Quality & Aluminium Castings

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The Cost of Quality

- **"Quality" is a measure of excellence or a state of being free from defects, deficiencies, and significant variations, where (high) quality is brought about by the strict and consistent adherence to measurable and verifiable standards to achieve uniformity of output that satisfies specific customer or user requirements.**

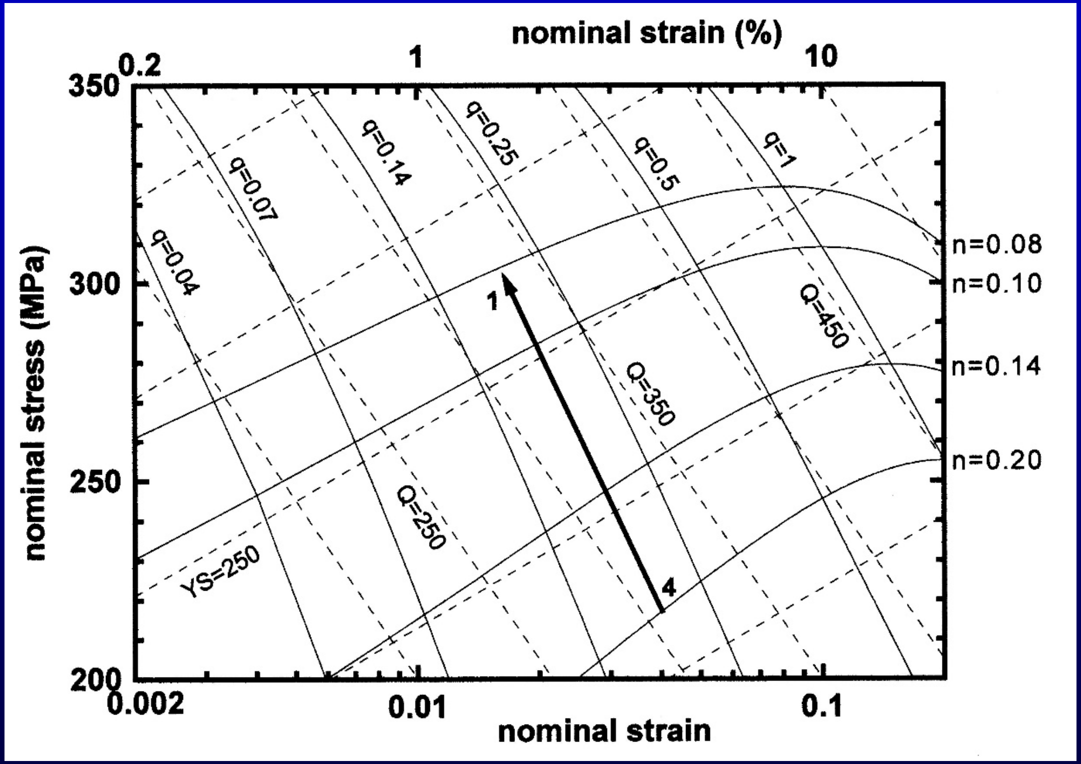
- **The "cost of quality" is actually the cost of poor quality, since non-conforming products increase total cost and lengthen (delivery) lead-time.**

Today’s Presentation

- Background of quality index models
- The Ludwik-Hollomon equation & flow curve analysis.
- The work of Cáceres et.al.
- Model development for F357 Alloy
- Use in process development
- Conclusions.

Quality Indices

- **Cáceres et.al**



An improved model based around flow curve analysis.

Cáceres, C H, Int. J. Cast Metals Research, 10, 1998, 293-299.

Also Drouzy et.al. *QI=UTS + 150logE_f*

The Role of Casting Defects on Failure (1)

- **Cáceres and Selling showed:**

- **Bulk volumetric porosity has almost <u>no correlation</u> to tensile properties;**

- **The number or fraction of <u>any type of defects</u> 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.)

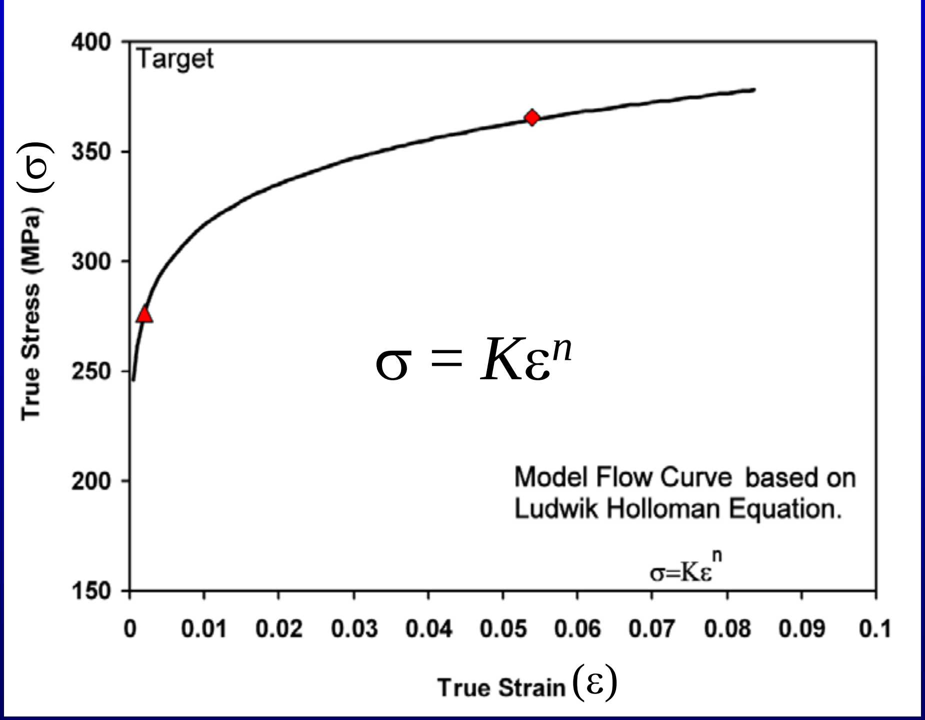
Combining the Models Based on the Ludwik-Hollomon Equation

- Sigworth & Cáceres (AFS 2004)

- Iron content,
- Solidification rate,
- Gas content,
- Grain refinement,
- Eutectic modification,
- Pressure,
- Metal cleanliness
- Heat treatment

Methodology: Flow Curve Based on the Ludwik-Hollomon Relationship

Target based on:
40KSI Y.S,
50KSI UTS,
6% El.



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.

Experimental Validation of the model

Background:

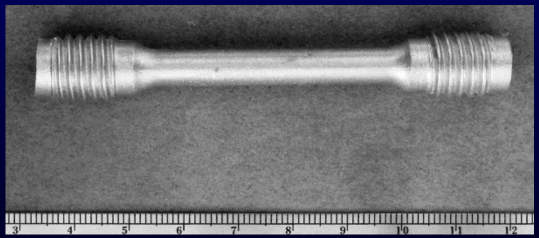
Investment cast aluminium products cannot in general be rapidly cooled due to the insulating ceramic shell used in their production. This has limited their use in demanding applications.

A slow cooling rate results in a coarse microstructure,
 which in turn adversely influences mechanical properties.

Model Derivation:

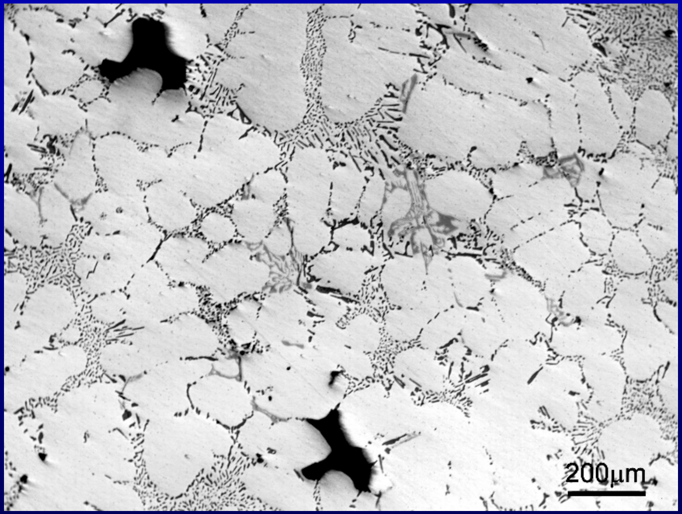
- **Investment Cast F357 alloy (Al-7Si-0.55Mg)**

- **Metal Temp. 730°C, Shell preheat >600 °C**
- **Degassed with Argon (R.P.T)**
- **Investment shells (2) were standard filtered 4-bar trees with 16 tensile samples per tree.**
- **Shell removed from oven, filled with molten Al, then immersed in quenching oil.**
- **T6 Heat treatment via standard ASM handbook procedures.**
- **Samples were not machined prior to tensile testing.**



