A study on the homogeneity of plastic deformation and its importance to tensile ductility in Al-Si-Cu-Mg (C355) investment castings.

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Company Overview

A W Bell is a global supplier of complex metal parts with high mechanical properties to aerospace, defence, space & biomedical industries.

To be the most innovative and customer-focused supplier of quality casting solutions globally.

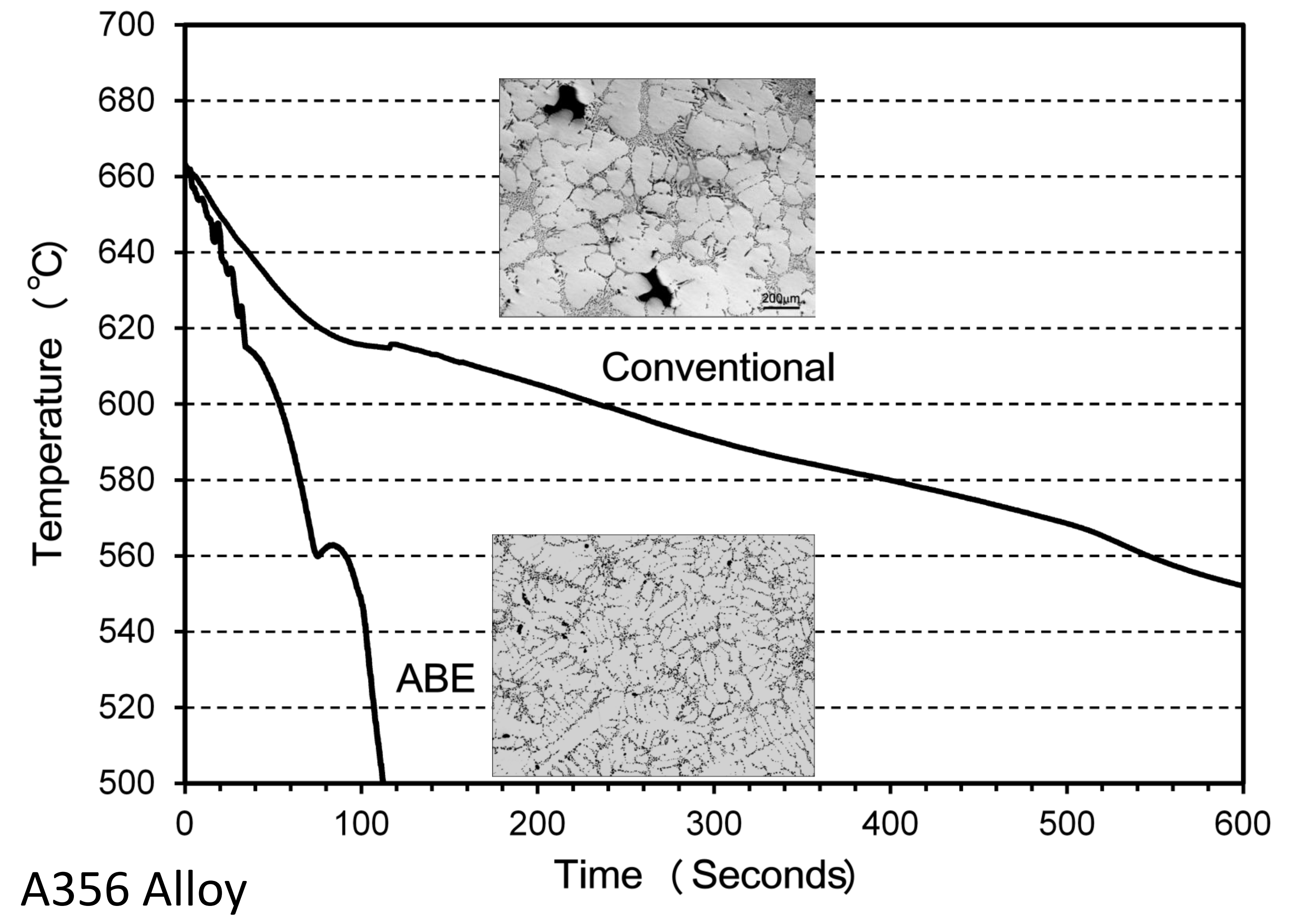
Company Vision

A Snapshot of C355 Alloy
(Al-5Si-1.2Cu-0.5Mg)

- Applications:
- Aircraft supercharger covers, fuel pump bodies, air compressor pistons, liquid and air cooled cylinder heads, liquid cooled aircraft engine crankcases, water jackets, blower housings.

- Weldable, castable.
- Maintains good mechanical properties at elevated temperatures.

AWBell ABE Process



Cooling rates are around 20X higher than conventional processing, producing a fine, high integrity microstructure.

Results of ABE Process in C355-T6 Alloy

Initial Production Results Looked Excellent Without System Design

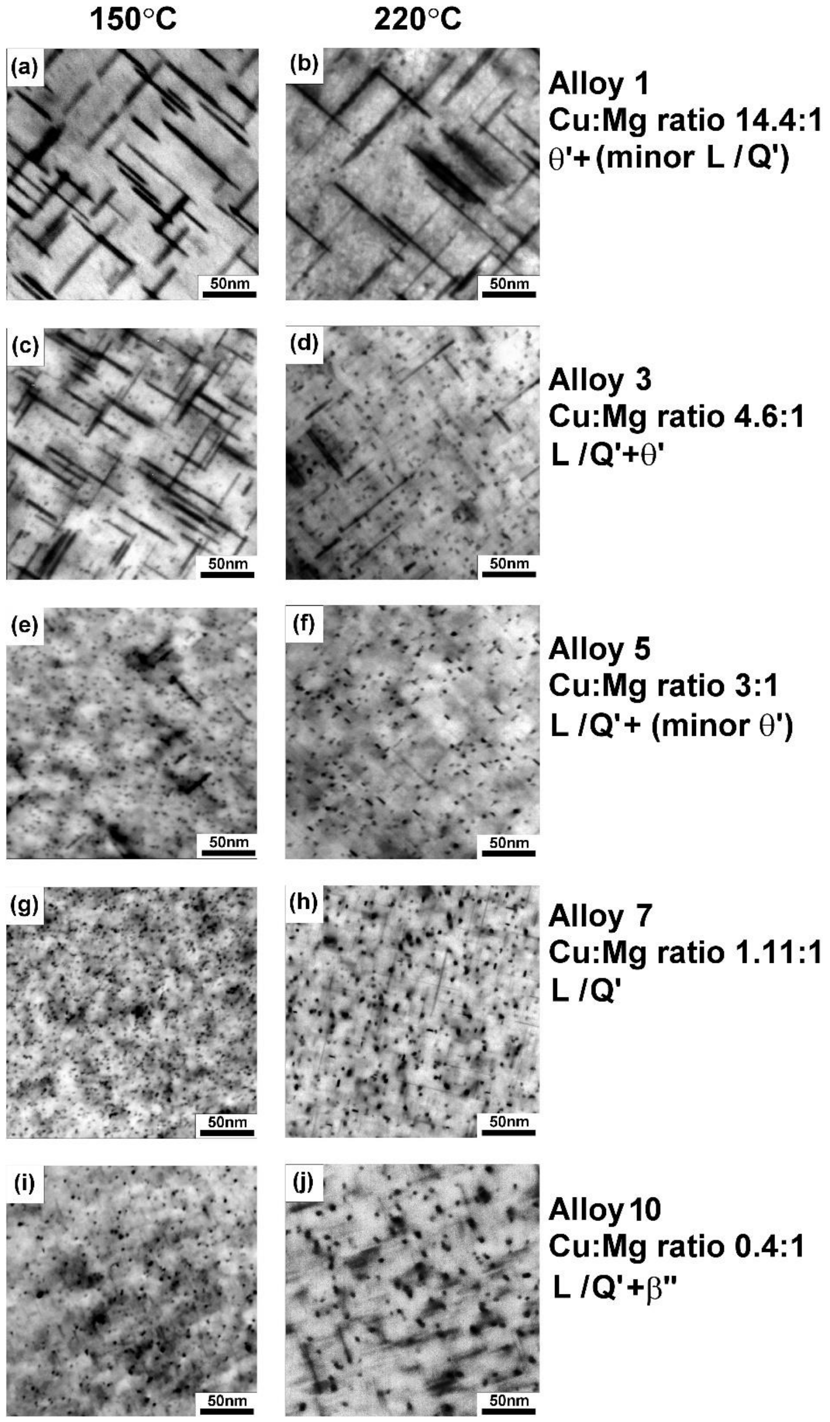
Alloy C355-T6	Yield Stress (MPa)	UTS (MPa)	Elongation (%)
AMS 4215 Target	207 MPa	255 MPa	1%
Typical	200 MPa	270 MPa	5%
Premium	235 MPa	317 MPa	6%
ABE Result	296 MPa	344 MPa	11%

