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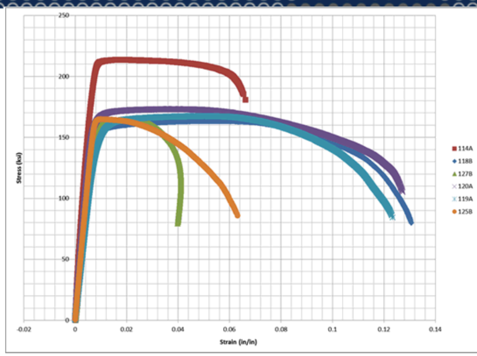

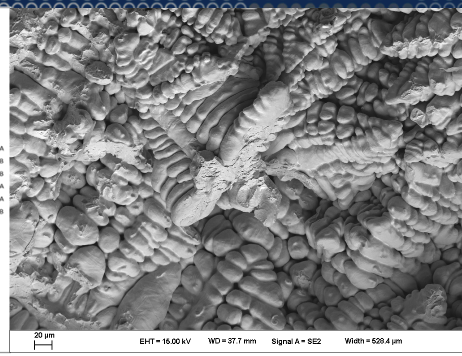

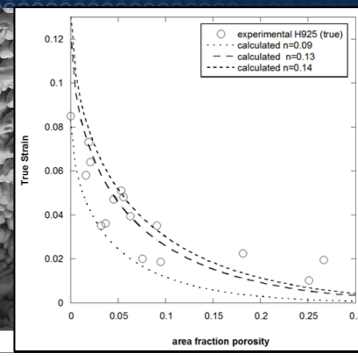

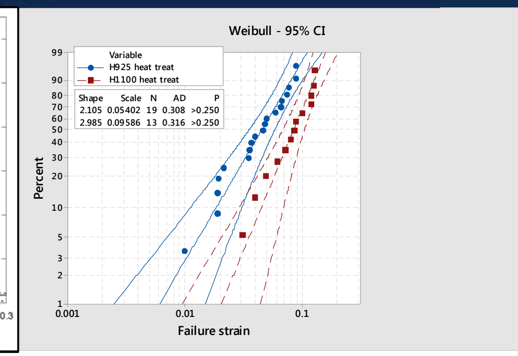

Weibull Statistical Analysis of Tensile Fractures of PH17-4 Stainless Steel Castings

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Sandia National Laboratories, Albuquerque, NM

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Goals

1. **Summarize PH17-4 Stainless Steel Casting Behavior: Effect of Defects on Tensile Ductility**
2. **Weibull Statistical Analysis of Strain-to-Failure**
3. **Apply the Analysis to Additively Manufactured (AM) PH17-4 Stainless Steel**

The focus of this presentation is on ductility…failure strain

Investment Cast PH17-4 Stainless Steel

- 17-4PH is a martensitic, precipitation-hardened stainless steel with 15.50-16.70%Cr and 3.60-4.60% Ni, and 2.80-3.50% Cu
  - Cast version known as CB7Cu
  - Cu-rich precipitates provide strengthening

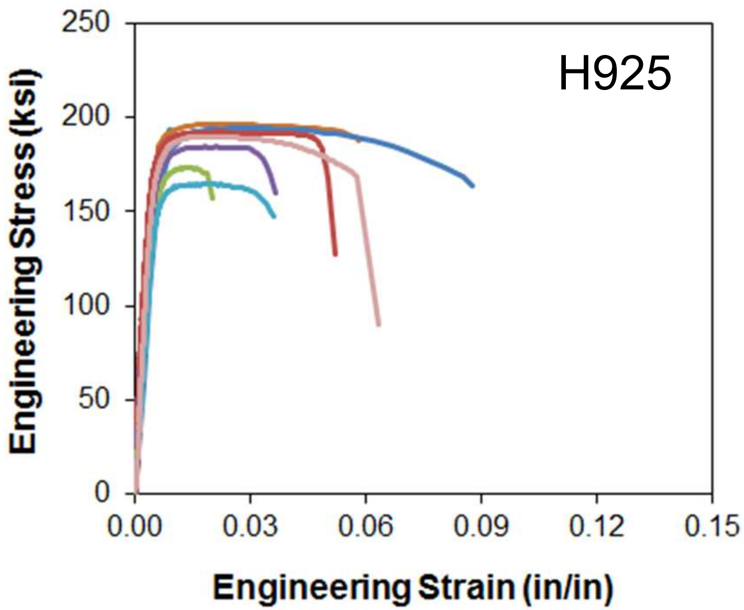
- The age-hardening (precipitation) temperature is the major factor in determining mechanical properties.

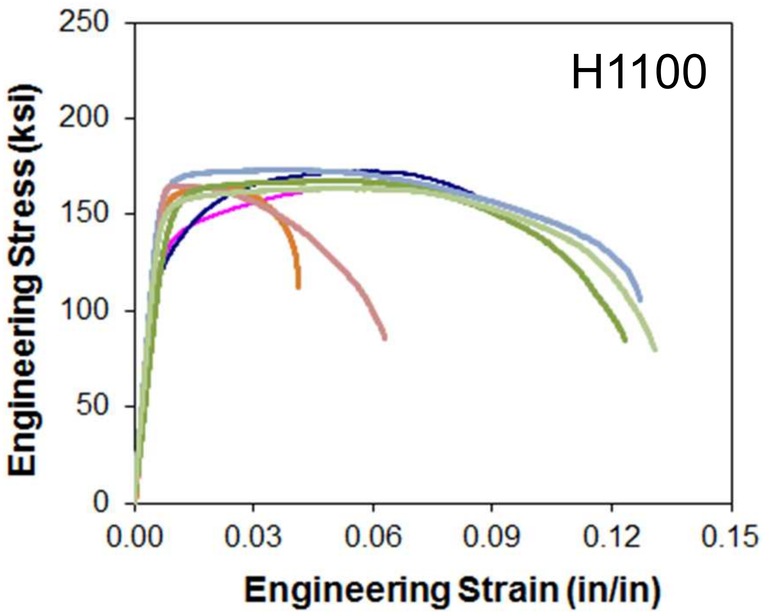
  H925, H1000, H1100… Higher aging temp, lower strength

- Two types of tensile samples: 1) Machined from thin-wall cast components or 2) Cylindrical cast tensile bars (.25" diam.)