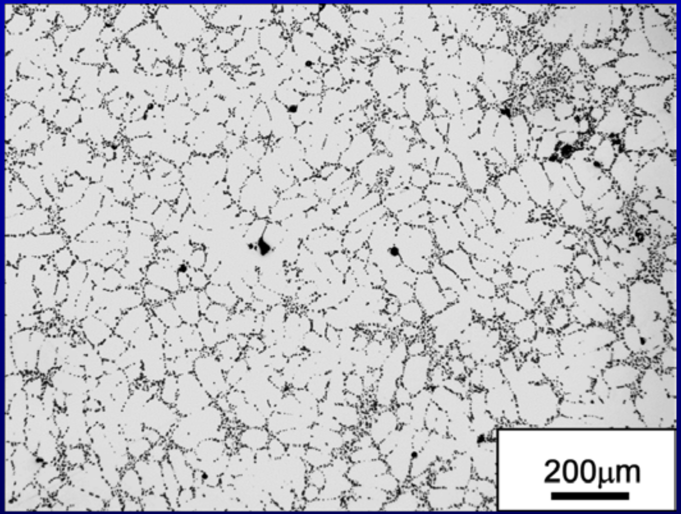
Microstructure

Standard F357



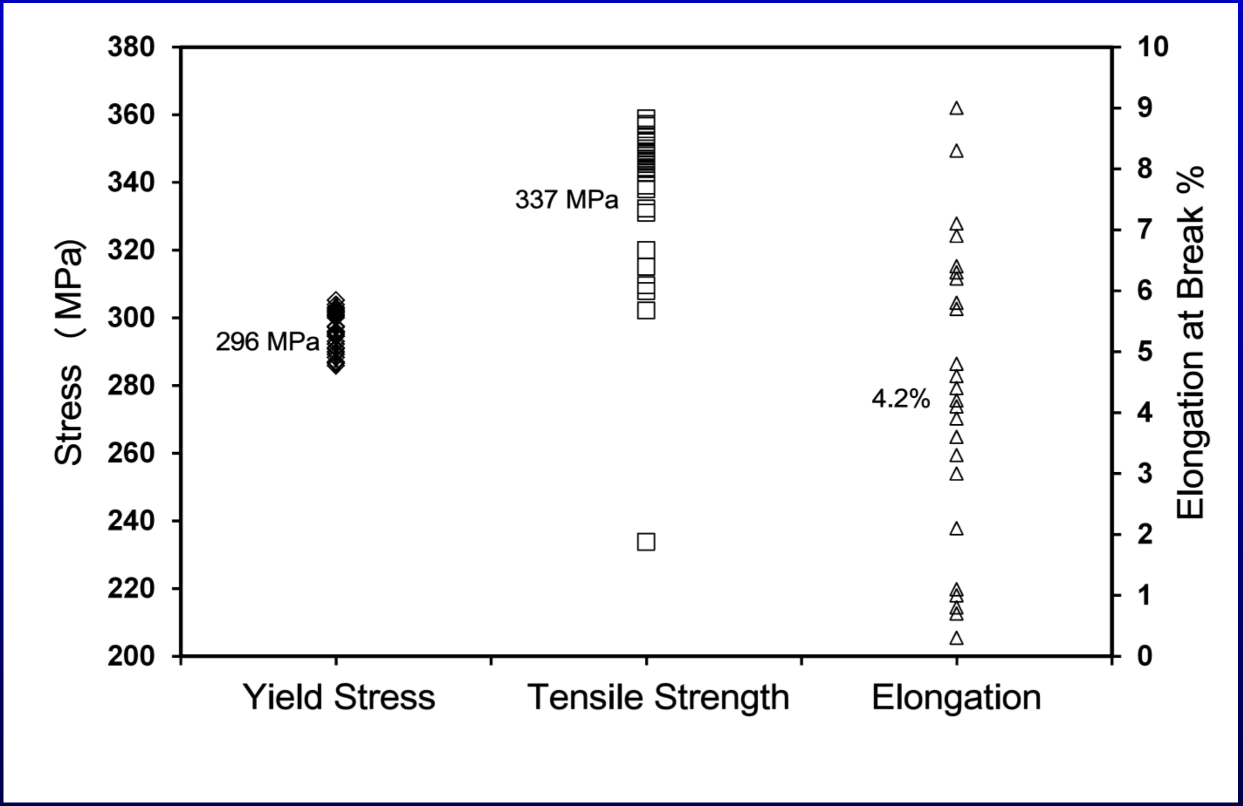
DAS 85.9 ± 24.8 µm

Oil cooled F357



DAS 47.1 ± 6.8 µm

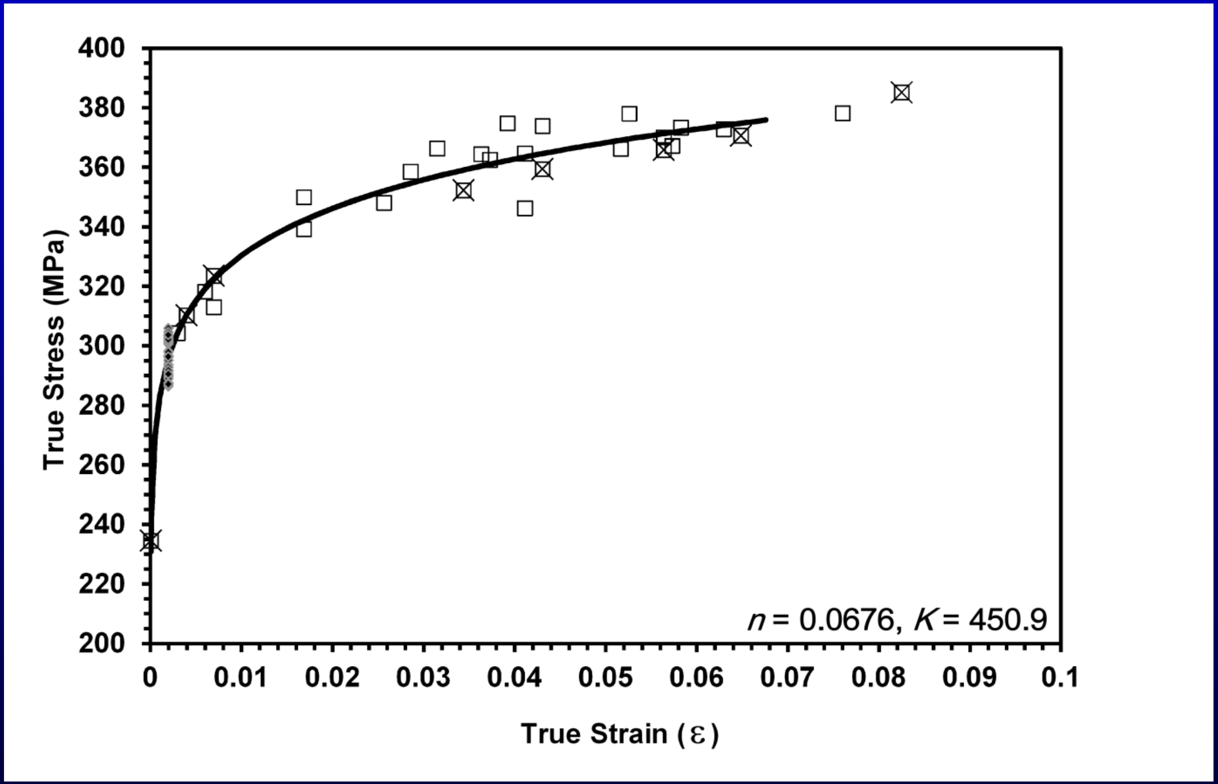
Tensile Properties



29 tensile test results

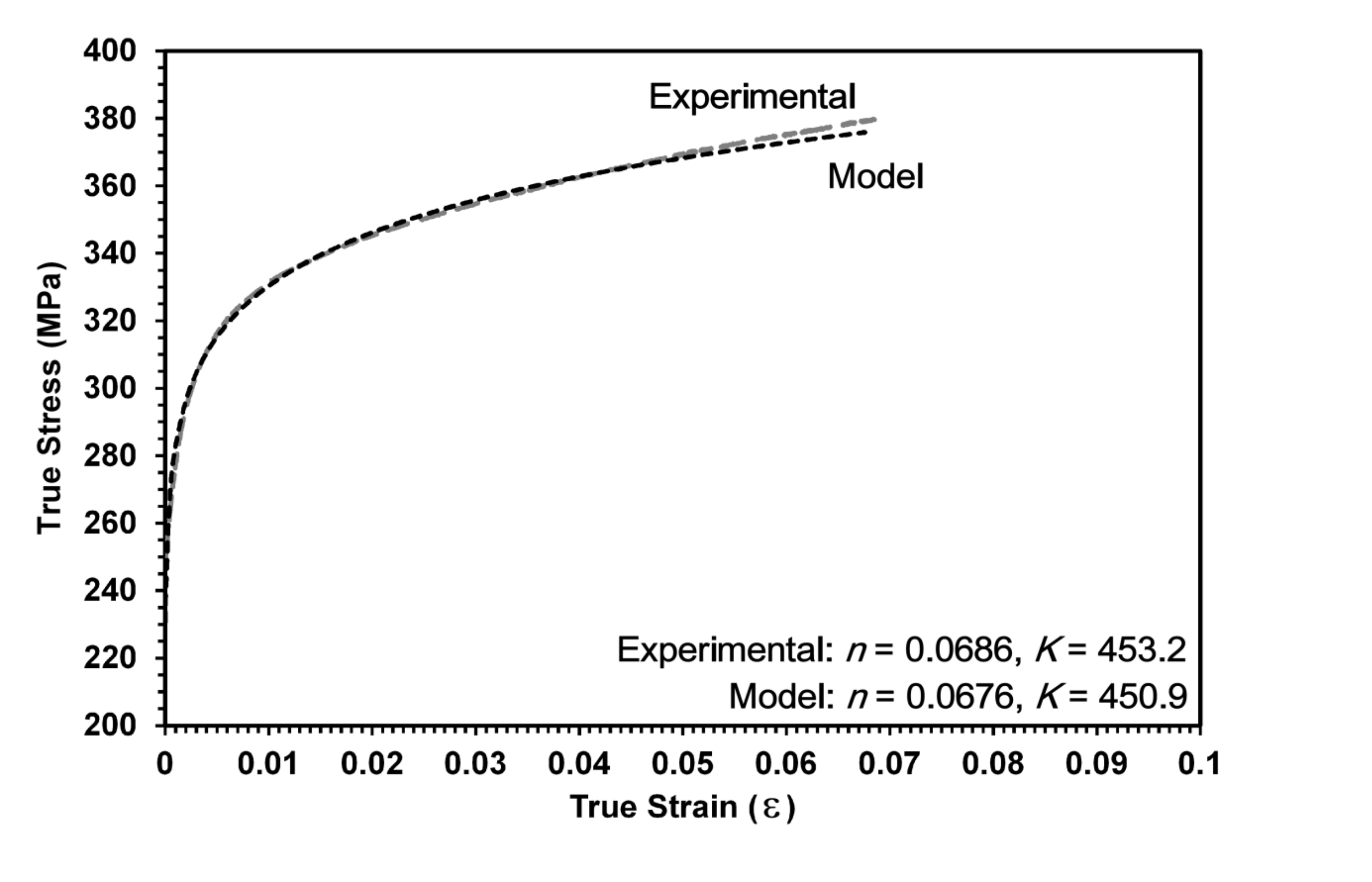
The very high scatter in elongation represents the defect distribution

Experimental Data With Model Flow Curve



The model flow curve was derived from all experimental data.

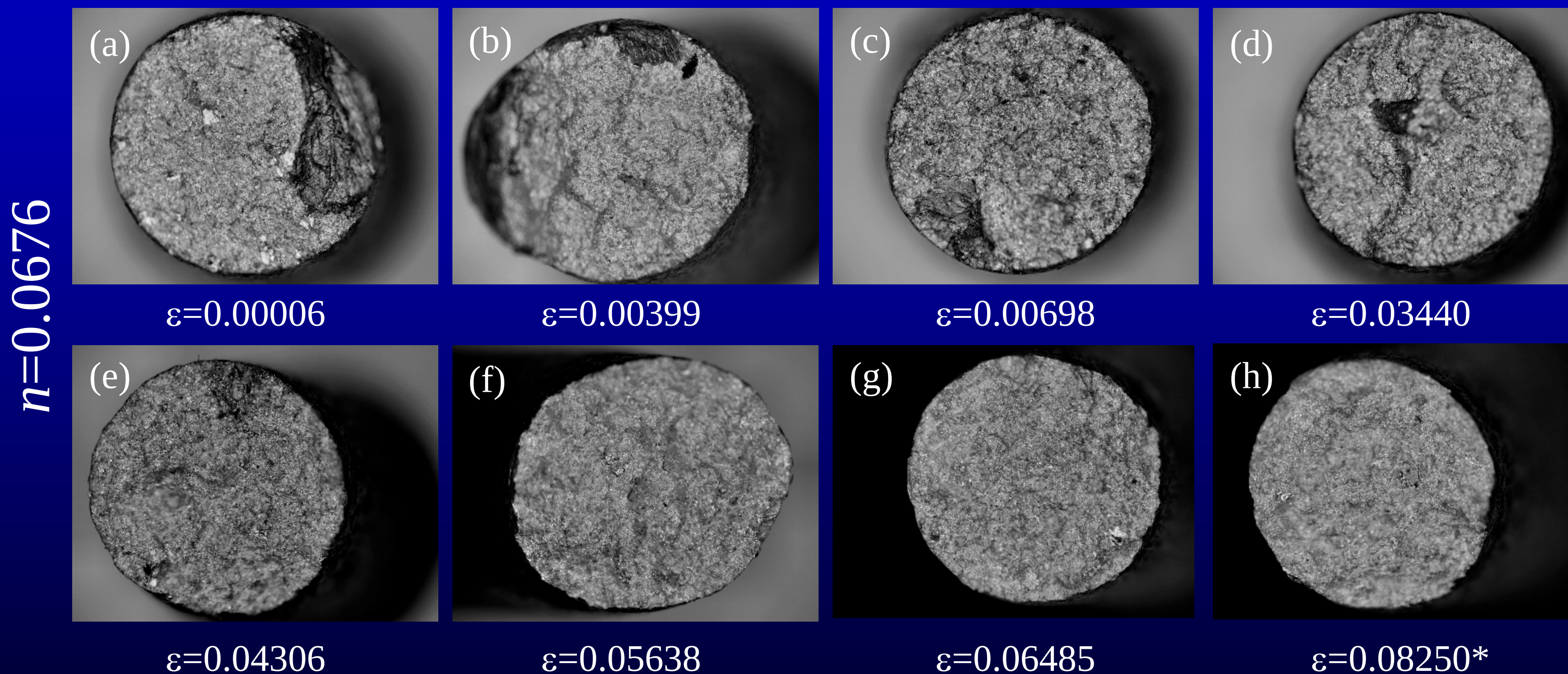
Validation of the methodology with the model flow curve.



