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

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Severe Plastic Deformation (SPD)

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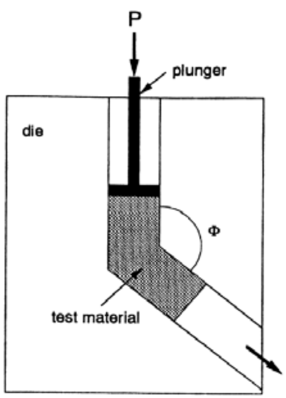
- SPD refers to a “new” class of mechanical deformation processes that imparts large plastic strains
  - ECAE/P, HPT, MAC, FSP, ARB ...
- Strains of the order of 4 or greater have been shown to result in grain refinement to produce ultra-fine grained (UFG) microstructure
- Fine grain (< 10 μm) materials 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.

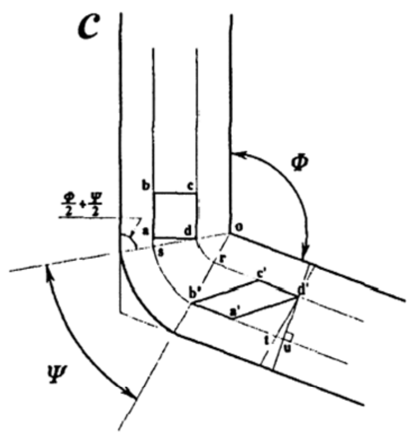
Potential Benefits of Ultrafine grain (UFG) Microstructures

- 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.

ECAP/ECAE

- 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)





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

G.M. Stoica and P.K. Liaw, JOM pp36-40, March 2001
M. Furukawa, et al., in "Ultrafine Grain Materials," R.S. Mishra ed., TMS, p125, 2000

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

Channel Size	Channel Angle	Channel Length	Final Billet Size	Accumulated Strain
12.5 mm (WSU)	120°	65 mm	12.5 × 12.5 × 50 mm	Up to 6 passes with ~0.67/pass
50 mm (AFRL)	90°	200 mm	50 × 50 × 150 mm	Up to 4 passes with ~1.15/pass
100 mm (IMCO/GD)	105°	350 mm	100 × 100 × 300 mm	Up to 4 passes with ~0.89/pass

Scale-up to Large Cross Section

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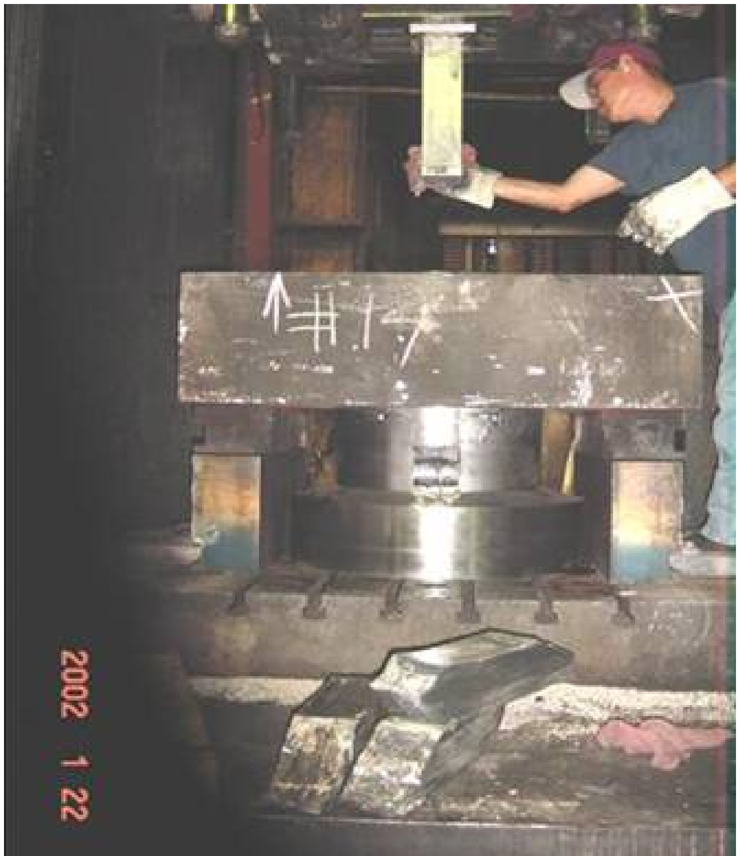
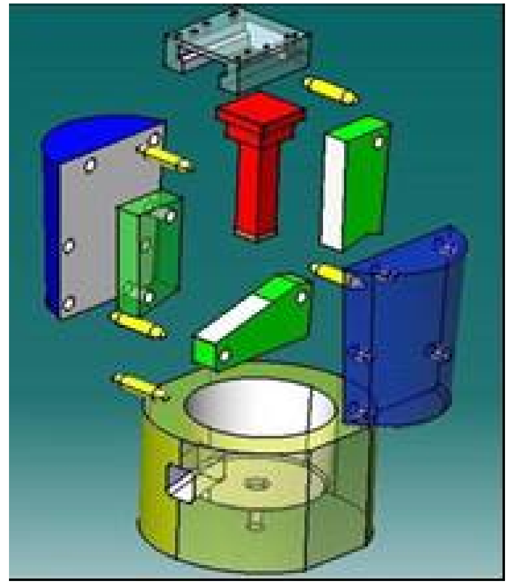
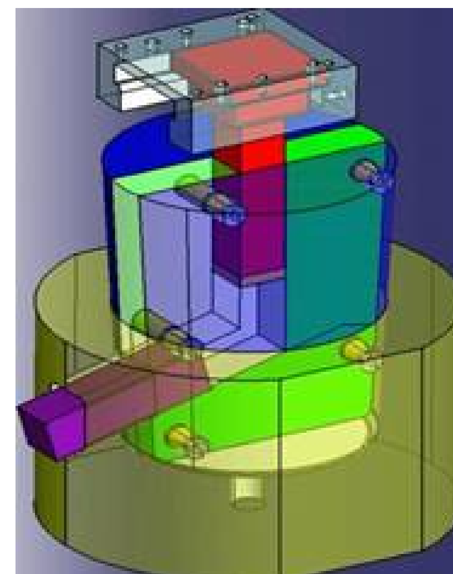