Ref: D.F. Susan, T.B. Crenshaw, and J.S. Gearhart, "The Effects of Casting Porosity on the Tensile Behavior of Investment Cast 17-4PH Stainless Steel", *J. Mat. Eng. Performance*, Vol. 24(8), 2917-2924, 2015.

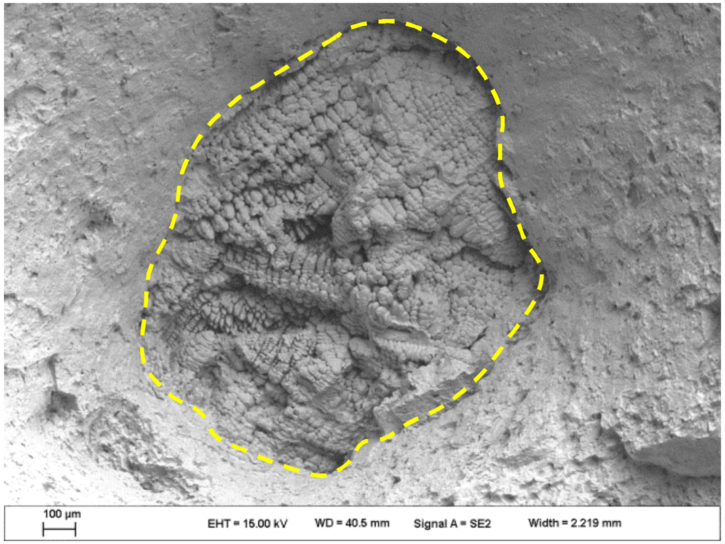
Strain-to-Failure Varies Significantly

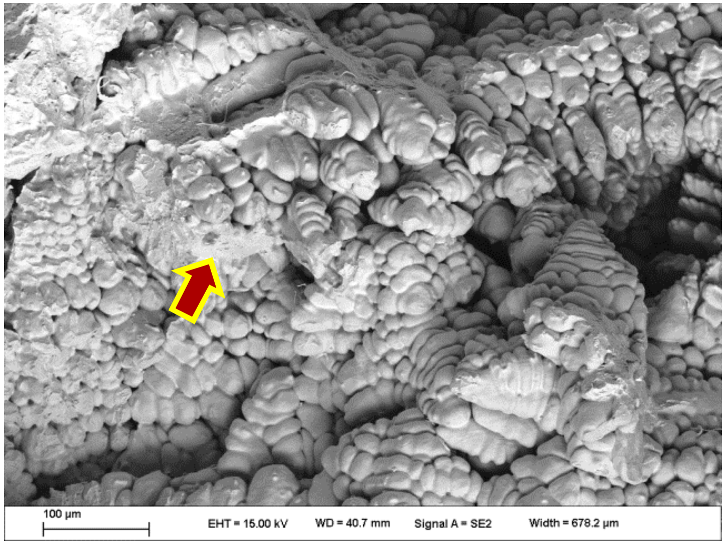


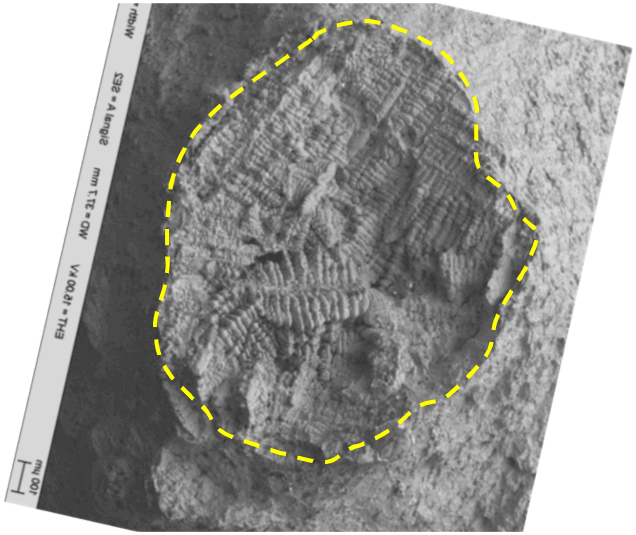


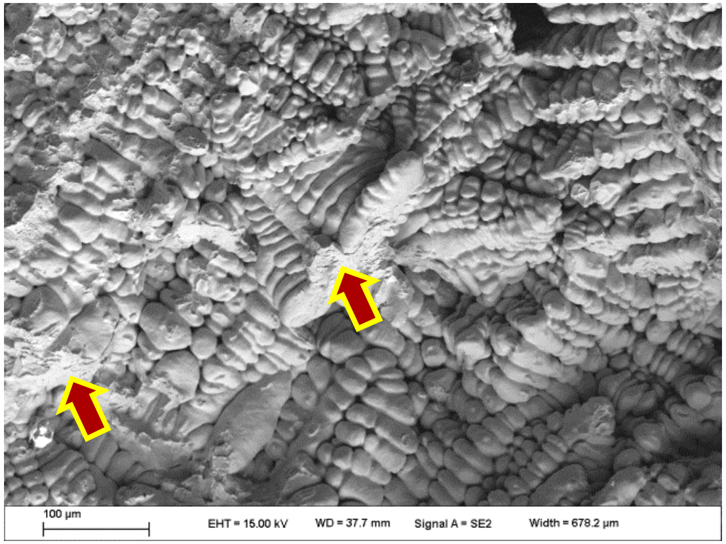
- Room temperature, strain rate ~1 x 10^{-3} sec^{-1}

