Scaling up of Equal Channel Angular Pressing (ECAP) for the Production of Forging Stock

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Severe Plastic Deformation (SPD)

- SPD refers to a “new” class of mechanical deformation processes that imparts large plastic strains
  - ECAE/P, HPT, MAC, FSP, ARB …
- Strains of the order of 4 or greater have been shown to result in grain refinement to produce ultra-fine grained (UFG) microstructure
- Fine grain (< 10 μm) materials exhibit superplastic behavior at high temperatures and slow strain rates
- Ultrafine grain (UFG) materials would exhibit superplastic behavior at lower temperature and higher strain rate.
Potential Benefits of Ultrafine grain (UFG) Microstructures

- Processing
  - Lower secondary forming temperature
  - Lower load or pressure for forging and extrusion
  - Increased die life
  - Decreased tonnage requirement for presses
  - Increased material yield in forgings
  - Fewer intermediate steps in forging complex shapes
  - Nearer to net shape forgings \(\Rightarrow\) Reduced machining
  - Improved machinability

- Service
  - Higher strength and better fatigue properties with fine microstructure
  - Ability to design lighter components with ultrafine grain materials.
Very extensively investigated process

Route $B_C$ (90° rotation between passes) produces equiaxed submicron size grains

Billet sizes from 10 mm to 50 mm cross section from a variety of materials (several Al alloys, steels, Mg alloys, Ti alloys)

$$\varepsilon = \left[ \frac{2 \cot \left( \frac{\Phi}{2} + \frac{\Psi}{2} \right) + \Psi \csc \left( \frac{\Phi}{2} + \frac{\Psi}{2} \right)}{\sqrt{3}} \right]$$


Objectives

- Scale up the ECAP process
  - Increase cross section to produce “industrial” sizes
- Demonstrate benefits of using SPD-UFG stock material in hot forging
  - Decreased forging temperature
  - Improved hot forging metal flow
  - Reduced forging stock size
  - Energy savings
Scale-up to Large Cross Section

- Commercially available AA6061
  - 12.5, 50, and 100 mm (0.5, 2.0 and 4.0 inch) square cross section bars were annealed (500°C, 1hr, FC)
- ECAP Processing
  - Route $B_c$ with 90, 105 and 120° angle dies

<table>
<thead>
<tr>
<th>Channel Size</th>
<th>Channel Angle</th>
<th>Channel Length</th>
<th>Final Billet Size</th>
<th>Accumulated Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5 mm (WSU)</td>
<td>120°</td>
<td>65 mm</td>
<td>$12.5 \times 12.5 \times 50$ mm</td>
<td>Up to 6 passes with ~0.67/pass</td>
</tr>
<tr>
<td>50 mm (AFRL)</td>
<td>90°</td>
<td>200 mm</td>
<td>$50 \times 50 \times 150$ mm</td>
<td>Up to 4 passes with ~1.15/pass</td>
</tr>
<tr>
<td>100 mm (IMCO/GD)</td>
<td>105°</td>
<td>350 mm</td>
<td>$100 \times 100 \times 300$ mm</td>
<td>Up to 4 passes with ~0.89/pass</td>
</tr>
</tbody>
</table>
Scale-up to Large Cross Section

100-mm ECAE/P
Scale-up to Large Cross Section
Scale up to Large Cross Section
Hardness

![Graph showing relationship between accumulated strain and hardness (HRE)]

- Hardness (HRE)
- Accumulated strain
- 12.5 mm
- 50 mm
- 100 mm
Scale up to Large Cross Section
TEM Microstructure

(a) 12.5 mm, ε~4
(b) 50 mm, ε~3.2
(c) 100 mm, ε~3.5
Scale up to Large Cross Section Forging Studies

- Materials Used
  - ECAP
    - 50-mm, 90° die angle, 3 and 4 passes
    - 100-mm, 105° die angle 4 passes
  - Conventional extruded stock
  - Fine-grain cast stock – an alternative source for fine grained stock
- Hot Forging
  - Small forging – 50 mm ECAP, Extruded stock, and Fine-grain cast stock
  - Complex forging – 50 mm ECAP and Extruded stock
  - Large forging – 100 mm ECAP and Extruded stock
- Forging done at Intercontinental Mfg. (IMCO)/General Dynamics
Scale up to Large Cross Section
Forging Studies

Aft cargo door latch forging
“Small forging”

Landing gear door bracket
“Complex forging”

~ 125 mm

~ 100 mm
Scale up to Large Cross Section Forging Studies

50-mm 3-pass ECAP

Forged at 315°C (600°F) 100% stock size

Forged at 370°C (700°F) 85% stock

Conventional Forging

Extruded Stock Forged at 450°C (840°F)

Fine Grain Cast Stock Forged at 443°C (830 °F)

50% reduction in the flash
Scale up to Large Cross Section Forging Studies

First Hit

Second Hit

50-mm 4-pass ECAP forged at 360°C (680°F)

Defect ground off before second hit

Extruded stock forged at 410°C (770°F)
Scale up to Large Cross Section Forging Studies

