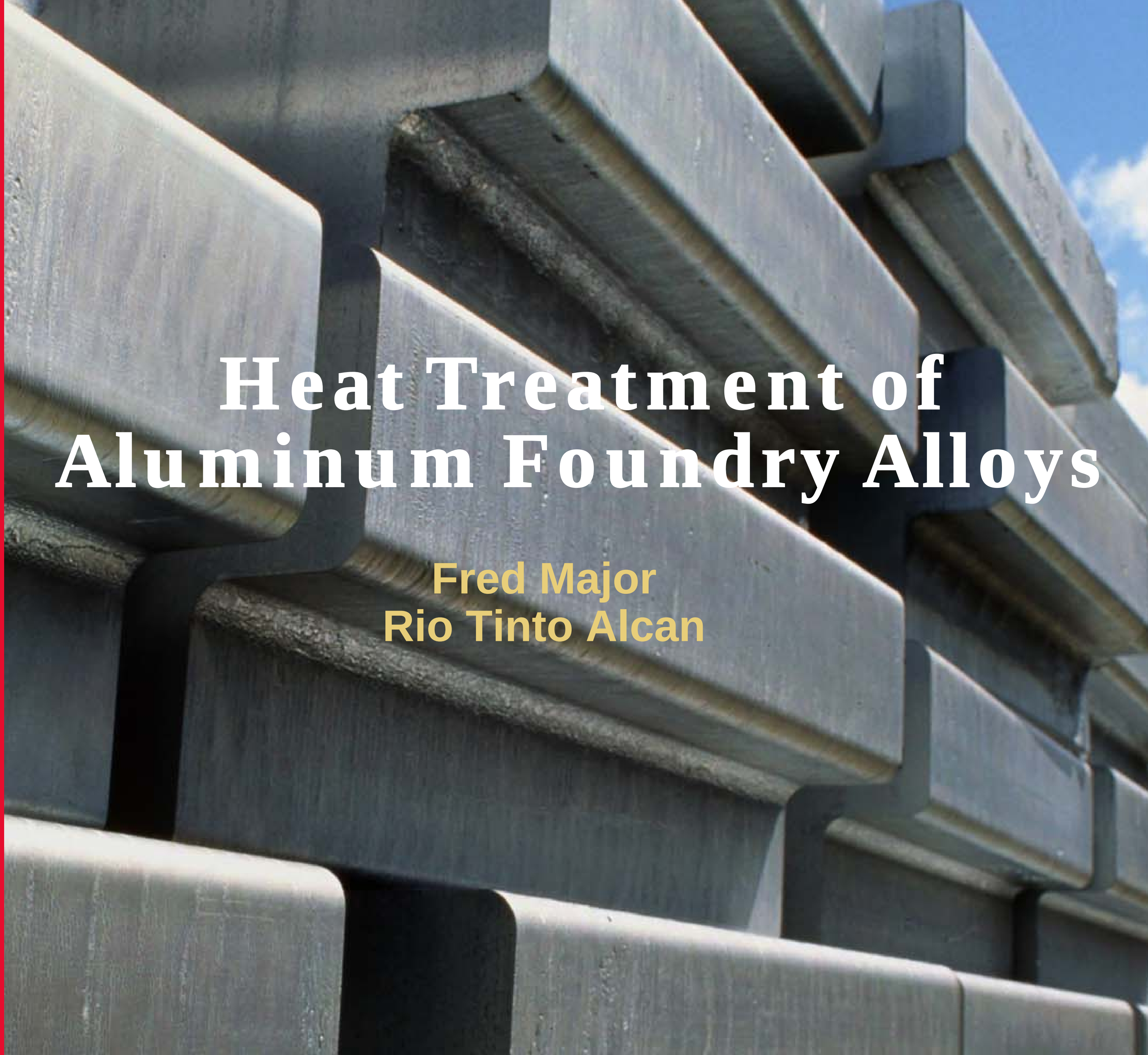

Heat Treatment of Aluminum Foundry Alloys

Fred Major
Rio Tinto Alcan

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OUTLINE

- Basics of Heat Treatment (What is happening to the metal at each step).
  - Atomic Structure of Aluminum – Deformation Mechanisms
  - Strengthening Mechanisms
  - Heat Treatment
    - Solutionizing
    - Quenching
    - Aging
    - Common Tempers
    - Impact of alloy element content and aging temperature
  - Microstructural Effects
    - DAS (ductility) and defect structure (fatigue)
  - Typical spreads encountered in commercial castings
    - USCAR Database examples
  - Quiz
- Alternatives to T6

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Basic Slip Systems in FCC Metals (Aluminum)

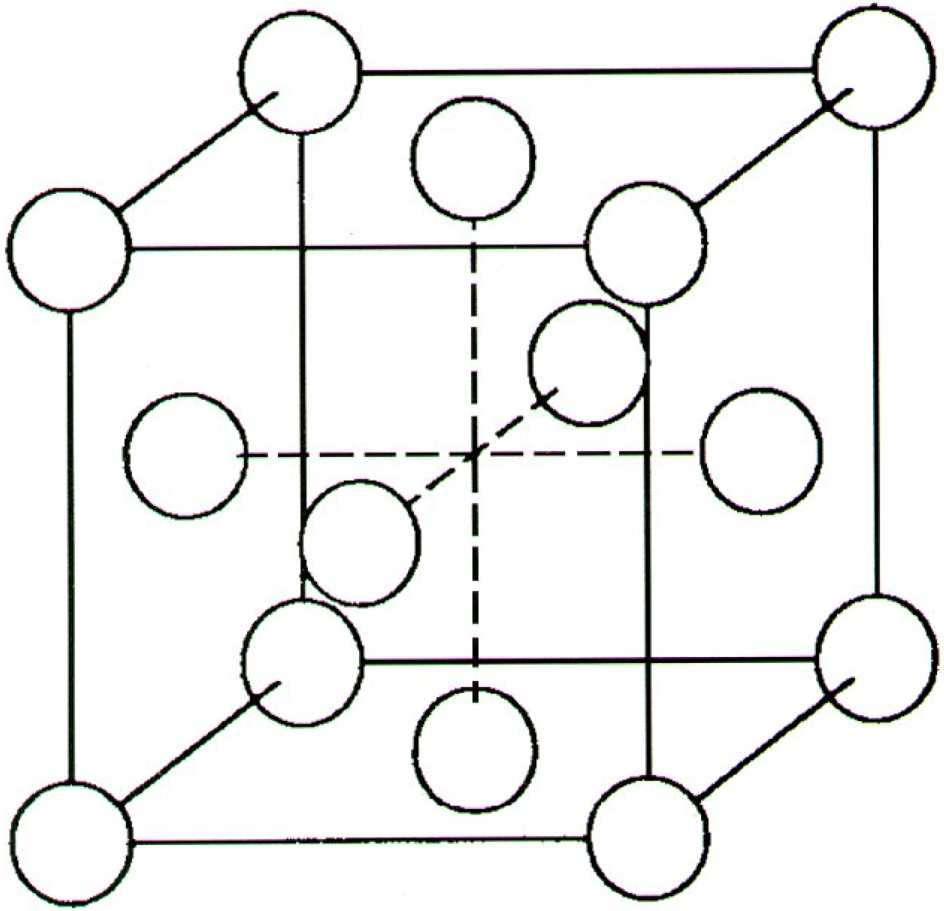
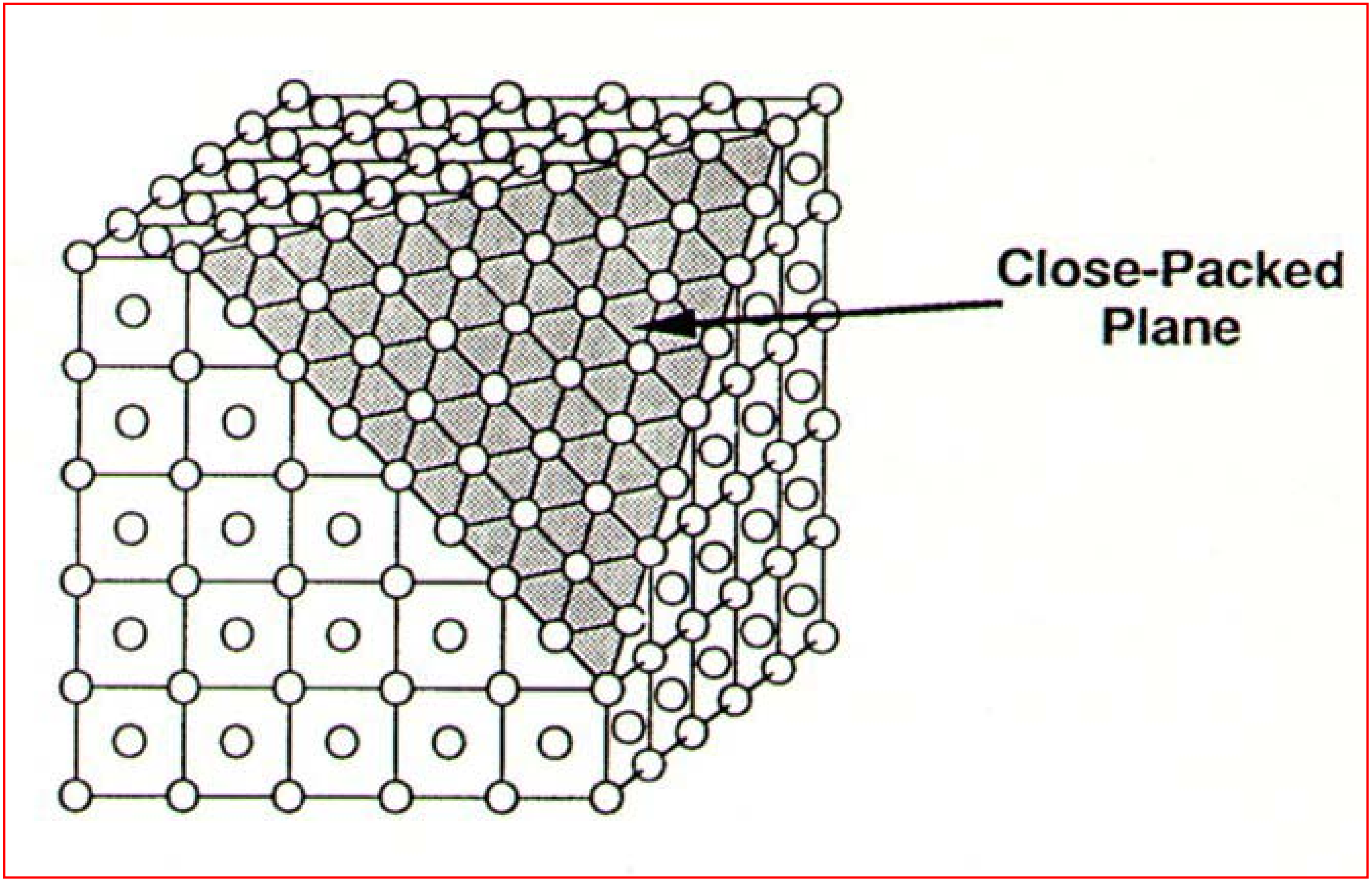


Fig. 15-6. A unit cell of the face-centered cubic (FCC) crystal lattice.

Unit Cell

Basic Slip Systems in FCC Metals (Aluminum)



Metals deform through the motion of layers of atoms, usually along the planes where they are most closely packed together.

Basic Slip Systems in FCC Metals (Aluminum)

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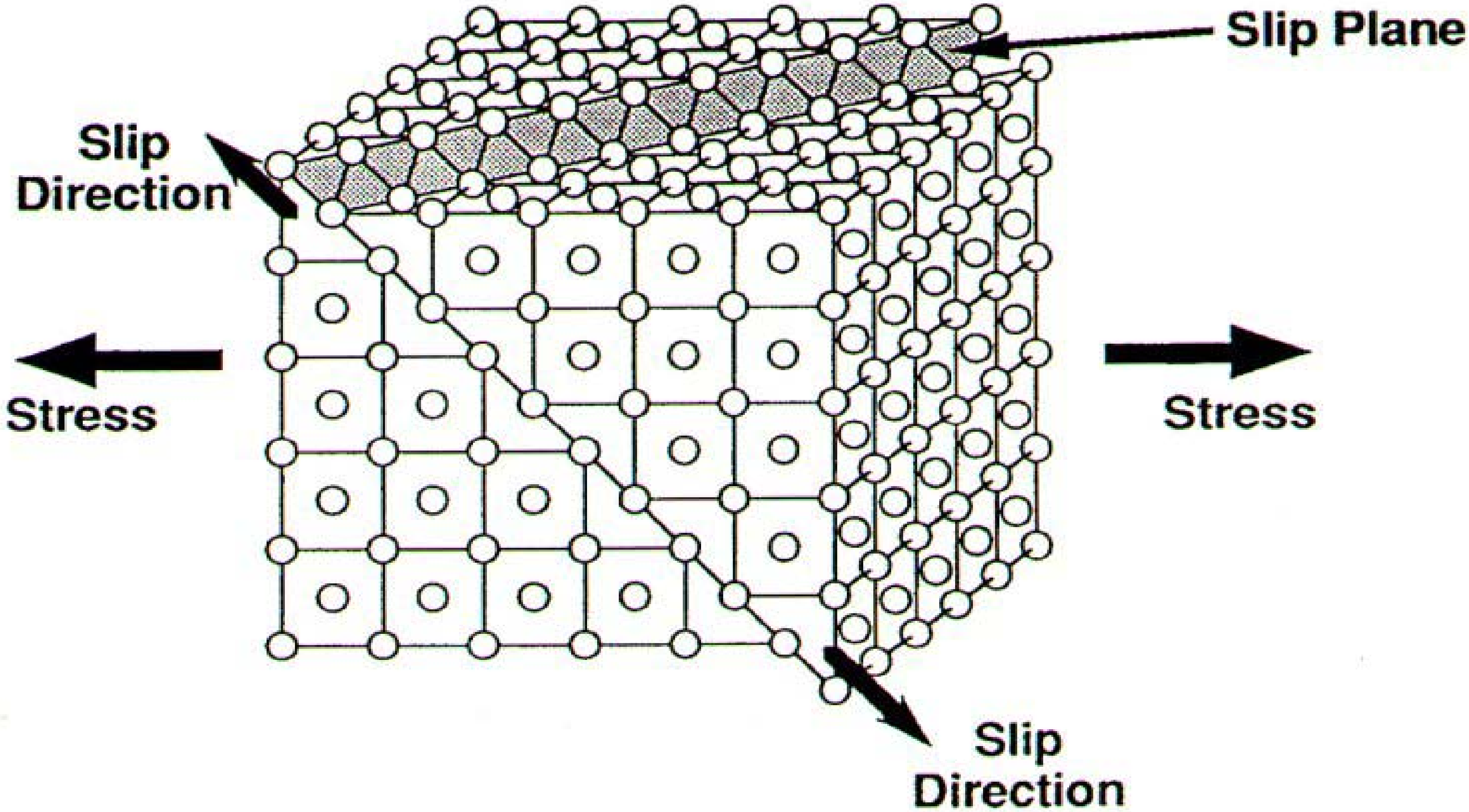

To perform the operation shown above on a perfect crystal would require enormous Force as every bond would have to be broken and reformed.

Metals are not observed to be that strong. Why?

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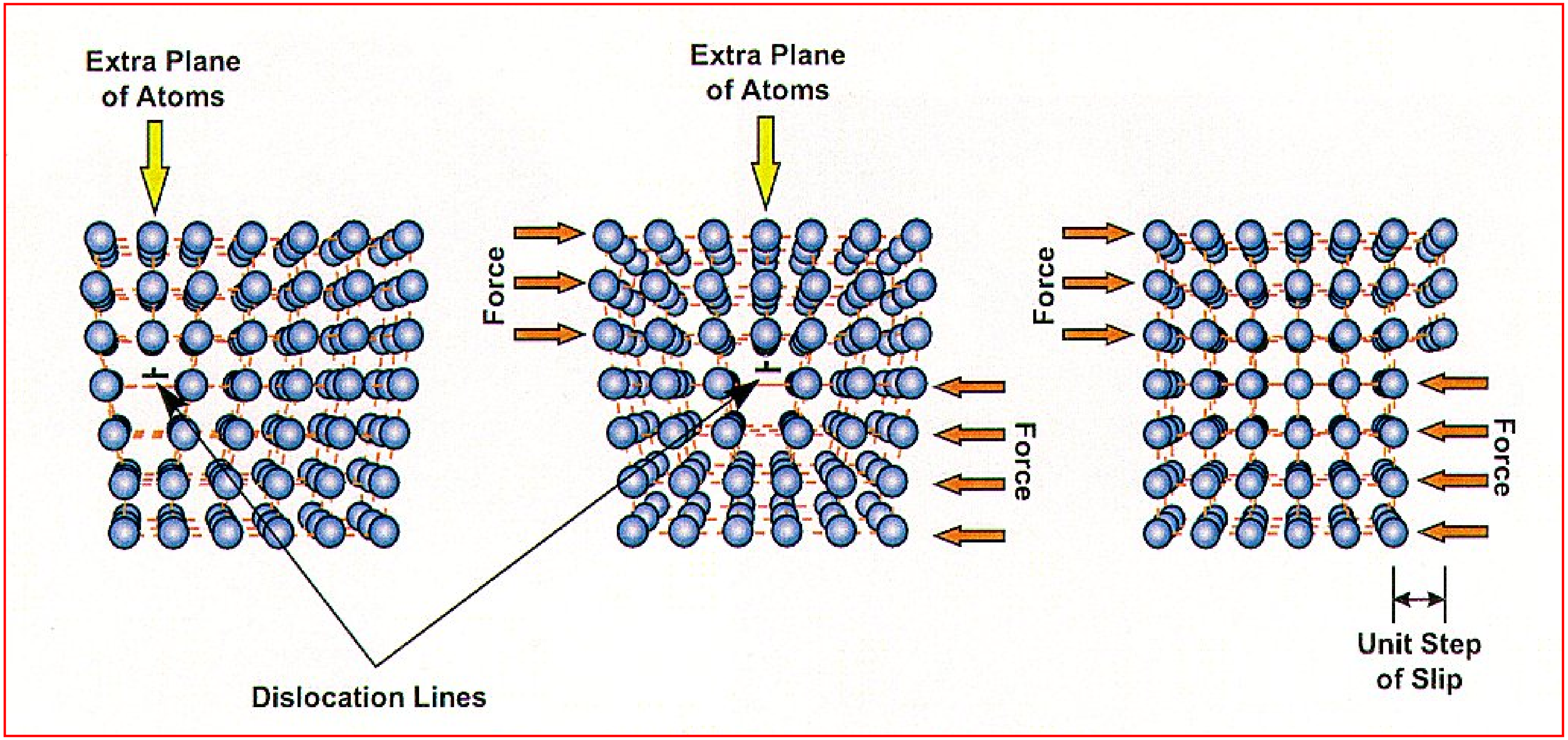
Dislocation Mechanism for Metal Deformation



Dislocations Provide a Mechanism that makes metals soft and ductile (most times, too soft)

- **Obstacles to dislocations strengthen the metal**
  - **May include particles, solute atoms, grain boundaries, other dislocations**
  - **One of the strongest obstacles: thermally precipitated phases**

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Crystals are never perfect; at least not outside of a laboratory