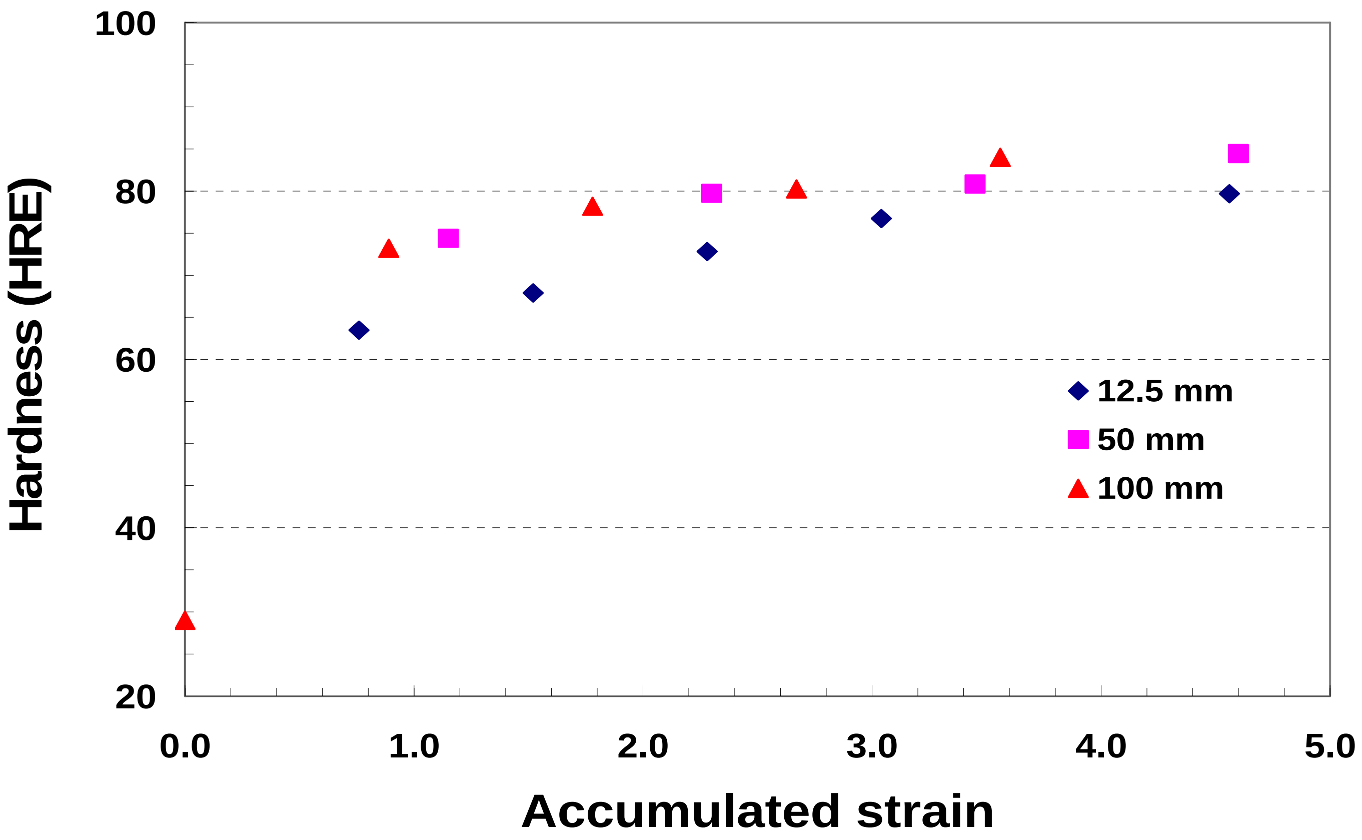




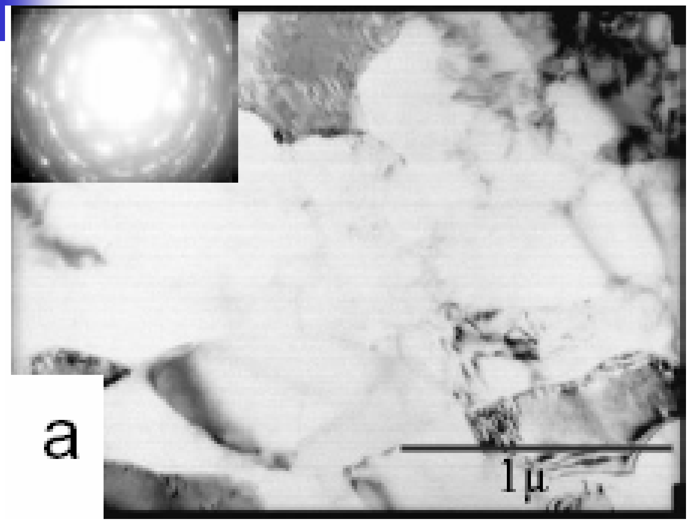
100-mm ECAE/P

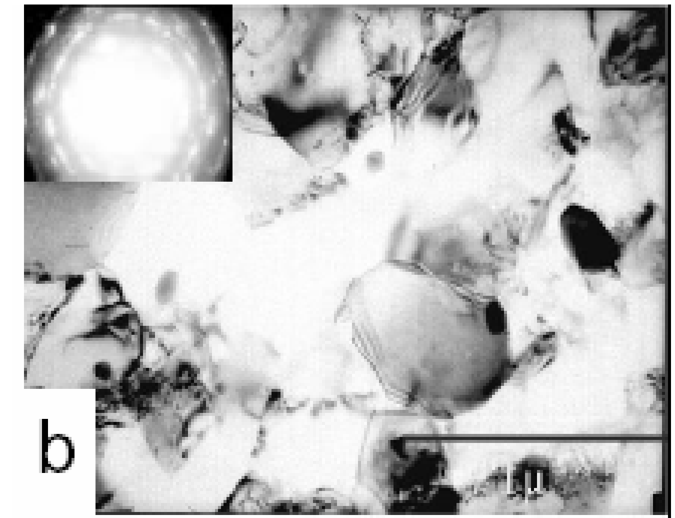
Scale-up to Large Cross Section

Scale up to Large Cross Section Hardness



Scale up to Large Cross Section
TEM Microstructure

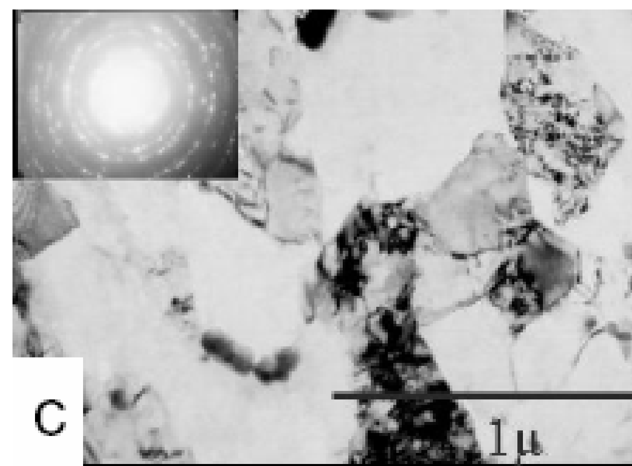




(a) 12.5 mm, ε~4

(b) 50 mm, ε~3.2

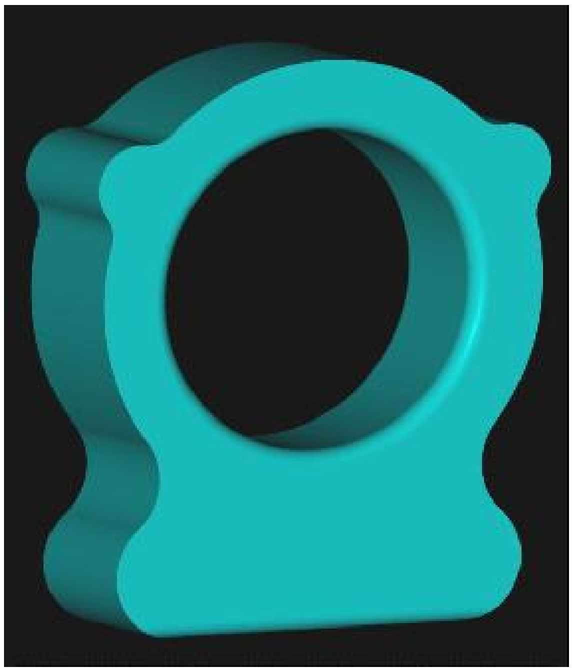
(c) 100 mm, ε~3.5