Area % Casting Porosity on Fracture Surfaces



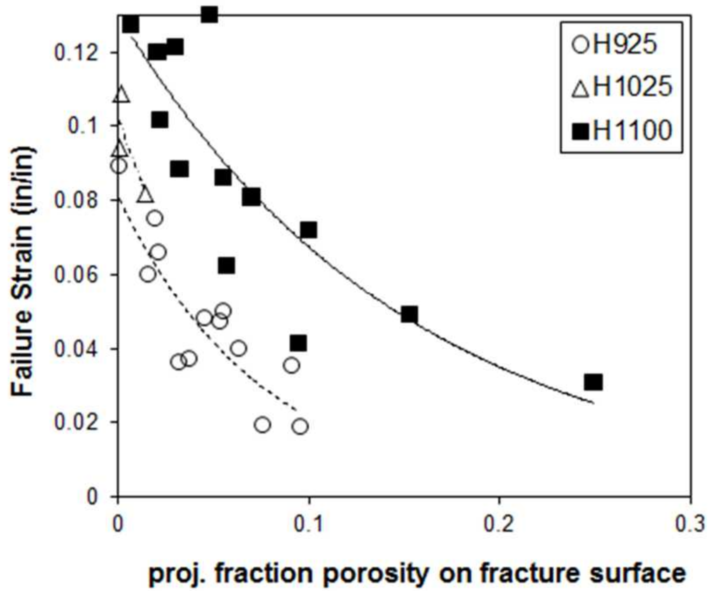


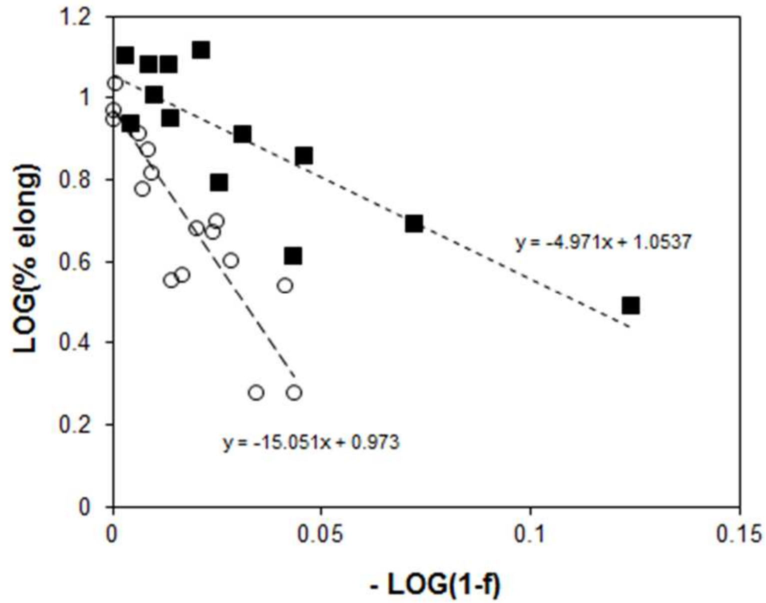




- Porosity area measured on fracture surfaces

Quantitative Analysis: Method 1
"Index of Defect Susceptibility"





$$e = e_0 \left[1 - f\right]^x$$

(Gokhale et al.)

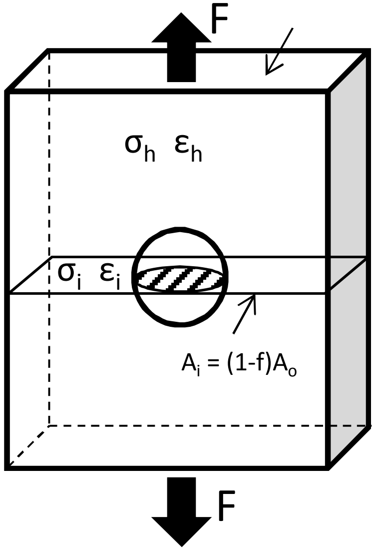
e = ductility (failure strain), f = area fraction defects

e_0 = ductility of a "defect-free" casting

x = index of defect susceptibility

- Heat treat condition is important in terms of influence of casting porosity. Good method for comparisons to other materials.

Quantitative Analysis: Method 2
"Critical Local Strain (Cáceres et al.)"



Initially:

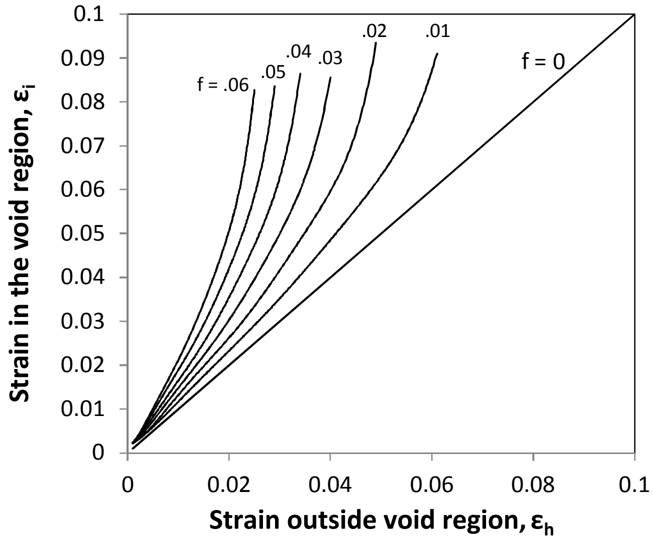
$A_h = A_o$

$A_i = A_o(1\text{-}f)$

Currently:

$A_h = A_o e^{-\varepsilon_h}$

$A_i = A_o(1\text{-}f)e^{-\varepsilon_i}$



$$\sigma_i(1-f)A_o e^{-\varepsilon_i} = \sigma_h A_o e^{-\varepsilon_h}$$ Load equilibrium (inside and outside of void region)