The results typically display excellent agreement

Al-Si7Mg0.5 (F357)

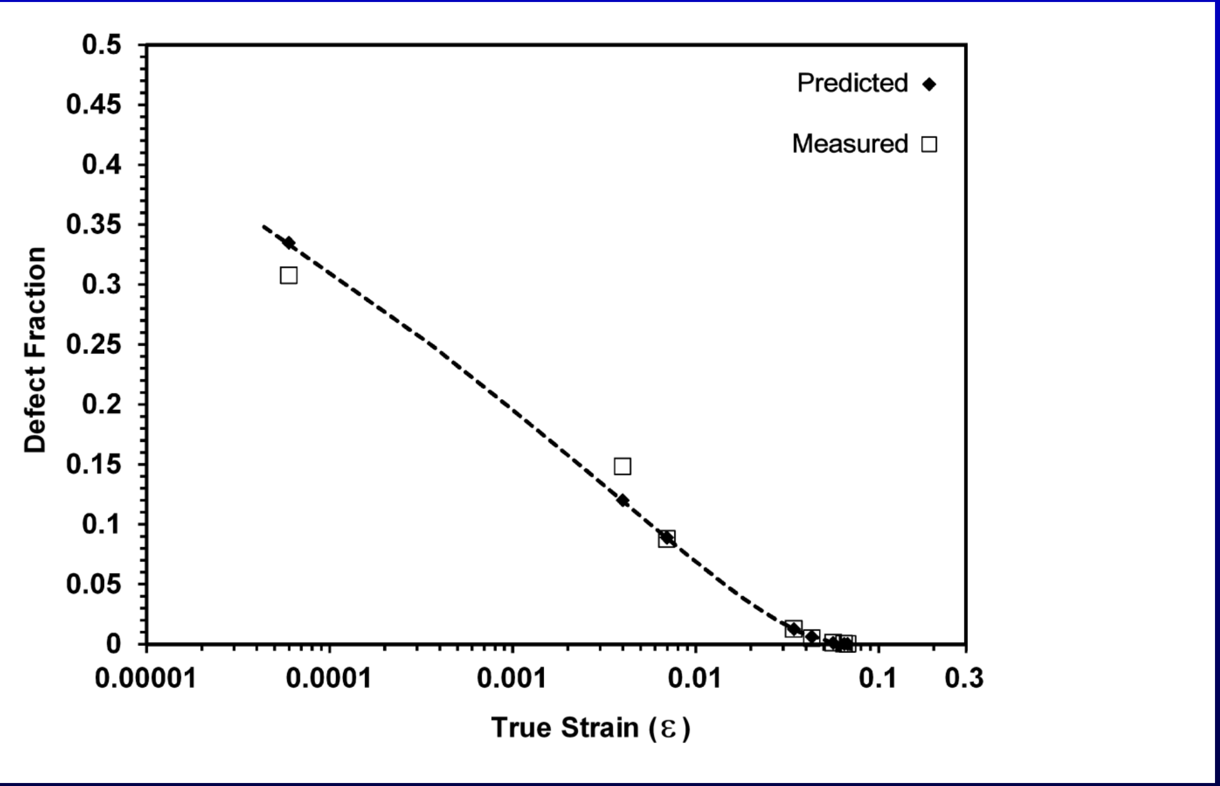
Despite the higher cooling rate and finer microstructure, oil cooled material is inherently susceptible to carbonaceous defects.



Original sample diameter prior to testing was 6.4mm. Area fraction defect quantified using color segmentation.

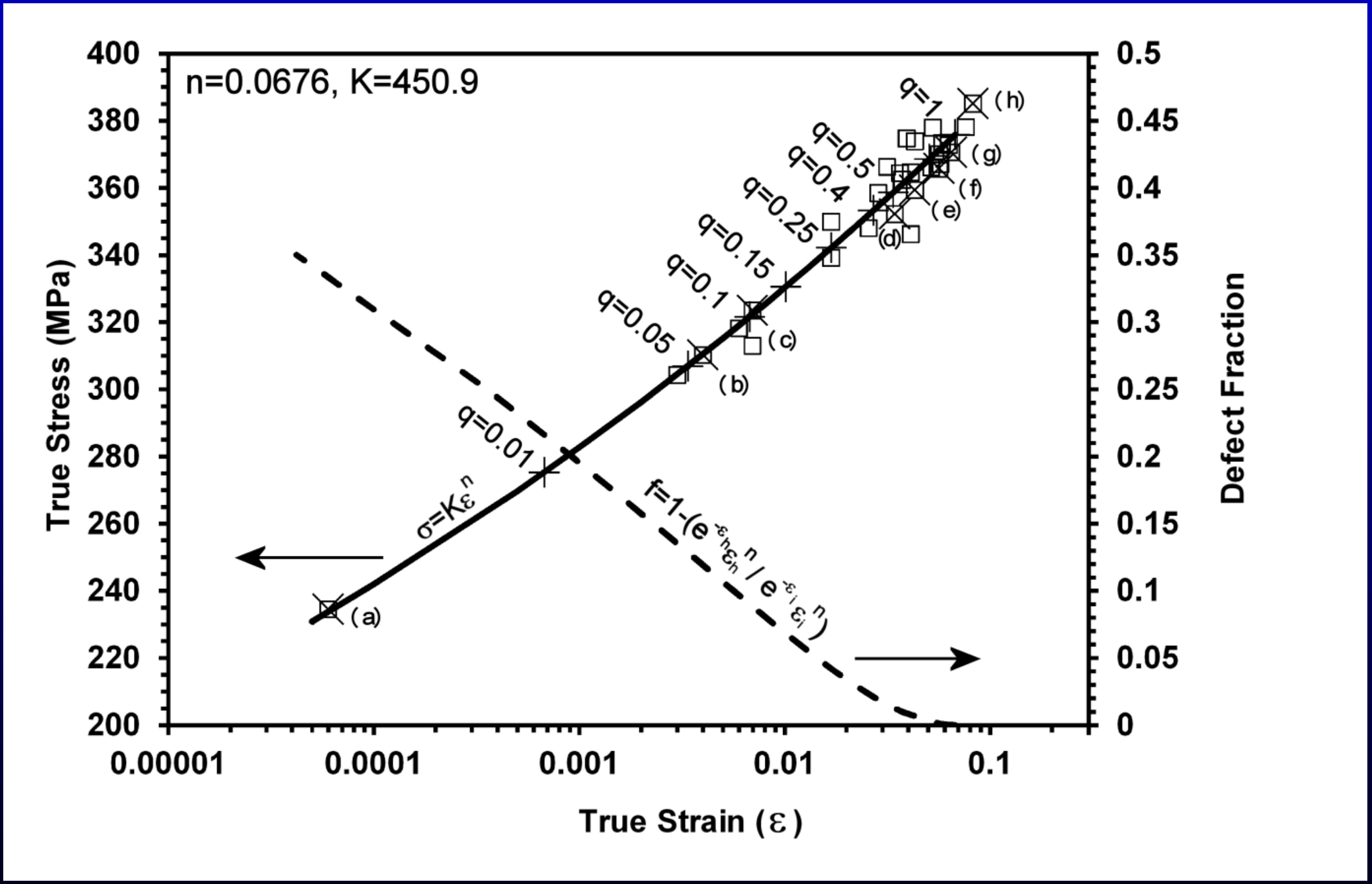
Lumley & Bell, AFS Transactions, 2013, paper 13-1567.

Predicted Versus Measured Defect Fraction



Quantitative analysis of defect fraction was conducted

Universal Quality Chart 357 Alloy



A Premium Casting Process Was Developed Using The Principles of the Model

Aluminium Billet Equivalent (ABE process)

Methodology:

Use of methods based on the Ludwik-Hollomon equation and derivation of the model flow curve.

Process optimization for:

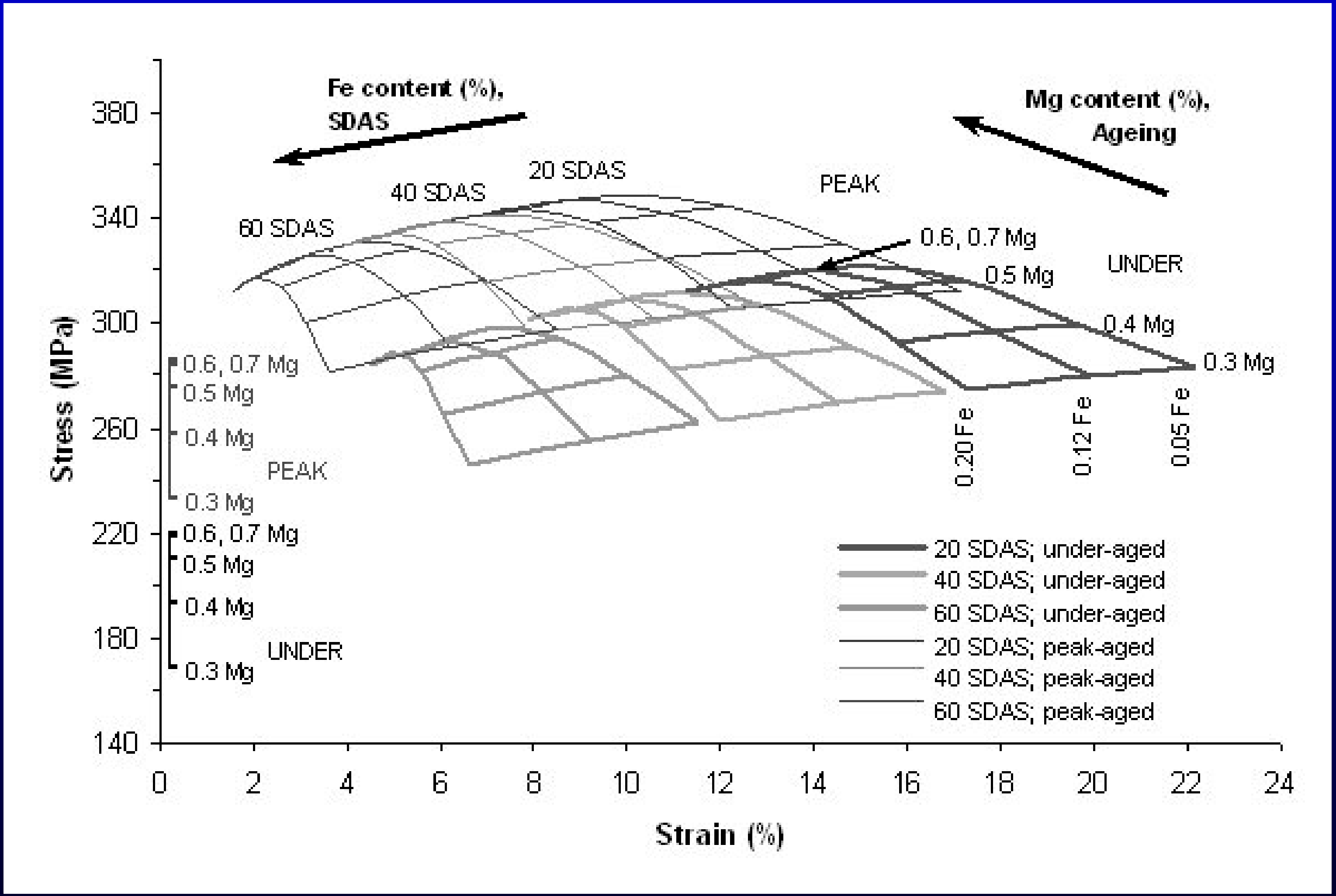
Metal Preparation;
Casting Process;
Alloy;
Heat Treatment;
Quality Analysis.

Rigorous methods of defect identification and elimination to optimize all processes.

Optimisation of Microstructure

Properly degassed (bubble dispersion and time)
Low Iron.
Rapid cooling rate.
Use all principles of passive fill.
Low oxide film count.
No carbonaceous defects!