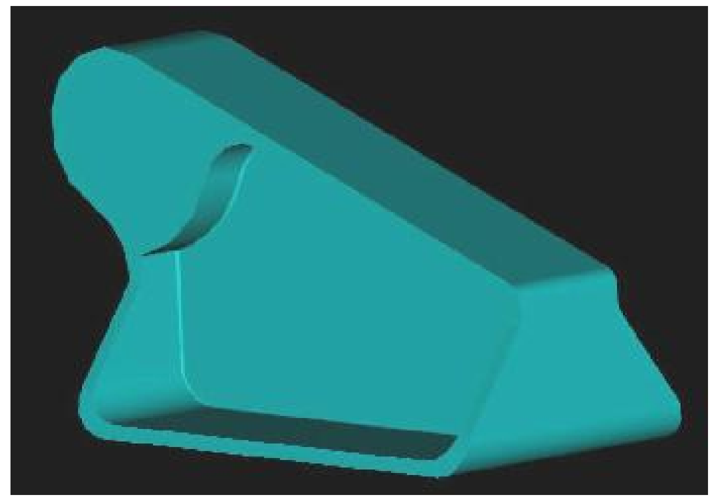
Scale up to Large Cross Section Forging Studies

- 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



~ 125 mm



~ 100 mm

Aft cargo door latch forging
“Small forging”

Landing gear door bracket
“Complex forging”

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

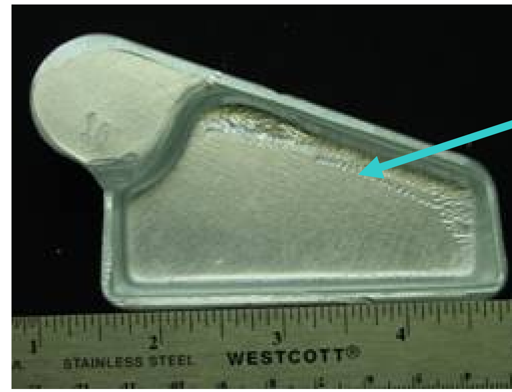
Extruded Stock
Forged at 450°C (840°F)