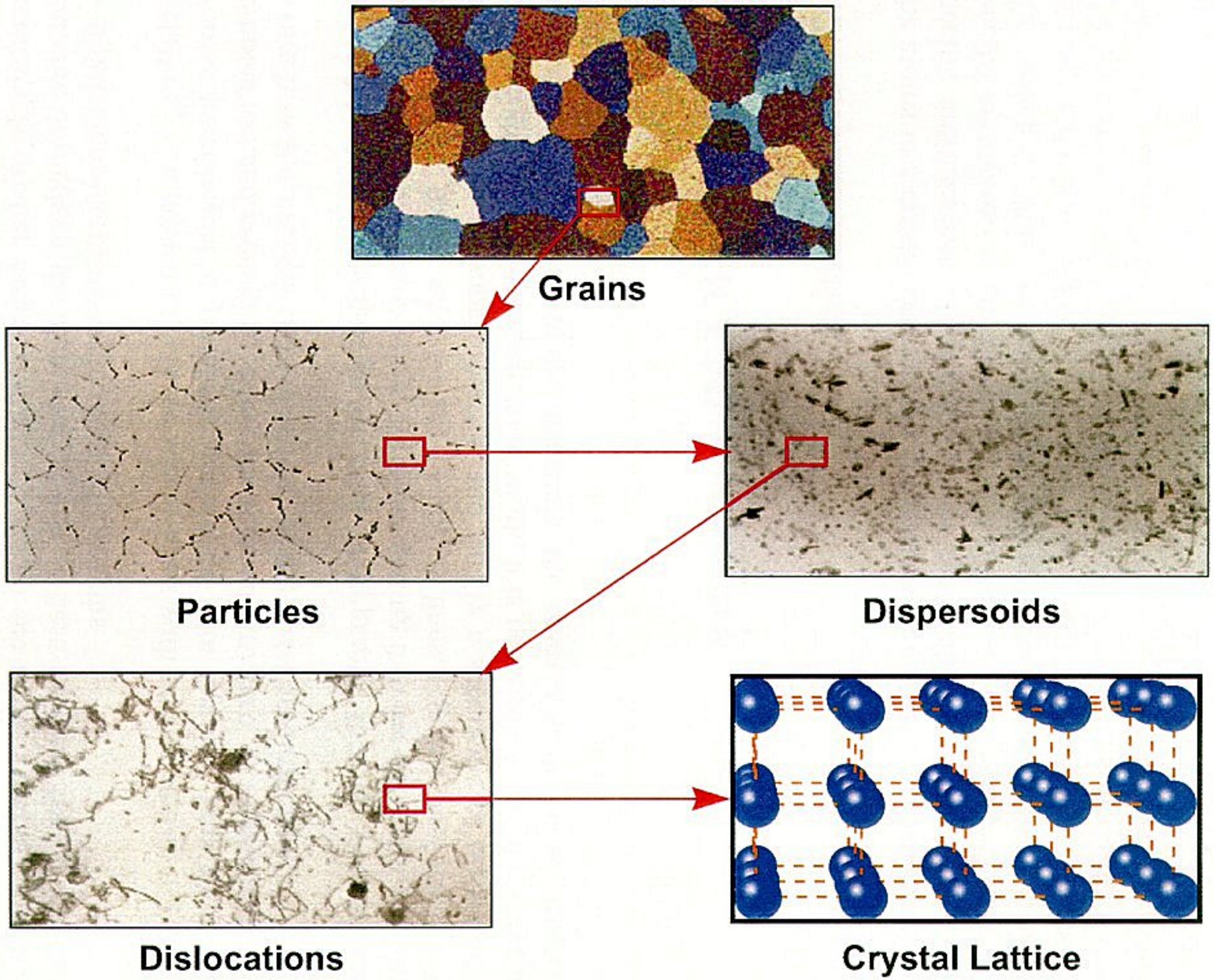


Figure 2.1 Structure of an Aluminum Alloy

Imperfections exist at Different Levels of Structure:

- **Macroscopic to**
- **Microscopic to**
- **Sub-microscopic**

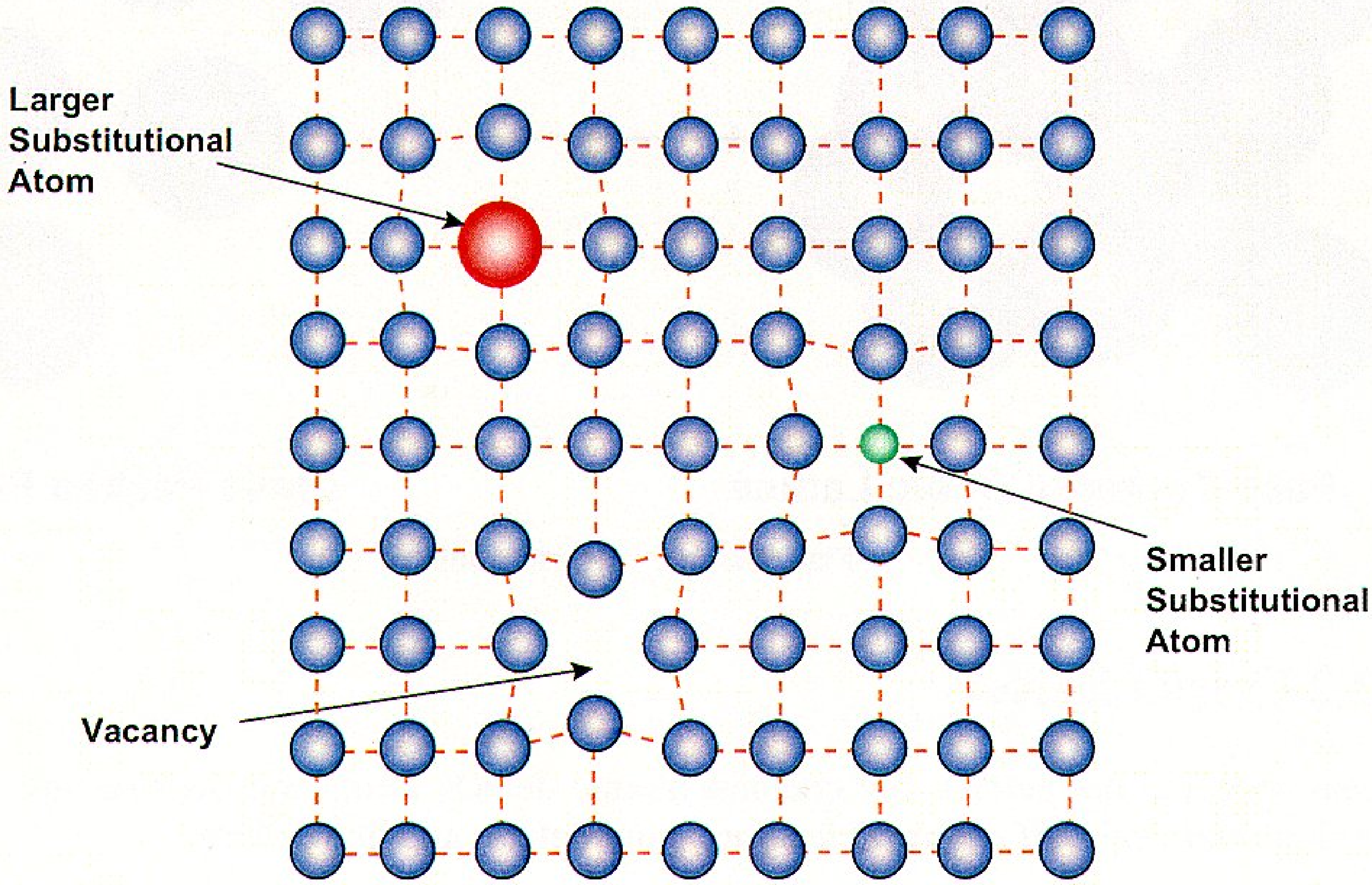
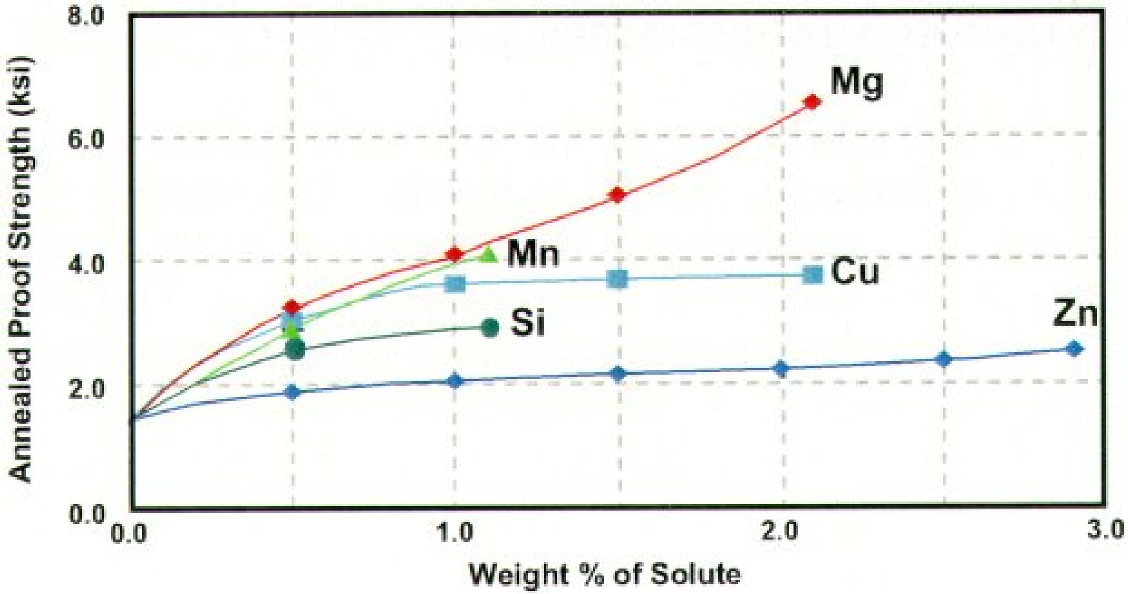
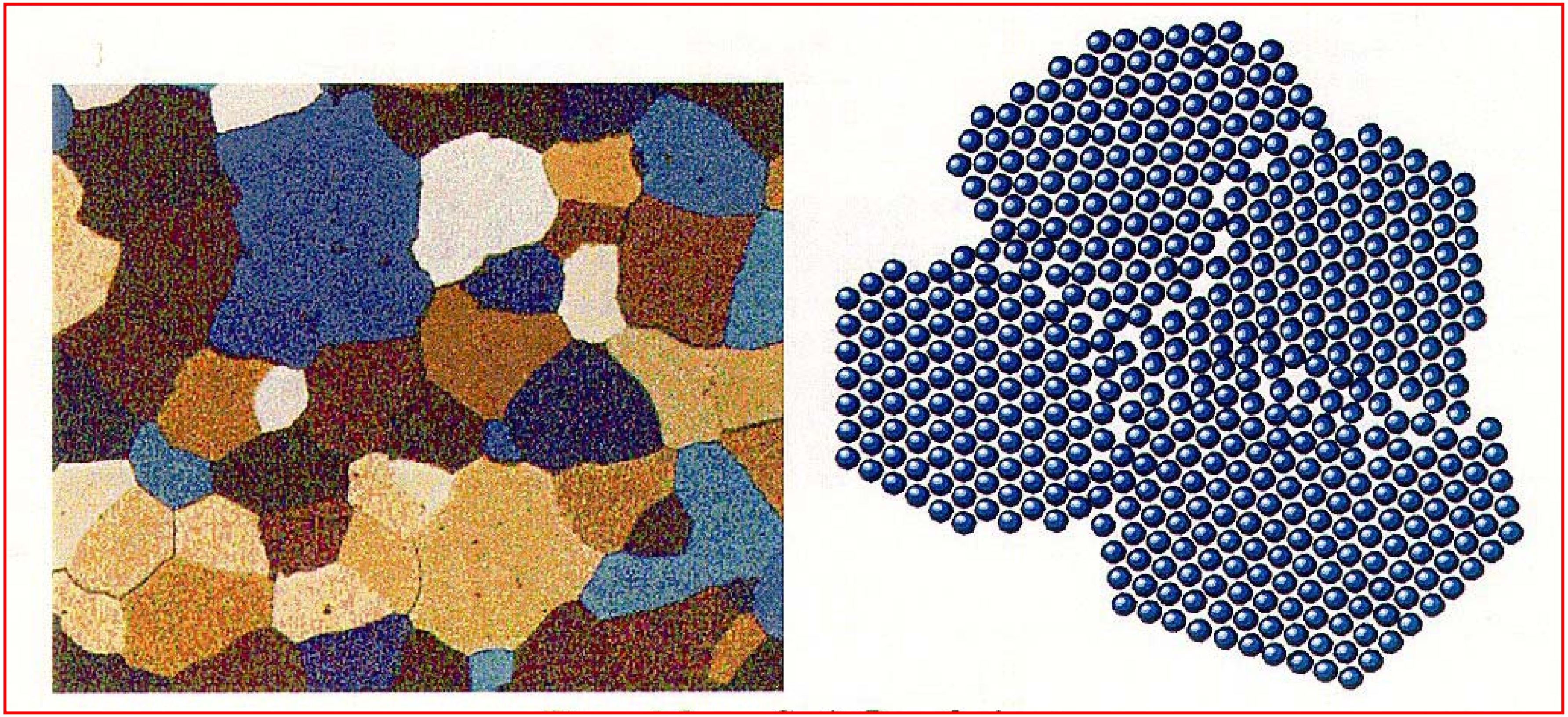


Figure 2.3 Lattice Defects



Atomic No.	25	14	26	24	29	30	13	22	40	12
Element	Mn	Si	Fe	Cr	Cu	Zn	Al	Ti	Zr	Mg
Atomic Rad. (picometers)	112	118	123	125	128	133	142	146	160	160



Grain Boundaries

- **Complex Effects - boundaries can focus intermetallics**
- **Form a break in the atomic lattice which can strengthen**
  - Only really effective at small grain sizes in 5XXX Al
  - Must be smallest feature or smaller microstructural features will control (rare in foundry alloys)

Stages in Precipitation Hardening

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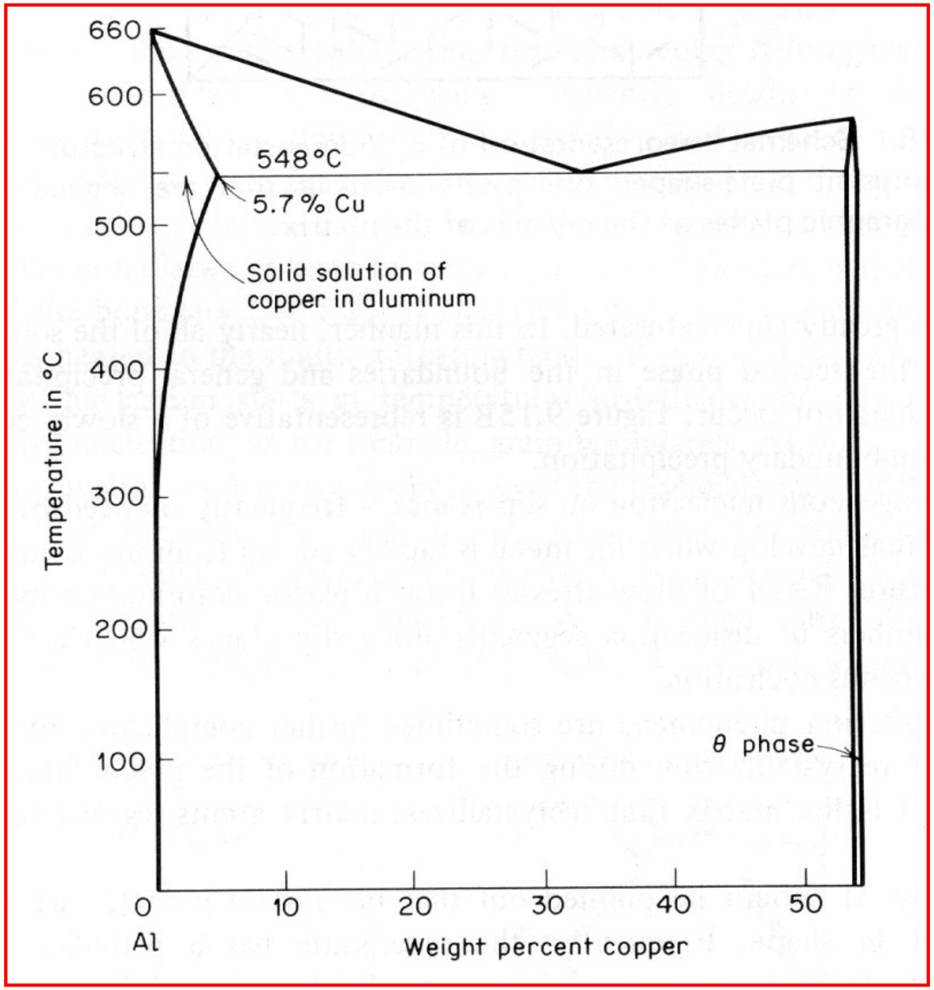
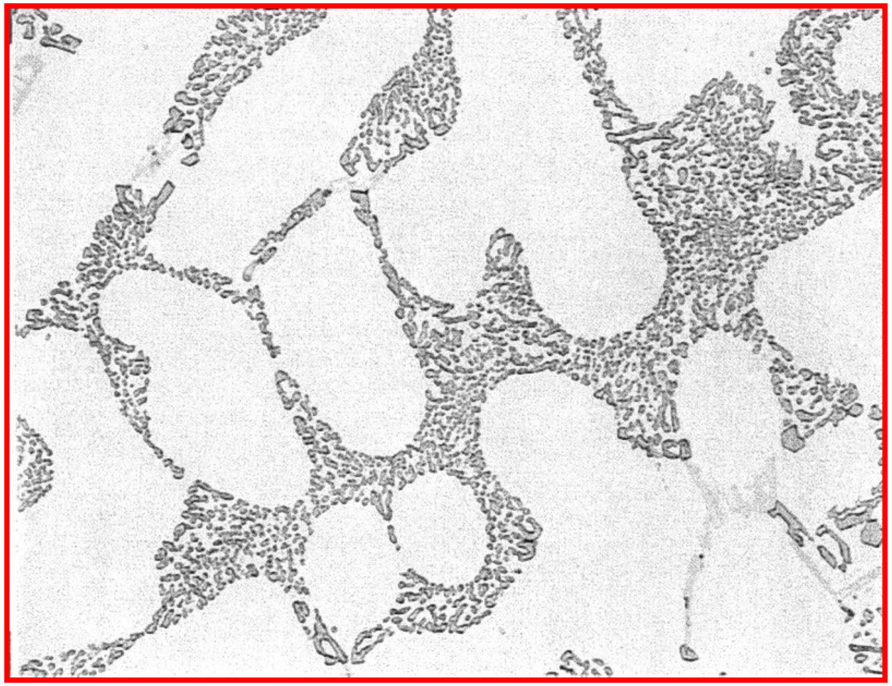