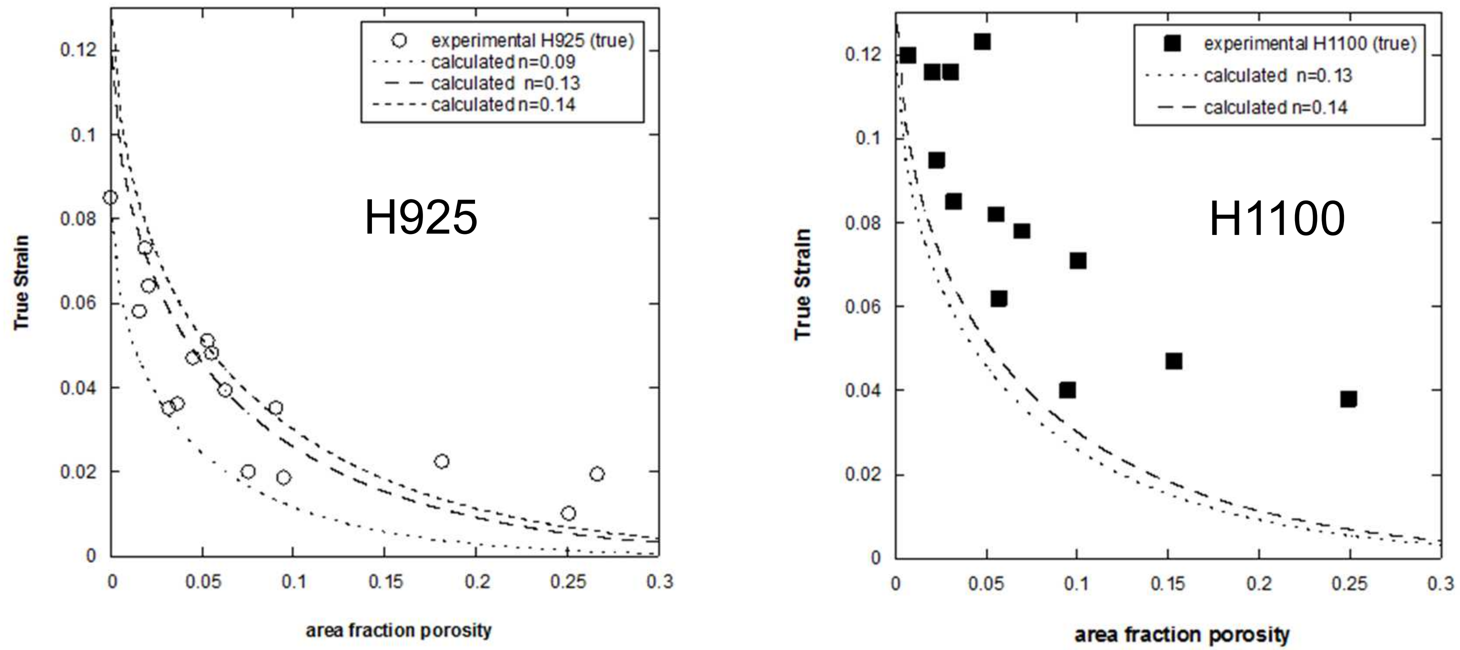
$$\sigma = K\varepsilon^n$$ (Constitutive equation, n = strain hardening exponent)

$$(1-f)e^{-\varepsilon_i}\varepsilon_i^n = e^{-\varepsilon_h}\varepsilon_h^n$$

- Solve numerically. Choice of n value is critical

(C. H. Cáceres, *Scripta Met. Mat.*, Vol 32(11), 1851-1856, 1995.)

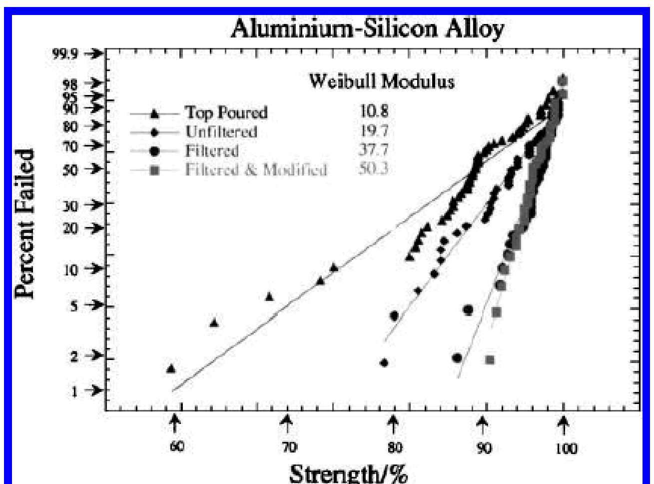
Quantitative Analysis: Method 2
“Critical Local Strain (Cáceres et al.)”



- H925, reasonable prediction of strain to failure with n = 0.13
- H1100 material exhibits more localized strain, necking. Model predictions are not as good. “post-uniform deformation leads to calculated values that underestimate the fracture strain (by the amount of non-uniform strain)” (C. H. Cáceres, Scripta Met. Mat., Vol 32(11), 1851-1856, 1995.)

Weibull Statistical Analysis. Method 3

- Weibull statistical analysis is often used to describe failure of ceramic materials…where failure is dominated by defects.
- There are some examples of Weibull analysis of metals castings, where defects are also important, at least for ductility.
  - Campbell 2006, Staley et al., 2007, Green and Campbell 1994, Campbell et al, 1998, Al-Si-Mg cast alloys, effects of porosity and entrained oxides
  - Cox and Harding, 2007. Effects of tilt filling etc., Taghiabadi et al., 2003
  - Papers by Teng et al., 2008, 2009, 2010, Aluminum (Si, Mg,…) cast alloys



16 Relative reliability of Al–7Si–0·4Mg alloy cast by different methods, assessed by Weibull plot, showing scatter of tensile strengths[27]