100 mm 4-pass ECAP 315°C (600°F) 90% stock size

Conventional extruded stock 427°C (800°F) 100% stock size

50% reduction in material scrapped in the trimmed flash
Potential Energy Savings
Time to reach temperature

Temperature, (°C)

Time (hours)
**Potential Energy Savings**

**Furnace gas consumption**

![Graph showing the relationship between temperature and gas consumption for furnace, with different symbols for 100 mm, 150 mm, and 200 mm.]
Potential Energy Savings
Weighted Energy Savings

<table>
<thead>
<tr>
<th>Forging Temperature (°C)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>316</td>
<td>33.7</td>
</tr>
<tr>
<td>371</td>
<td>18.2</td>
</tr>
<tr>
<td>427</td>
<td>8.9</td>
</tr>
<tr>
<td>471</td>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>°F</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>316</td>
</tr>
<tr>
<td>700</td>
<td>371</td>
</tr>
<tr>
<td>800</td>
<td>427</td>
</tr>
<tr>
<td>880</td>
<td>471</td>
</tr>
</tbody>
</table>
Assumptions
- 130 forging plants with an average production of 2 million lb/yr
- Assume material yield is 70%
  - SPD billets reduce scrap by 50%
- ~1800 BTU/lb for heating forging billet
- ~2200 BTU/lb for melting aluminum
- 4% loss as dross, with energy content of 55,000 BTU/lb

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**Scale-up to Large Cross Section Potential Energy Savings during Forging**

<table>
<thead>
<tr>
<th></th>
<th>Energy (BTU/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Consumption</td>
</tr>
<tr>
<td>Heating</td>
<td>4.68E+11</td>
</tr>
<tr>
<td>Remelting</td>
<td>2.45E+11</td>
</tr>
<tr>
<td>Dross</td>
<td>2.45E+11</td>
</tr>
<tr>
<td>Total</td>
<td>9.58E+11</td>
</tr>
</tbody>
</table>

**Projected saving** 40.53%

*Data from Dr. Qingyou Han, ORNL*
Assumptions

- 130 forging plants with an average production of 910,000 kg/yr
- Assume material yield is 70%
  - SPD billets reduce scrap by 50%
- ~4200 kJ/kg for heating forging billet
- ~5100 kJ/kg for melting aluminum
- 4% loss as dross, with energy content of 128,000 kJ/kg

Scale-up to Large Cross Section
Potential Energy Savings during Forging

<table>
<thead>
<tr>
<th>Kg/year</th>
<th>Energy (J/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Consumption</td>
</tr>
<tr>
<td>US Aluminum Forging</td>
<td>1.18E+08</td>
</tr>
<tr>
<td>Current Scrap</td>
<td>5.06E+07</td>
</tr>
<tr>
<td>Reduced Scrap</td>
<td>2.53E+07</td>
</tr>
<tr>
<td></td>
<td>Total</td>
</tr>
</tbody>
</table>

Projected saving: 40.53%
Scale-up to Large Cross Section
Response to T6 Heat Treatment

Aging Time, (hours)

Hardness (HRE)

FG Cast
ECAP
Extruded

Solutionize 521°C (970°F) 3 hr Quench
Hold at RT for 36 hr
Age 177°C (350°F) up to 8 hr
Scale-up to Large Cross Section Properties of Forged Parts

<table>
<thead>
<tr>
<th>Stock Material</th>
<th>Forging Temp.</th>
<th>As Forged Hardness $R_E$</th>
<th>As Forged GS</th>
<th>T6 UTS MPa (Ksi)</th>
<th>T6 YS MPa (Ksi)</th>
<th>T6 Elong. %</th>
<th>T6 GS μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-inch 3P ECAE/P</td>
<td>393°C 740°F</td>
<td>14</td>
<td>5.8 μm</td>
<td>320 (46.5)</td>
<td>297 (43.1)</td>
<td>15.8</td>
<td>31 μm</td>
</tr>
<tr>
<td>4-inch 4P ECAE/P</td>
<td>315°C 600°F</td>
<td>31</td>
<td></td>
<td>319 (46.2)</td>
<td>297 (43.1)</td>
<td>17.7</td>
<td></td>
</tr>
<tr>
<td>Extruded</td>
<td>460°C 860°F</td>
<td>31</td>
<td>20 μm</td>
<td>305 (44.2)</td>
<td>283 (41.0)</td>
<td>16.2</td>
<td>32 μm</td>
</tr>
<tr>
<td>Fine Grain Cast</td>
<td>416°C 780°F</td>
<td>13</td>
<td>50 μm</td>
<td>282 (40.9)</td>
<td>275 (39.8)</td>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td>Minimum Specifications</td>
<td></td>
<td></td>
<td></td>
<td>262 (38)</td>
<td>242 (35)</td>
<td>7.0</td>
<td></td>
</tr>
</tbody>
</table>

Properties and microstructure are as good or better than conventional materials.
Summary

- ECAP can be scaled up to produce “industrial” size billets and used as forging ingots
- SPD AA-6061 has “lived” up to the anticipated benefits
  - Lower forging temperatures
  - Decreased material usage
  - Up to 40% saving in energy used for forging
- Faster heat treatment after forging
- Properties and microstructure same or better than conventional materials.