Agile Production of Sheet Metal Aviation Components Using Disposable Electromagnetic Actuators

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Basics of Electromagnetics

- **Induction**
  - Current creates a magnetic field → “Induces” current in adjacent metal

- **Magnetism**
  - Current in opposite directions → Repulsion

- These principles are the basis of electromagnetic forming
Electromagnetic Forming

- Capacitor bank stores electrical energy
- Energy supplied to actuator through high current switch
- Induces a current in workpiece → Strong repulsive force
Electromagnetic Forming Benefits

- Agile
  - Only significant capital cost is capacitor bank
  - Single-sided tools
  - Flanging, drawing, shearing, embossing, ring expansion/shrinking
    - Requires only new coil, die

- Increased formability
  - High Strain Rate Forming
  - Formation of more complex part designs
  - Can often form in T6 (full-hard) condition

- Hybrid Forming (Traditional + Electromagnetic)
Introduction to Components

- "Flanged"
  - Material: AA-6061
  - Temper Condition: T6
  - Sheet Thickness: 1.6 mm
  - Convex Area
  - Flat Area
  - Joggles

- "Curved"
  - Material: AA-6061
  - Temper Condition: T6
  - Sheet Thickness: 0.64 mm
  - Part Radius $R$: 69.85 mm
  - $R$
Effects of Experiment Variables

![Graph showing the relationship between formed radius and charging energy for different actuators and tool radii.](image)

**A**

- **Axes:**
  - Y-axis: Formed Radius $R$ in mm
  - X-axis: Charging Energy in kJ

- **Legend:**
  - Formed with 1 in. actuator
  - Formed with .5 in. actuator
  - Tool radius
  - Only preformed

**B & C**

- Images showing the effect of increasing charging energy on EMF formed samples with .5 in. actuator and 1 in. actuator.

**D**

- Image illustrating a formed object with a radius $R$. 

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**Notes:**
- The graph illustrates how varying the charging energy affects the formed radius for different actuators and tool radii.
- Increasing charging energy leads to a decrease in formed radius for both EMF-formed and non-EMF-formed samples.
- The tool radius significantly impacts the formed radius, with smaller tool radii resulting in smaller formed radii.
Conclusions – Curved Component

- Up to 87% of springback in the part was eliminated
  - Target radius – 70 mm
  - In experiments, radius reduced from 310 mm to 101 mm
- Narrow coils lead to greater maximum forming, wide coils lead to more consistent and controllable results
- Target radius was not achieved
  - More robust coils for higher forming energy
  - Coil designs that form the part in the middle as well as edges
1. Optimization of the current production process for the example part
   – Decreasing the production costs
   – Reducing lead time
   – Eliminating manufacturer reliance on external certified vendors (i.e. heat treatment)

2. Development of a production method for parts with similar geometric properties to the example part
   – Easily adaptable to similar shapes (Agile Hybrid Metal Forming)
Current Production Process

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- Cutting of the blanks
- Annealing blanks to T0 condition
- Hydroforming
- Hardening to T6 condition
- Manual calibration
- Packing and shipping to customers
- External vendor
- CDi
The Problems

- Eliminating the two heat treatment steps (forming at a T6 condition)
  - Problem: crown, wrinkles and springback
  
  
  Solution: electromagnetic calibration after hydroforming
Single shot coil

Material:
AA6061 covered with Kapton tape

Thickness: 0.02 inch

Advantages and disadvantages:
- Cheaper than copper
- Lower tooling costs (possible to laser cut)
- Lower conductance than copper
Flanged Component Setup

Coil (connects to the capacitor bank)

Die

Blank holder

Rubber pad
Flanged Component Results

**Before EMF Calibration:**

- C
- Wrinkle
- Crown

**Deviations from target geometry:**
- 6.6% ± 2.0 mm
- 10.93% ± 1.5 mm
- 13.22% ± 1.0 mm
- 16.62% ± 0.5 mm
- 30.22% ± 0.0 mm
- 16.07% ± 0.5 mm
- 4.57% ± 1.0 mm
- 1.01% ± 1.5 mm
- 0.61% ± 2.0 mm
- 0.15% ± 2.0 mm

**Effect of Charging Energy and Tool Material**

- Deviation less than ± 2.0 mm:
  - 100%
  - 90%
  - 80%
  - 70%
  - 60%
  - 50%
  - 40%
  - 30%
  - 20%
  - 10%
  - 0%

- Charging Energy in kJ:
  - 0
  - 3.0
  - 4.0
  - 5.0
  - 6.0
  - 7.0

- Press Force: 2000 lbs

**After EMF Calibration:**

- Deviation from target geometry:
  - 0.24% ± 1.0 mm
  - 3.31% ± 0.5 mm
  - 40.97% ± 0.0 mm
  - 55.42% ± 0.5 mm
  - 0.06% ± 1.0 mm

- Charging Energy: 4.8 kJ
- Press Force: 2000 lbs

- Calibrated with EMF (steel tool)
- Calibrated with EMF (Garolite® G10)
- Only preformed
Visual Comparison

Hydroformed part

Calibrated part
Visual Comparison

Part Accuracy Increases with:

- Increasing charging energy
- Softer tool material (Garolite G-10)
- Press force had little effect on final shape
Conclusions – Flanged Component

- Reduced springback
- No wrinkles
- Shape nearly within specifications (including joggles)
- Average part angle at the flange – 90.3 (Target was 90)

- Crown not completely eliminated, but within specifications
New Method – Exploding Foil Forming

- Capacitor bank discharges large current into actuator
- Actuator transfers current to metal foil
- Foil explodes due to large current, creating a high-pressure wave
- Pressure wave pushes flyer into part at high velocity
Results – Exploding Foil Forming

Part is completely within dimensional tolerances

- Part remains in T6 temper condition throughout entire process – no heat treatment required
- Exploding foil process shows significant improvements over hydroforming or electromagnetic forming

Hydroforming only:

Hydroforming then explosive foil calibration:
Conclusions

• Electromagnetic calibration using disposable actuators is a feasible approach

• There is clear room for improvement relative to current production processes

• The use of electromagnetic forming or explosive forming techniques allow complex parts to be formed in the T6 (full-hard) condition

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