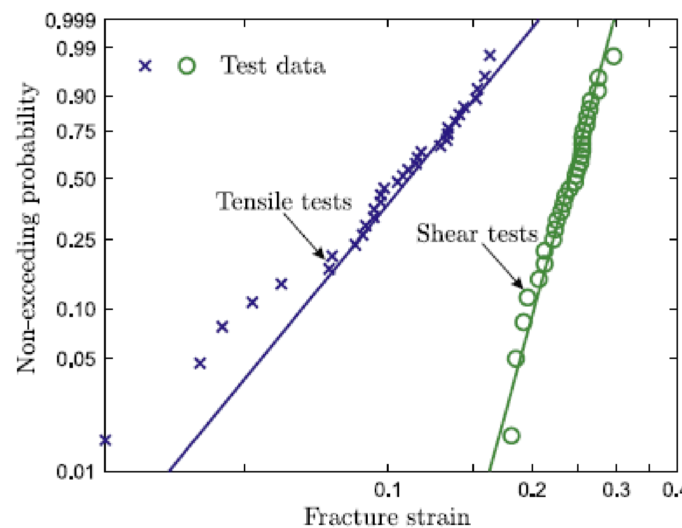
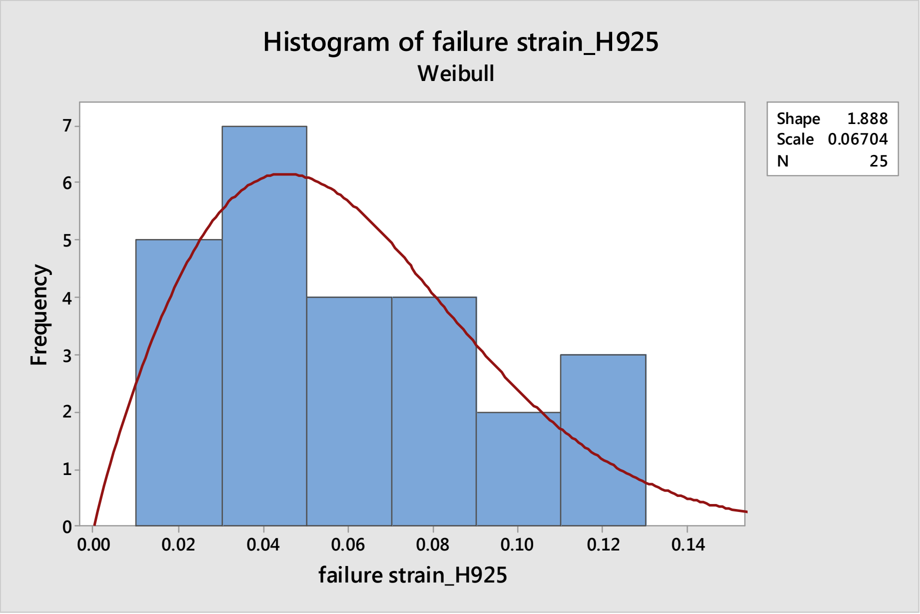
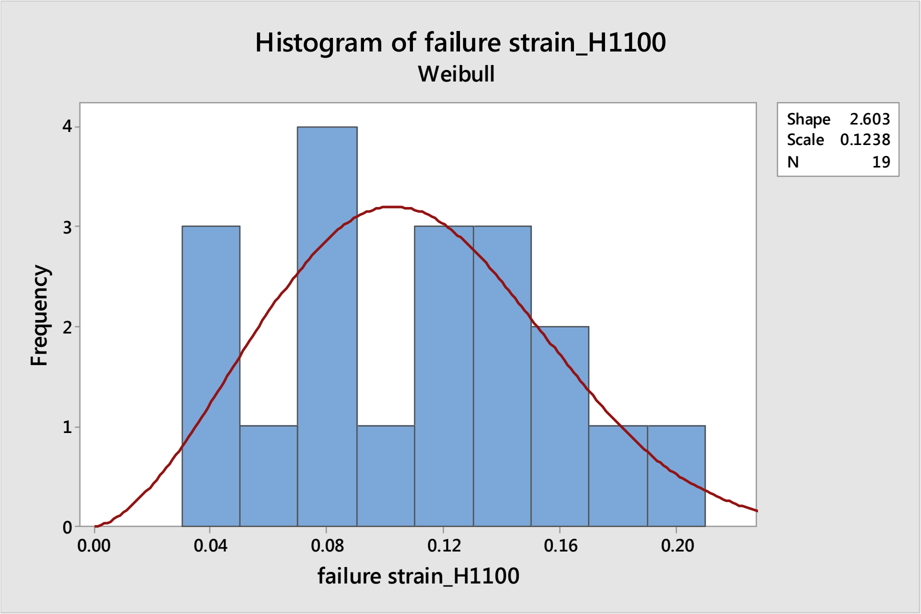


Fig. 17. Weibull probability plots of the tensile and the shear fracture strains.