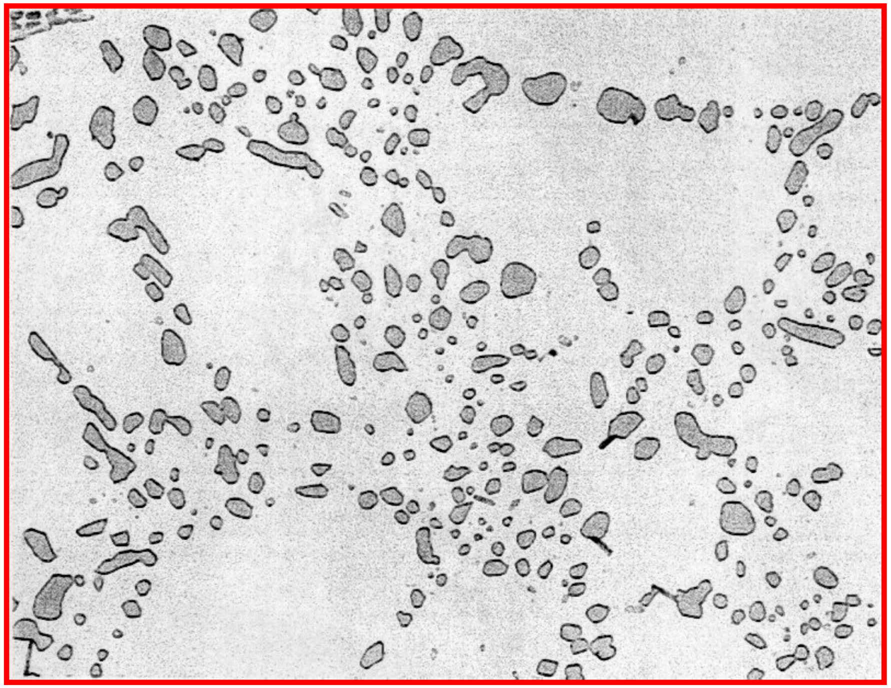
Solutionizing Stage

- **Take metal temperature up to just short of the liquidus**
  - Do not melt the casting
  - Dissolve all of the solute into the aluminum
- **Quench the metal**
  - Create a Super-Saturated Solid Solution
  - Hot water quench most commonly used

LPPM A356 Wheel - Rim Region



F Temper



T6 Temper

AFS Modification Rating = 5
Note Si phase coarsening

DAS = 24μm

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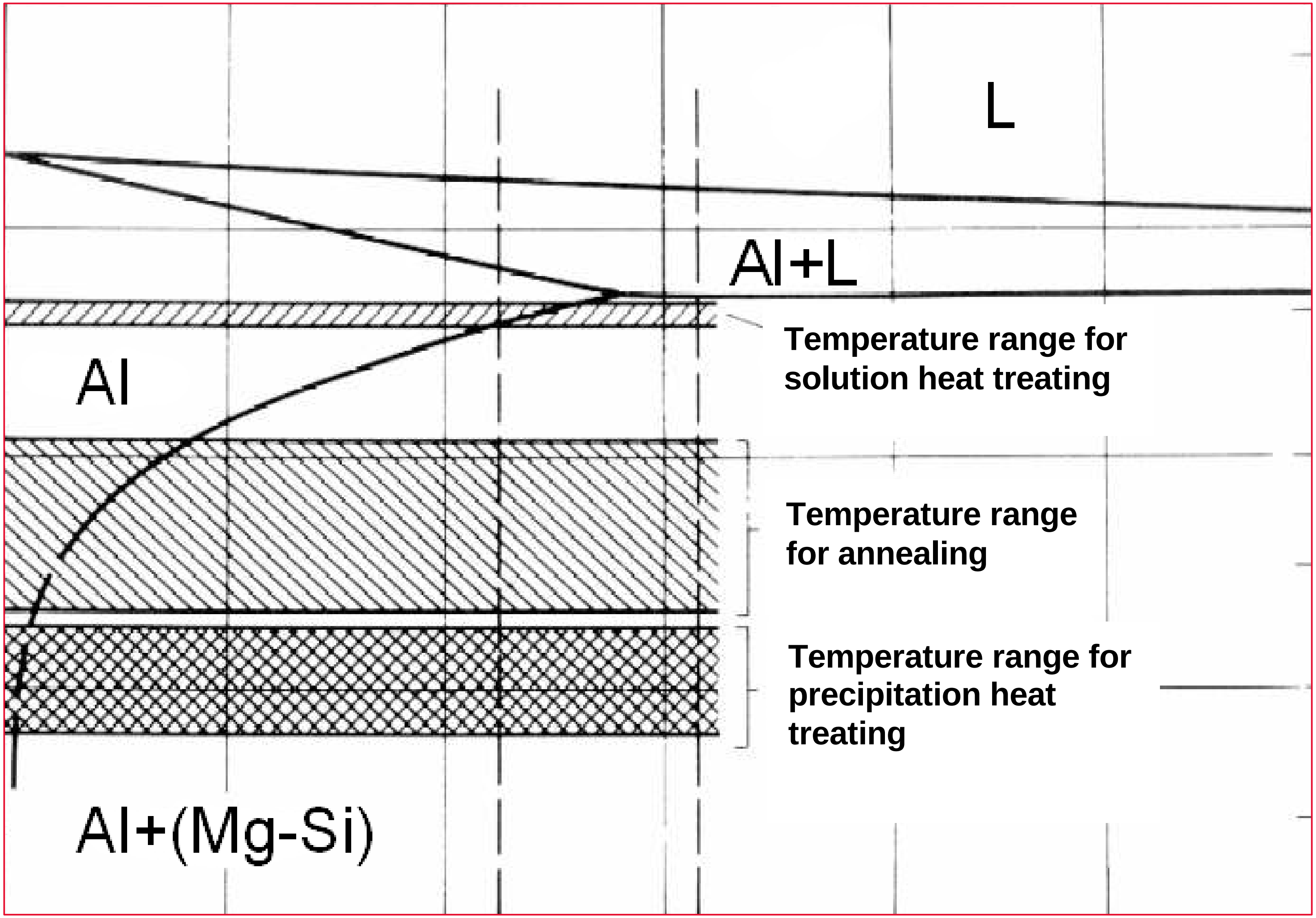
Temperature Ranges for Solution Heat Treatment and Precipitation Heat Treatment



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Quench Sensitivity

- Need to quench after solution treatment at a rapid enough rate to retain the alloying elements in solution so they can be precipitated during ageing
- Quenching too quickly leads to residual stresses and cracking
- Need to use the minimum quench rate possible which avoids precipitation of alloying elements
- Quench sensitivity refers to how much the age hardening response is reduced by slow quenching
- Aim to reduce quench sensitivity to allow slower cooling rates?
  - Use less concentrated alloys
  - Changes of minor alloy elements
  - Only quench quickly over critical temperature range

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TTT and “C” Curves

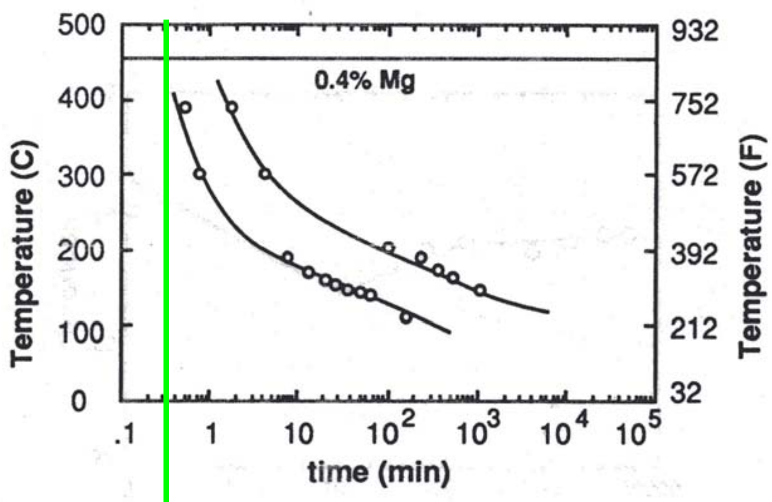

Fig. 4 TTT curves for A356 alloy containing 0.4% Mg.

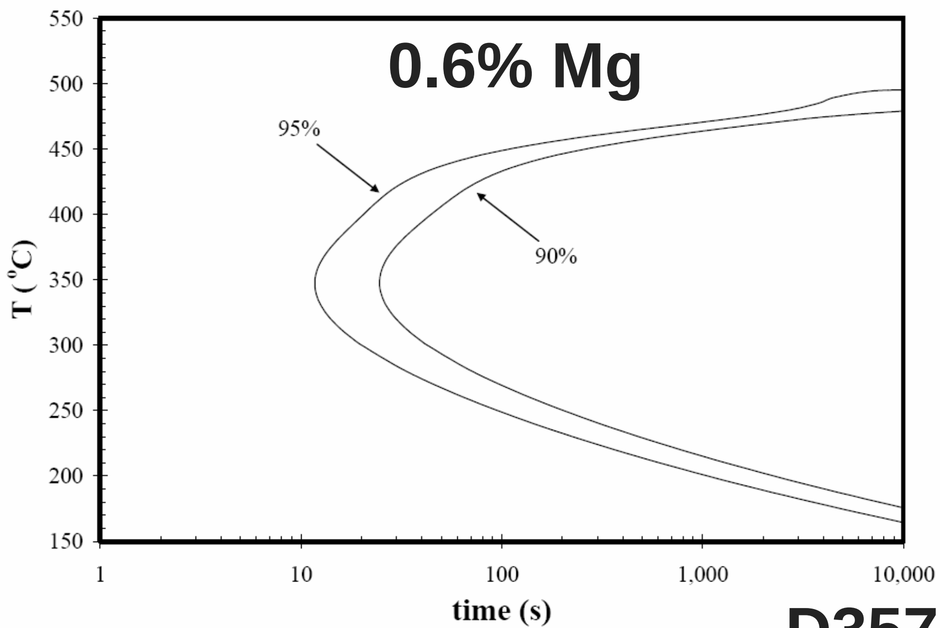

Figure 9. 95% and 90% iso-yield strength contours.

D357

0.2 – 0.3 min
12 – 18 s

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Complications wrt Foundry Alloys

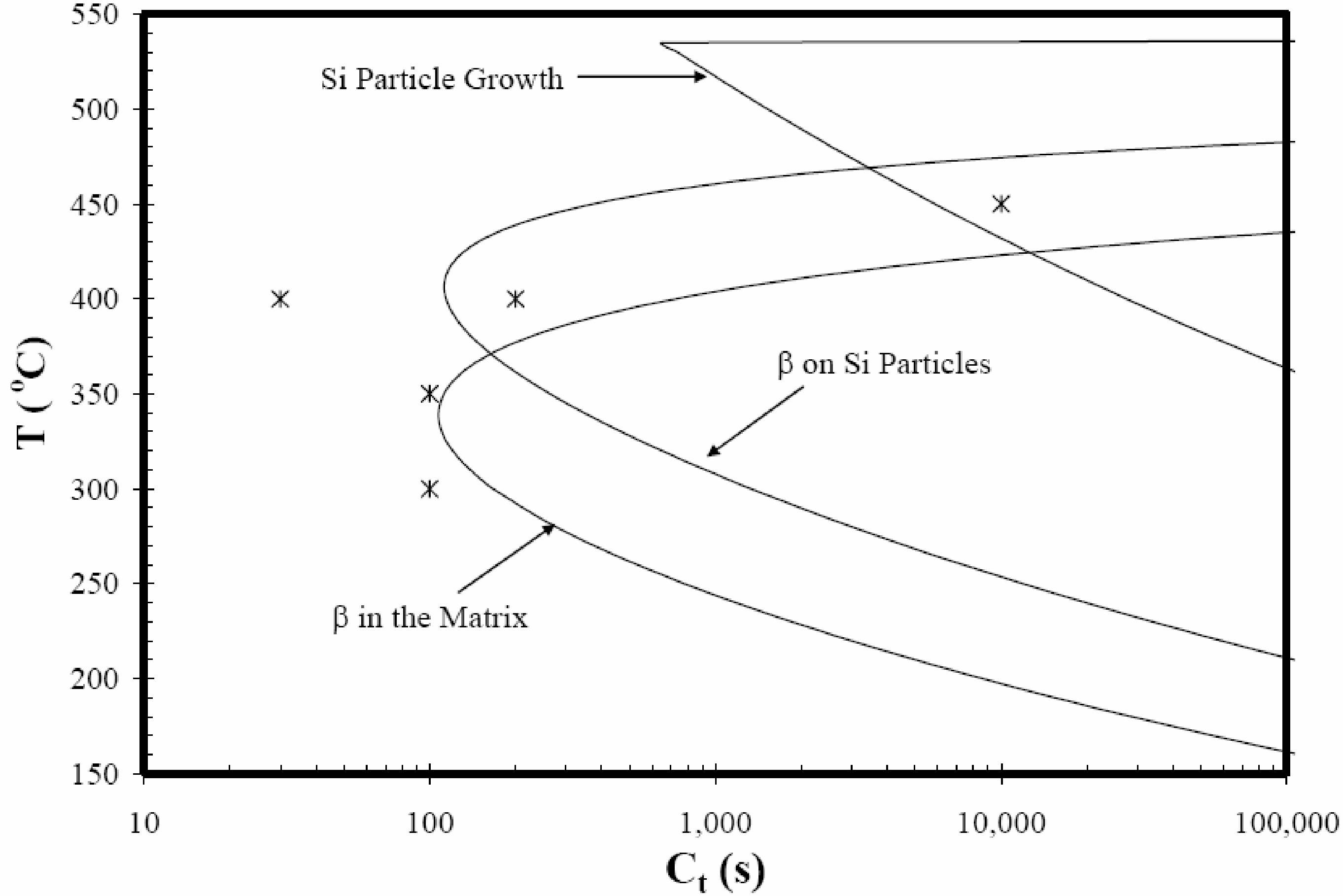


Figure 6. Critical times for the three quench precipitates. Hold times and temperatures for micrographs in Figures 2-5 are also indicated.

Si can be drained from the matrix to existing Si particles
Mg can be lost by growth on existing Si particles

Raise temperature again to harden:

SSS ➔ GPZ ➔ θ'' ➔ θ' ➔ θ

SSS: Super Saturated Solid Solution

Weak and Very Soft

GPZ: Guinier Preston Zones

Stronger

θ'' + θ': Increasing coherent precipitation

Stronger Still

θ: Large Incoherent Particles ($CuAl_2$ or Mg_2Si)

Soften Again (overaged)

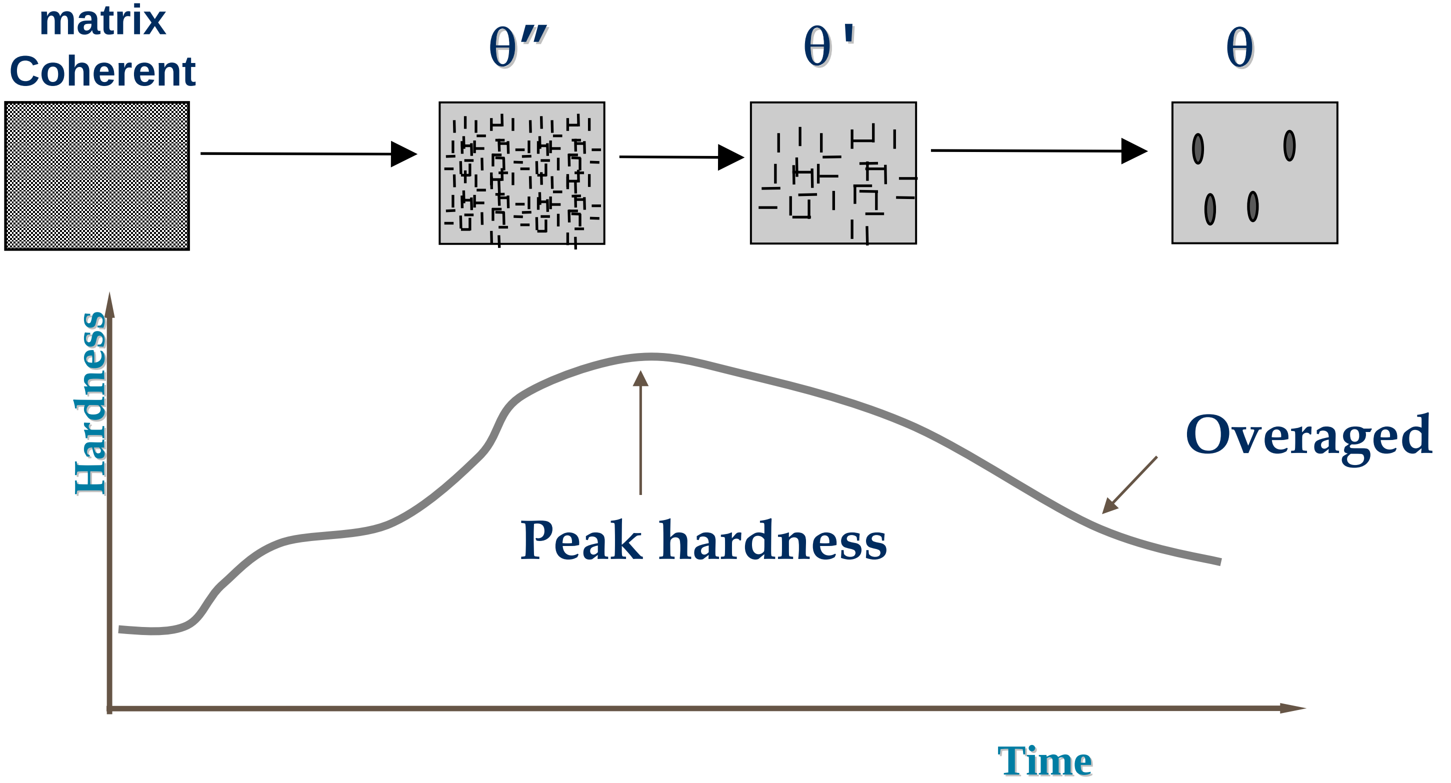
Decomposition - Effect on Hardness

- e.g. Al-Cu alloys

Guinier-Preston Zones
Ordered solute rich clusters
1 or 2 atom planes in thickness
Same crystal structure as matrix
Coherent

Intermediate Precipitates
Larger than GPZ
Distinct crystal structure
q" coherent
q' semi-coherent

Equilibrium Precipitate
Large particles
Different crystal structure to matrix
Incoherent