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



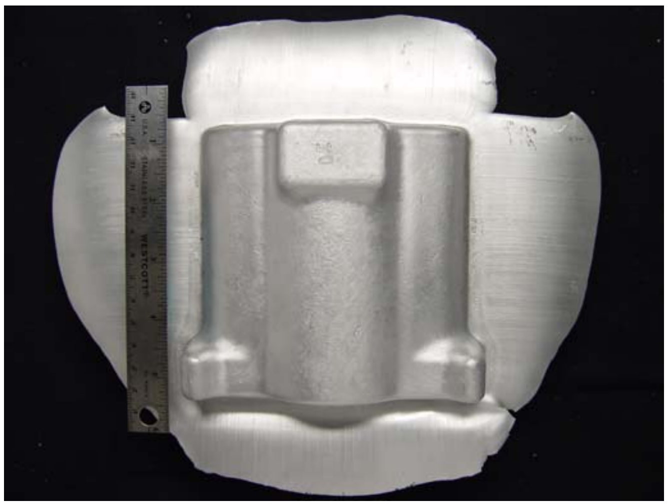
Defect ground off before second hit

Second Hit

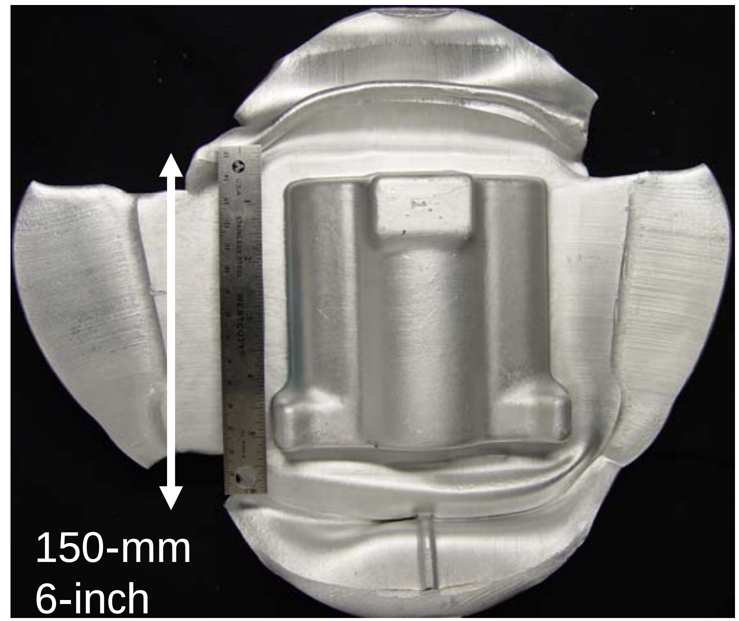