Histograms of Strain-to-Failure for Cast PH17-4 Stainless Steel





19 samples H925 Room temp
3 samples H1025 Room temp
and 3 tests at -10˚C H925

19 samples H1100 Room temp

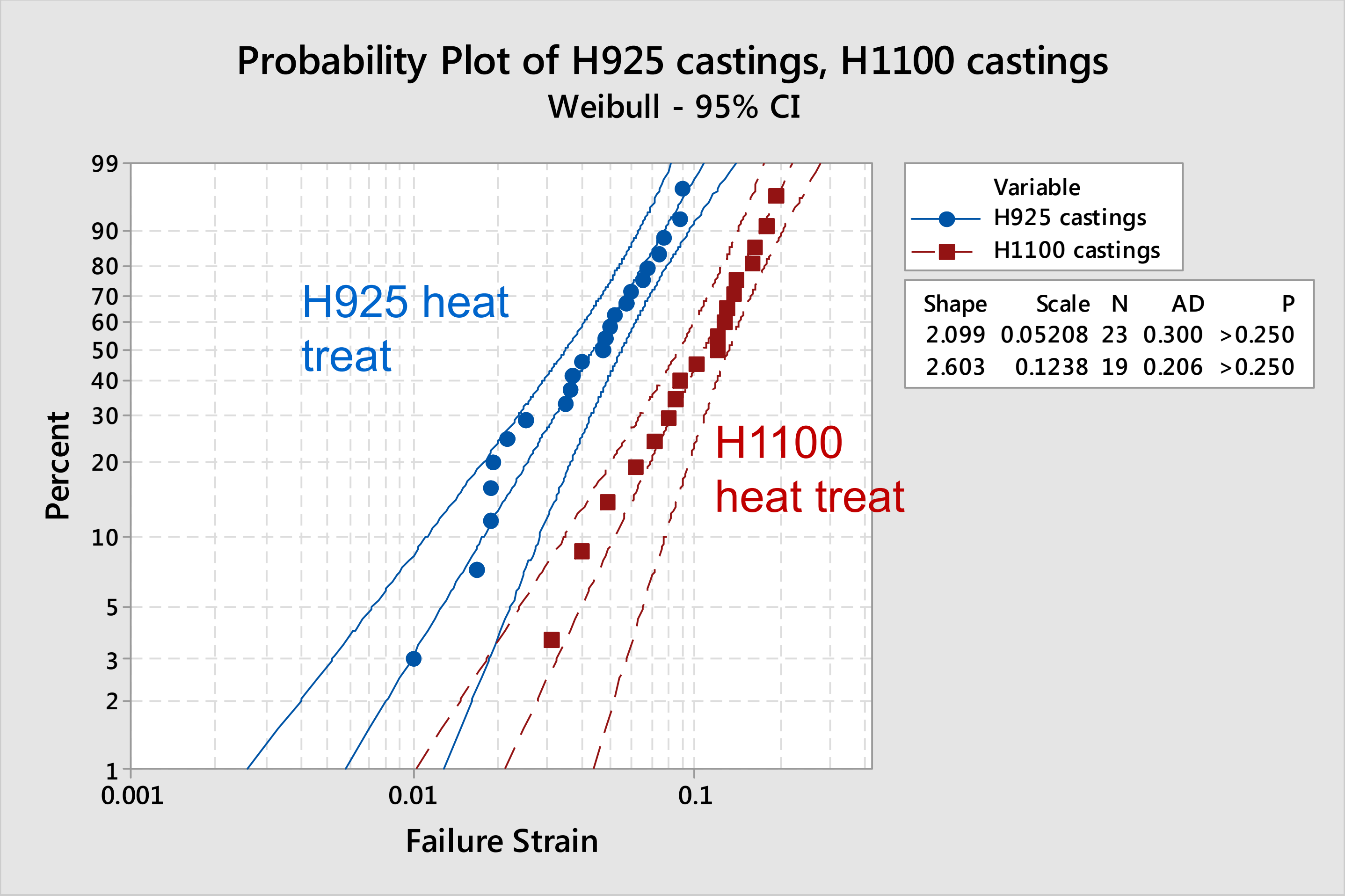
$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