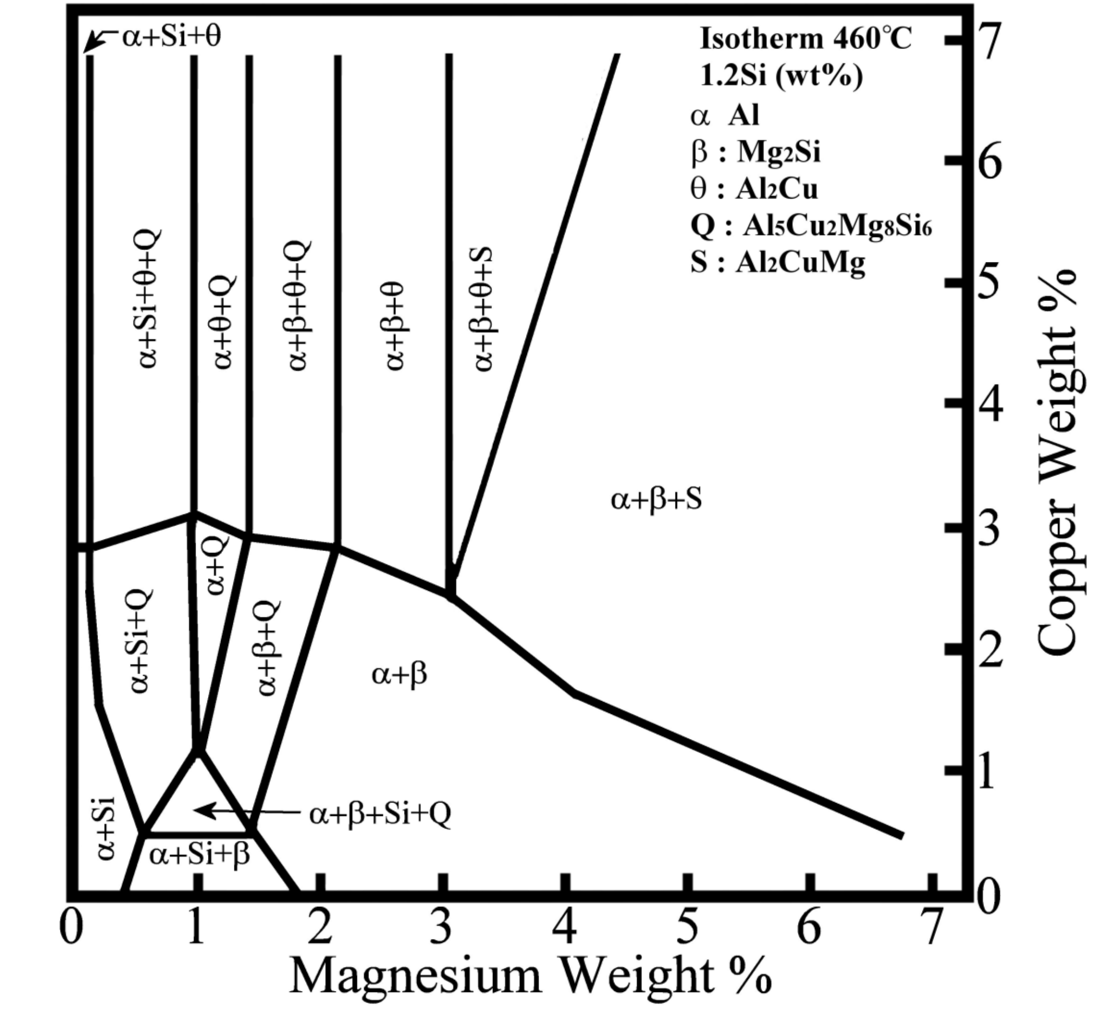
Typical and Premium values from ASM Metals Handbook, Aluminum and Aluminum Alloys, 1994.

Hypothesis:

By instituting good casting practice, alloy design and heat treatments designed for maximum homogeneous deformation, the theoretical limits of maximum ductility in Al-Si alloys might no longer apply. If deformation is particularly homogenous, the material will in theory keep necking without unstable failure.

Some background first…….





Previous work showed alloys with high L/Q precipitate content could have anomalous tensile ductility under some conditions.

Optimum ratio close to 1:1 at% Cu:Mg.

L: Laths with a $\{100\}_\alpha$ habit plane. Unknown structure. Precursor to Q′
O.R. $[100]_L//[100]_\alpha$ and $[010]_L // [010]_\alpha$.
Q′: Laths with long axis parallel to the <100>α direction & $\{150\}_\alpha$ habit planes. Hexagonal. O.R. $[100]_\alpha // [0001]_{Q'}$ and $(020)_\alpha//(21\bar{3}0)_{Q'}$

R.N. Lumley, I.J. Polmear and P.R. Curtis, Met. & Mat. Trans. A, Vol.40, #7, p.1716-1726 (2009).

Composition of Test Alloy

C355 i.a.w. AMS 4215	**Al**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Sr**	**Other each**	**Other, total**
Range	Bal.	4.5-5.5	0.2 Max	1.0-1.5	0.10 Max	0.40-0.6	0.10 Max	0.20 Max	--	0.05	0.15
Designed Alloy Actual	Bal.	5.31	0.07	1.08	<0.01	0.44	0.06	0.09	0.014	<0.01	<0.03
Atomic %	93.8	5.1	0.03	0.46	0	0.49	0.02	0.05			

At% ratio Cu:Mg = 0.94

Manufacturing Process:

Premium Investment Casting ABE process used.
Cast together with production parts.

Metal Pour Temperature 720°C
Shell temperature 600°C

~80% revert, ~20% primary

16 bar testbar trees with bottom filter X2. 28 testbars in data set.

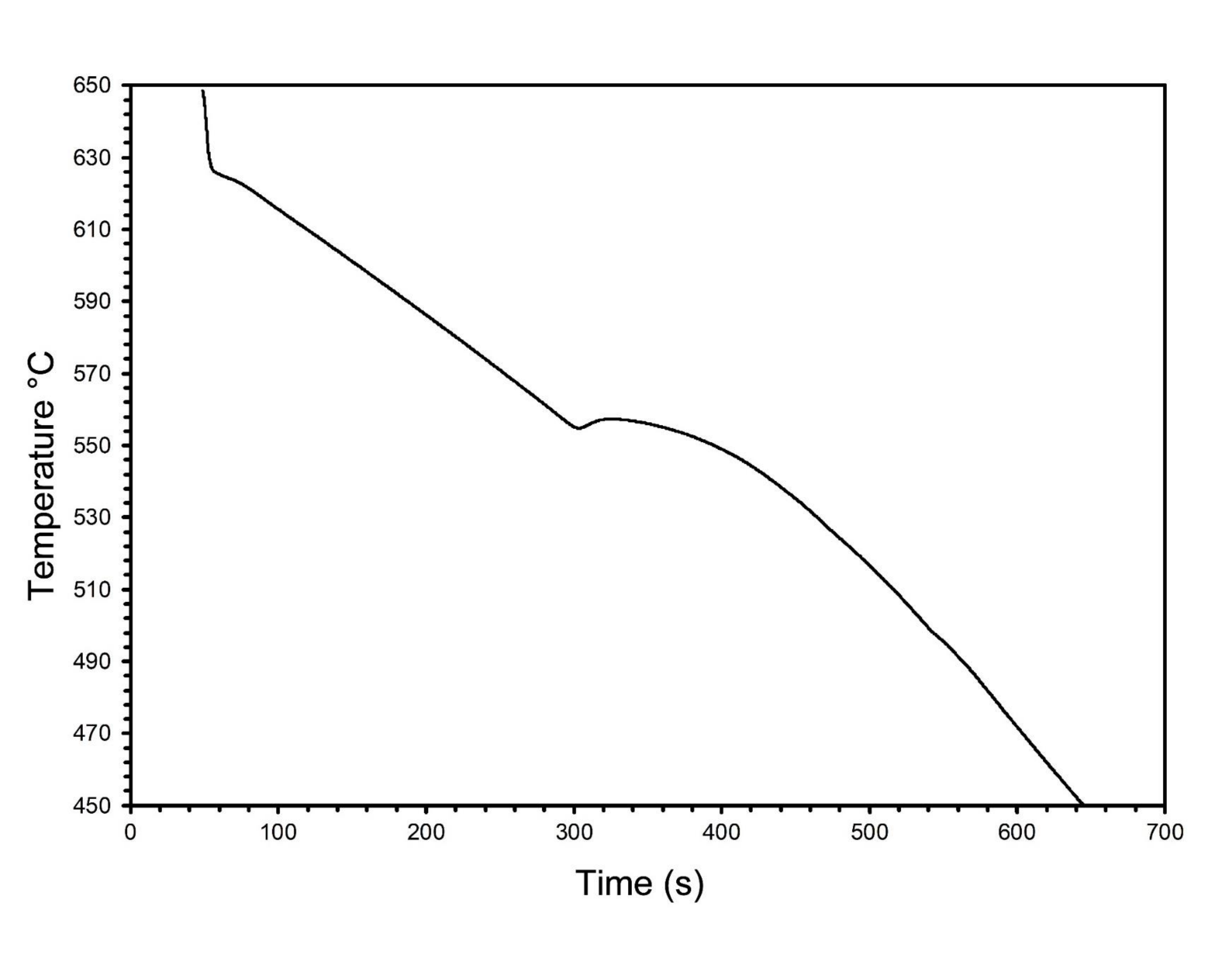
Testbars cast to shape in accordance with ASTM B557

Heat treated in accordance with AMS 2771.

Heat treatment was performed to optimize homogeneity of plastic flow.