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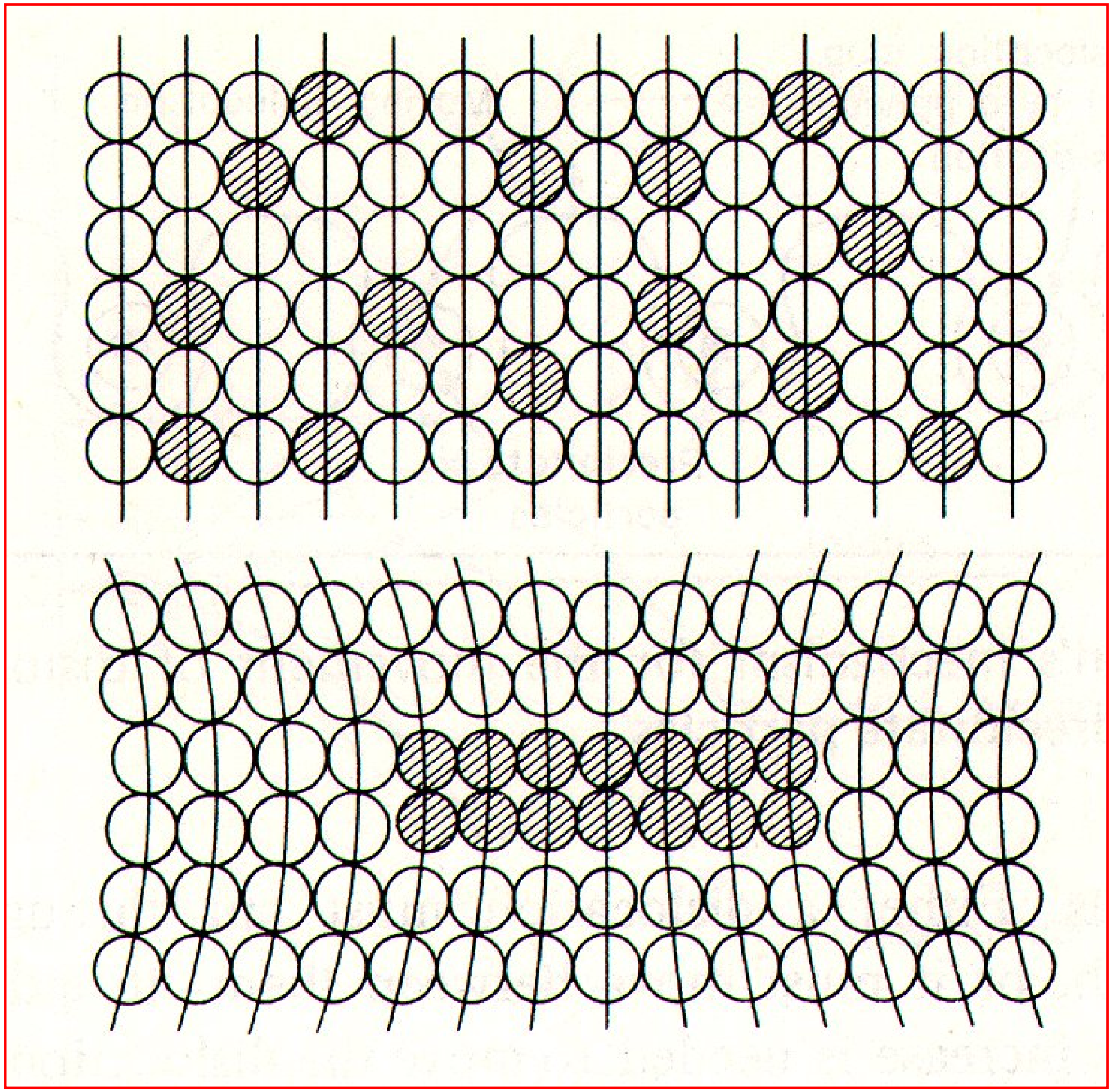
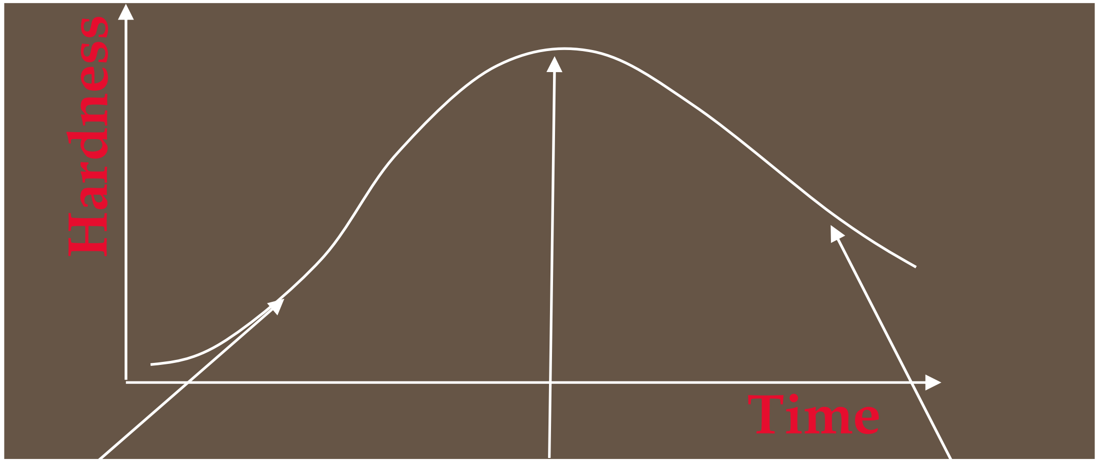
Initial Coherent Precipitate Formation



Coherent Precipitates:

- Share the matrix crystal structure
- Cause coherency strains when they achieve sufficient size.
- Strains which can be relieved by dislocations
- Will pin dislocations since these would increase the strain if they were to move away
  - •i.e. higher forces required to move pinned dislocation and alloy is stronger.

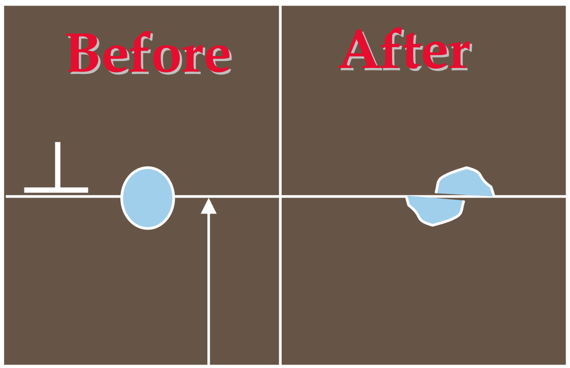
Peak in Hardness Curve



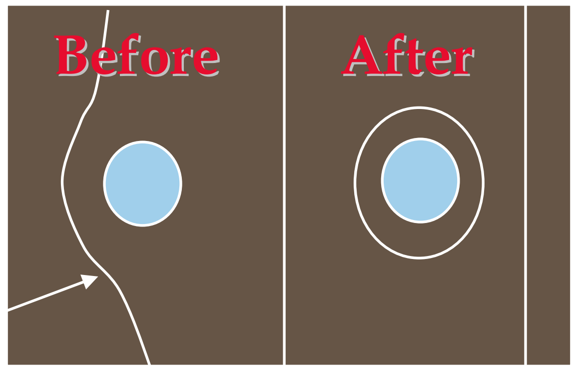
Very small, coherent precipitates or zones. Dislocations can pass by cutting

Peak aged semi coherent resistant to cutting and bowing - effective barrier to dislocation motion

Large, incoherent precipitates. Dislocations can pass by bowing



Slip Plane



Dislocation Line

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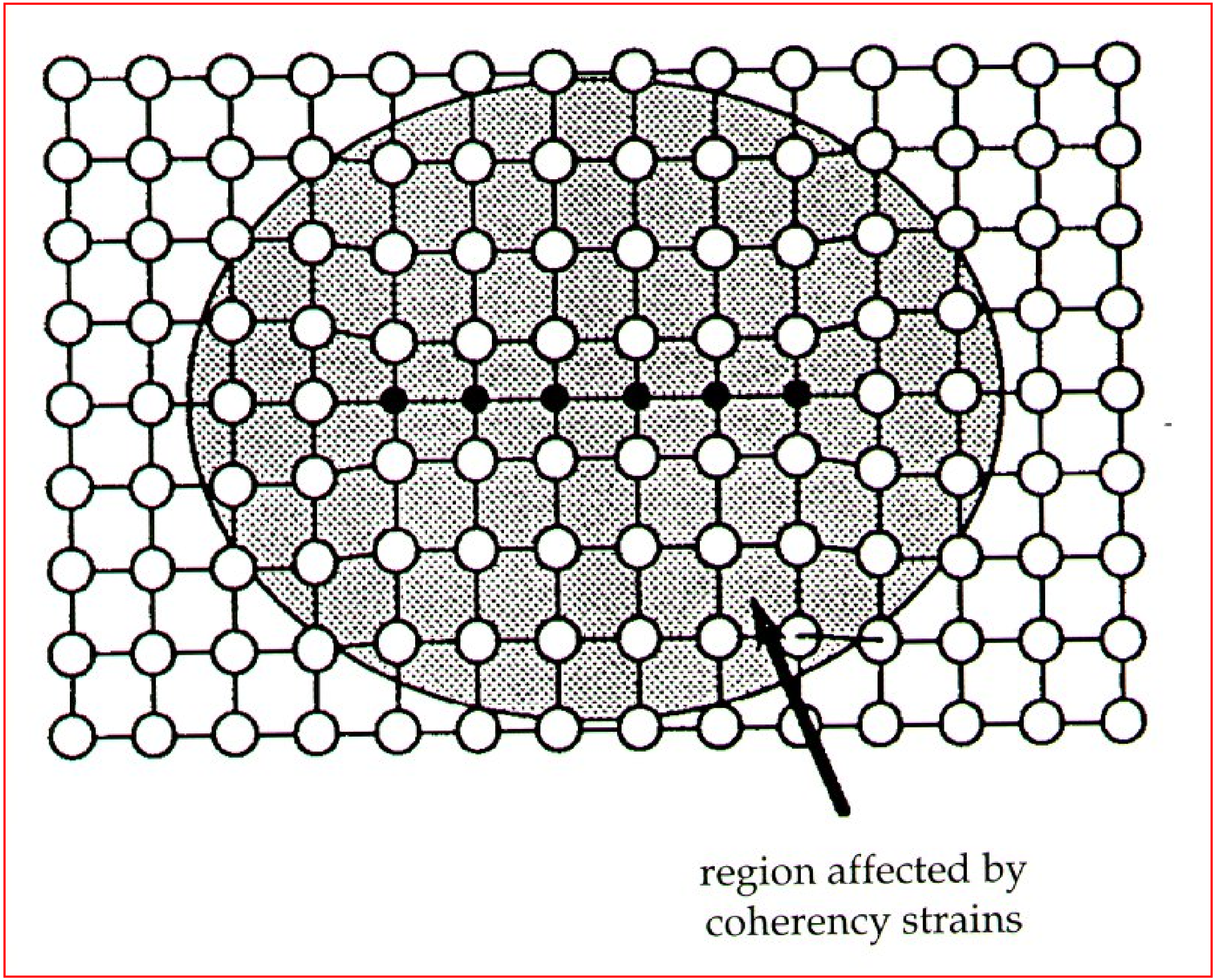
Coherency Strains Caused by Precipitates



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Precipitation Systems in Common Al Alloys

Table 15-1.
Precipitation Hardening Systems in Aluminum[1,6]

Alloy System	Aging Sequence[1]	PRECIPITATE INFORMATION				
		Type	**Coherency**[2]	**Structure**[3]	**Shape**	**Max. Size**[4,5]
Al-Cu	$SS \rightarrow GP \rightarrow \theta'' \rightarrow \theta' \rightarrow \theta$	GP	C	unknown	disk	6x100 Å
		θ''	C	Tetr	disk	40x1000 Å
		θ'	$C \rightarrow N$	Tetr-2	disk	150x6000 Å
	(terminal phase: $CuAl_2$)$\rightarrow$	θ	N	BC Tetr		
Al-Cu-Mg	$SS \rightarrow GP \rightarrow S'' \rightarrow S' \rightarrow S$	GP	C	unknown	unknown	16 Å dia.
		S''	C	unknown–Ord	rod	unknown
		S'	C	Ortho	unknown	100 Å dia.
	(terminal phase: $CuMgAl_2$)$\rightarrow$	S	N	FC Ortho		
Al-Mg-Si	$SS \rightarrow GP \rightarrow \beta'' \rightarrow \beta' \rightarrow \beta$	GP	C	unknown	needle	60x1000 Å
		β''	C	Mono	needle	60x2000 Å
		β'	C	Hex	rod	unknown
	(terminal phase: Mg_2Si)$\rightarrow$	β	N	FC C		
Al-Zn-Mg (Zn>Mg)	$SS \rightarrow GP \rightarrow \eta' \rightarrow \eta$	GP	C	unknown	sphere	35 Å dia.
		η'	SC	Mono	sphere	300 Å dia.
	(terminal phase: $MgZn_2$)$\rightarrow$	η	N	Hex		
Al-Mg-Zn (Mg>Zn)	$SS \rightarrow GP \rightarrow T' \rightarrow T$	GP	C	unknown	sphere	1000 Å dia.
		T′	SC	C	unknown	unknown
	(terminal phase: $Mg_3Zn_3Al_2$)$\rightarrow$	T	N	BC C		

Notes:
1. SS = supersaturated solid solution, GP = Guinier-Preston zones.
2. Coherency: C = coherent, SC = semi-coherent, N = noncoherent.
3. Crystal Structure: BC = body-centered, FC = face-centered, C = cubic, Hex = hexagonal, Ord = ordered, Ortho = orthorhombic, Mono = monoclinic, Tetr = tetragonal, Tetr-2 = tetragonal with different composition.
4. Compare the precipitate size to the atomic radius of Al, 2.86 Å.
5. The terminal phase does not have a fixed shape or a maximum size.

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Heat Treatment of Aluminum Castings

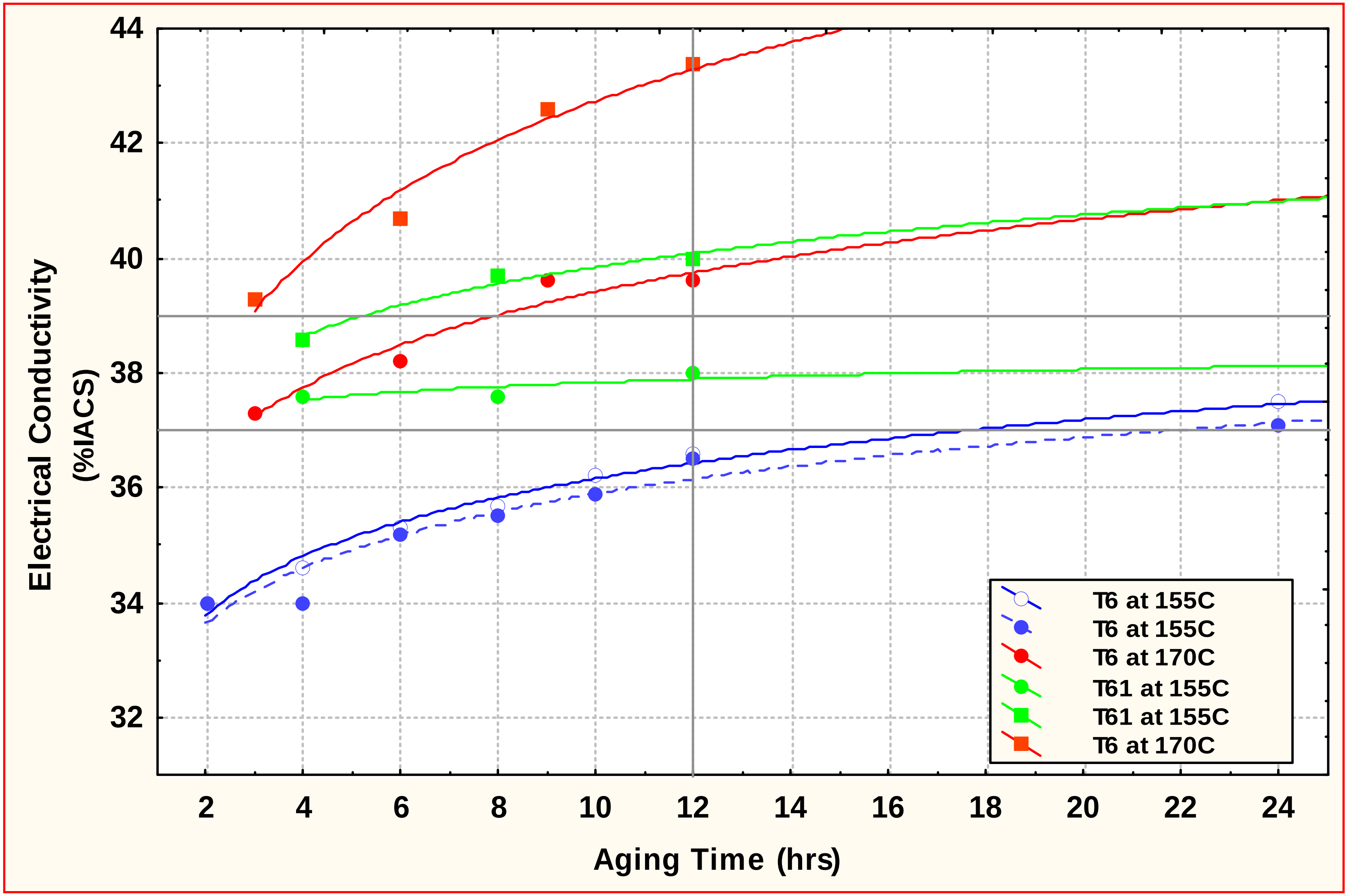
Common Temper Designations: XXX - Z where Z is:

- **F for foundry (more generally as-fabricated) temper**
  - **Castings supplied as-cast**
  - Cheapest but not consistent, unstable if warmed up
  - Properties are part and process dependent
- **T5**
  - Artificially aged from the F-temper
  - Frequently called a stabilization treatment
    - Used to prevent growth in service
- **T4**
  - Solutionized and Water Quenched
  - Dimensionally unstable temper
  - Highest Ductility and conductivity (Castings can be straightened)
  - Usually used to set up casting for a subsequent artificial aging treatment
  - A206.0 - T4 castings are used for fracture toughness
  - Also helps burn out cores

- **T6 and T61 Tempers**
  - Artificially aged from the T4 temper
  - Gives maximum strength and hardness
  - Aging temperatures vary between 155^{o}C and 200^{o}C
- **T7 Temper**
  - Higher temperature aging treatment
  - Also a stabilization treatment
    - More predictable properties
  - Intentionally over-age the part
  - Not as strong but better ductility
  - Aging temperatures usually exceed 225^{o}C
  - Frequently used on very strong alloys to maintain ductility
- **Wheel Tempers**
  - Variations on T6 which allow for in-process aging
    - •Clear coating
    - •Anything involving a paint-bake cycle

Typical Aging Curves for A356-T4

Conductivity Aging Curves for A356-T4



Electrical Conductivity: A function of Heat Treatment: Atoms in solution reduce the conductivity of Al. A good test for the state of the metal if you have a meter.