2-parameter Weibull

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}$$

3-parameter Weibull

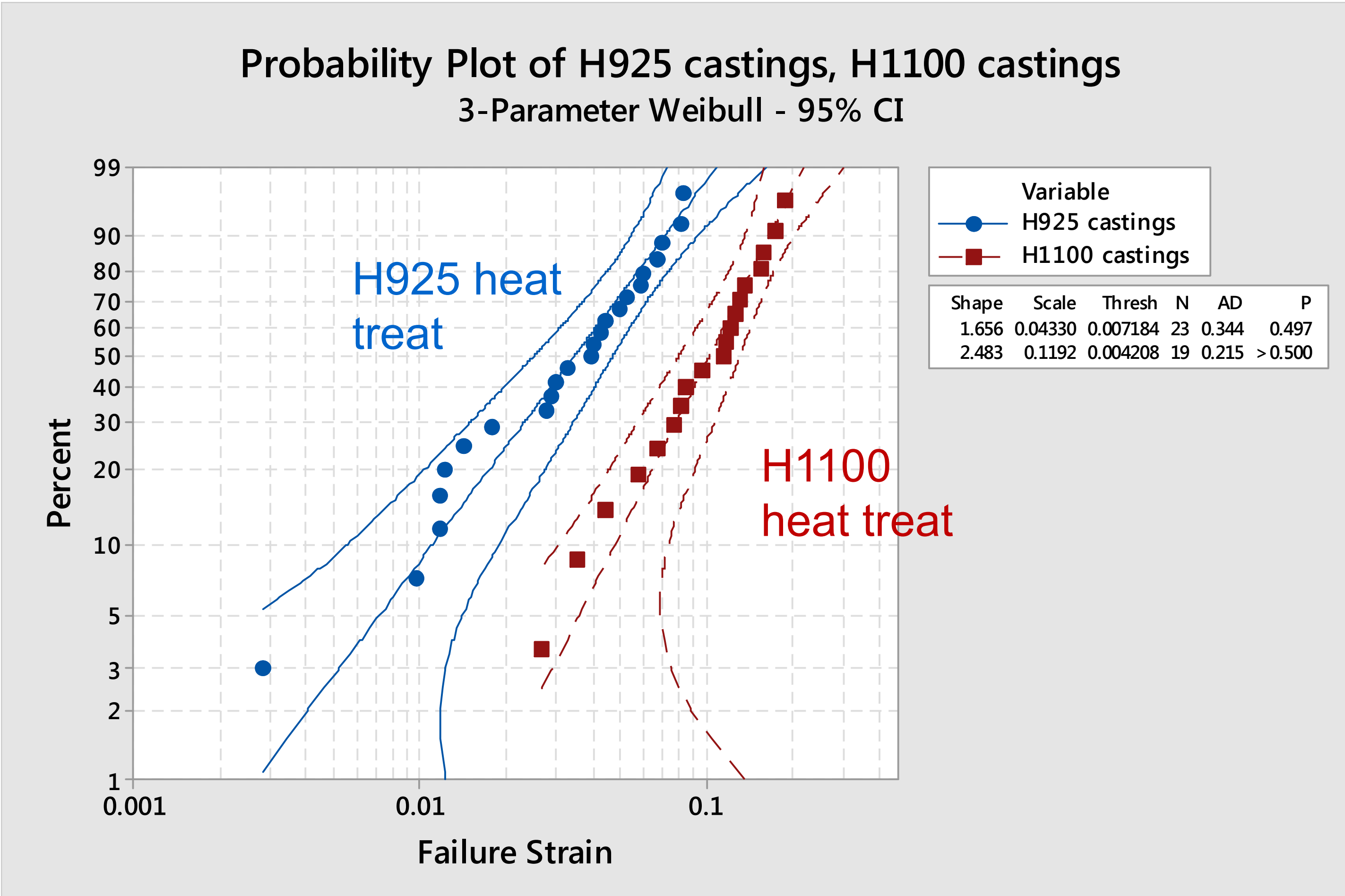
Weibull Distributions, 2-parameter



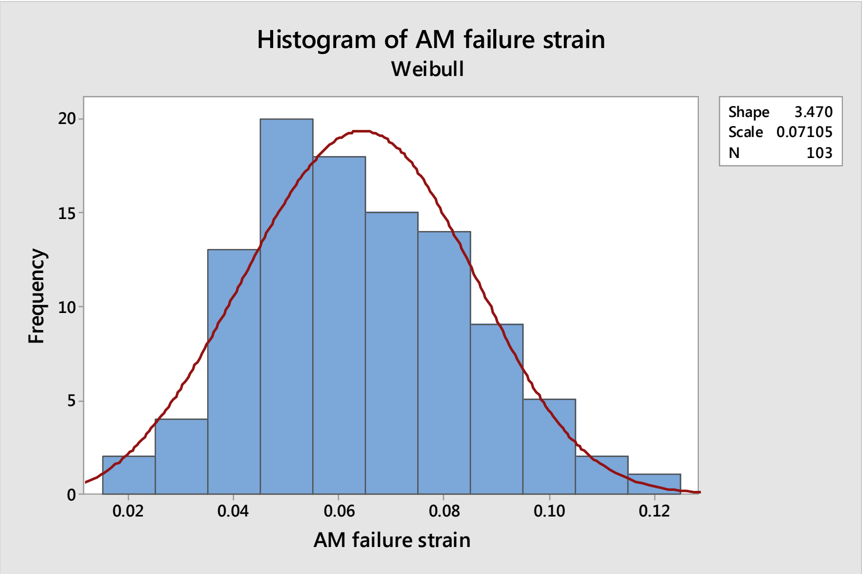
Shape	Scale	N	AD	P
2.099	0.05208	23	0.300	>0.250
2.603	0.1238	19	0.206	>0.250

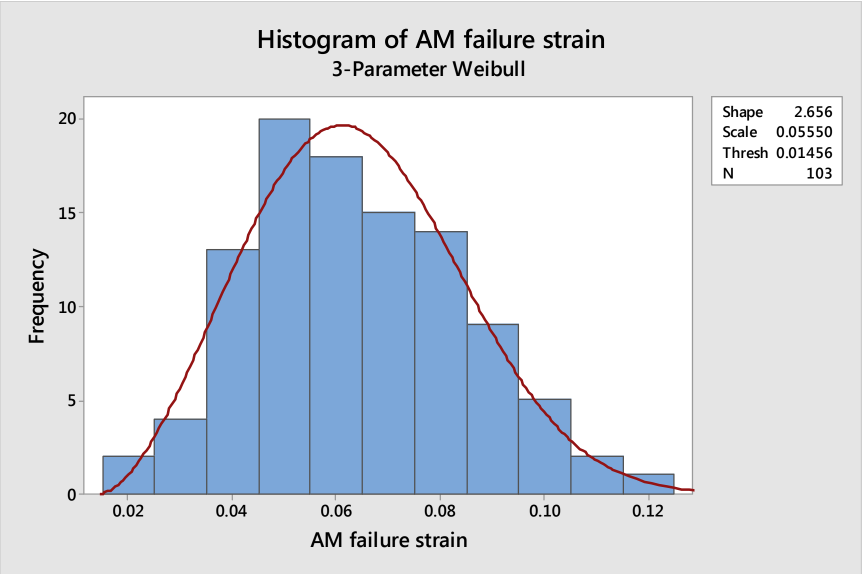
All distributions determined with 95% confidence