(Strictly controlled quenching conditions, heating rate controlled ageing conditions)

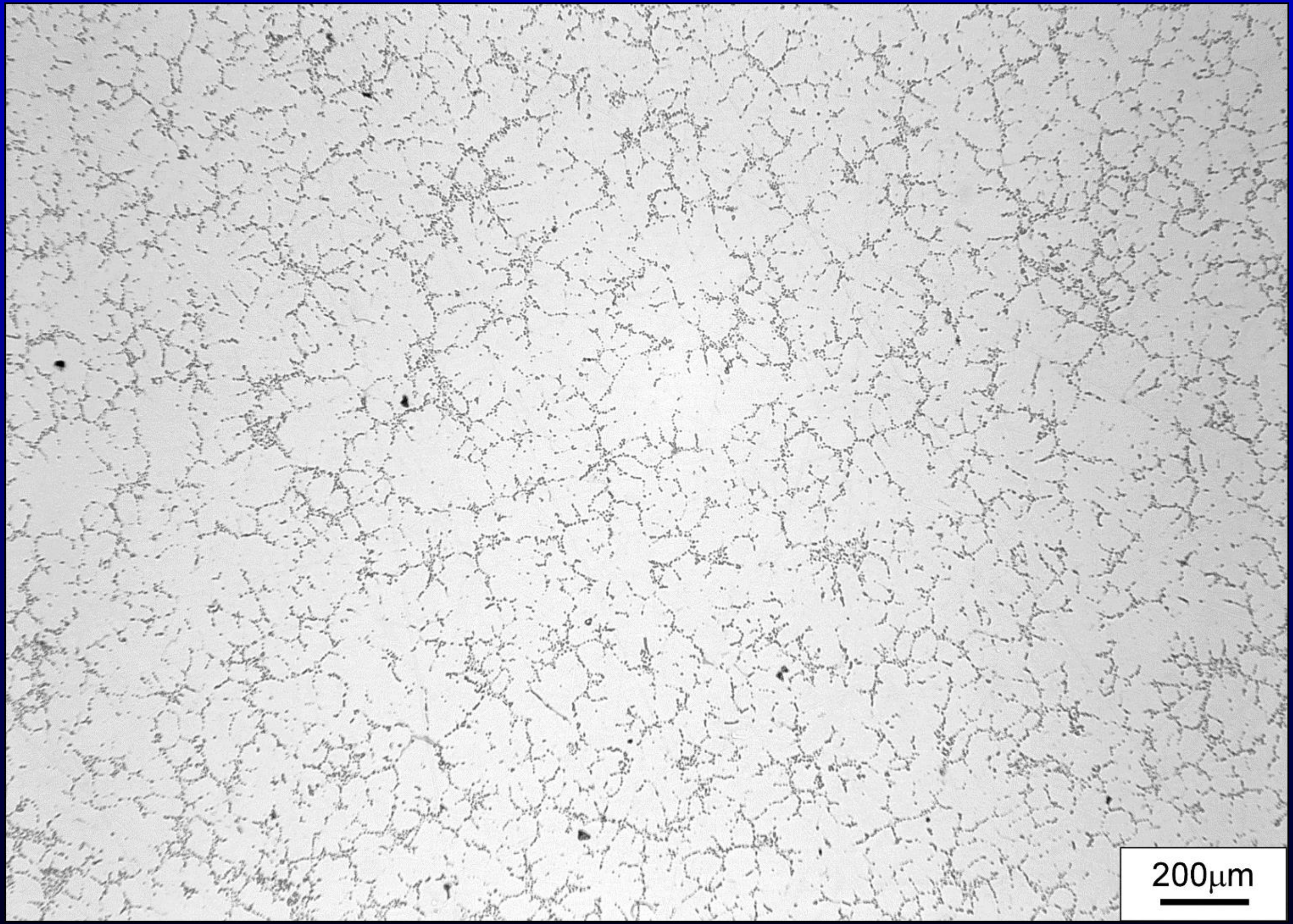
Thermal Analysis



Onset of solidification: ~626°C
Onset of eutectic solidification: ~556°C
Finish of solidification ~522°C
Last incipient melt ~ 496°C

QuiK Cup no Te + PicologTC-08 datalogger

Microstructure (Heat Treated)

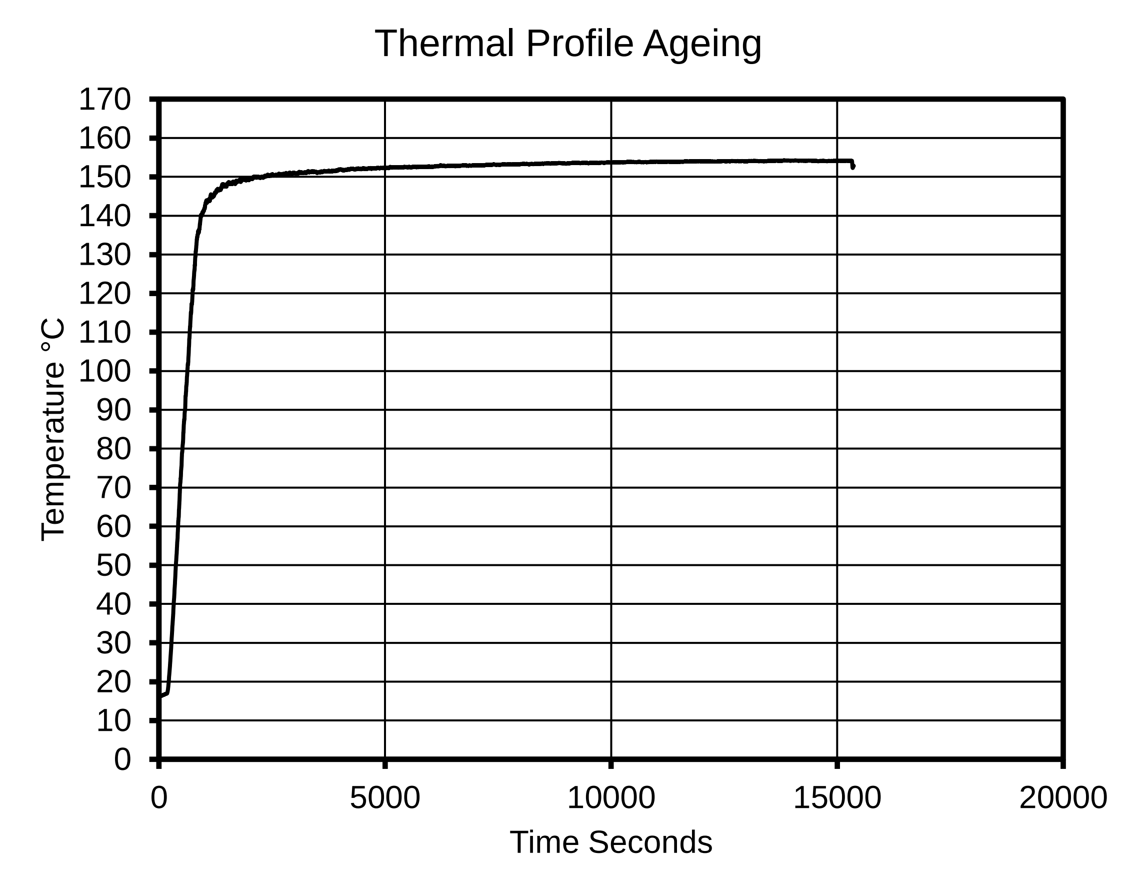


Many cells, dendrites are short range order.

DAS = 38μm
Cell size ~100-300 μm

Heat Treatment Procedure: AMS 2771

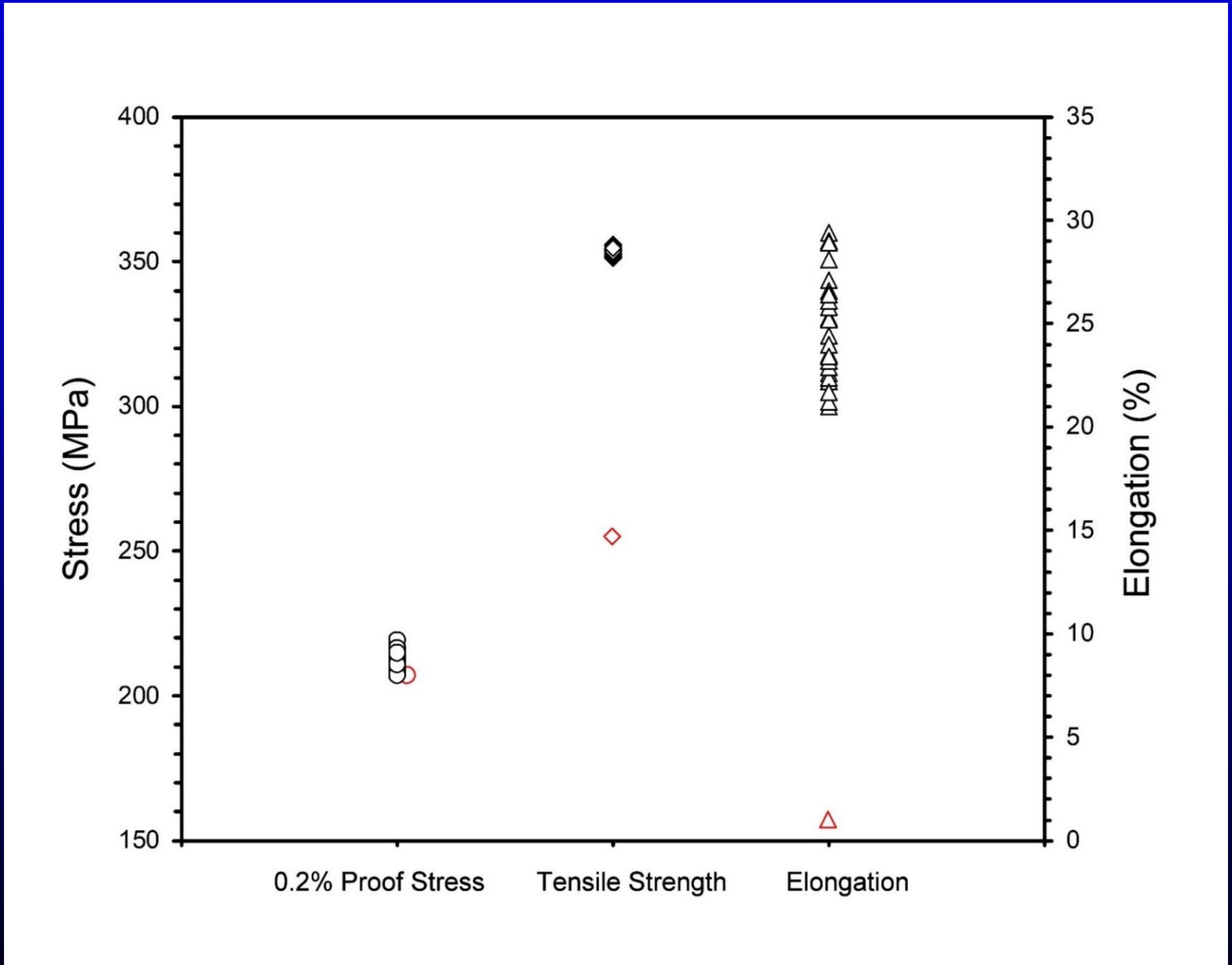
Strict control of heating and cooling conditions.
ST 16h @ 529°C, HWQ@80°C, Age 4h@155°C