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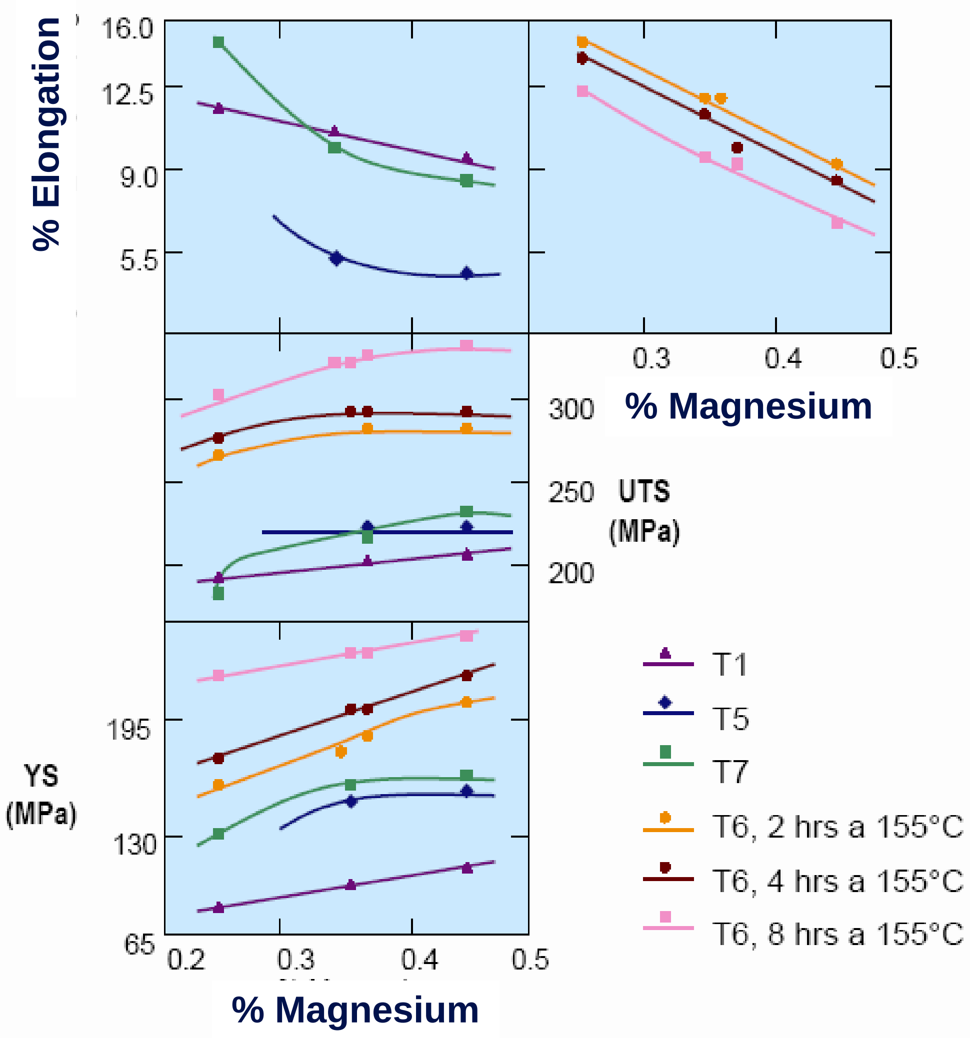
Interaction – Chemistry/Aging Time



D.Apelian, S Shivkumar and G. Sigworth AFS Trans 89-137

Separately Cast PM Bars (ASTM B108)

- Strength and Hardness Increases with aging time and Mg content.
- Ductility generally drops with increasing strength at a given freezing rate.

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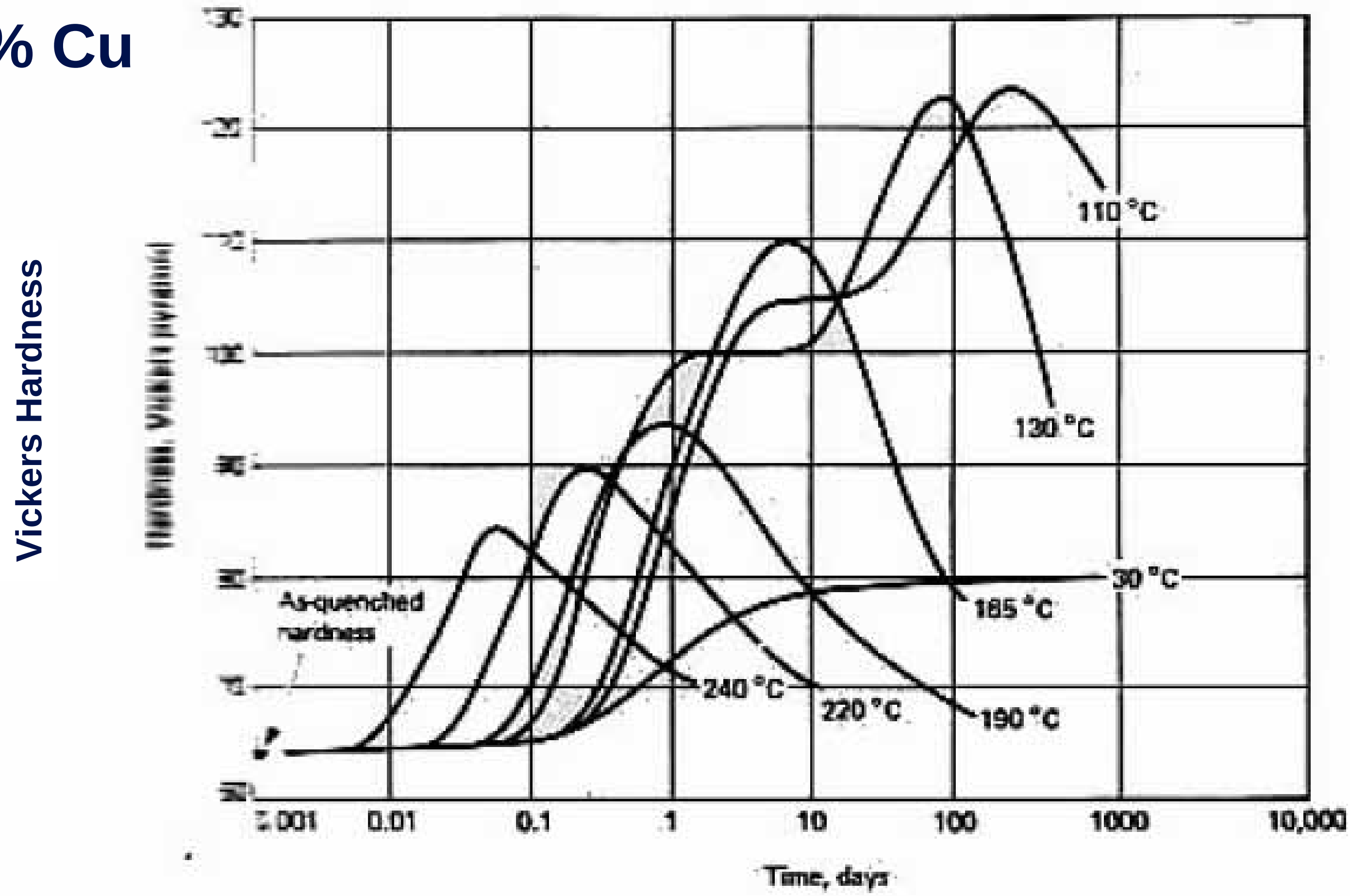
Aging Response with Aging Temperature

Al-4% Cu



H.K.Hardy J.Inst Metals Vol 79 , 1951, p 321

The Alloy was solution annealed for at least 48 h at 520 then water quenched to 25°C

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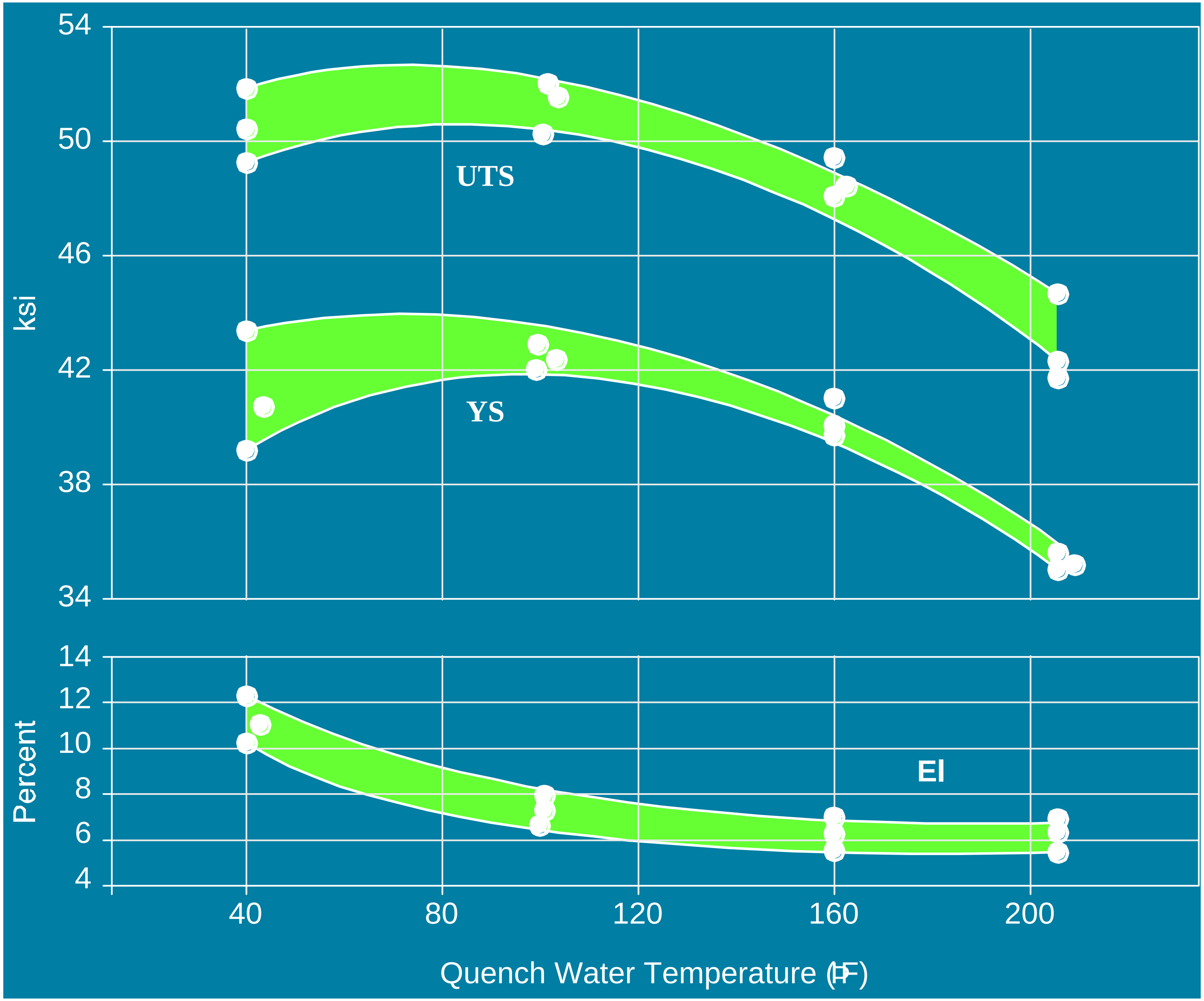

Source: Kermit J. Oswalt, "The Development and Application of High Strength Aluminum Casting Material Specifications", in Current aluminum research and applications : CARA 87.
Publisher Des Plaines, Ill. : American Foundrymen's Society, c1988.

A356-T6 vs. A356-T61

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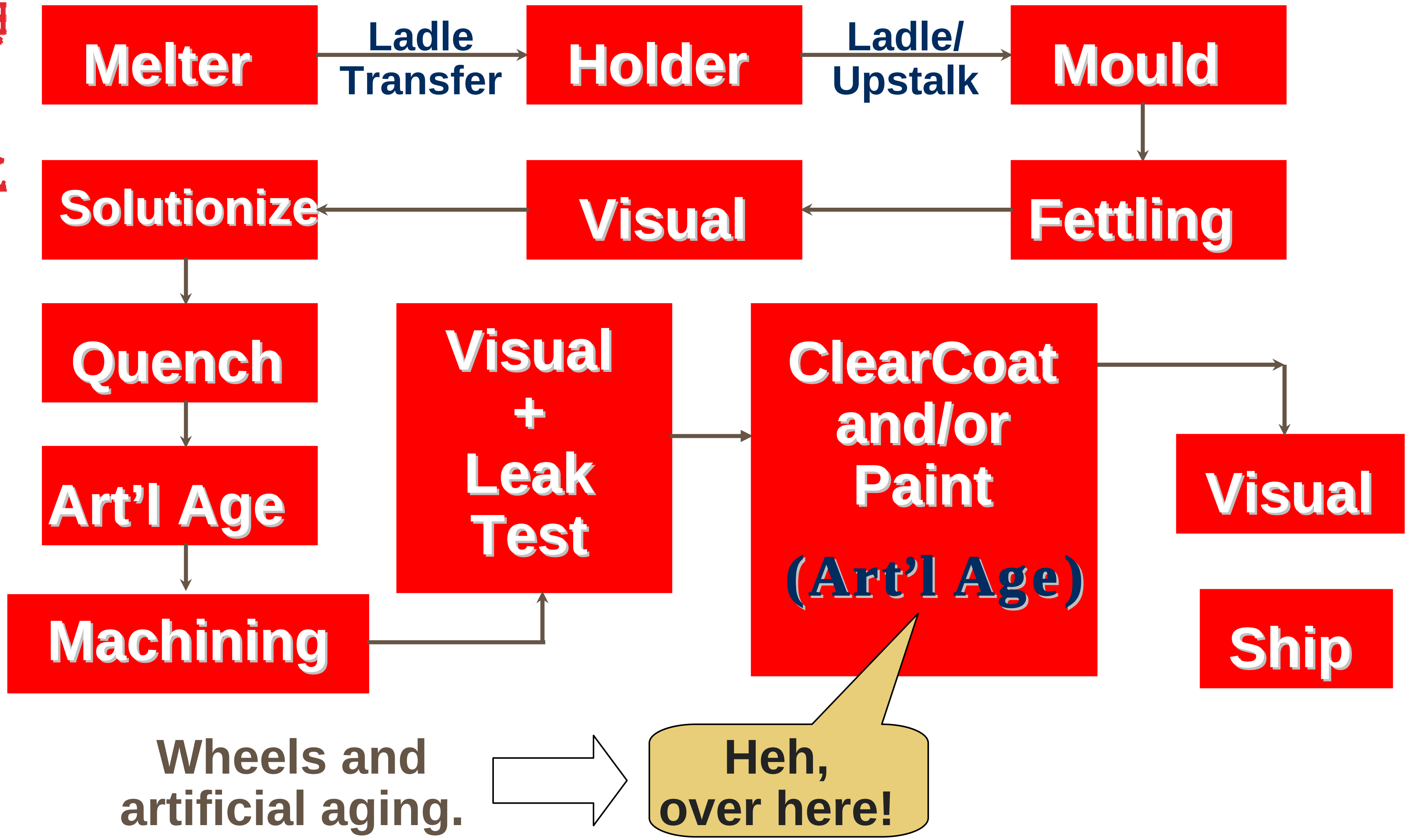
T61

- **Solutionize, water quench and then natural age for minimum 8 hours**
- **Then artificially age**
- **Natural Age Serves as an Inoculation Step**
  - **Pre-cursors to the final aging precipitates form (GP Zones)**
- **Natural Age allows premature loss of hardening elements**
- **Alters the subsequent response to artificial aging**
- **Subsequent aging yields a different distribution of precipitates**
- **Advantage 1:Natural age time can be used for straightening if needed**
- **Advantage 2: tighter range of properties – reduces the scatter**

T6

- **Solutionize, water quench and then artificially age (immediately)**
- **Must be consistent to avoid increasing scatter in the results**

Flow Chart - Wheel Plant

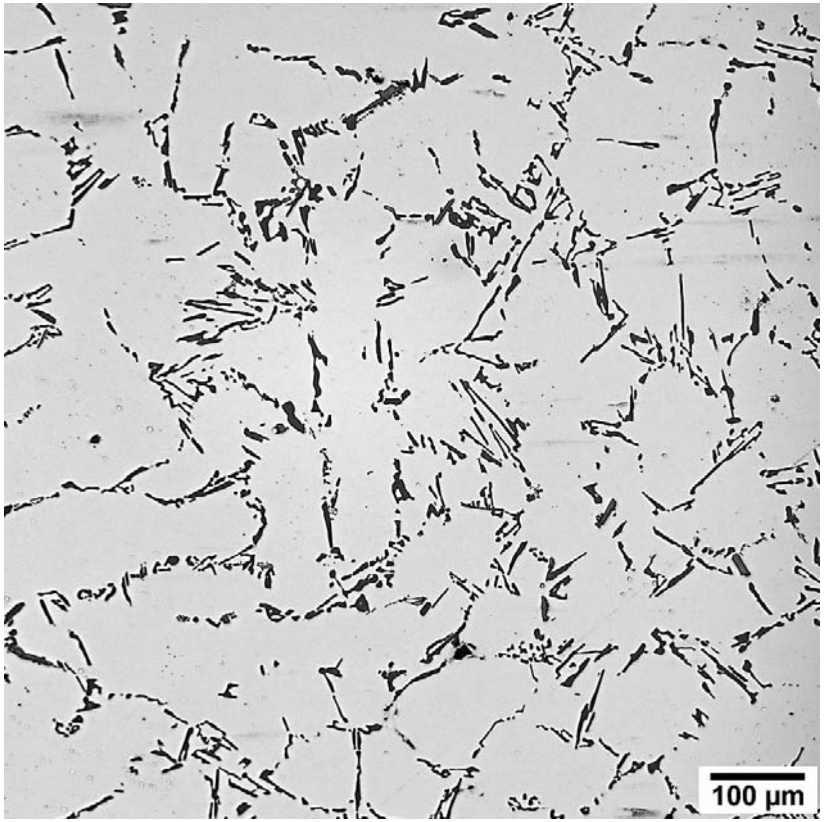


Purpose of Solutionizing Stage for Al-Si-Mg Casting Alloys

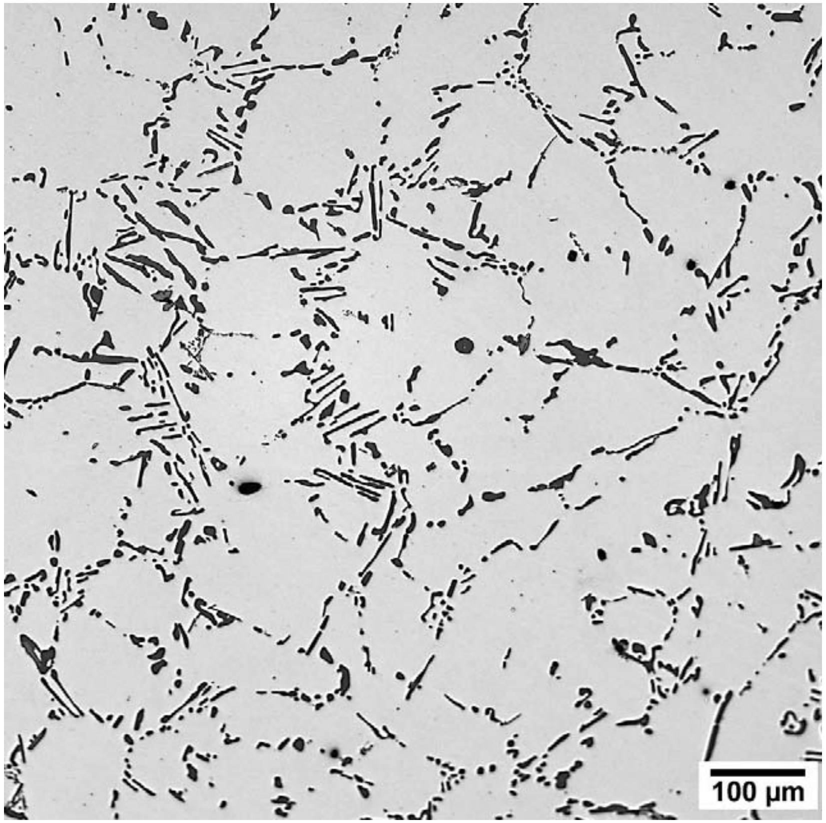
- **Solutionizing Serves two Functions:**
  - Dissolution of Mg and even homogenisation of the alloy
  - Thermal modification of the Si phase
  - Historically, heat treatments were developed with both purposes in mind for unmodified alloys.

- **Today**
  - Modern casting processes produce much finer as-cast microstructures.
  - Chemical, as opposed to thermal, modification is common
    - **Less so in aerospace**
  - Heat treatments can be adjusted accordingly.