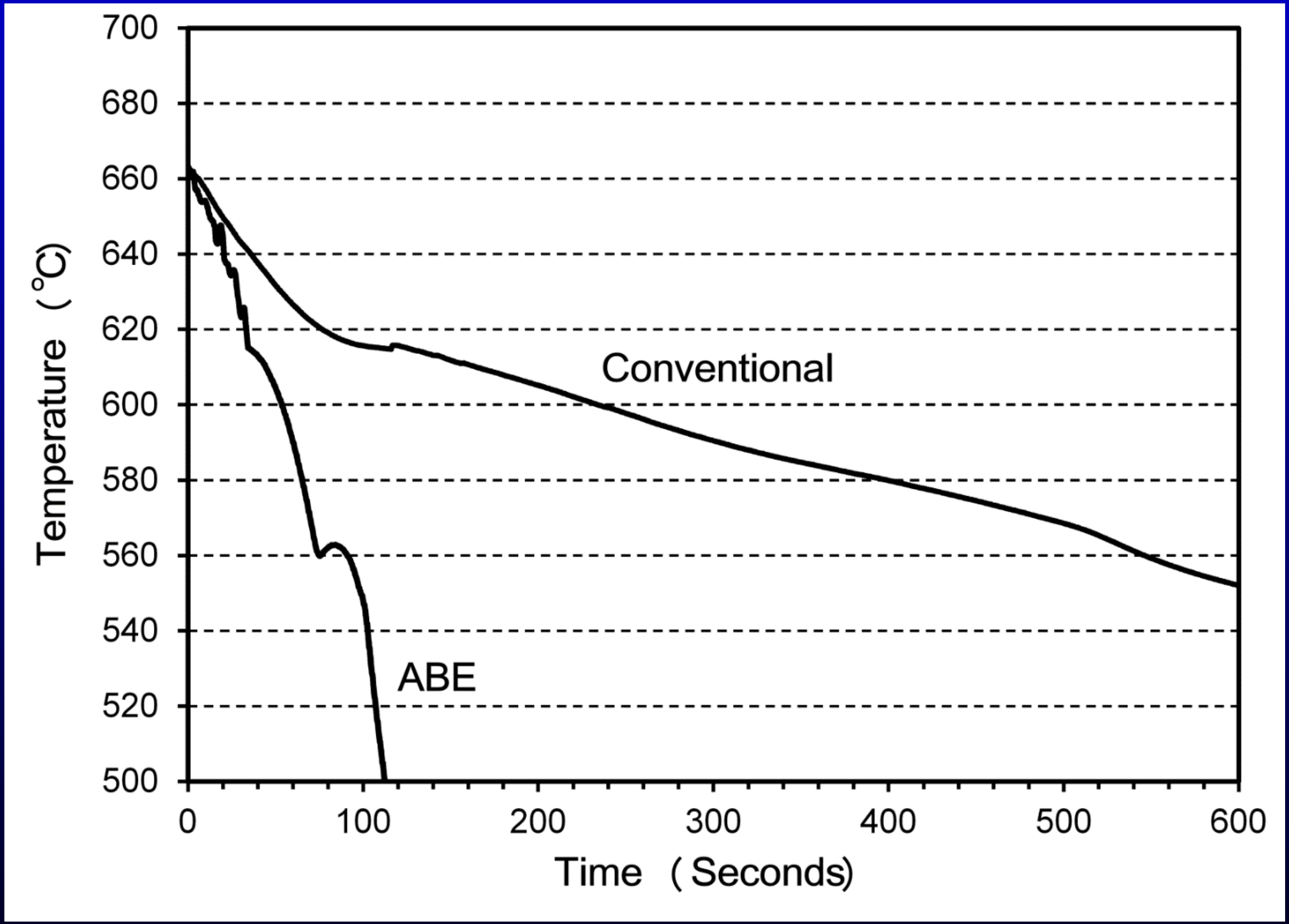
The role of microstructural scale (SDAS), alloy chemistry and casting quality.



Taylor, 2000

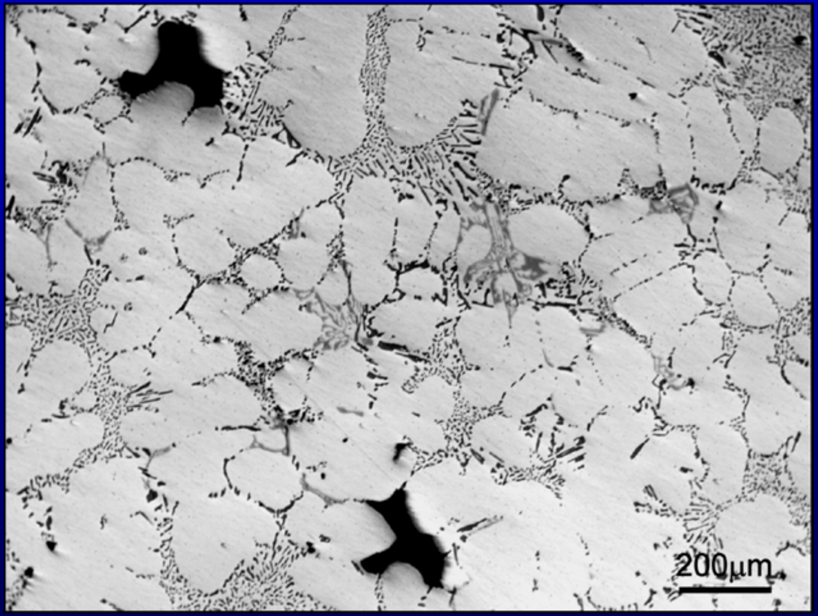
A new method was developed to rapidly cool investment castings.

Cooling rates are around 20X higher than conventional processing

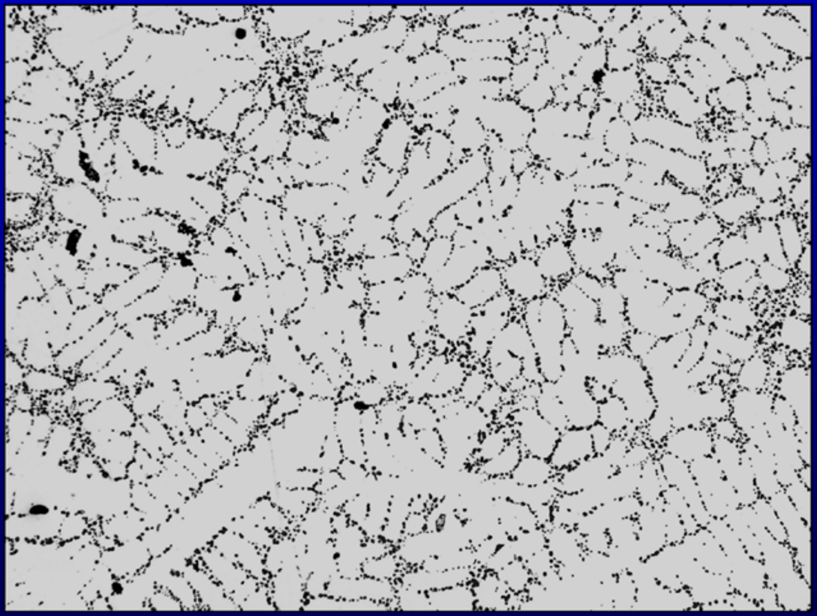


Al-Si-Mg Alloy

ABE Microstructures are very fine compared to conventional investment castings

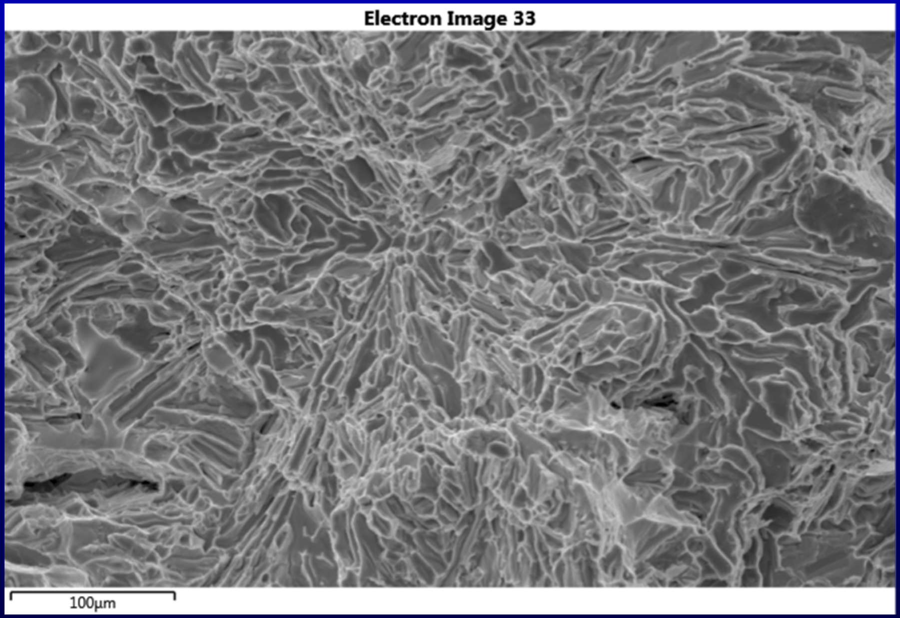


Conventional

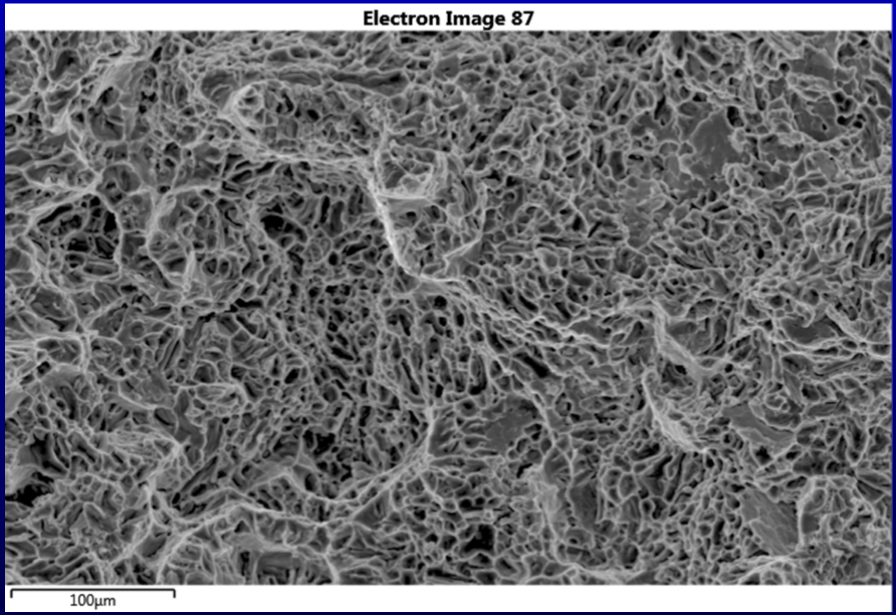


ABE

ABE Microstructures display significantly different fracture surfaces



Conventional

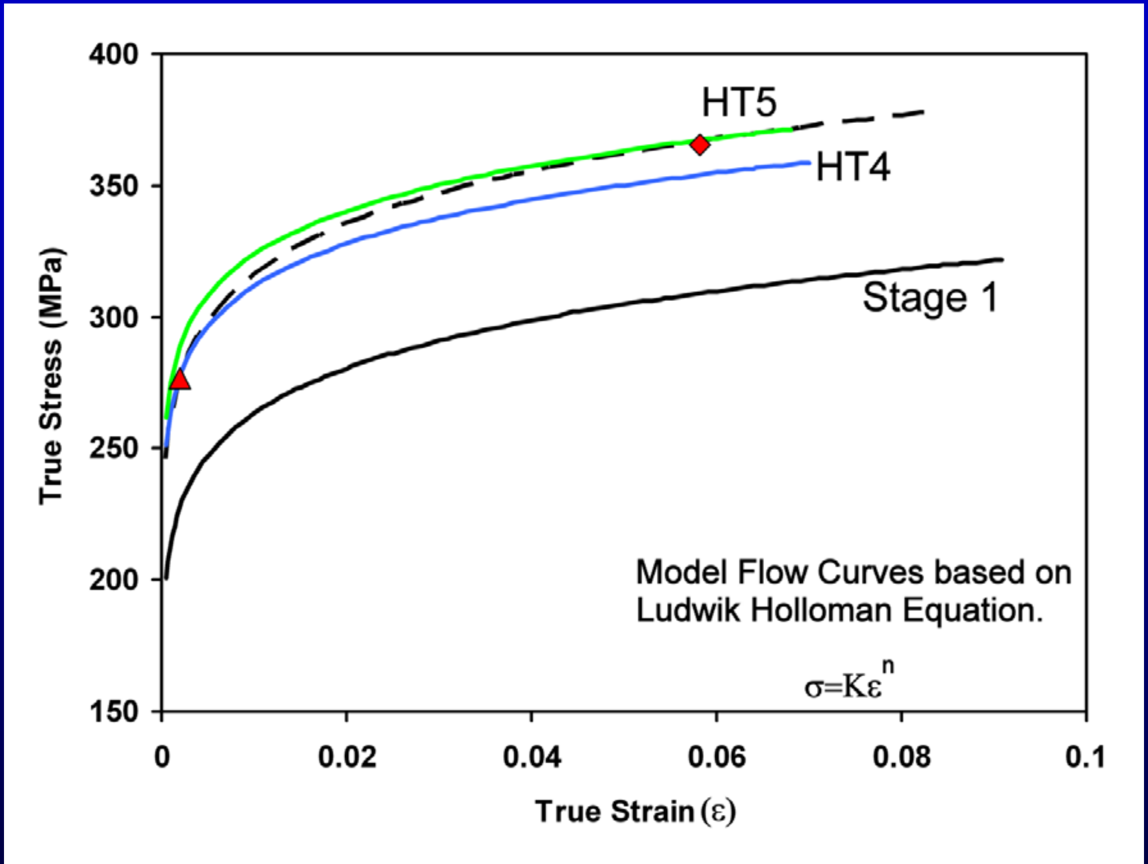


ABE

Optimization of Heat Treatment

Use flow curve analysis as a predictive tool to fast track heat treatment optimization.