Heating rate to ~140°C is almost linear

Tensile Properties Were Exceptional

Averages:
0.2% p.s. = 212.3 MPa
UTS = 353.7 MPa
El.= 24.3%



Strain rate 10mm per minute.

Extensometer removed at 20% elongation.

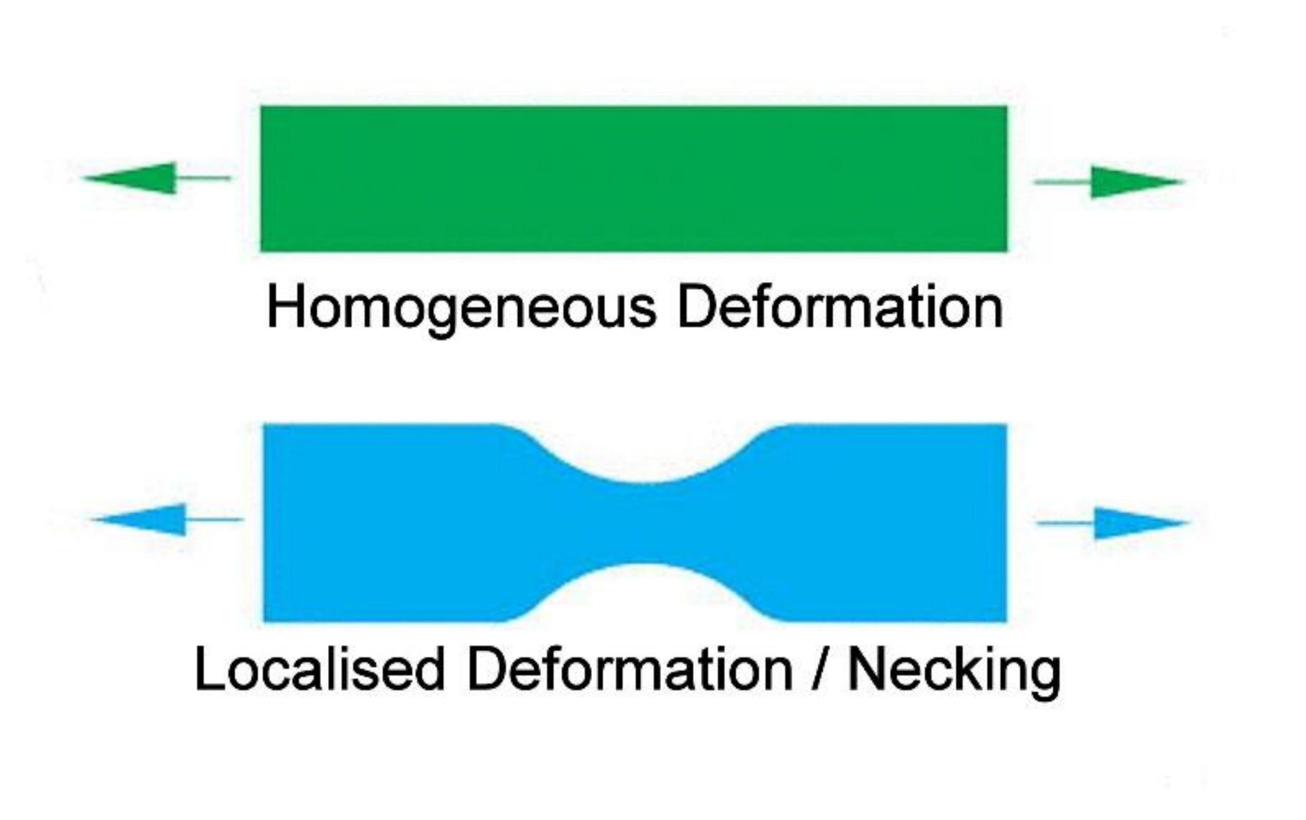
Final elongation result measured manually.

28 test results.

Testing conducted at CSIRO with thanks to Gary Savage.

Red = AMS 4215

Homogeneous Plastic Deformation



Almost no necking, & only at above 20% elongation

Test bars to ASTM B557, cast to shape, no machining.

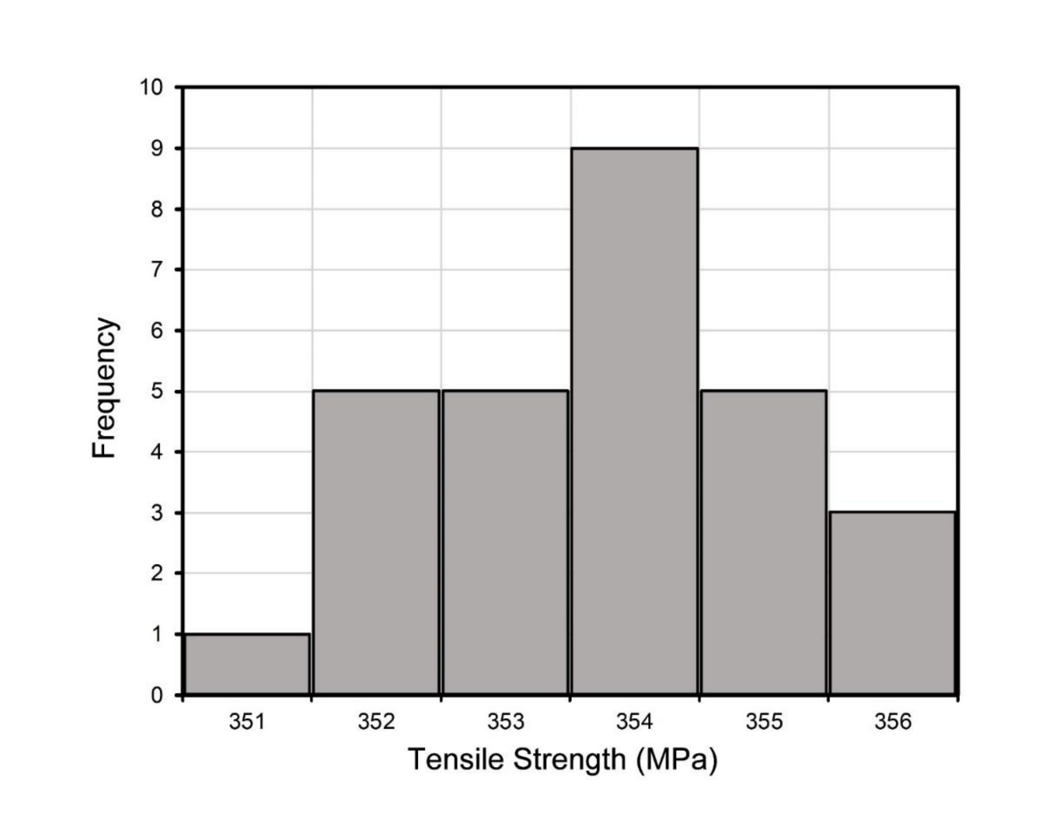
The relative quality of the material was assessed

1. Quality Index QI = UTS +150 Log E
2. True Stress True Strain Evaluation
3. Equivalent Defect Fraction
4. Weibull Statistics