50-mm 4-pass ECAP forged at 360°C (680°F)

Extruded stock forged at 410°C (770°F)

Scale up to Large Cross Section Forging Studies



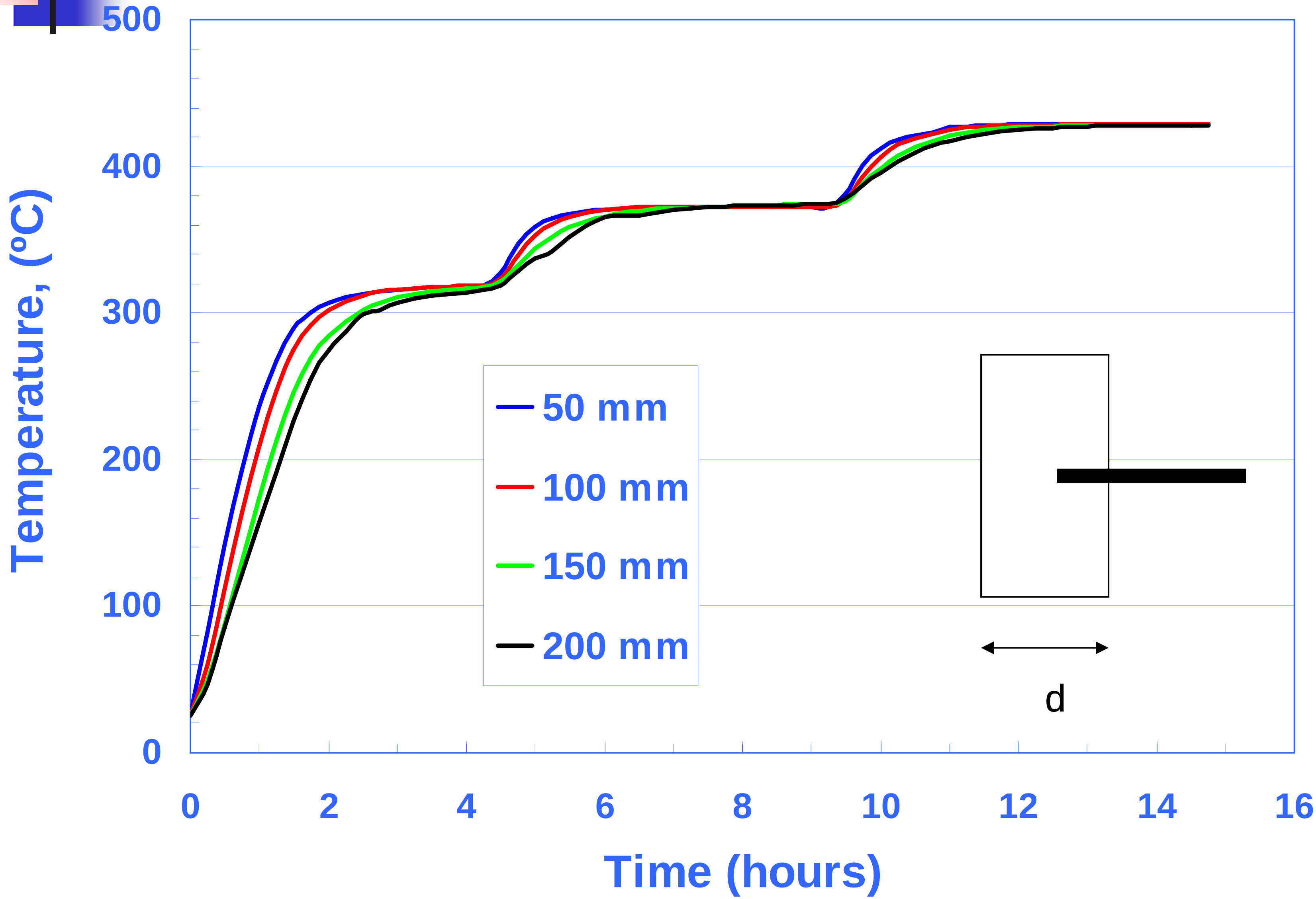
100 mm 4-pass ECAP
315°C (600°F) 90% stock size