Optimization of Heat Treatment



The model flow curve can be used to predict forward as a means to choose the optimum heat treatment procedure.

The Role of Alloy Composition

To reduce variability, narrow the alloy specification.

Alloy composition & process refinement

A357 nominal specification limits:

Al-(6.5-7.5)Si- (0.4-0.7)Mg-(0.2)Cu-(<0.2)Fe-(<0.1)Mn-(<0.1)Zn-(0.04-0.2)Ti-(<0.15) other

Four Compositions Tested:

1. No Sr, No Cu

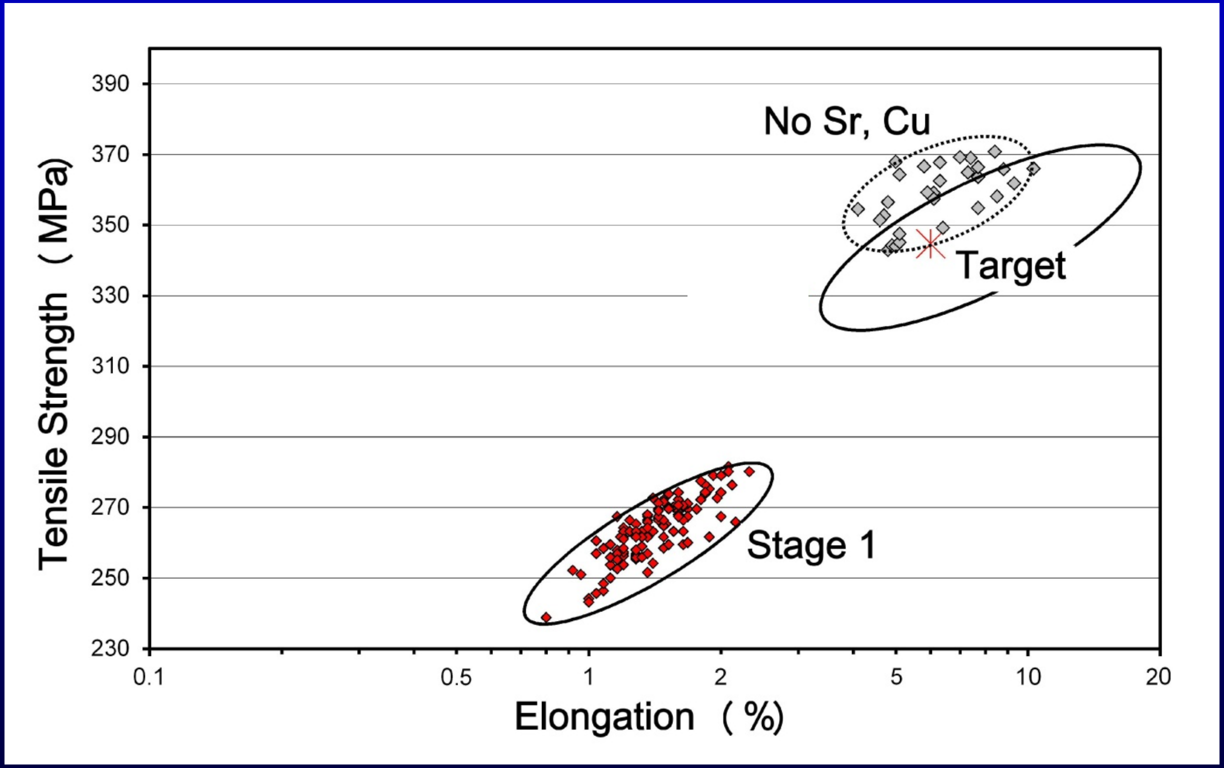
2. Added Sr for modification, Cu for strength (can the work hardening rate be increased and increase the value of strain hardening exponent, *n*?)

3. Medium Mg, Medium Cu (increase Y.S.)

4. Low Mg, Medium Cu (decrease Y.S., increase ductility?)

Alloy 1 (using ABE process)

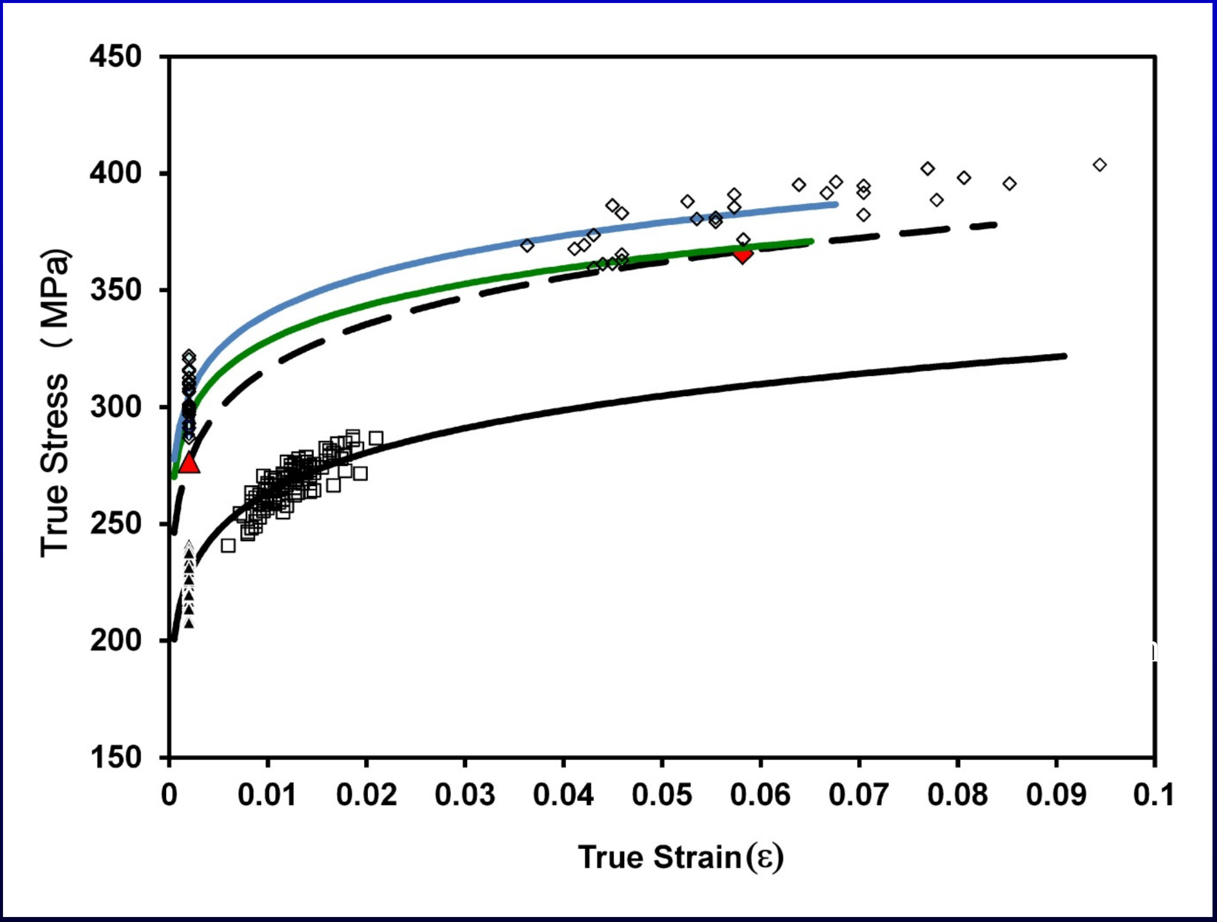
35.7 μm DAS



No Sr, Cu

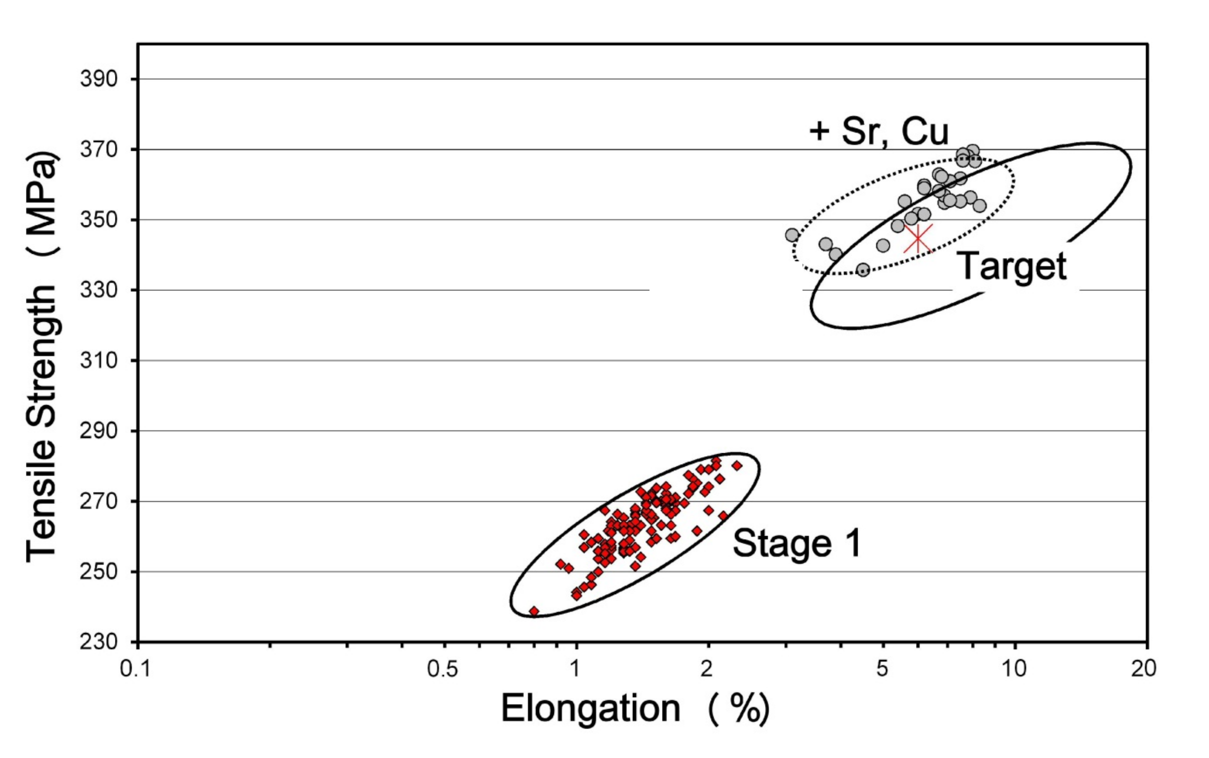
55% meet or exceed target

Alloy 1 flow curve shows an improvement in work hardening rate

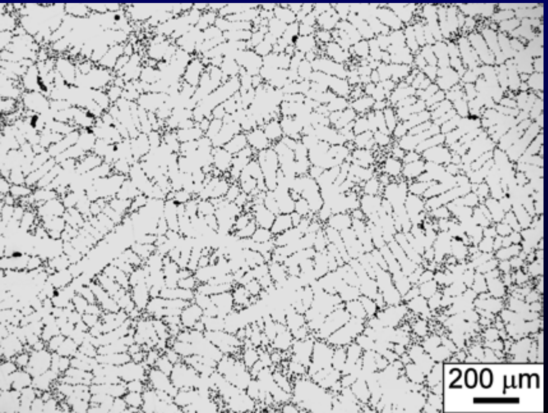


No Sr, Cu

Alloy 2 (using ABE process)