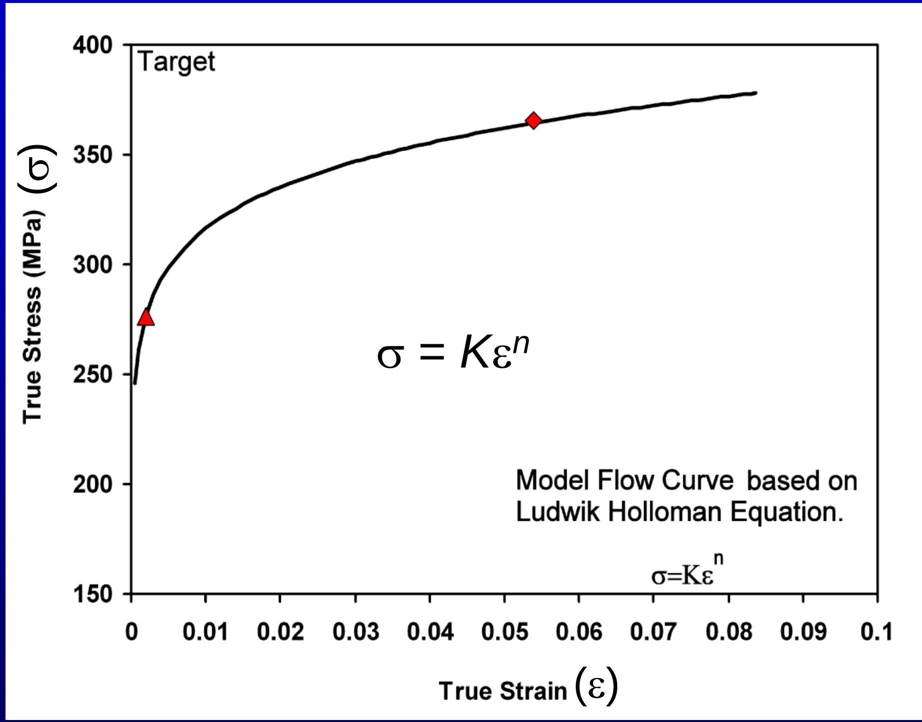
Quality Index QI = UTS+ 150 Log E

561.4 MPa +/-6.86

Reflects the very low variability in the UTS



Methodology:
Flow Curve Based on the Ludwik-Hollomon Relationship



Where σ = true stress, ε= true strain, K = the strength coefficient, n = strain hardening exponent.

n may be shown experimentally to be equivalent to the true strain, ε, at the onset of necking.

When ε=n, the Considère criterion is met, we have maximum σ & necking begins.
The material is defect free when the experimental flow curve equals theoretical.
Defects cause premature failure and flow curve deviation.

The Role of Casting Defects on Failure (1)

- **Cáceres and Selling showed:**

- **Bulk volumetric porosity has almost no correlation to tensile properties;**

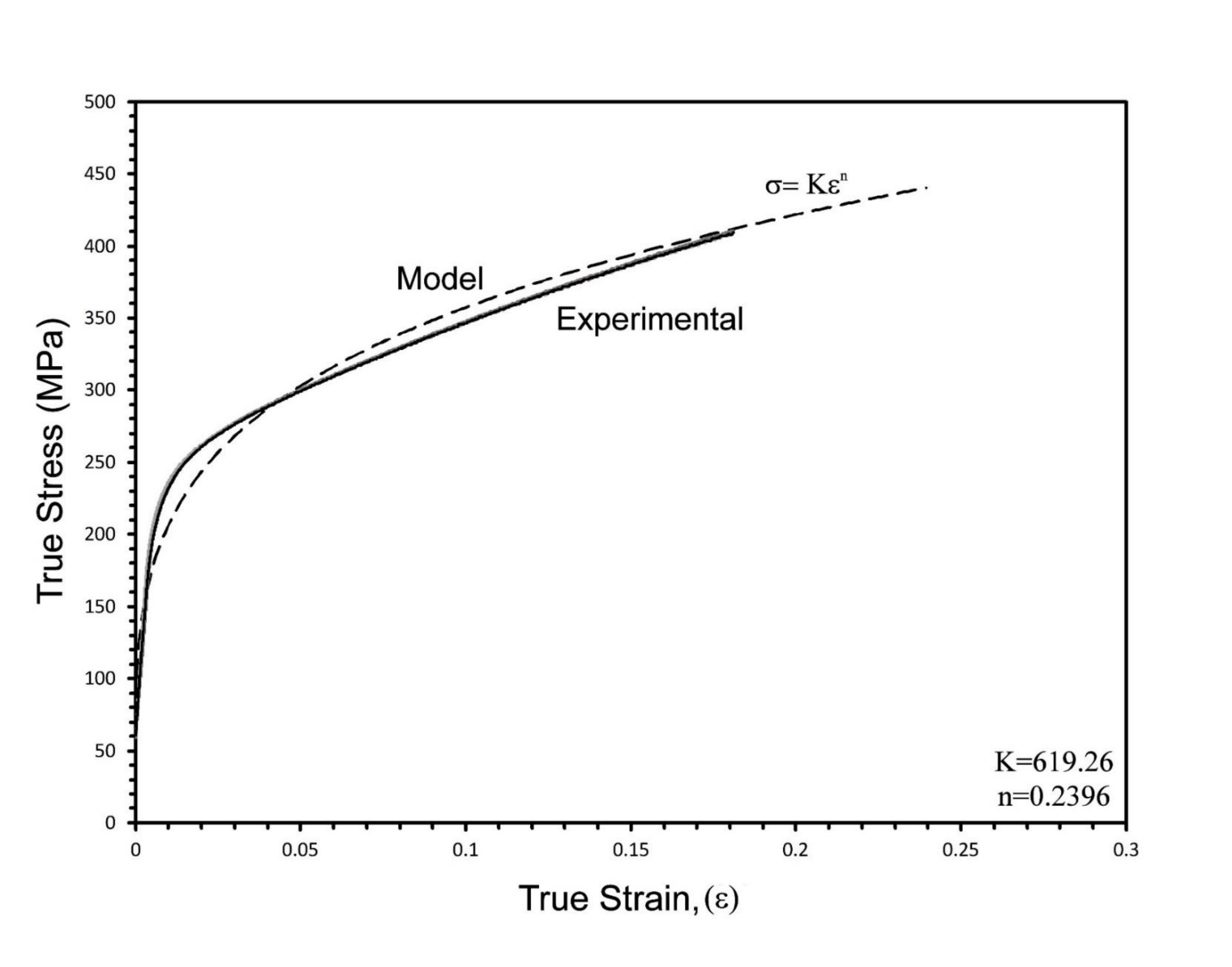
- **The number or fraction of any type of defects present on the fracture surface was directly related to the tensile behavior and failure.**

The Role of Casting Defects on Failure (2)

- Cáceres and Selling proposed a model:
- Based on the relationship between a cross sectional area not containing a defect, A_o, and the cross sectional area containing a defect, A_i,
- If the material follows the Ludwik-Hollomon equation then :
- $(1-f)e^{-\varepsilon_i} \varepsilon_i^{n} = e^{-\varepsilon_h} \varepsilon_h^{n}$
- Which relates the strain inside the defect to the strain outside the defect. To then solve for the defect area fraction (f) thus gives:
- $f=1-(e^{-\varepsilon_h} \varepsilon_h^{n} /e^{-\varepsilon_i} \varepsilon_i^{n})$

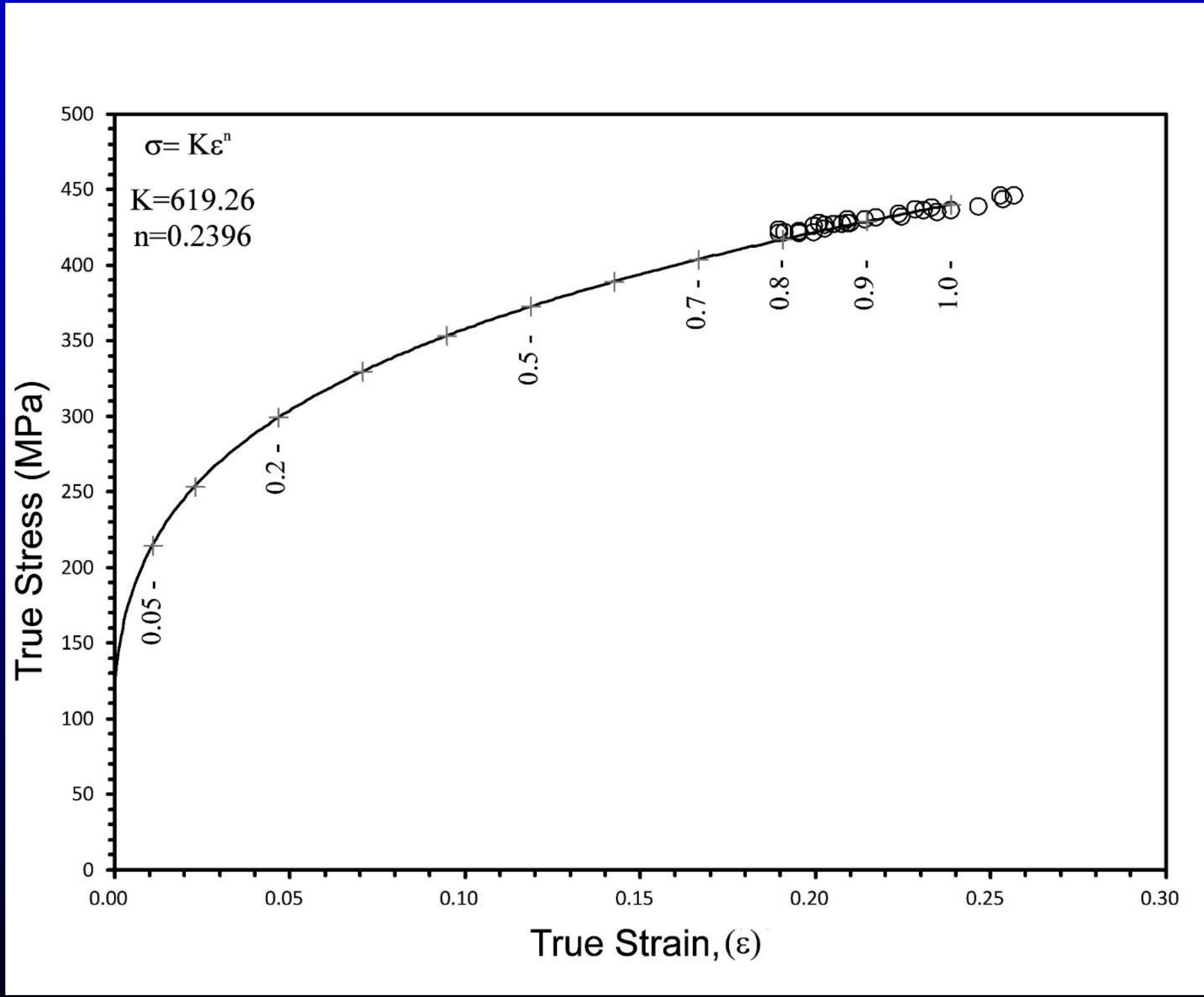
(Where σ_i and ε_i are the true stress and strain inside the defect, and σ_h and ε_h are the true stress and strain outside the defect.)

