parameters held constant:
  - wire feed speed, voltage, beam current, translation speed

- Single-variable parametric study
  - Number of build deposit layers
  - Clamp position / clearance
  - Plate thickness
  - Machined build lands
  - Elastic / plastic pre-strain
  - Selective pre-heating / cooling / insulation

- Measurements to determine effect of parametric study on panel distortion and residual stresses and to validate FEA
  - Melt pool depth
  - Temperature distribution
  - Residual stresses
  - Panel distortion
Outline

- Background and Objectives
- DMD Process – Electron Beam Freeform Fabrication (EBF³)
- Analytical and Experimental Approaches
- Results
- Summary and Future Plans
Melt Pool Geometry and Temperature Profile Measurements

- Experimental measurements for FEA input parameters

  - Melt pool depth estimated at 0.015 in.
  - Multiple cross sections of single and two layer builds
  - Based on maximum depth

  - Thermocouples embedded from back side of build substrate
  - Terminate at various depths below surface
  - Placed on and adjacent to build line
Experimental Measurement of Melt Pool Temperature

- Test 1, TC 0.025" underneath surface
- Test 2, TC 0.025" underneath surface and 1/4" from center line

Cleaning Pass

1st Build Layer

2nd Build Layer
Distortion as a Function of Number of Build Deposit Layers

- FEA, 1 deposit layer
- FEA, 2 deposit layers
- FEA, 3 deposit layers
- FEA, 4 deposit layers
- FEA, 5 deposit layers
- FEA, 6 deposit layers
- Exp., multi-layer deposit

Y-Displacement (inch) vs. Distance from Build Centerline (inch)
In-plane Stress ($\sigma_x$) Distribution
(Single layer deposit; 1 in. clamp clearance)
Residual Stress Distribution
ASTM E837 (Hole Drilling)

![Graph showing residual stress distribution](image)
Distortion as a Function of Clamp Clearance

- FEA, 3 layers, 1 in. clamp clearance
- FEA, 3 layers, 2 in. clamp clearance
- FEA, 3 layers, 3.5 in. clamp clearance
- Exp., multi-layer, 1 in. clamp clearance
- Exp., multi-layer, 3.5 in clamp clearance
In-plane Stress ($\sigma_x$) Distribution
(Clamped at 1.0 in or 3.5 in. from Build Centerline)
Distortion as a Function of Plate Thickness
(clamped at 1.0 in. from build centerline)
Build Plate with Machined Build Land

Machined build plate

Detail A

0.060 in build land  0.030 in build land
Build Plate with Machined Build Land

- Plane of symmetry
- Layers of deposition
- Machined landing
- Substrate
- Clamp
Distortion as a Function of Machined Build Land Height

Y-Displacement (inch) vs. Distance from Build Centerline (inch)

- FEA; No landing
- FEA; 0.040 in. high
- FEA; 0.080 in. high
- FEA; 0.120 in. high
- Exp.; 0.030 in. high
- Exp.; 0.060 in. high
In-plane Stress ($\sigma_x$) Distribution With and Without Build Land

No Build Land

0.04 in. Build Land

1 in. clamp clearance

CL

psi

54000.
46800.
39600.
32400.
25200.
18000.
10800.
3600.
-3600.
-10800.
-18000.
-25200.
-32400.
-39600.
-46800.
-54000.
Elastic / Plastic Pre-strain Setup

- Clamp
- Substrate
- Steel bar
- Platen

Clamp

Substrate

Steel bar

Platen
Effect of Pre-strain on Panel Distortion
(clamped at 3.5 in. from build centerline)
Distortion as a Function of Build Plate Pre-heat Temperature

![Graph showing distortion as a function of build plate temperature]
Effect of Localized Cooling on Panel Distortion
(Cooled at Bottom of Build Plate to 50°F, 70°F and 90°F)
Summary of Experimental Results on Panel Distortion

![Graph showing Y-Displacement (inch) vs. Distance from Build Centerline (inch)]

- Baseline
- Active cooling
- Pre-heat
- Pre-strain
- Build land; 0.030
- Build land, 0.060
Outline

• Background and Objectives
• DMD Process – Electron Beam Freeform Fabrication (EBF³)
• Analytical and Experimental Approaches
• Results
• Summary and Future Plans
Summary

- **2-D thermo-mechanical model developed to characterize distortion and residual stresses in integral structure produced by DMD**
  - Demonstrated as a tool to guide experimental development of DMD fabrication process for aero structures

- **Distortion and residual stresses are local to deposit**
  - Most distortion develops during deposition of the first few layers;
  - Little change in distortion or residual stresses after fifth deposit layer
  - Most of distortion is localized just beneath the build

- **Thicker build plates and the use of build lands results in greatest decrease in levels of distortion**

- **Pre-straining shown to reduce distortion**
  - Difficult to implement, particularly for complex stiffener arrays

- **Clamp position has complex effect on distortion and stresses**
  - Overall distortion reduced with decreasing clamp clearance
  - Larger clamp clearances induce bending

- **Use of pre-heat and active cooling show minor influence on panel distortion**
  - Generate changes in thermal gradients in the build plate
Future Plans

- Refinements to the FEA Model including
  - 3-D analysis
  - Additional alloy systems
  - Document procedures for the FEA process

- Experiments involving DOE on intrinsic processing parameters
  - Beam power
  - Accelerating voltage
  - Wire feed speed
  - Translation speed

- Use of vibratory stress relief