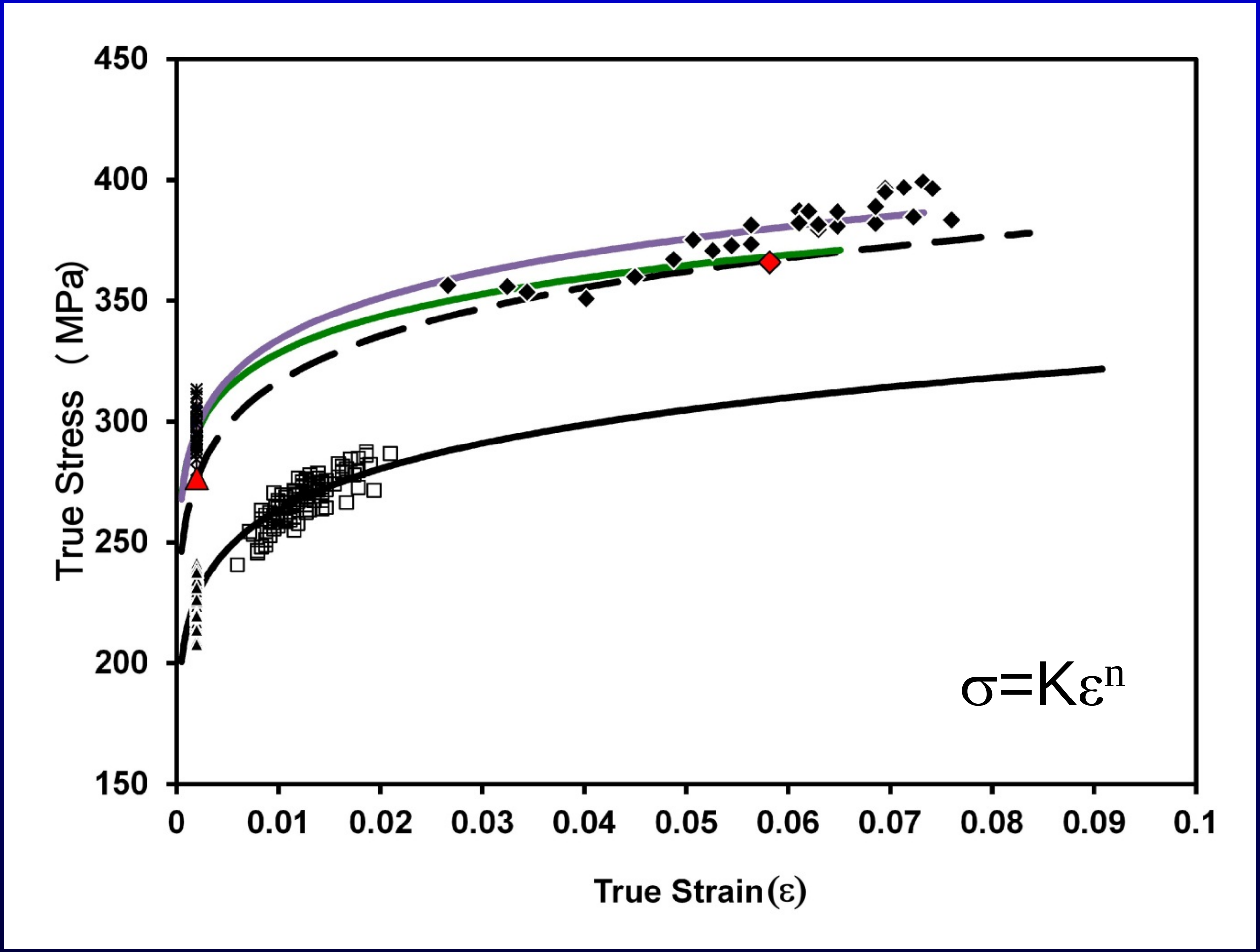


30.4 μm DAS



73% meet or exceed target

Alloy 2: Improvements in work hardening rate and elongation are possible with a small Cu addition

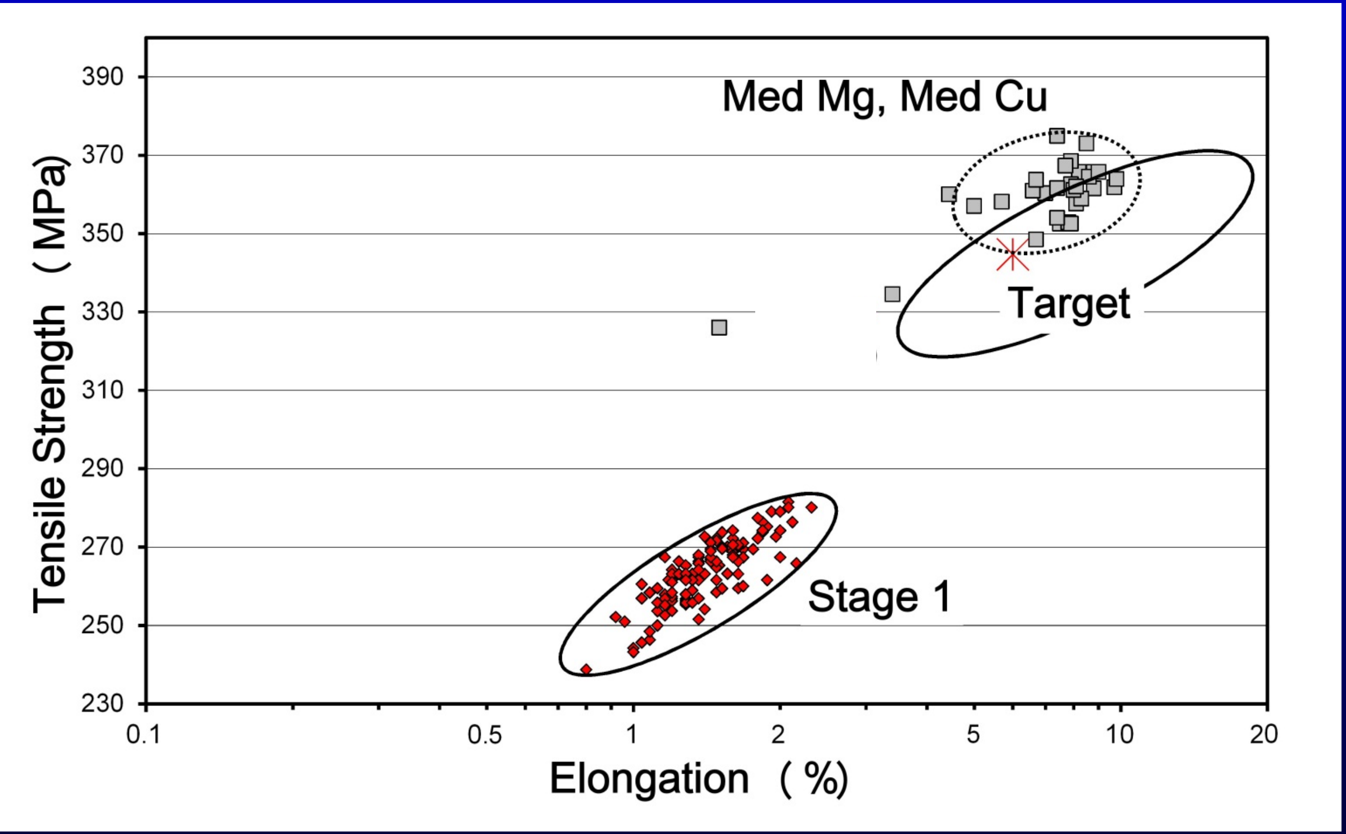


+Sr, Cu

Increased value of strain hardening exponent *n* and strength coefficient *K* means greater UTS and elongation possible

Alloy 3 (using improved ABE process)

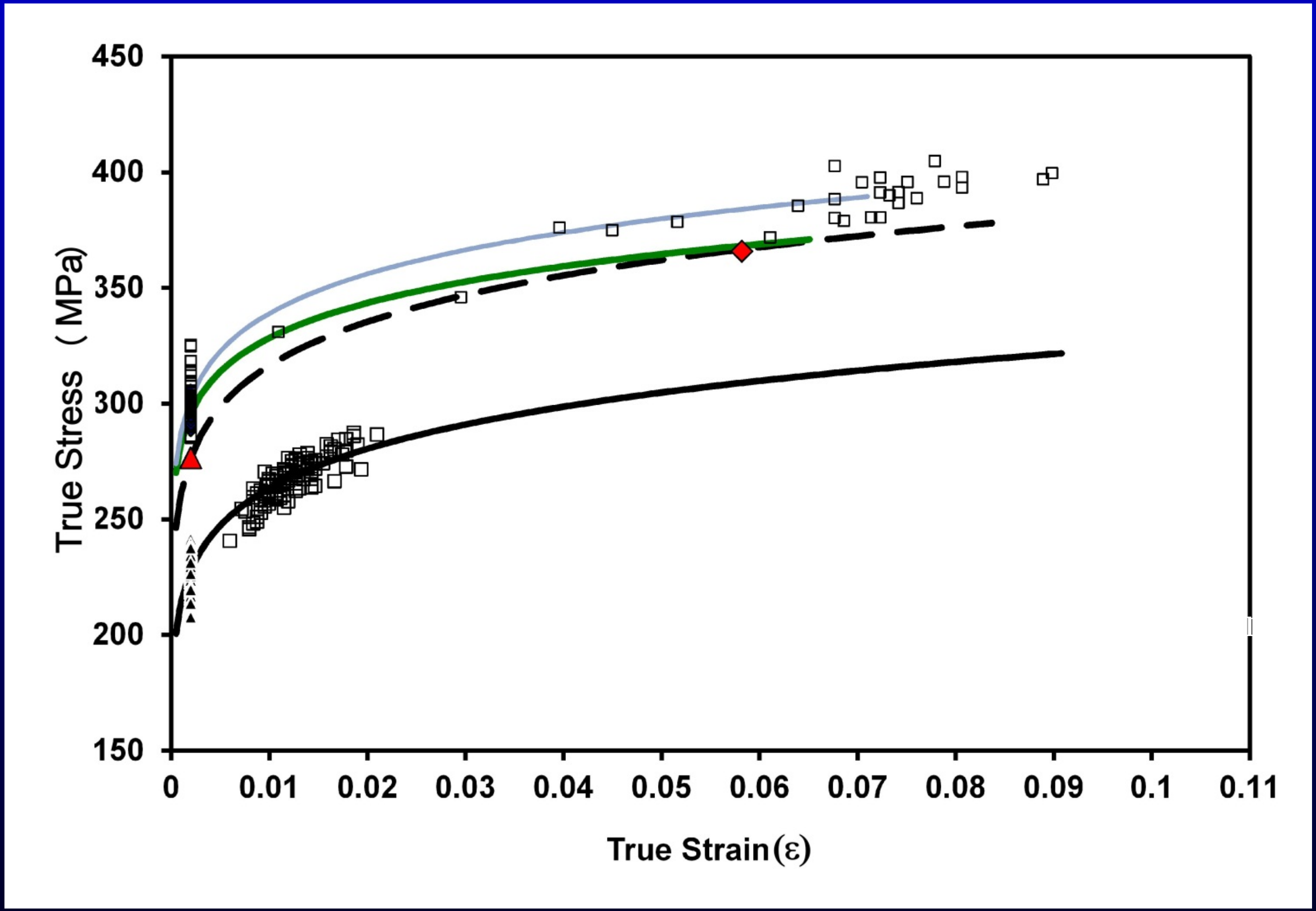
Remnant low values due to a single surface defect type



83% meet or exceed target

Alloy 3 improved A.B.E process showed higher potential UTS.