A Model True Stress – True Strain Flow Curve was Developed



(Typically valid up to the onset of necking)

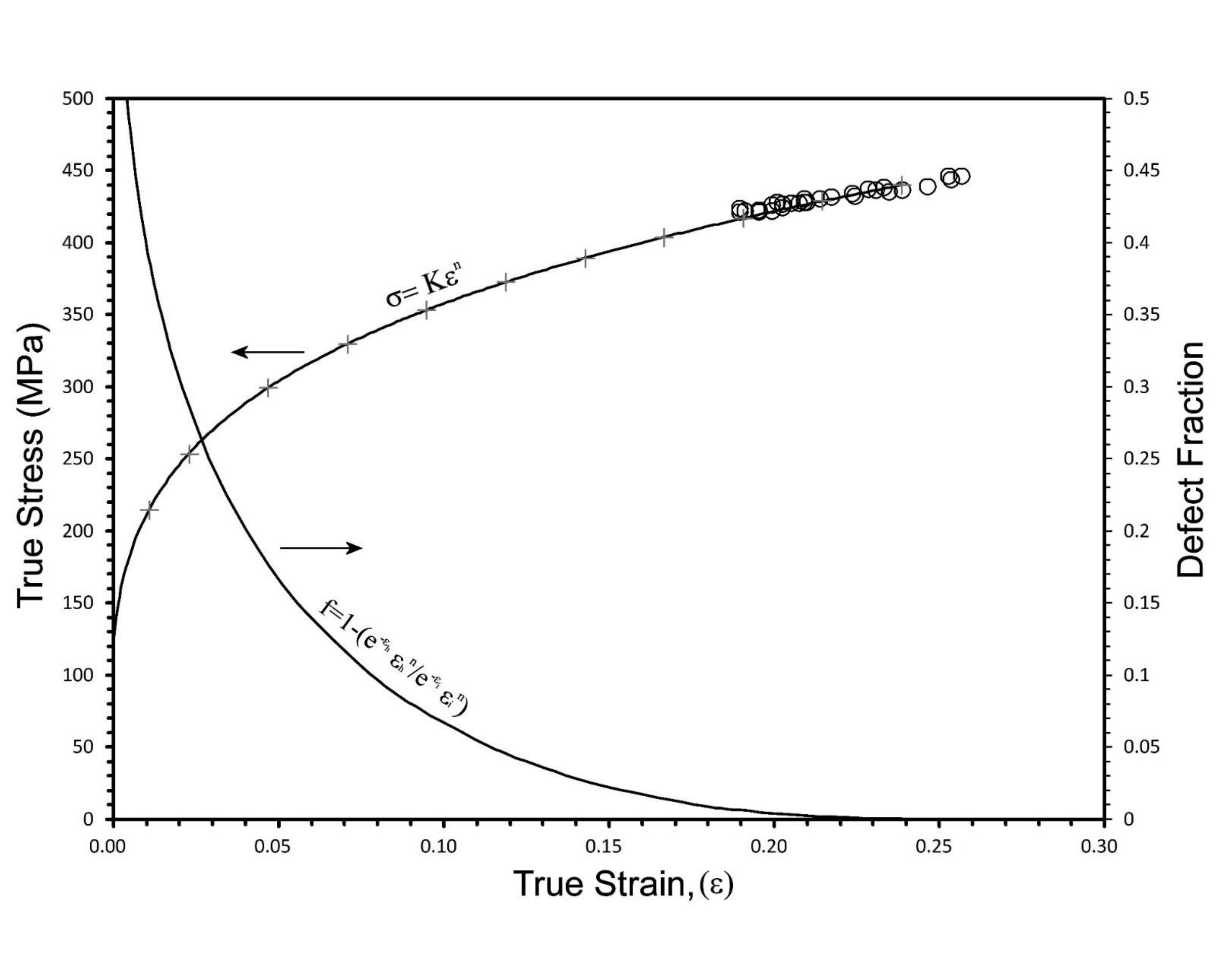
If we assume negligible necking occurs we can consider using all of the elongation result



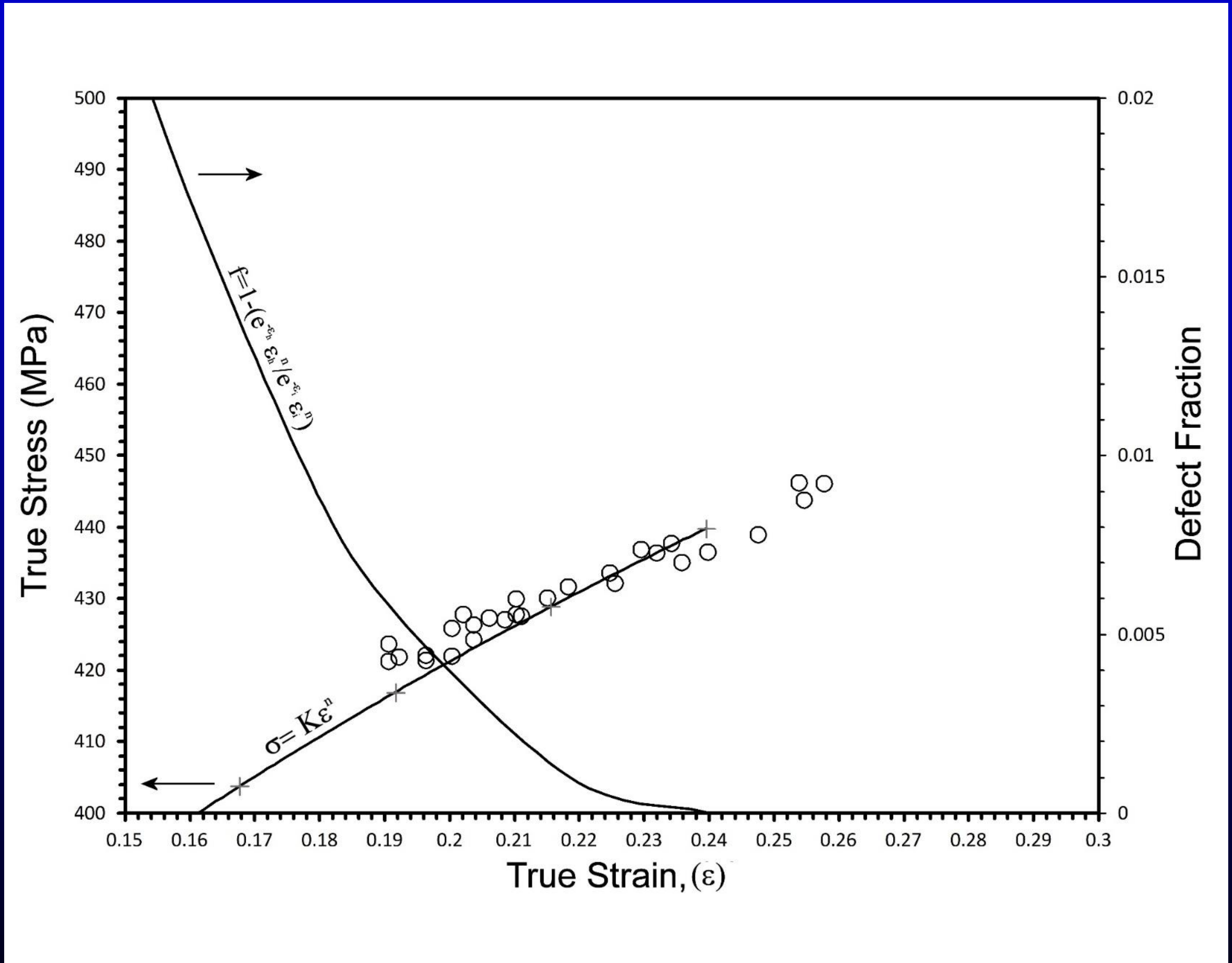
Q values show >0.8 to >1.0 Corresponds to true strain above ~0.19.
Average = 0.22. (Q=0.92)

Theoretical maximum =0.24 (where n = ε).