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



Potential Energy Savings
Furnace gas consumption

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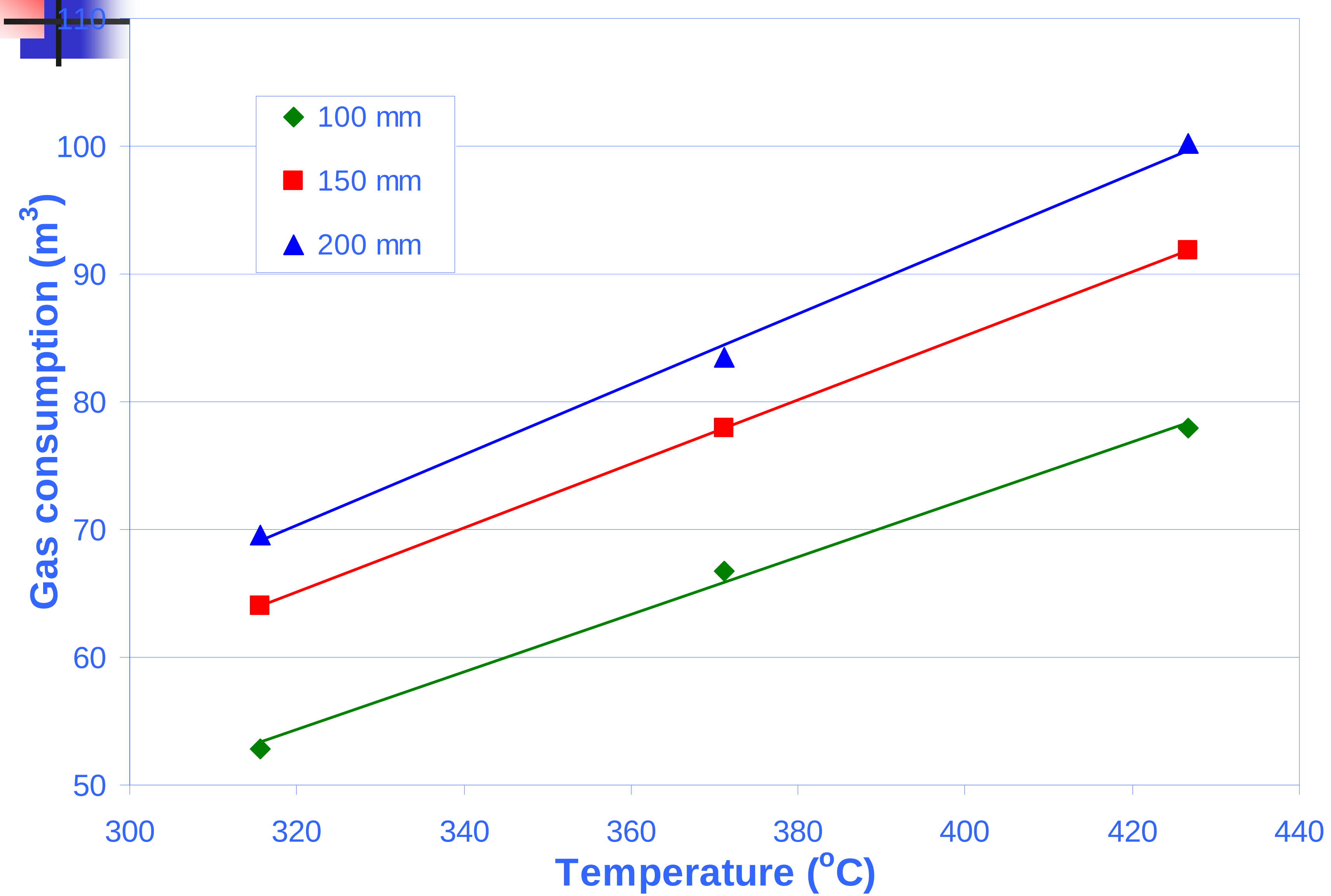
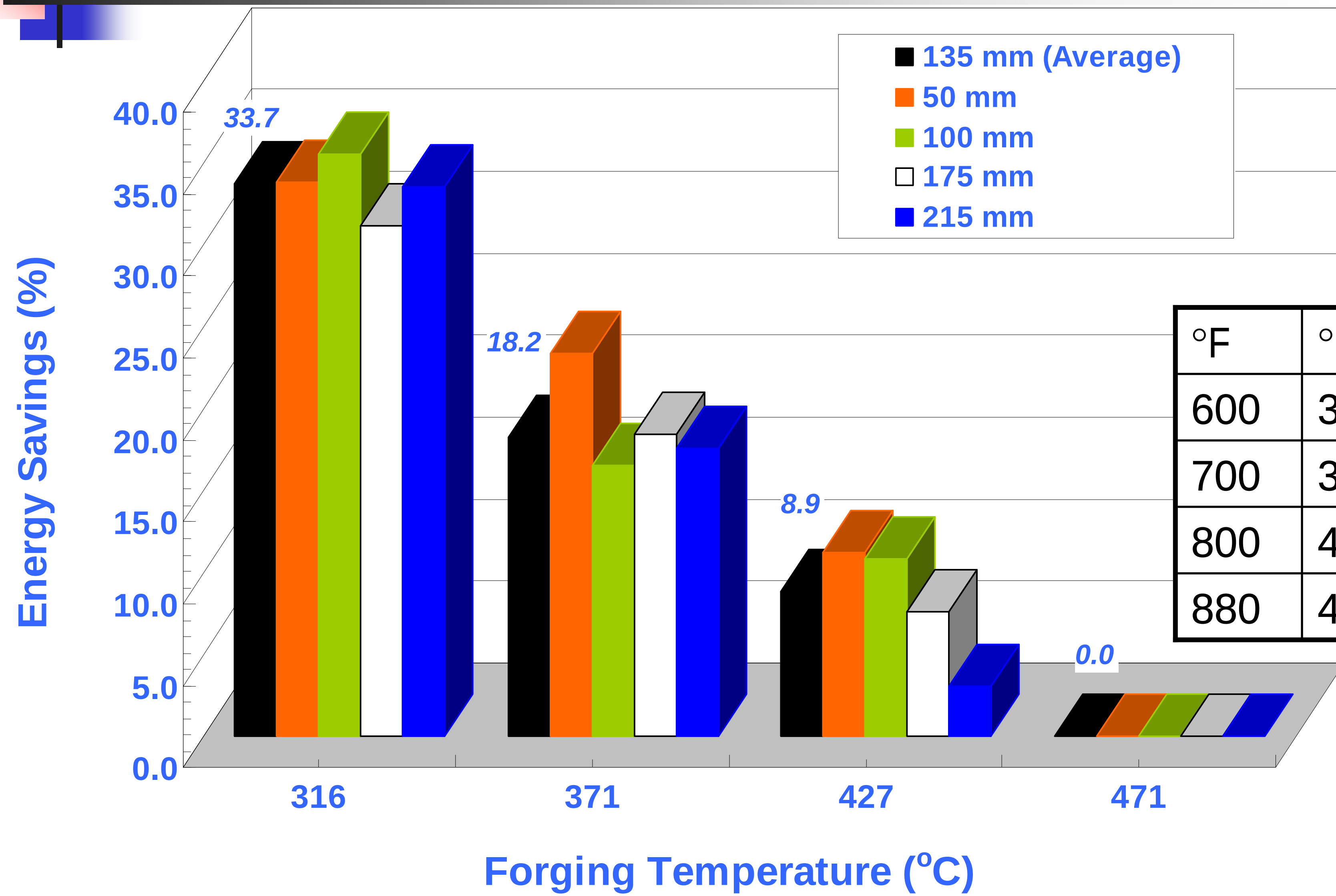