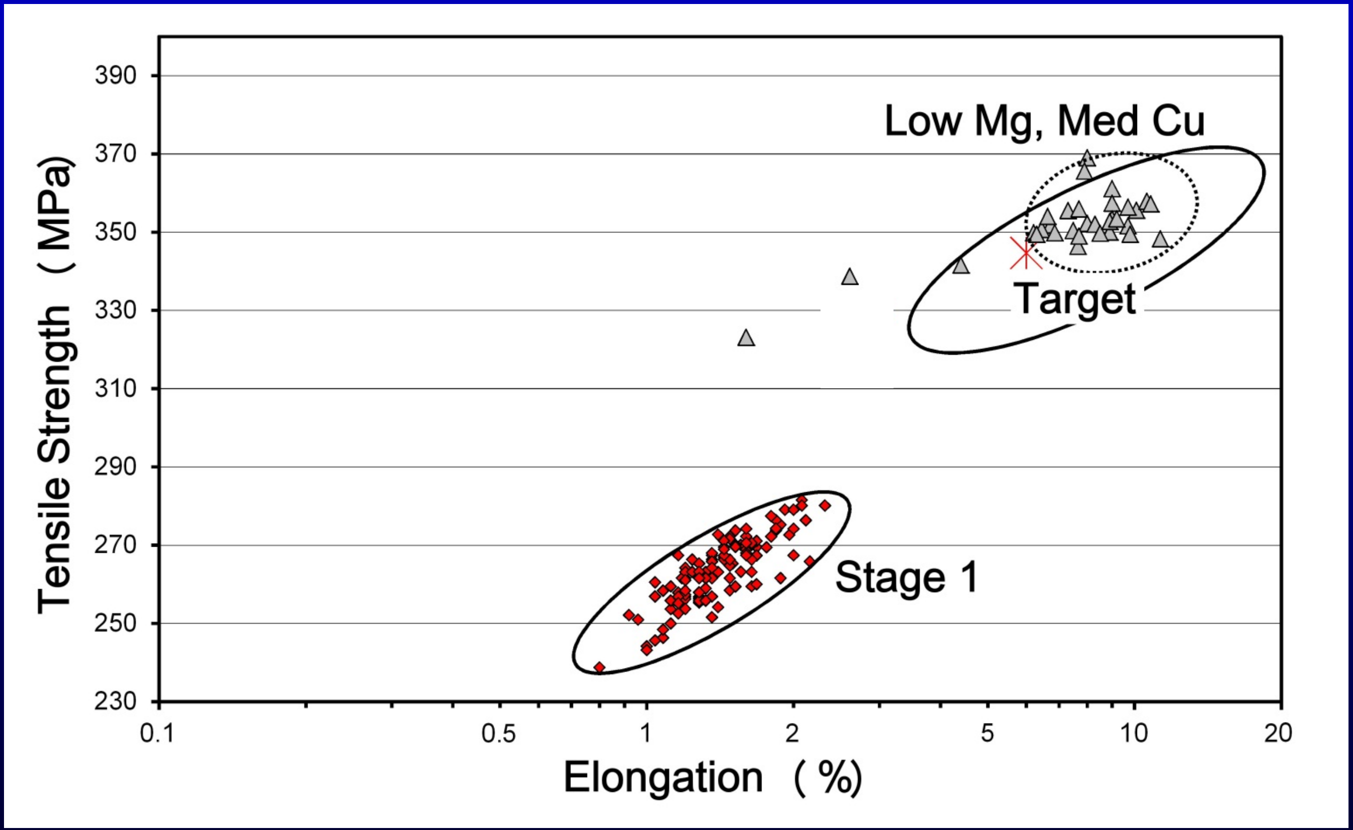
Remnant low values due to a single surface defect type



Med Mg, Med. Cu

Alloy 4 (using improved A.B.E process)

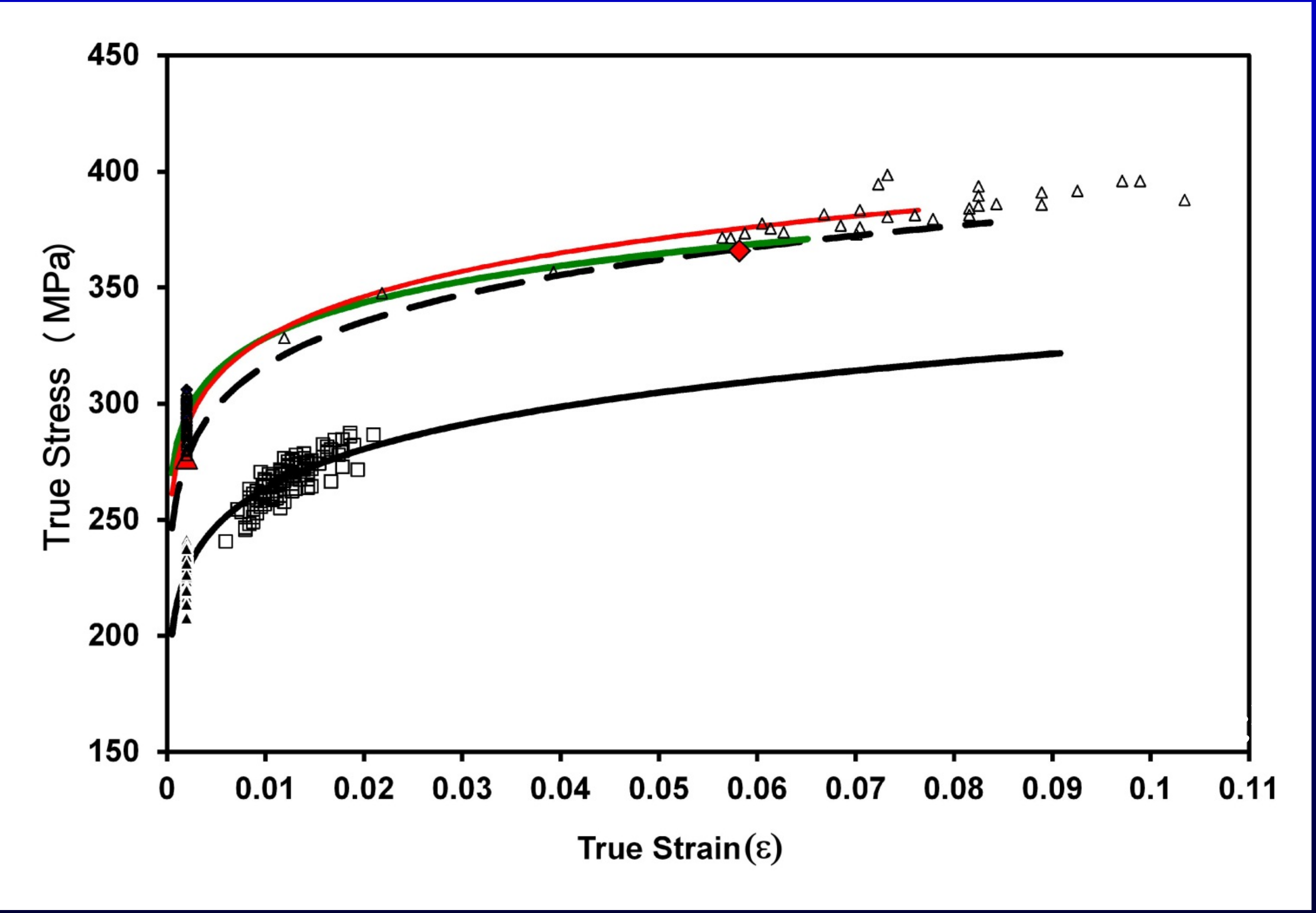
Remnant low values due to a single surface defect type