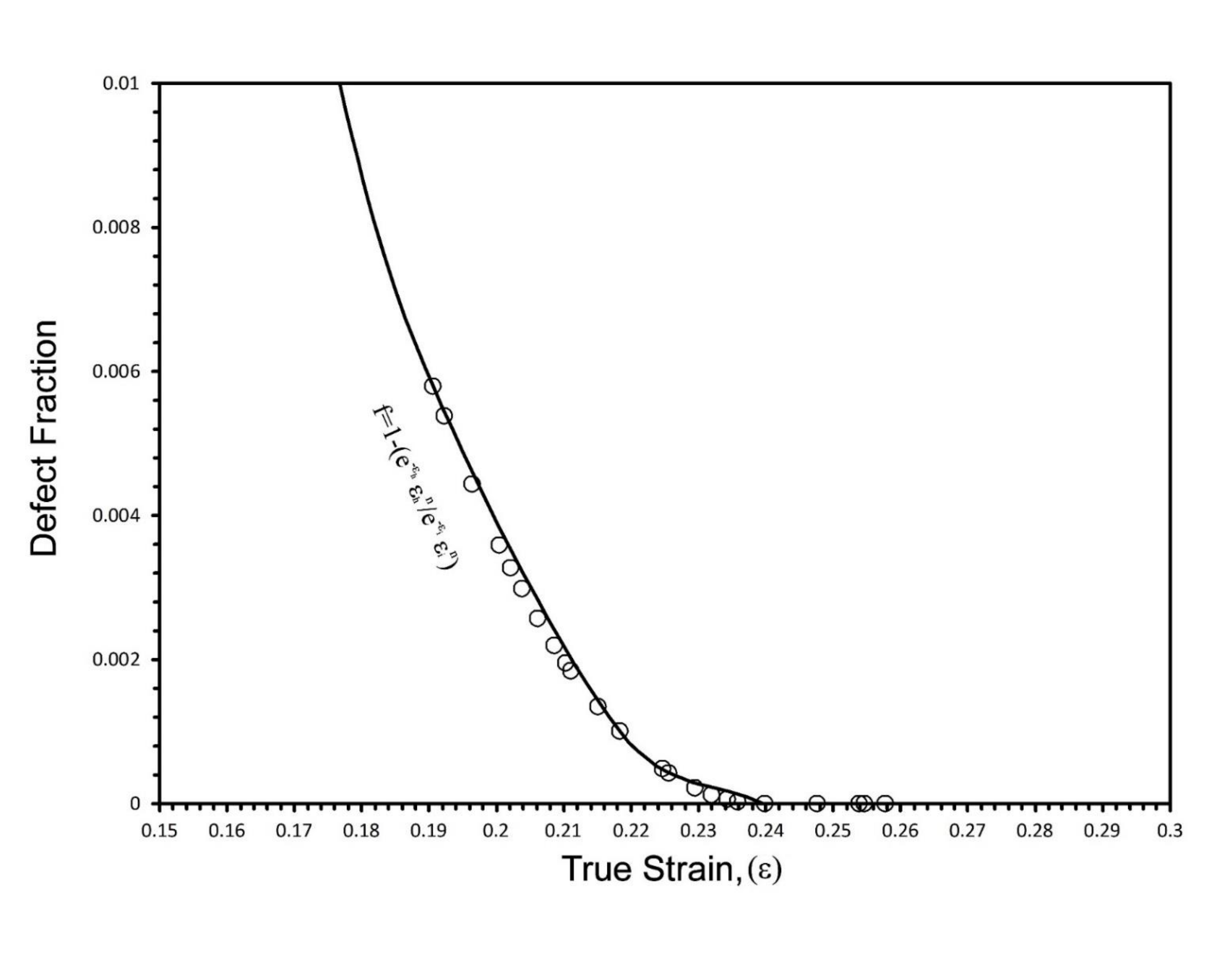
Solving for Defect Fraction (Linear Scale)



Solving for Defect Fraction (Linear Scale)



Solving for Equivalent Defect Fraction of the Experimental Results



100% <0.6% Defect Fraction; 57% of results <0.2% Defect Fraction; 43% <0.1% Defect Fraction

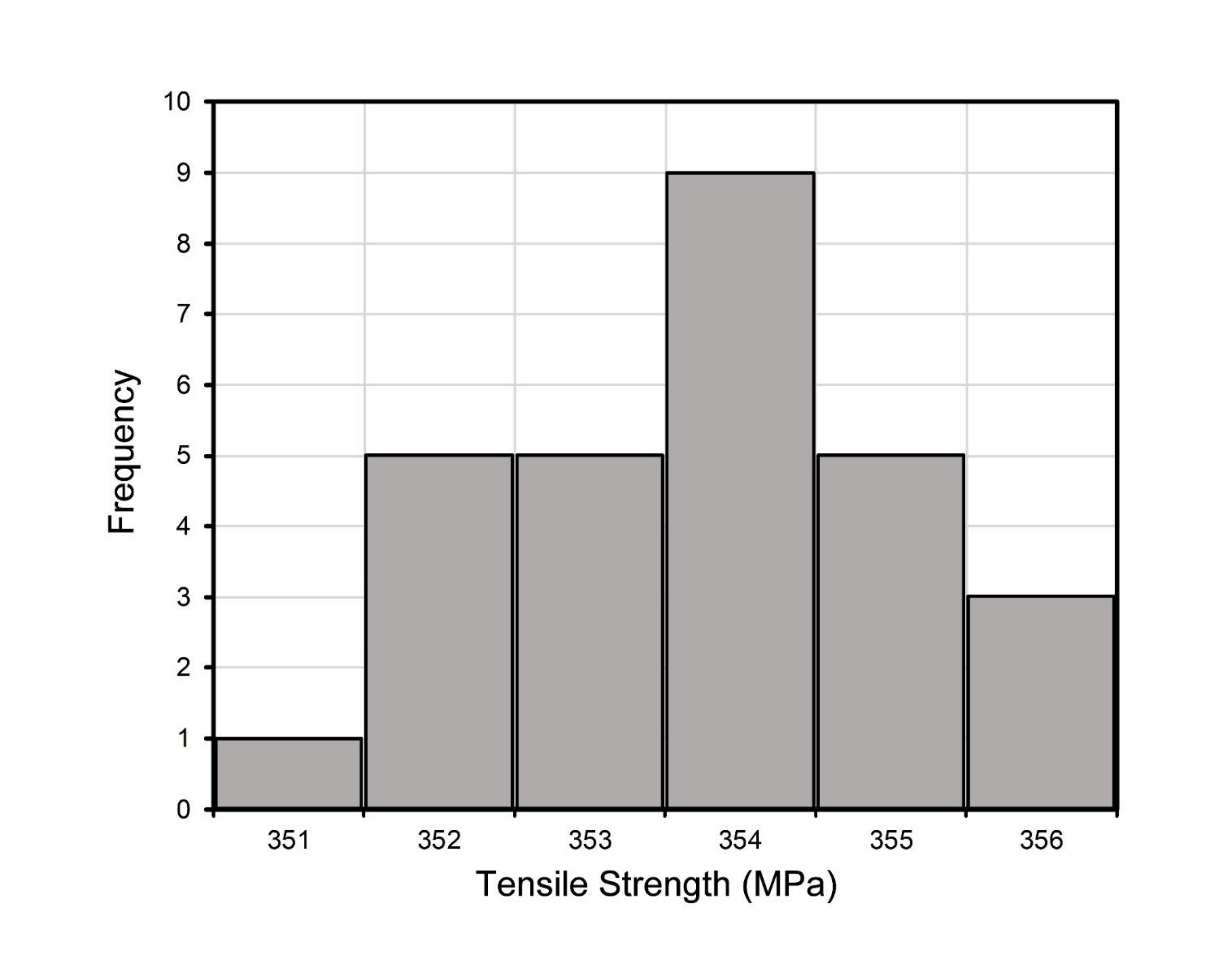
Weibull Statistics

A Weibull Modulus value of around 100 is typical for aerospace castings.