Potential Energy Savings
Weighted Energy Savings



°F	°C
600	316
700	371
800	427
880	471

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

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	lb/year
US Aluminum Forging	2.60E+08
Current Scrap	1.11E+08
Reduced Scrap	5.57E+07

	Energy (BTU/year)	
	Current Consumption	Projected Saving
Heating	4.68E+11	1.54E+11
Remelting	2.45E+11	1.23E+11
Dross	2.45E+11	1.11E+11
Total	9.58E+11	3.88E+11
Projected saving		**40.53%**

- 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

Data from Dr. Qingyou Han, ORNL

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

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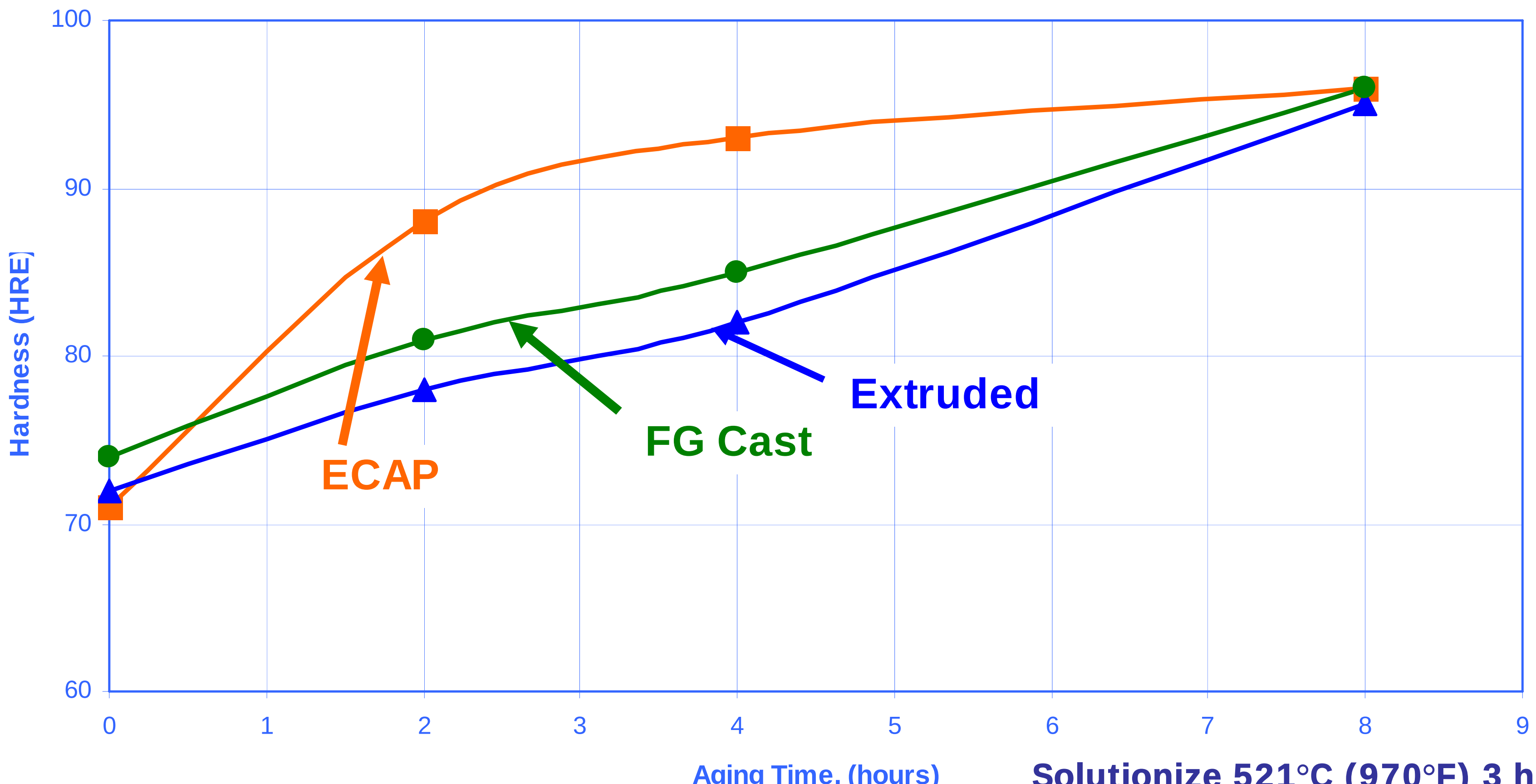
	Kg/year
US Aluminum Forging	1.18E+08
Current Scrap	5.06E+07
Reduced Scrap	2.53E+07

	Energy (J/year)	
	Current Consumption	Projected Saving
Heating	4.94E+14	1.63E+14
Remelting	2.59E+14	1.29E+14
Dross	2.59E+14	1.18E+14
Total	1.01E+15	4.10E+14
Projected saving		**40.53%**

- 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 Response to T6 Heat Treatment



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

Stock Material	Forging Temp.	As Forged Hardness R_E	As Forged GS	T6 UTS MPa (Ksi)	T6 YS MPa (Ksi)	T6 Elong. %	T6 GS
2-inch 3P ECAE/P	393°C 740°F	14	5.8 μm	320 (46.5)	297 (43.1)	15.8	31 μm
4-inch 4P ECAE/P	315°C 600°F	31		319 (46.2)	297 (43.1)	17.7	
Extruded	460°C 860°F	31	20 μm	305 (44.2)	283 (41.0)	16.2	32 μm
Fine Grain Cast	416°C 780°F	13	50 μm	282 (40.9)	275 (39.8)	19.7	243 μm
Minimum Specifications				262 (38)	242 (35)	7.0	

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.