91% meet or exceed target

Alloy 4 improved A.B.E process eliminated most low values

Remnant low values due to a single surface defect type

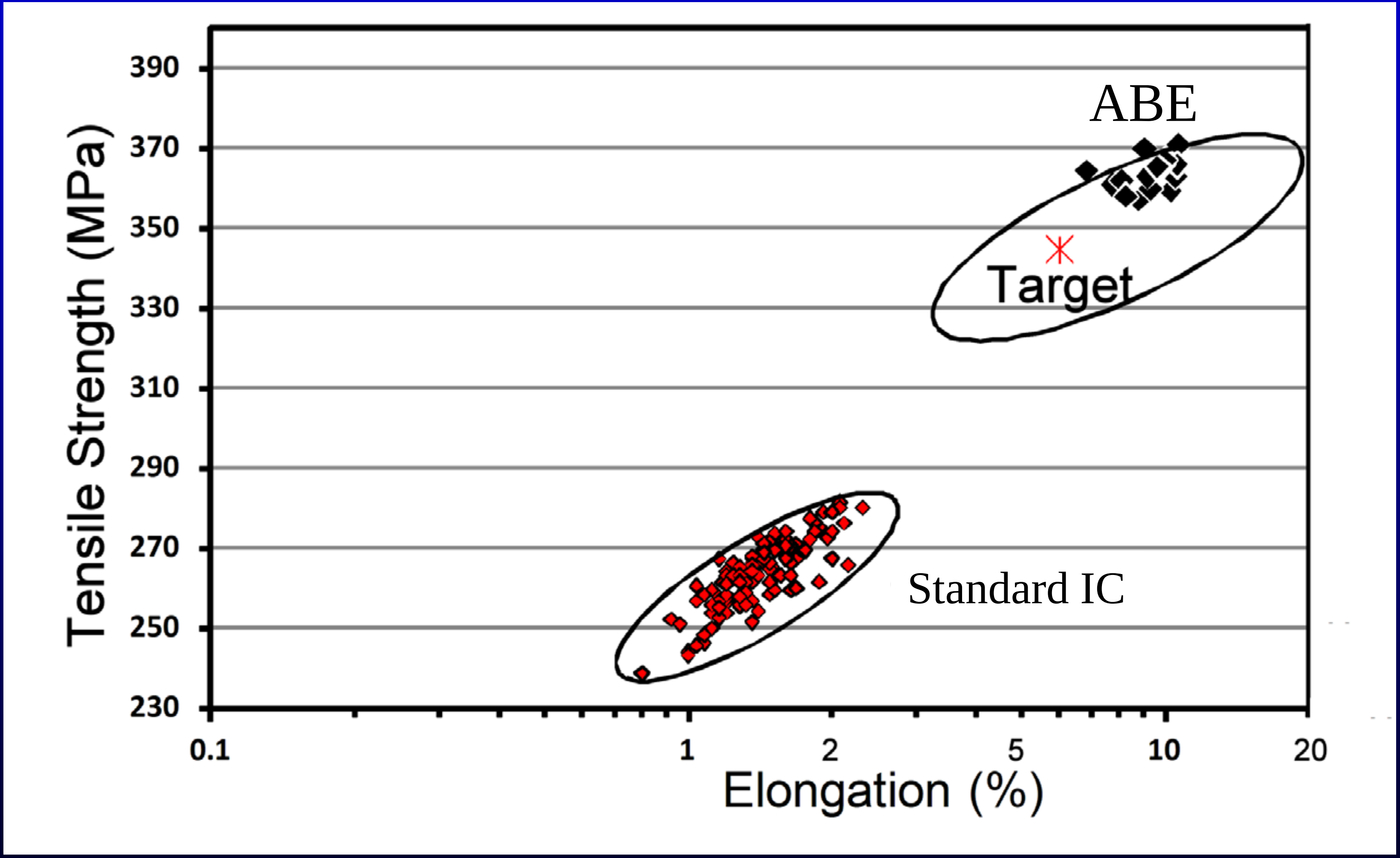


Small increase in *K*, good increase in *n*

Low Mg, Med. Cu

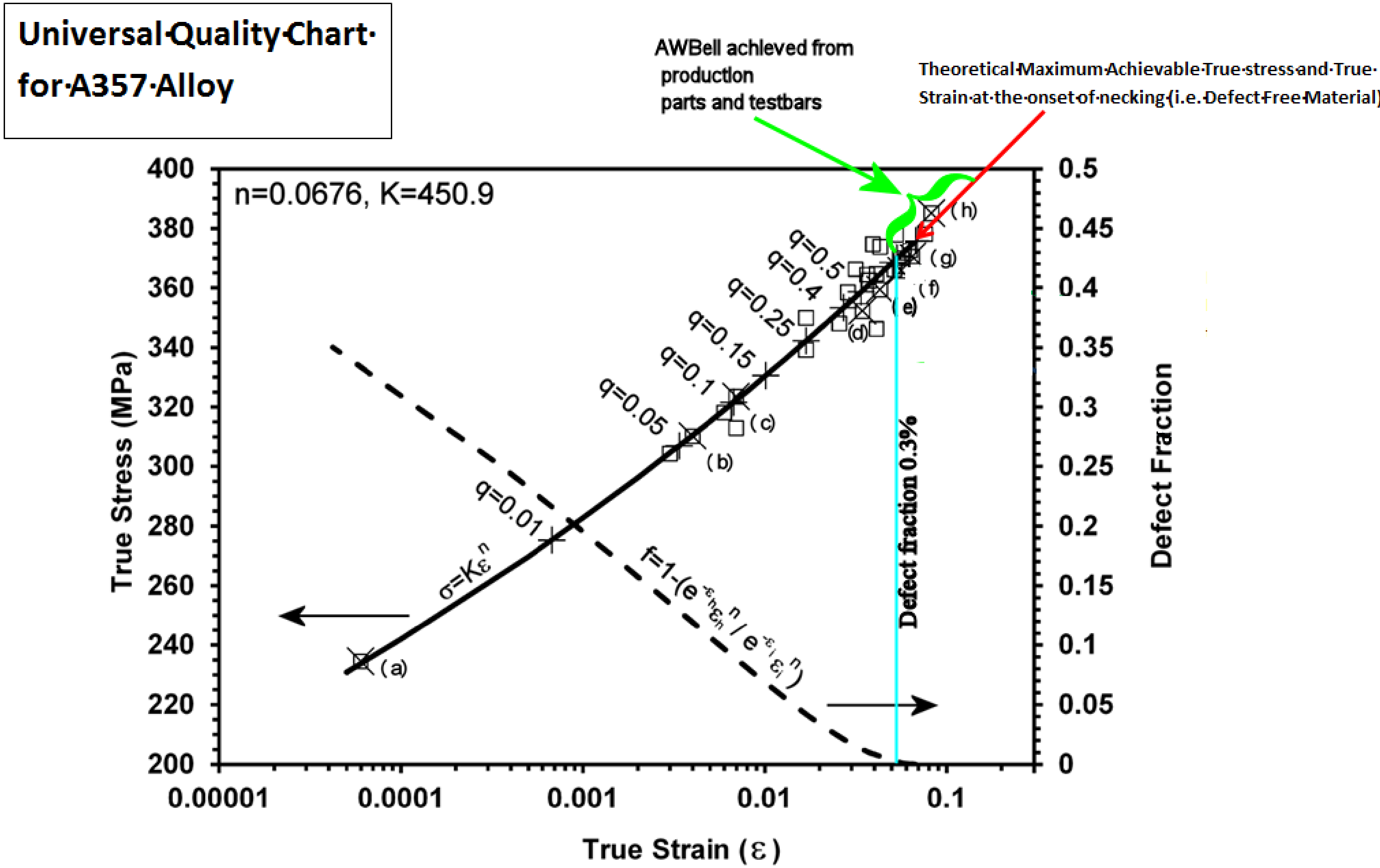
Final Result

Be- Free 357 (Al-7Si-0.55Mg): Standard Vs. ABE



299 MPa Y.S., 360 MPa UTS, 9.2% El (averages)

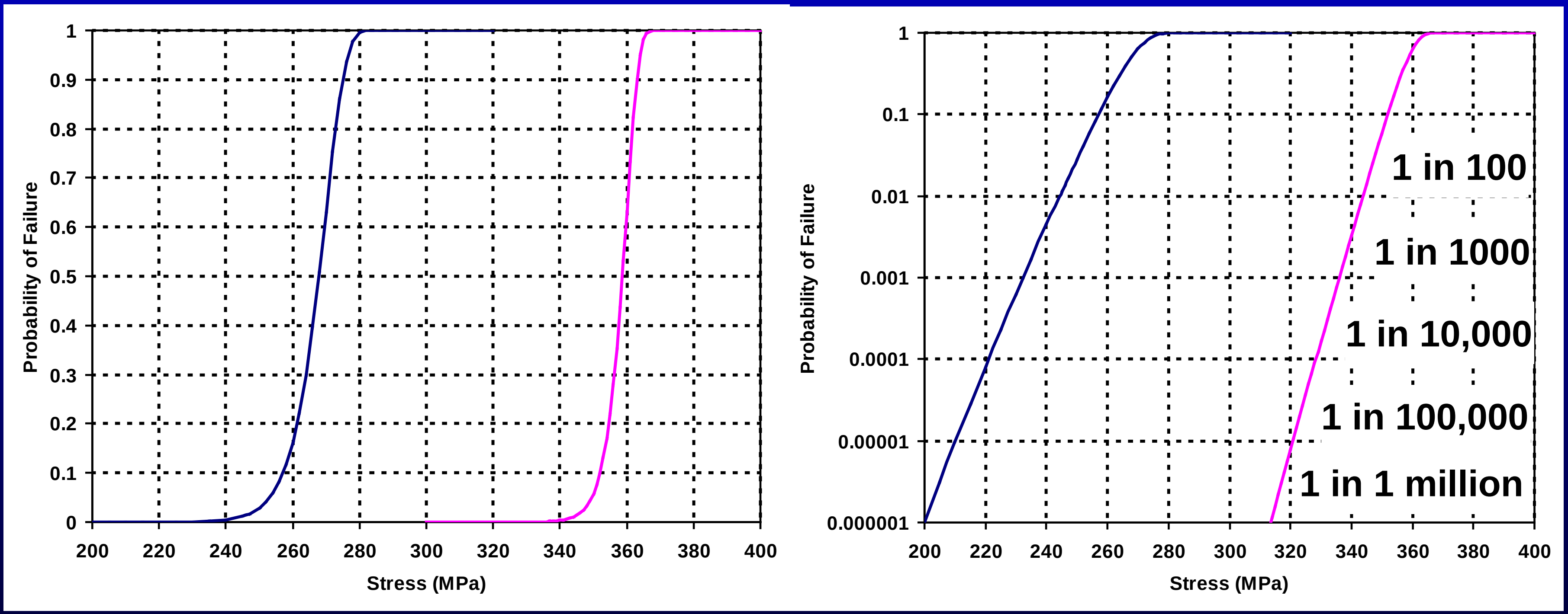
Comparison to Castings



Quality Chart from: R.N. Lumley, S.J. Bell, Derivation and Experimental Validation of a Quality Model for Investment Cast A357 Alloy. AFS Transactions 2013, American Foundry Society, paper 13-1567.

Using Weibull statistics for quality analysis and product improvement

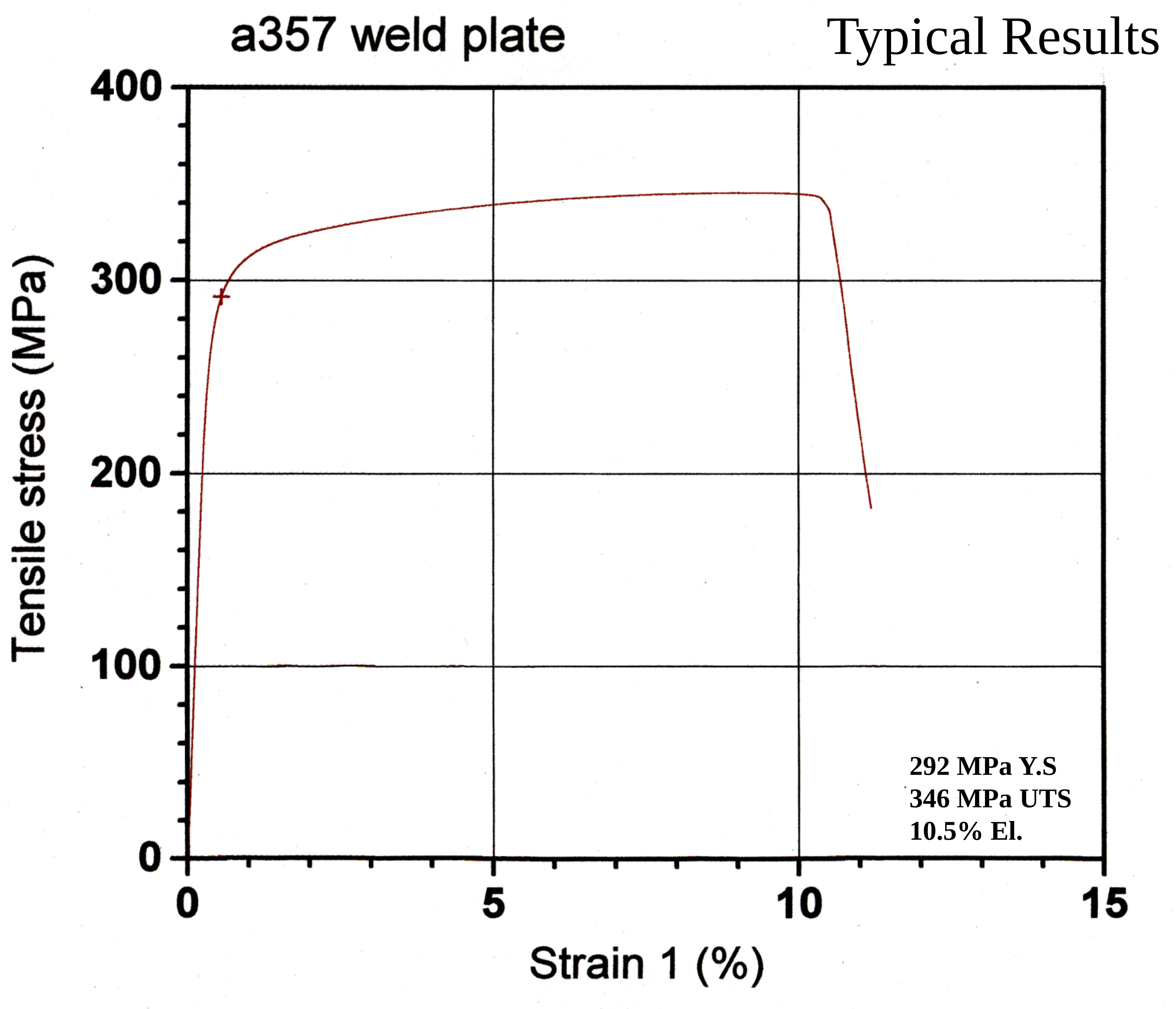
Material may have the same average yield stress (e.g. 275 MPa), but different quality.



These approaches work for all types of castings

For ABE process: $q > 0.85$

Typical Results



Testbars machined from flat castings

Typical Tensile Properties for Investment Cast Aluminium

METRIC

	Yield Stress	Tensile Stress	Elongation
Standard A357-T6	281 MPa	296 MPa	3%
ABE A357-T6	299 MPa	360 MPa	9%
Standard A356-T6	231 MPa	281 MPa	3%
ABE A356-T6	231 MPa	313 MPa	11%

IMPERIAL

	Yield Stress	Tensile Stress	Elongation
Standard A357-T6	41 KSI	43 KSI	3%
ABE A357-T6	43 KSI	52 KSI	9%
Standard A356-T6	33.5 KSI	41 KSI	3%
ABE A356-T6	33.5 KSI	45 KSI	11%

F35 Projects: Northrop Grumman EODAS

Completed FAI on Three Parts 2014; production 2015, largest customer 2016-2020

Cast & Machined by AWBell

Special Process Approvals: Pyrometry, Heat treatment, Welding

ABE Process Development and Productionization

to Achieve a World Leading Aluminium Casting System

Conclusions

- **Quality of castings may be evaluated accurately by use of a model based on a first principles approach utilizing flow curve analysis.**

- **The method predicts the defect fraction present on the fracture surface, thereby providing a meaningful representation of casting quality, *q*.**

- **This may provide an assessment of quality and the variables influencing product or process development.**

- **The model also may be used to predict "what's possible". This allows for a systematic approach to product and process improvement.**

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