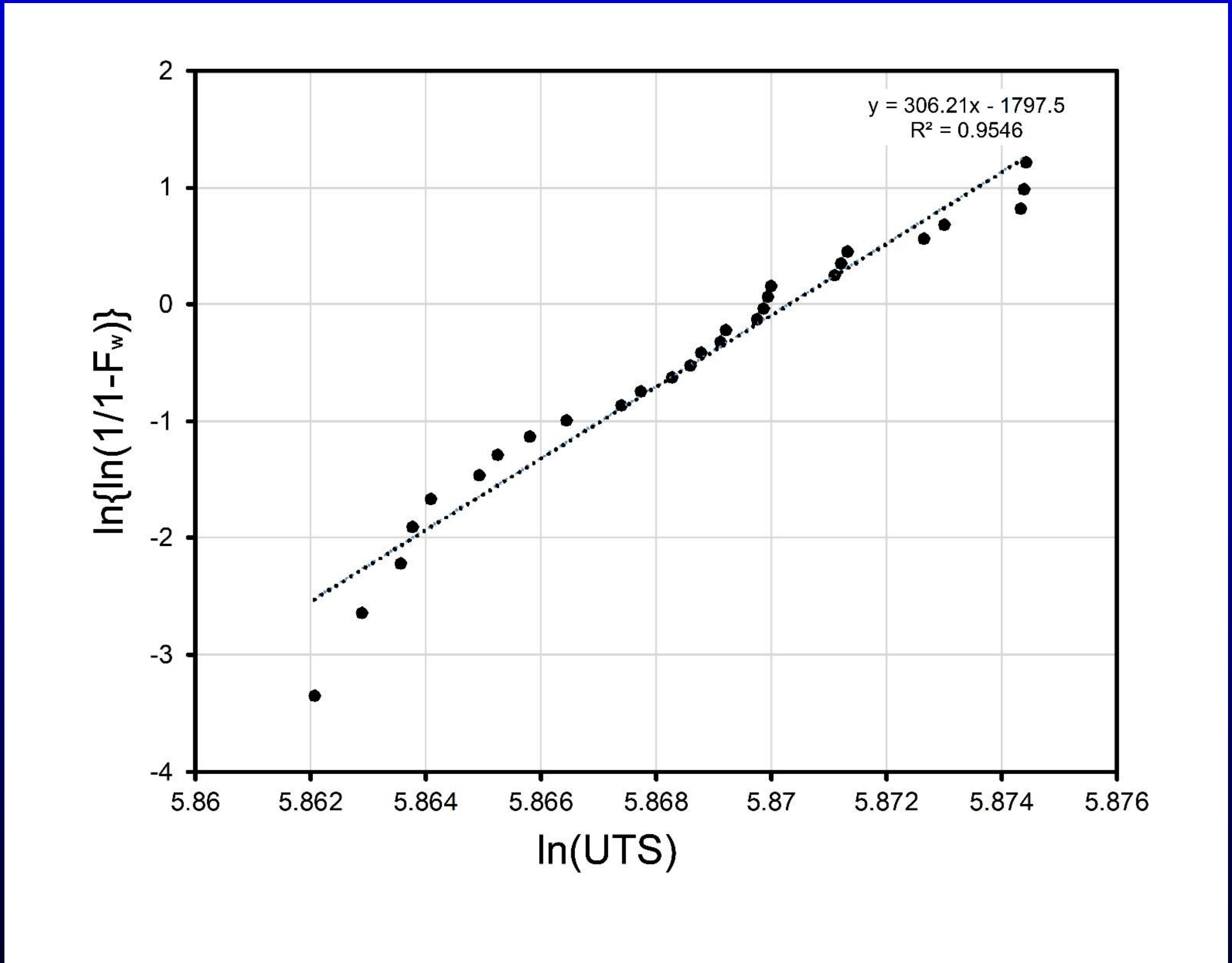
Above 150 is typical for wrought aluminium.

Probability of Failure plots and (initial) extreme value analysis.

Tensile Strength Distribution



Weibull Plot

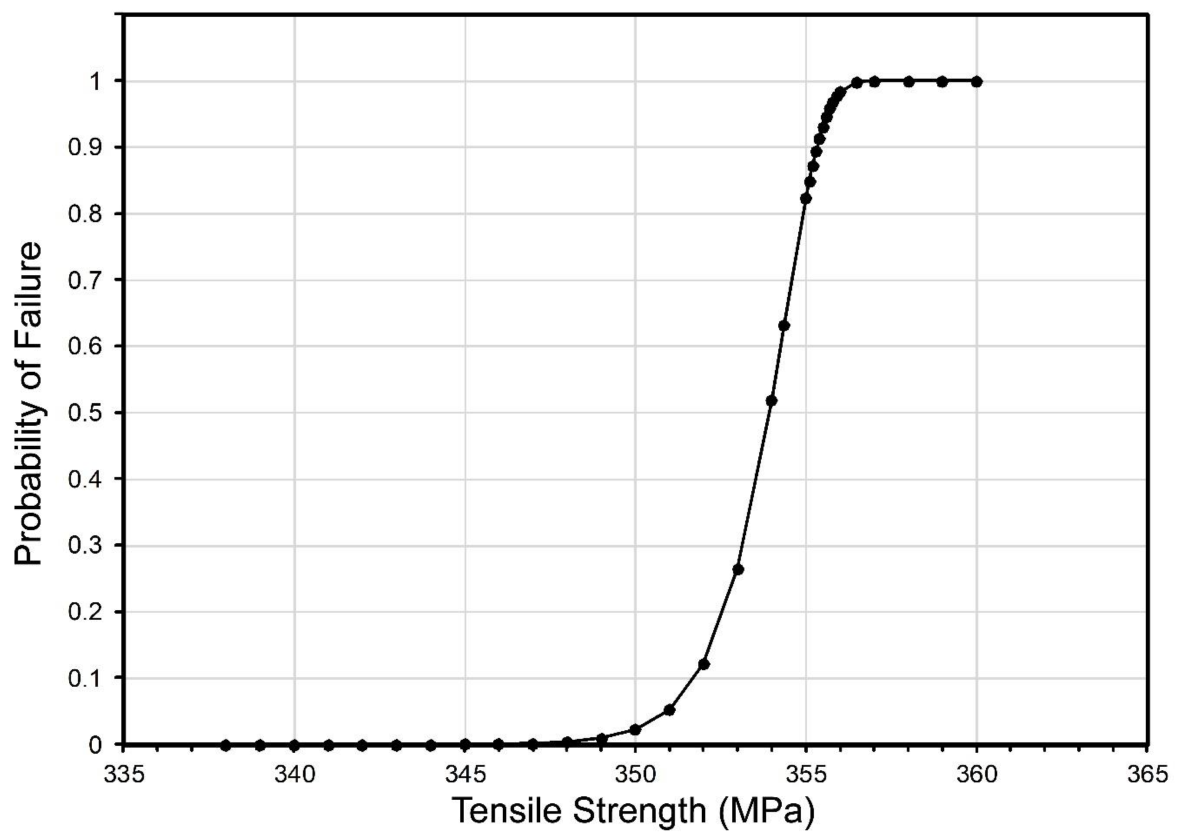


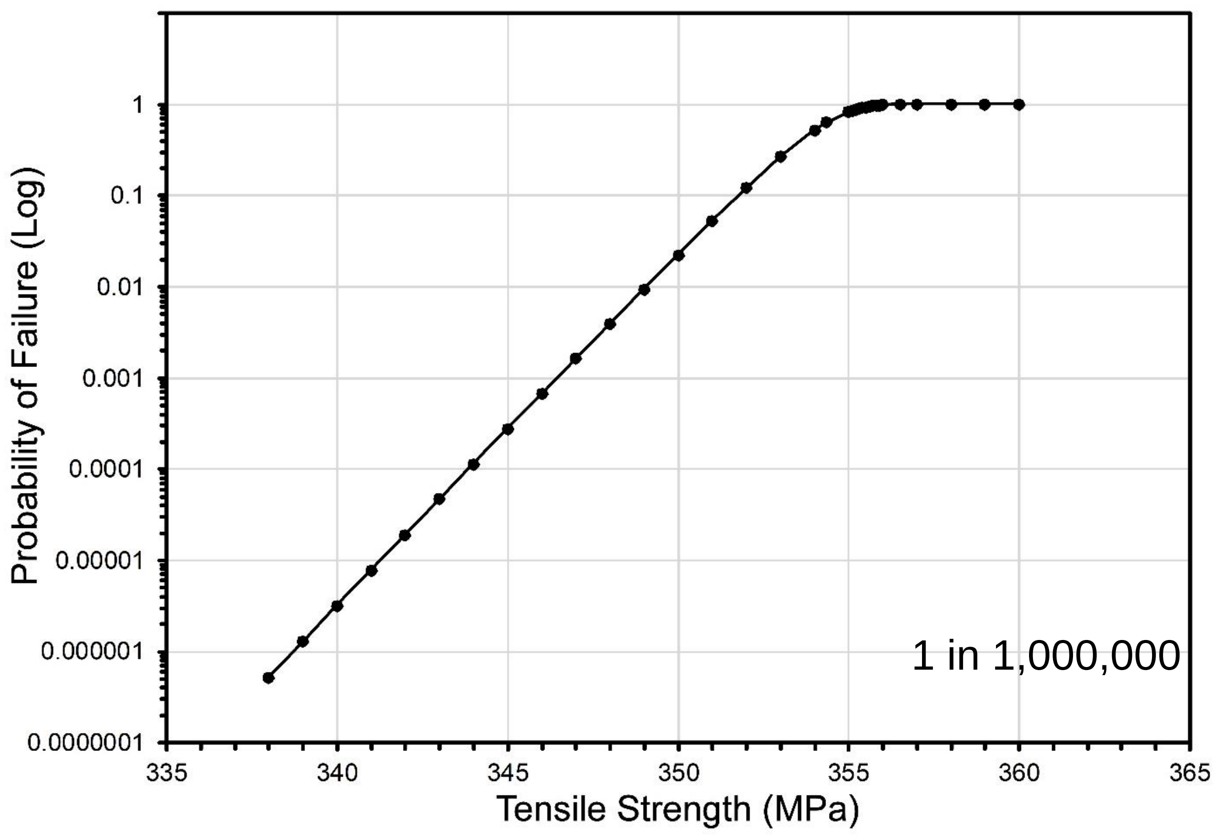
Weibull Modulus = 306.2

Position Parameter = 354.36MPa

(value at which 37% survive)

Probability of Failure





Conclusion

By instituting good casting practice, alloy design and heat treatments, if deformation is particularly homogenous, the material will keep necking without unstable failure and greater than 20% ductility can be achieved in Al-Si-Cu alloys.

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