Evolution of Microstructure with Solutionizing Time



90 Minutes of Solutionizing



12 Hours of Solutionizing

DAS = 70μm

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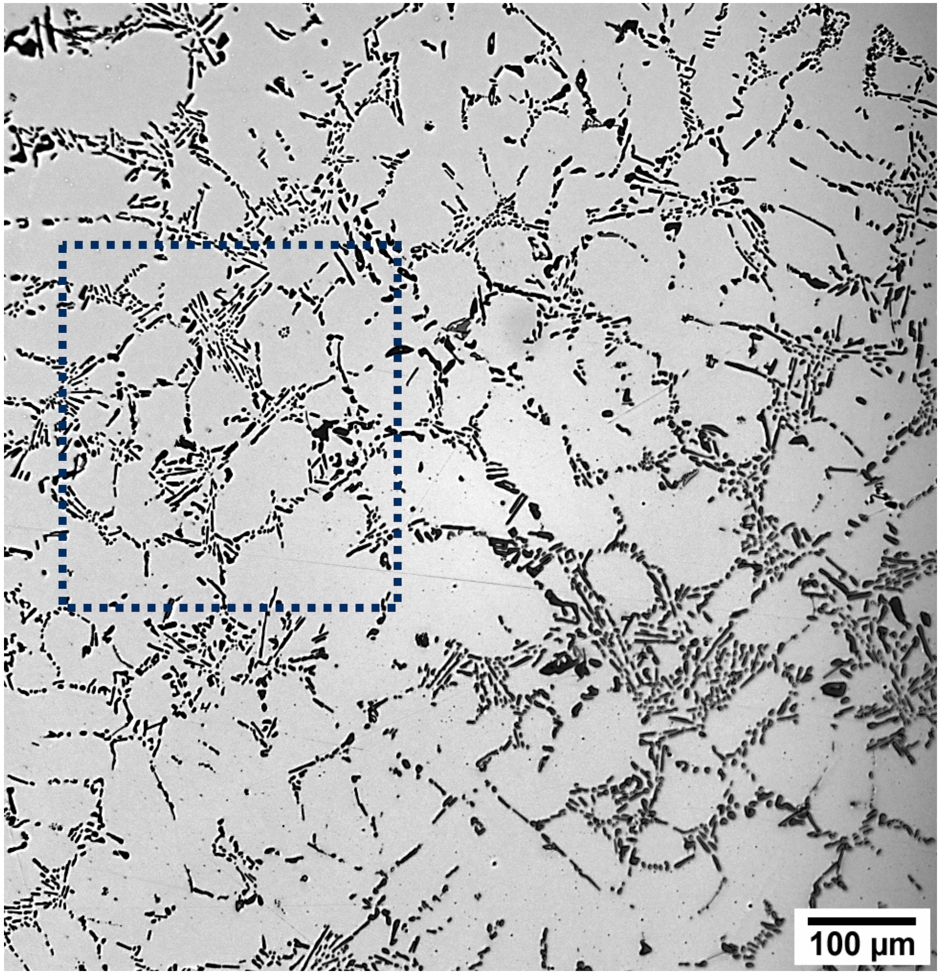
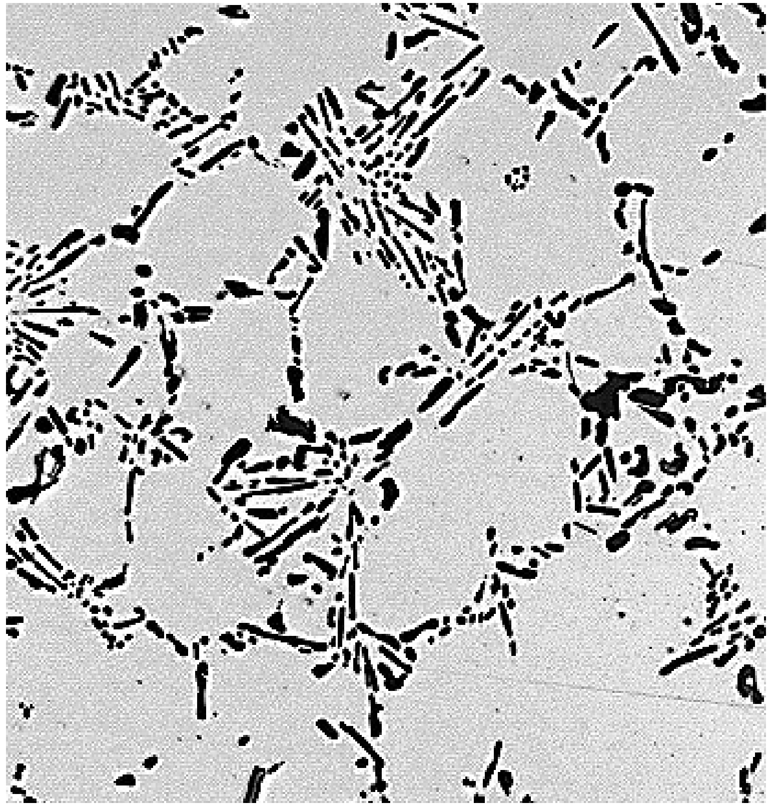
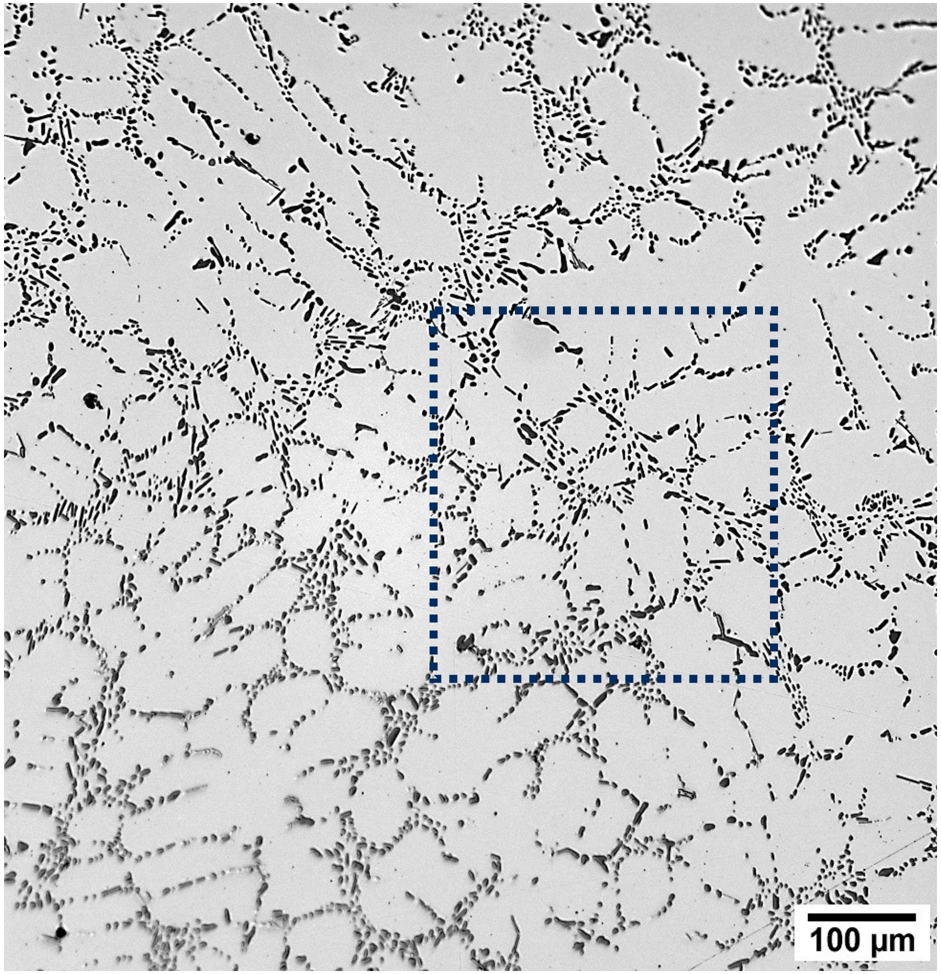
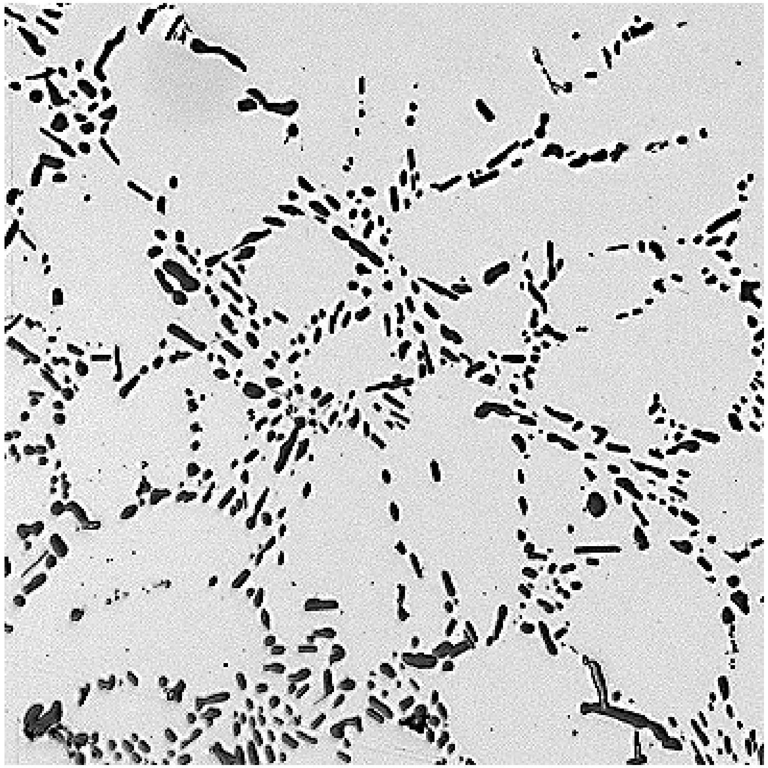




90 Minutes of Solutionizing

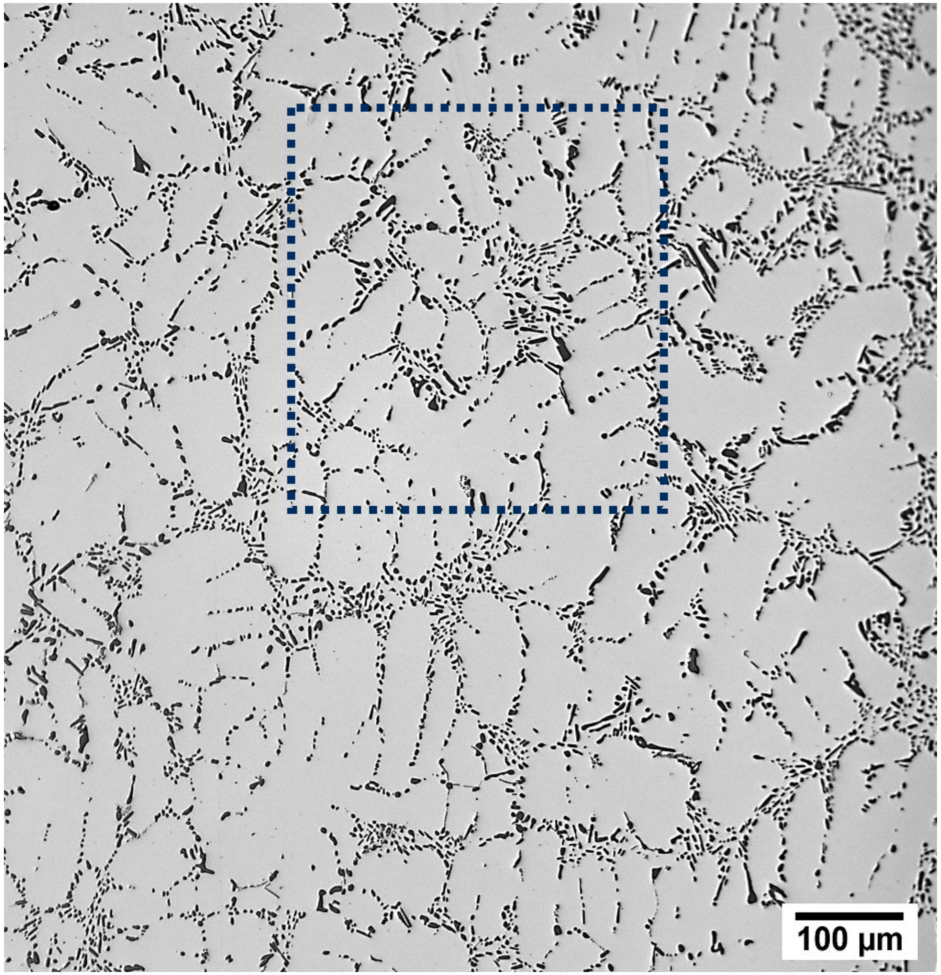
DAS = 38μm

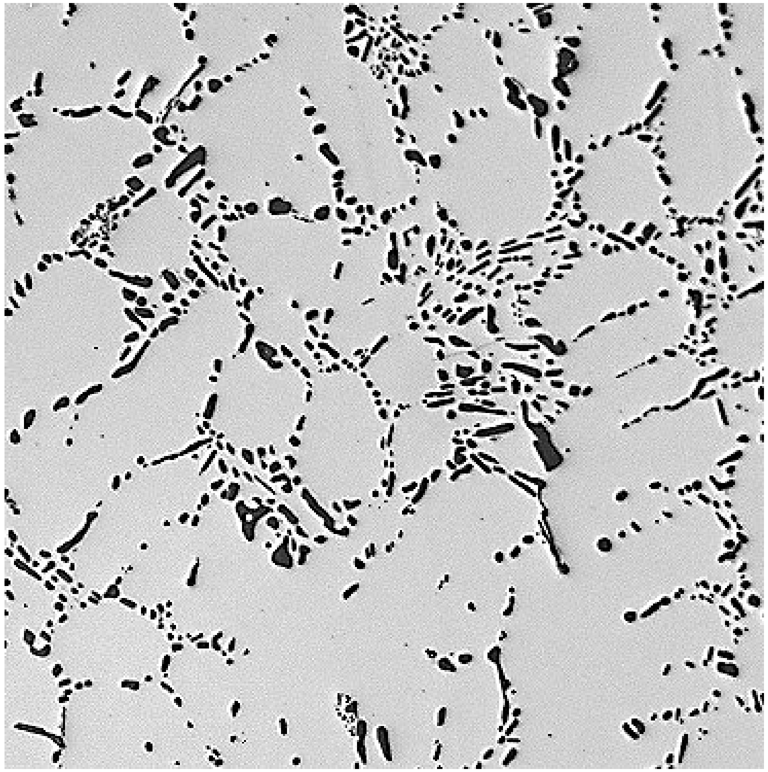




4 Hours of Solutionizing

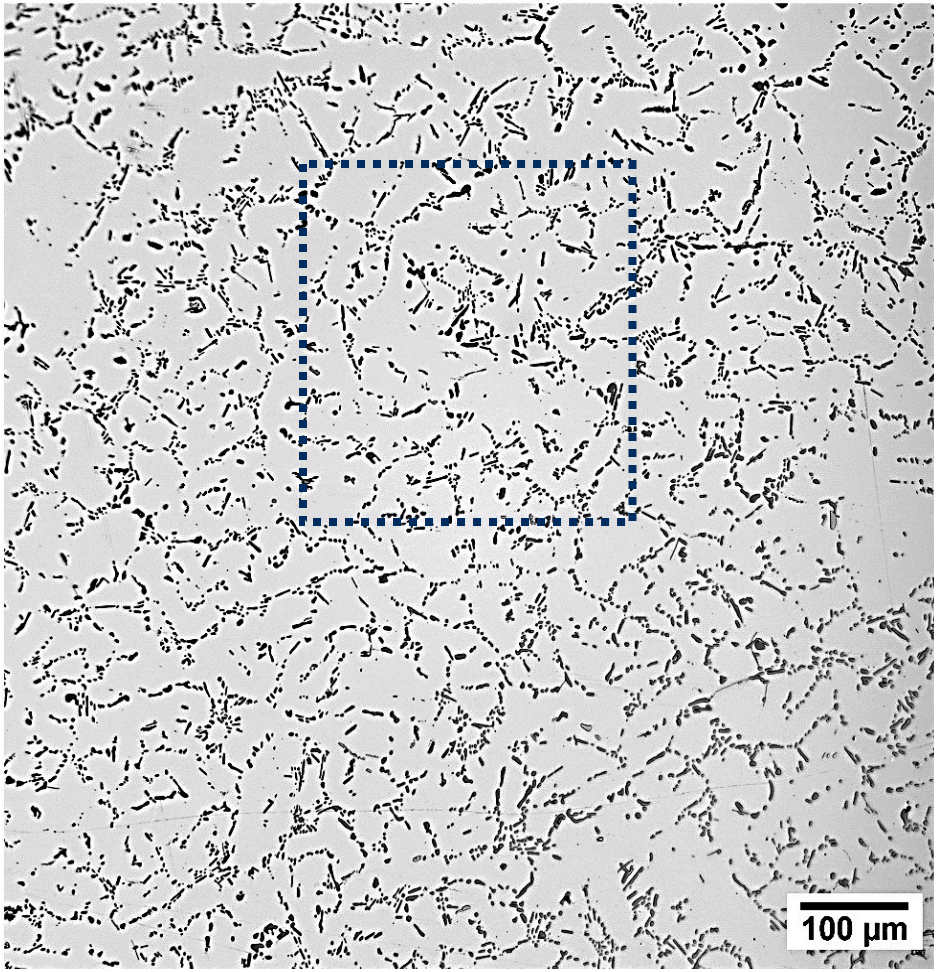
DAS = 38μm

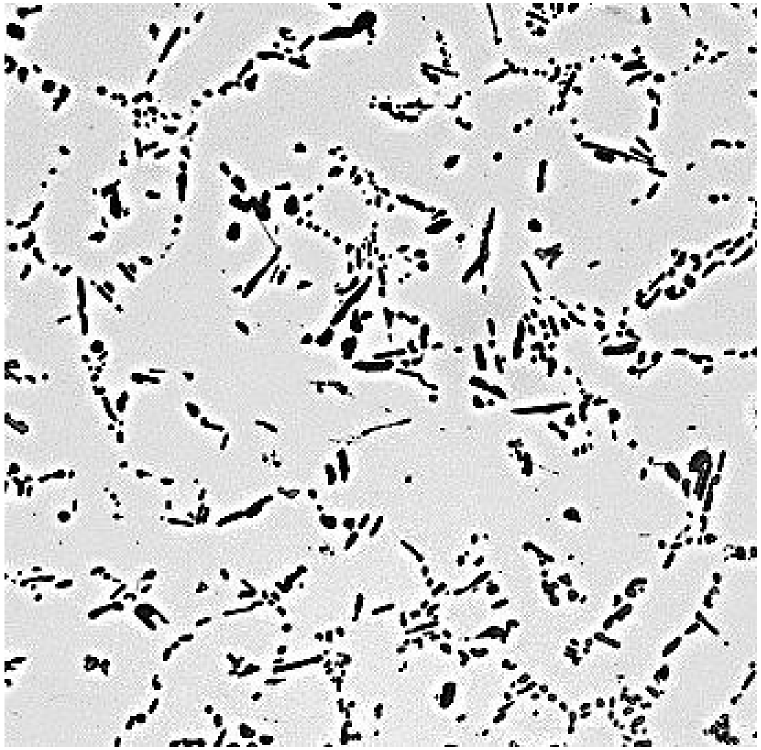




6 Hours of Solutionizing

DAS = 38μm





90 Minutes of Solutionizing

DAS = 25μm

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USCAR Materials Property Database

United States Council for Automotive Research

- Has provided funding for many automotive related R&D Topics
- The Light Alloy Casting Project Generated a Database of Measurements
- 12 Production Castings were analyzed in depth to build this database
  - Yield Strength, UTS, 4D and 5D Percent Elongations, %Red'n Area
  - True Fracture Strength, True Fracture Ductility
  - Strength Coefficient, k and Strain Hardening Coefficient, n
  - Precision Modulus, Poissons' Ratio
  - Hardness
  - Compressive Elastic Modulus and Yield Strengths
  - Fracture Toughness
  - Crack Growth Rate

  - Chemistry – Si, Fe, Cu, Mn, Mg, Zn, Ti
  - Density
  - Thermal Expansion Coefficient
  - Thermal Conductivity
  - Specific Heat

  - Metallographic Analysis

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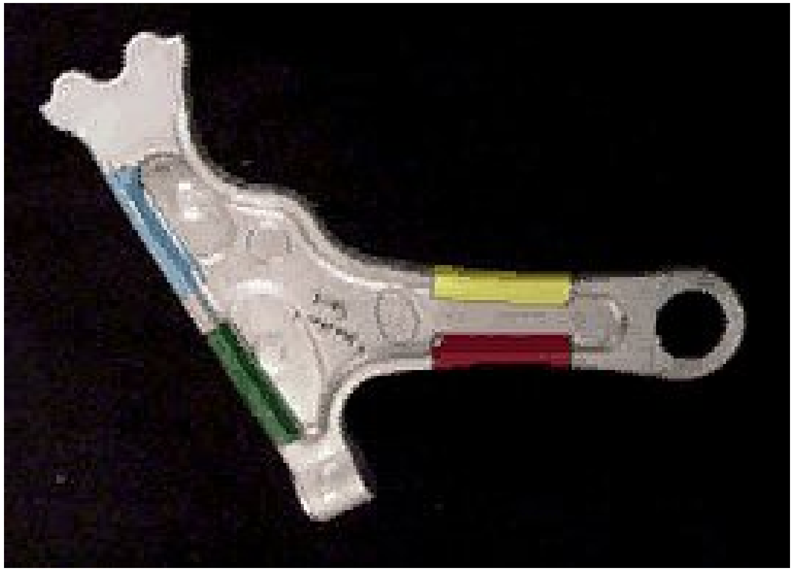
USCAR Materials Property Database

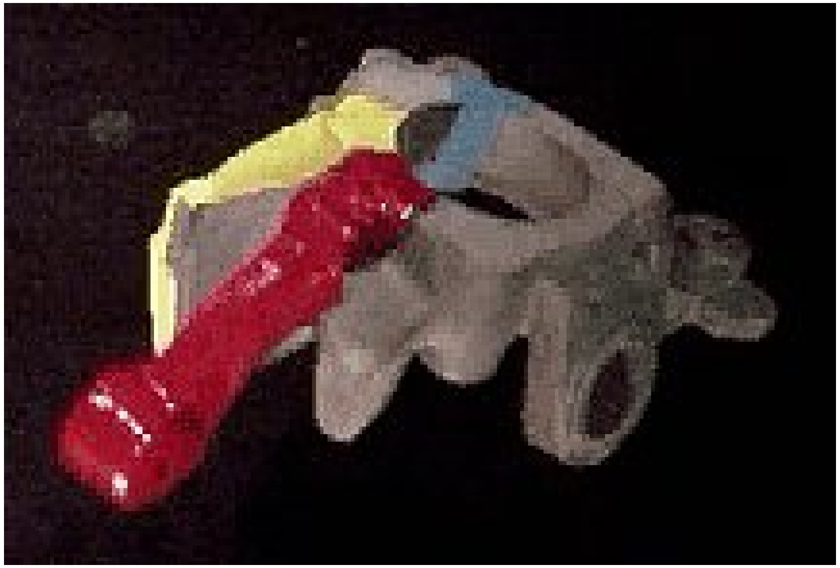
United States Council for Automotive Research

- Fatigue Properties
  - Initial cycle stress range (msi, mpa)
  - Initial cycle maximum stress (psi, mpa)
  - Initial cycle minimum stress (psi, mpa)
  - Half life stress range (psi, mpa)
  - Half life maximum stress (psi, mpa)
  - Half life minimum stress (psi, mpa)
  - Half life plastic strain(%)
  - Half life elastic strain(%)
  - ni,Cycles to crack initiation
  - nt,Cycles to failure
  - S'y, Cylic yield strength (0.2% Offset)
  - n', Cyclic strain hardening exponent
  - K', Cyclic strength coefficient (psi, mpa)
  - s'f, Fatigue strength coefficient (psi, mpa)
  - b, Fatigue strength exponent
  - e'f, Fatigue ductility coefficient
  - c, Fatigue ductiliy exponent

Example Parts

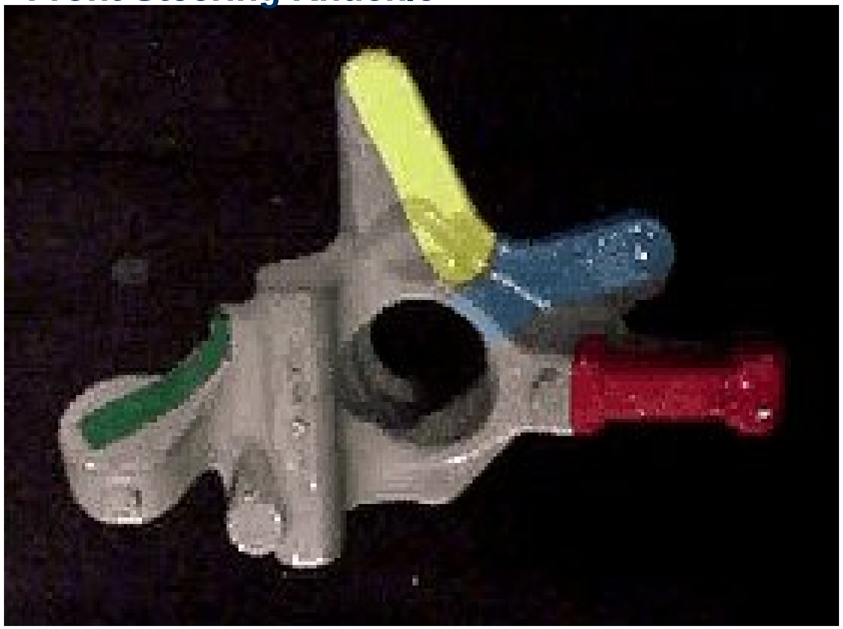


Front Lower Control Arm

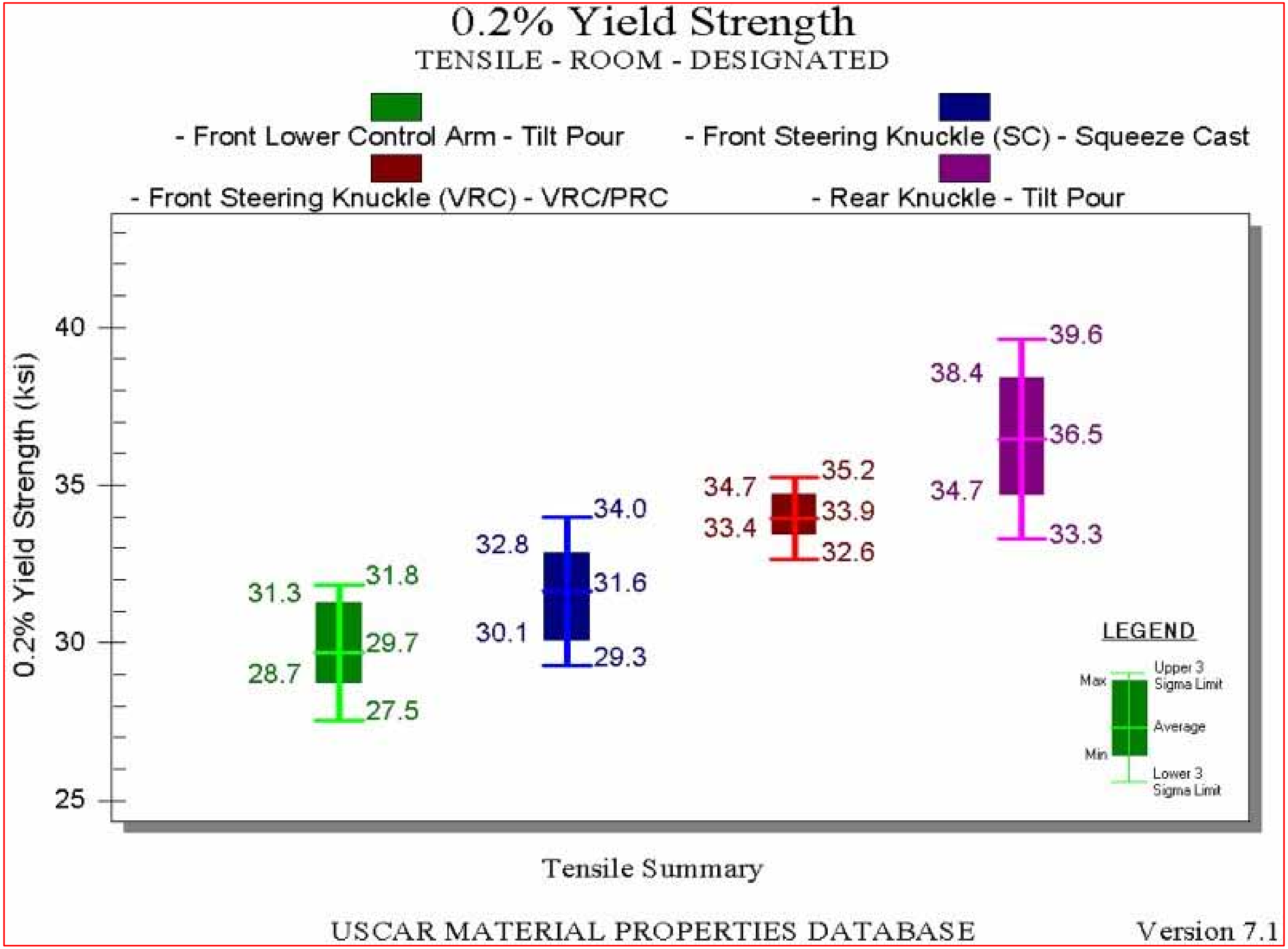


Front Steering Knuckle

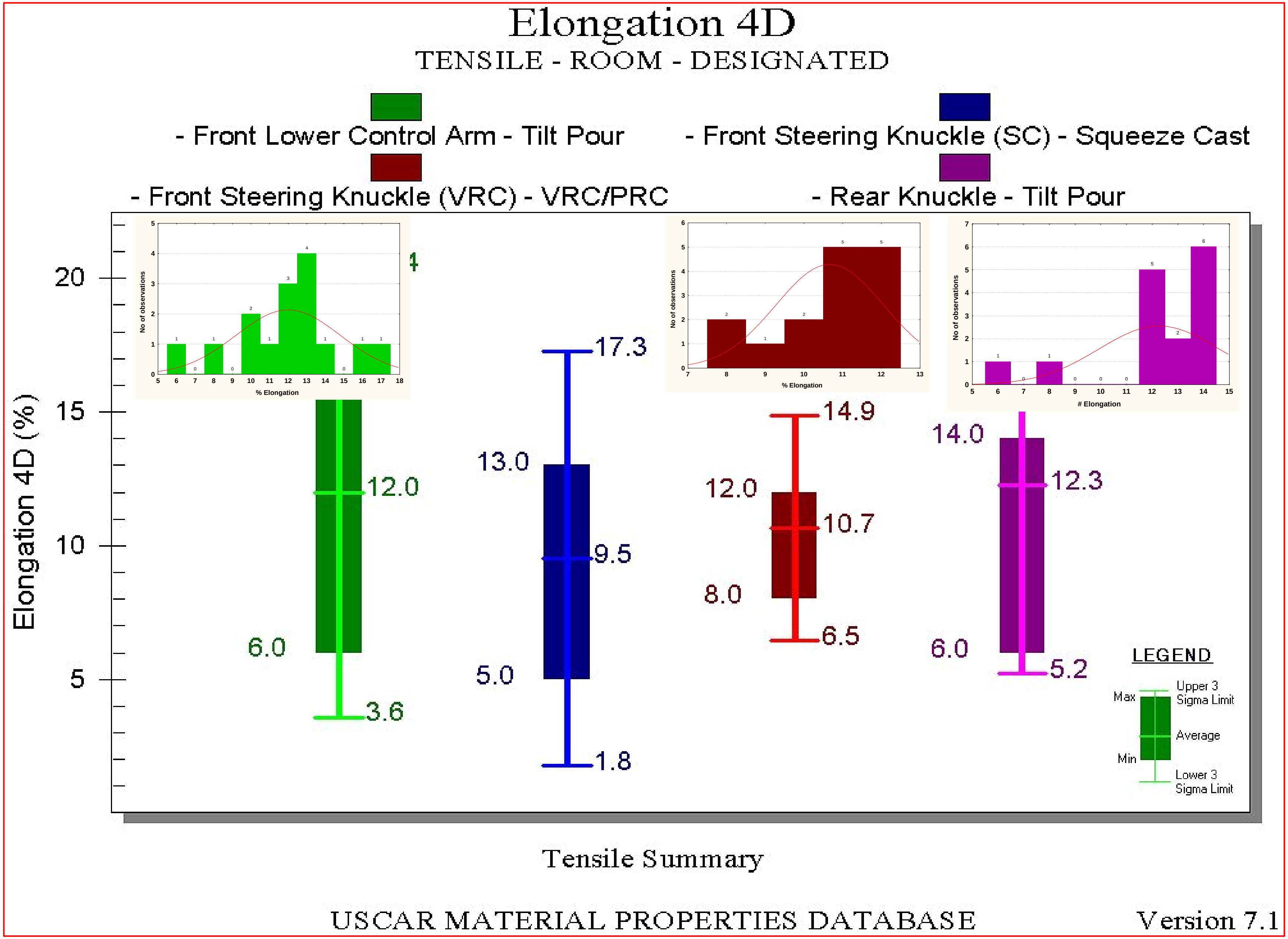
Front Steering Knuckle



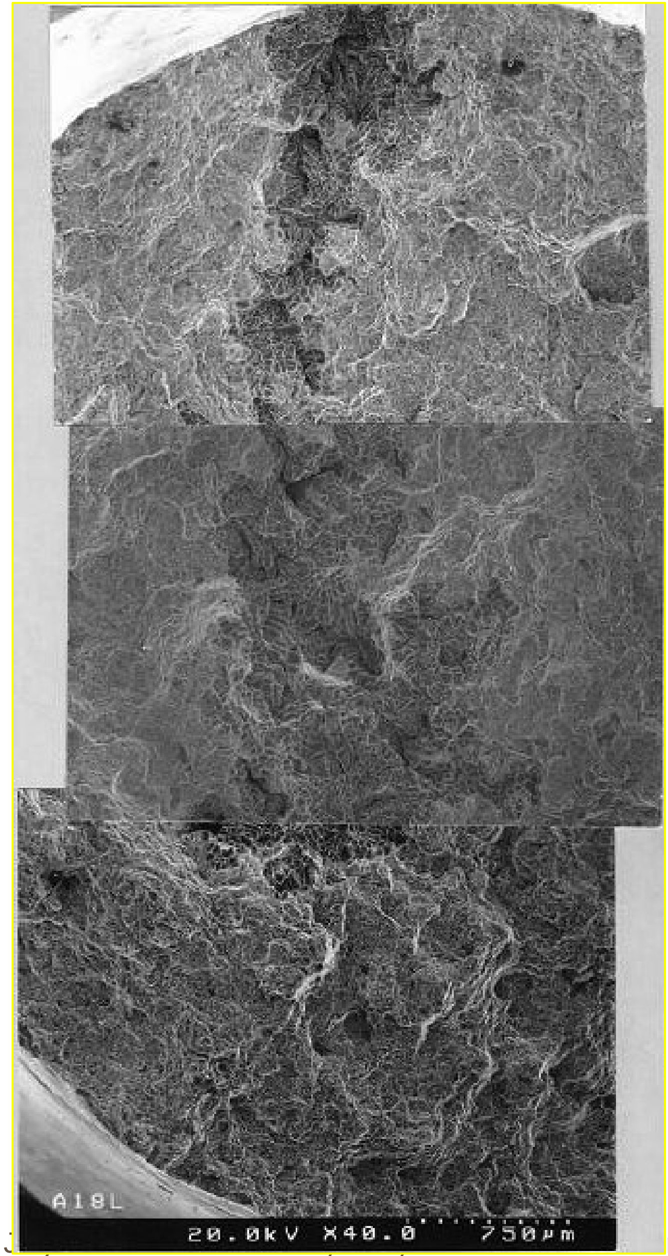
Rear Knuckle


0.2% Yield Strength
TENSILE - ROOM - DESIGNATED
- Front Lower Control Arm - Tilt Pour
- Front Steering Knuckle (SC) - Squeeze Cast
- Front Steering Knuckle (VRC) - VRC/PRC
- Rear Knuckle - Tilt Pour
0.2% Yield Strength (ksi)
40
35
30
25
31.3
31.8
29.7
28.7
27.5
32.8
34.0
31.6
30.1
29.3
34.7
35.2
33.9
33.4
32.6
38.4
39.6
36.5
34.7
33.3
LEGEND
Max
Upper 3 Sigma Limit
Average
Min
Lower 3 Sigma Limit
Tensile Summary
USCAR MATERIAL PROPERTIES DATABASE
Version 7.1

RioTintoAlcan



Correlation to Low Ductility Samples



Attempts to draw correlations between microstructural Measurements and the Variance in the Database

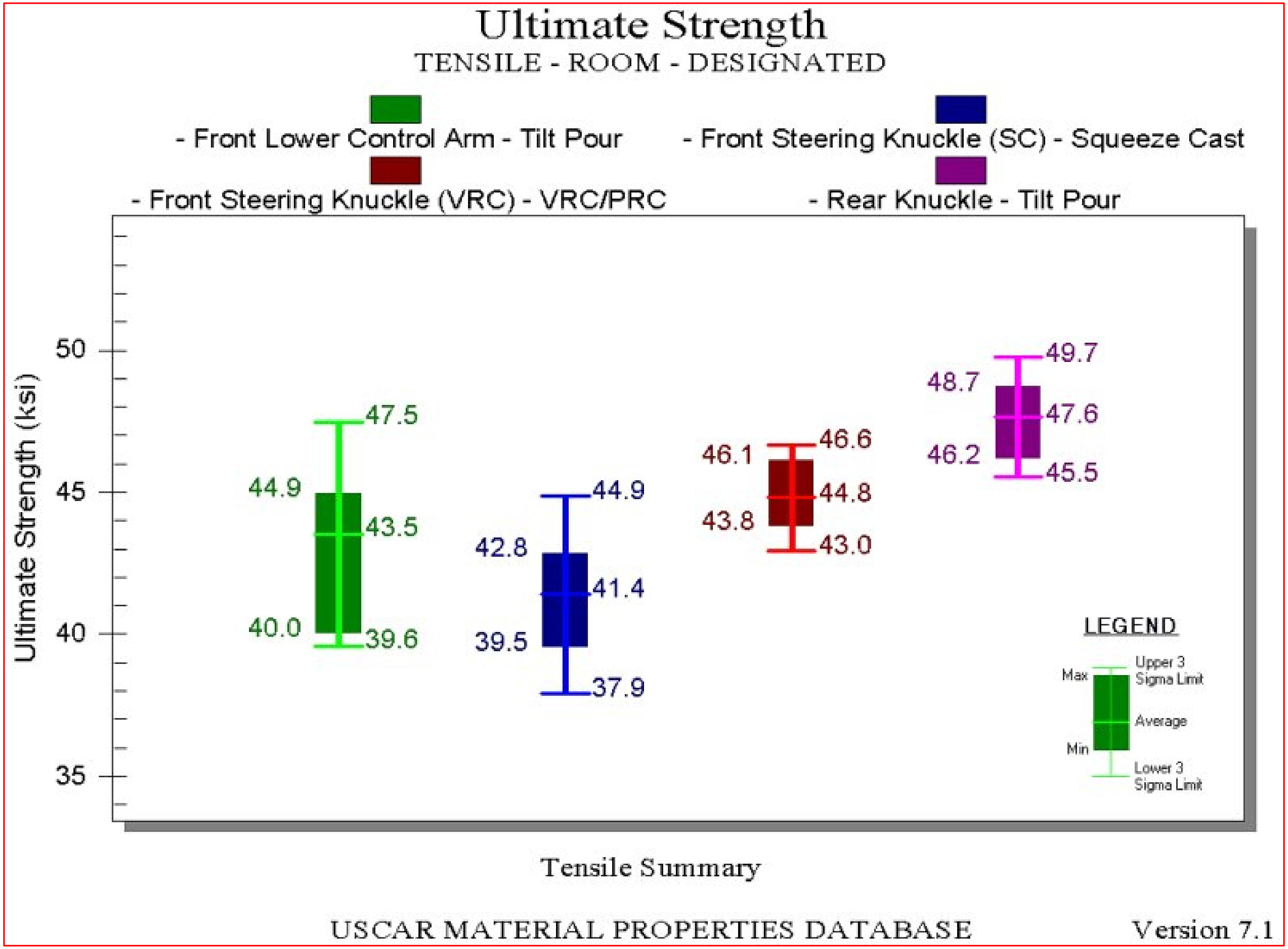
Looked at:

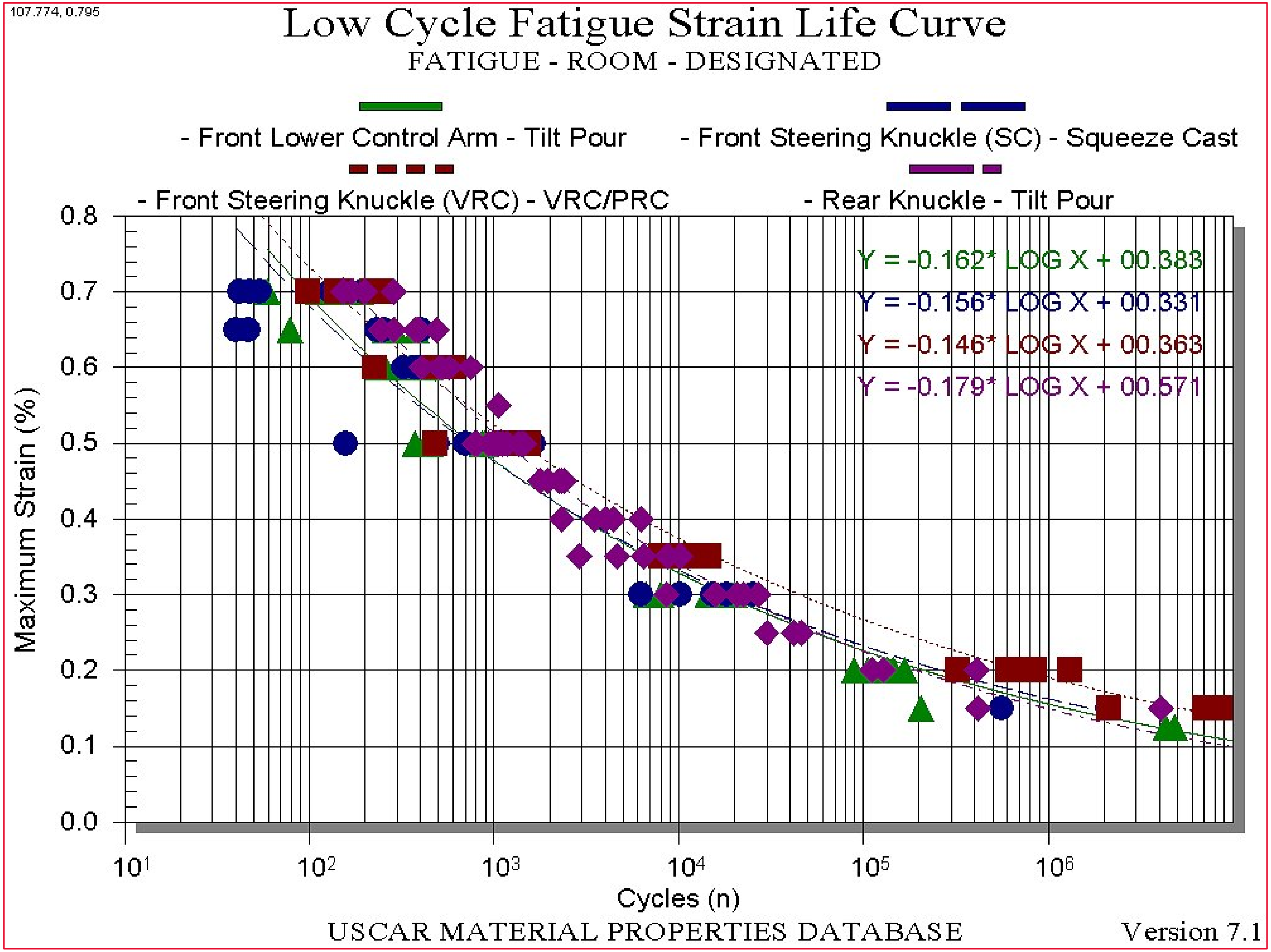
- Percent Porosity – generally very low (0.05%)
- Porosity Distribution and size (20 µm to 3 mm)
- Si Morphology – size and spacing

Concluded that:

- None of the bulk measurements correlated well to the ductility
- Low values arose from large pores that happened to be in the gauge region of the excised tensile bar
- High ductility values came from sound bars

RioTintoAlcan

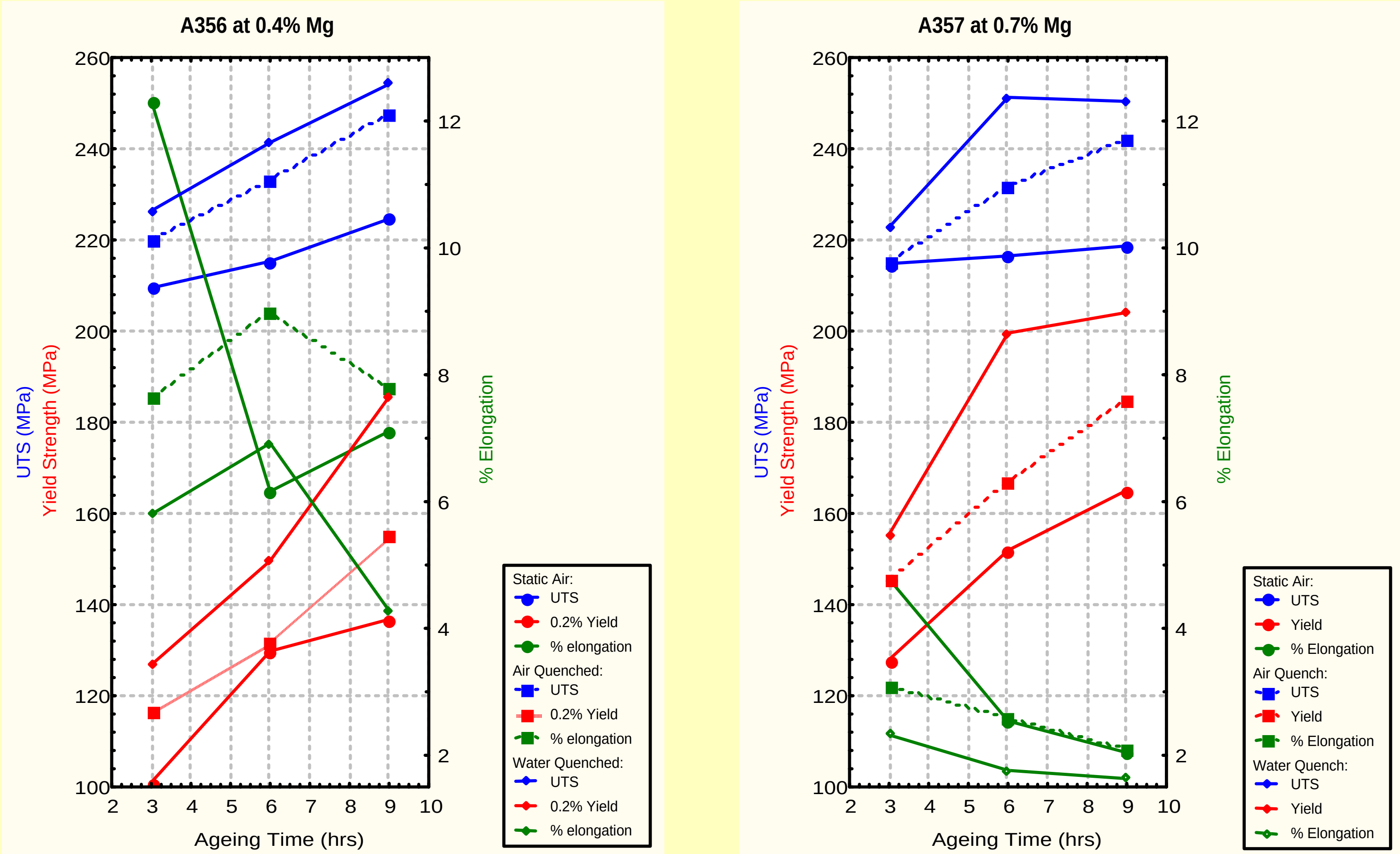



107.774, 0.795
Low Cycle Fatigue Strain Life Curve
FATIGUE - ROOM - DESIGNATED
- Front Lower Control Arm - Tilt Pour
- Front Steering Knuckle (SC) - Squeeze Cast
- Front Steering Knuckle (VRC) - VRC/PRC
- Rear Knuckle - Tilt Pour
Y = -0.162* LOG X + 00.383
Y = -0.156* LOG X + 00.331
Y = -0.146* LOG X + 00.363
Y = -0.179* LOG X + 00.571
Maximum Strain (%)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10¹
10²
10³
10⁴
10⁵
10⁶
Cycles (n)
USCAR MATERIAL PROPERTIES DATABASE
Version 7.1

Stahl Mould Properties Attainable Via Die Quenching

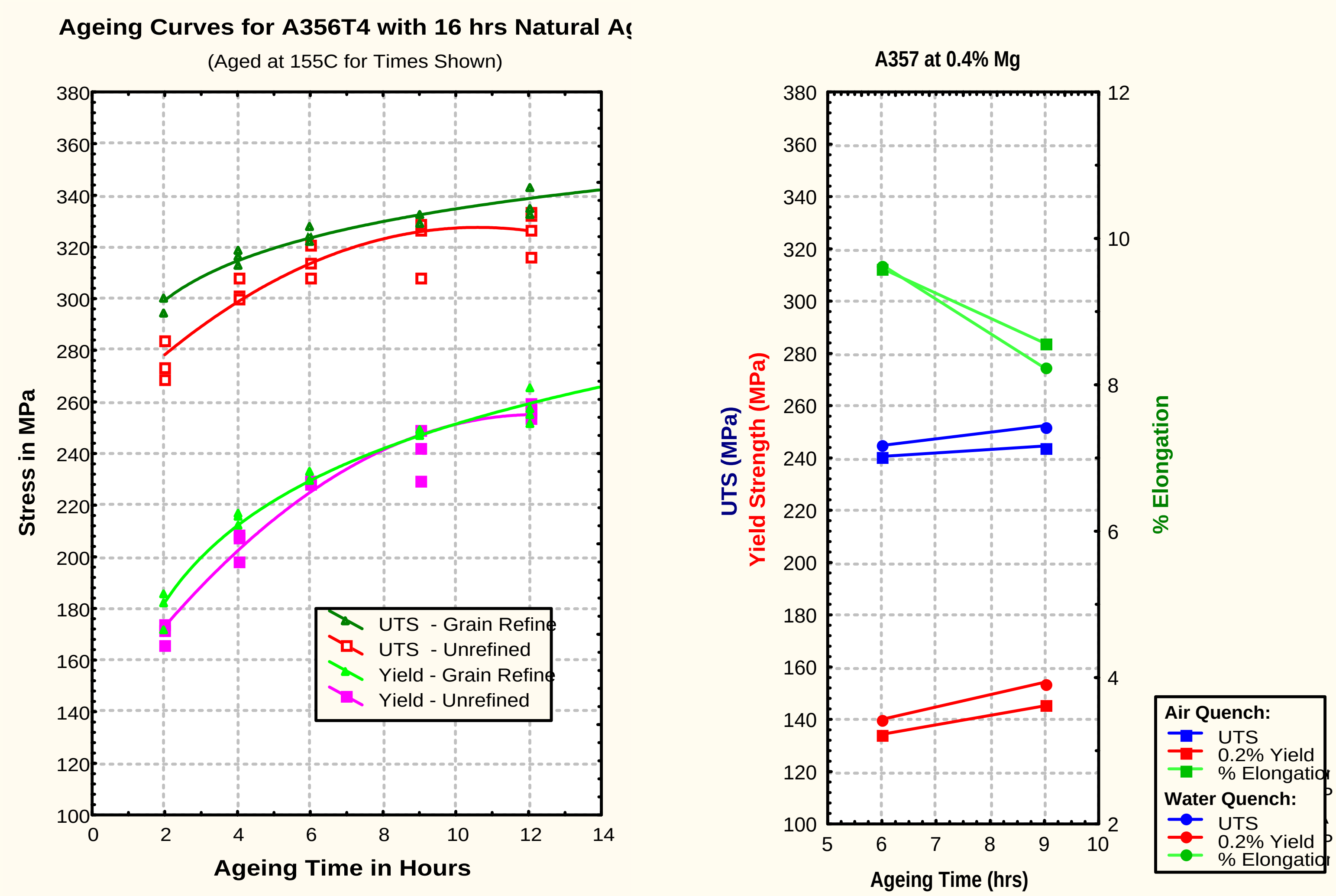
T5 Mechanical Properties with Part Cooling Technique

(Cooling Applied to Stahl Type SCBs Immediately after Removal from Die)



RioTintoAlcan

Strength Comparison: Modified T5 to T61 (0.4% Mg)



RioTintoAlcan

Strength Comparison: Modified T5 to T61 (0.7% Mg)

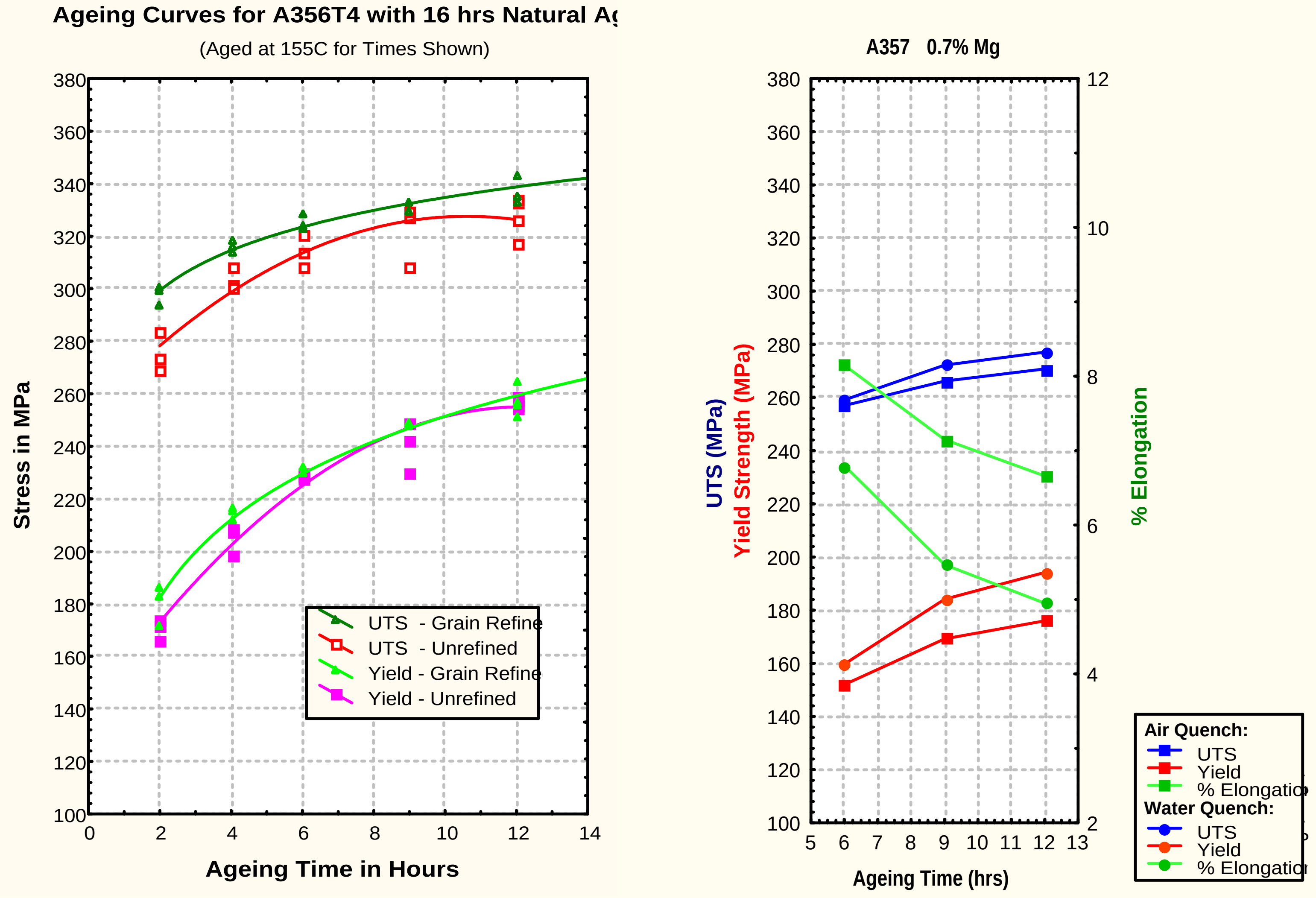


Table 2 Comparison of semisolid forging and permanent mold casting for the production of aluminum automobile wheels

See Example 1.

Process	Weight direct from die or mold, kg	Weight direct from die or mold, lb	Finished part weight, kg	Finished part weight, lb	Production rate per die or mold, pieces per hour	Aluminum alloy	Heat treatment	Ultimate tensile strength, MPa	Ultimate tensile strength, ksi	Yield strength, MPa	Yield strength, ksi	Elongation, %
Semisolid forging	7.5	16.5	6.1	13.5	90	357	T5	290	42	214	31	10
Permanent mold casting..............	11.1	24.5	8.6	19.0	12	356	T6	221	32	152	22	8