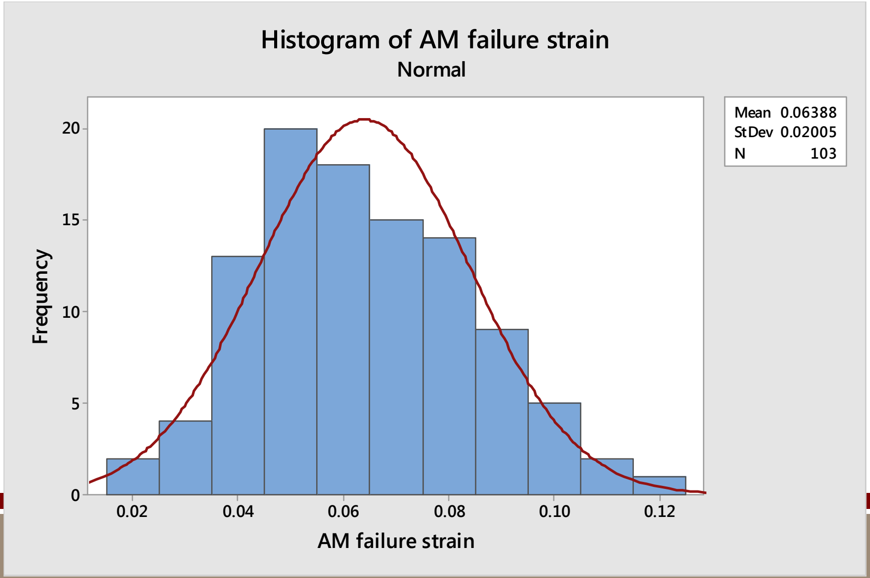
Weibull Distributions, 3-parameter



Histogram of Strain-to-Failure for **AM** Material

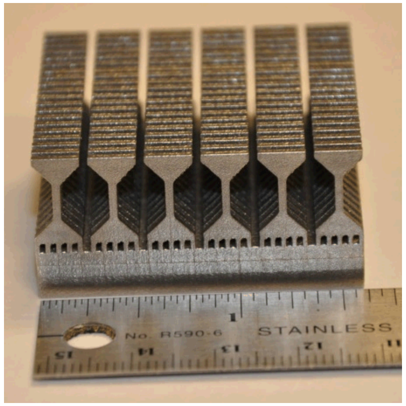




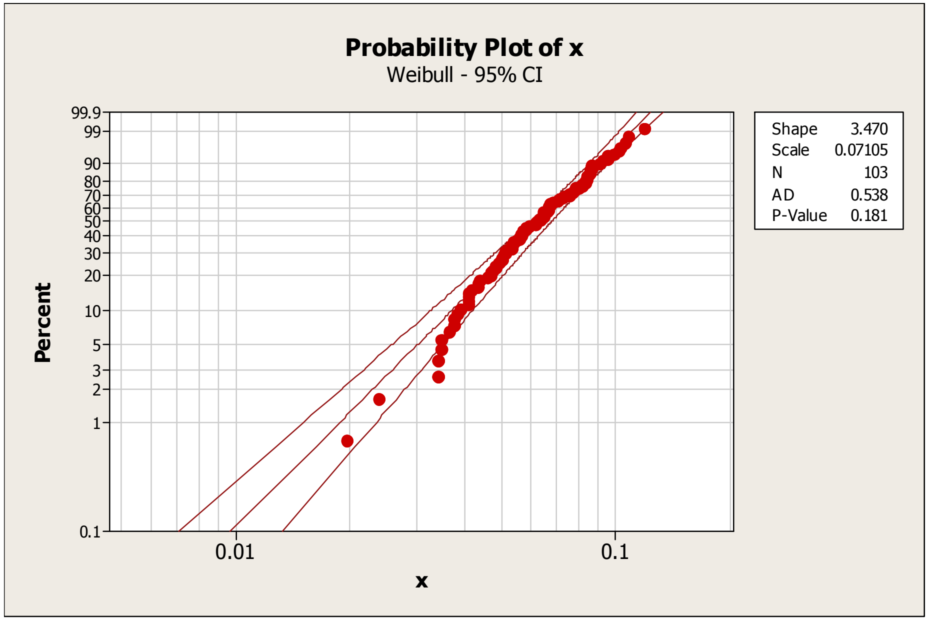


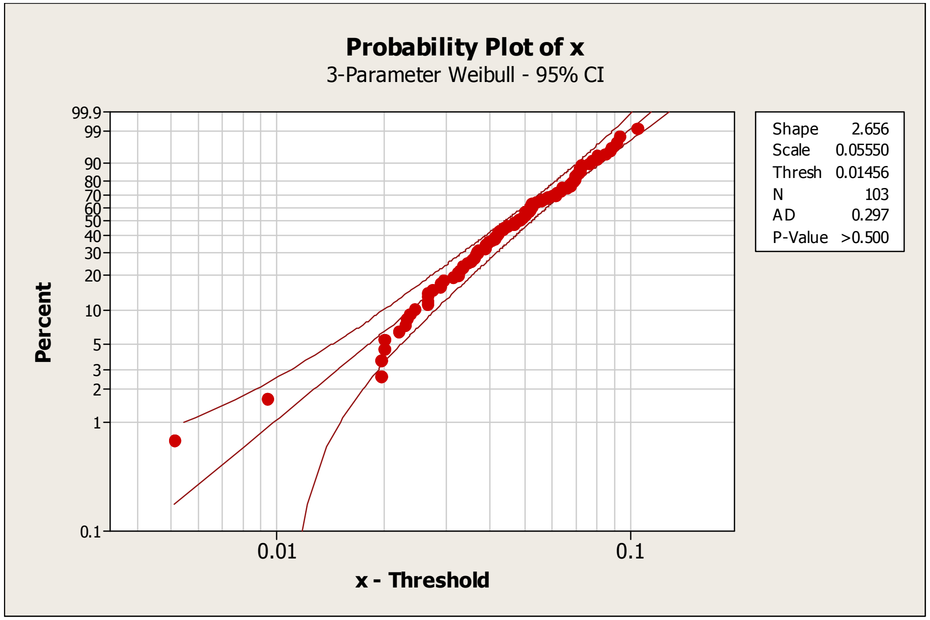
103 samples of AM material (laser powder bed processed)

H900 heat treat



Comparison to Additive Manufactured (AM) PH17-4 Stainless Steel

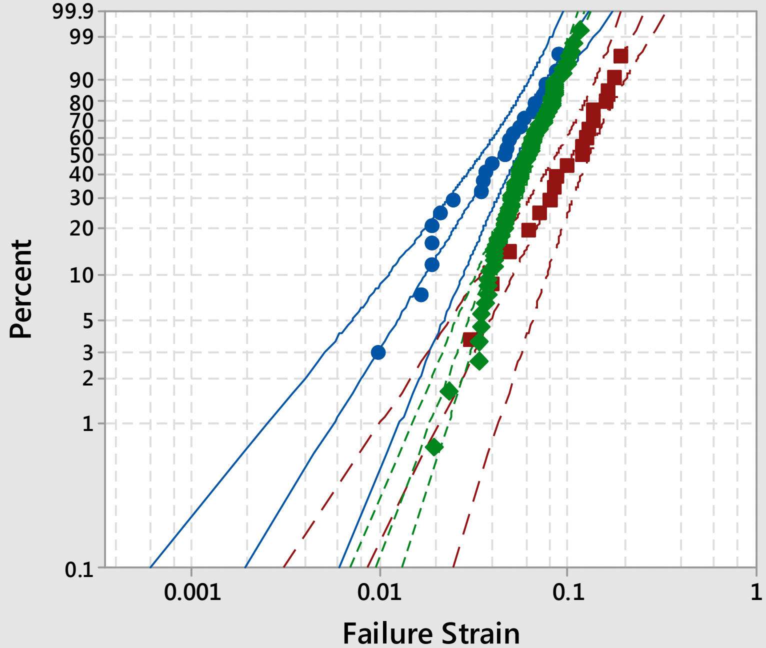




2-parameter Weibull
A 10% failure probability is associated with about 2-3% strain

3-parameter Weibull
A 10% failure probability is associated with about 1-2% strain

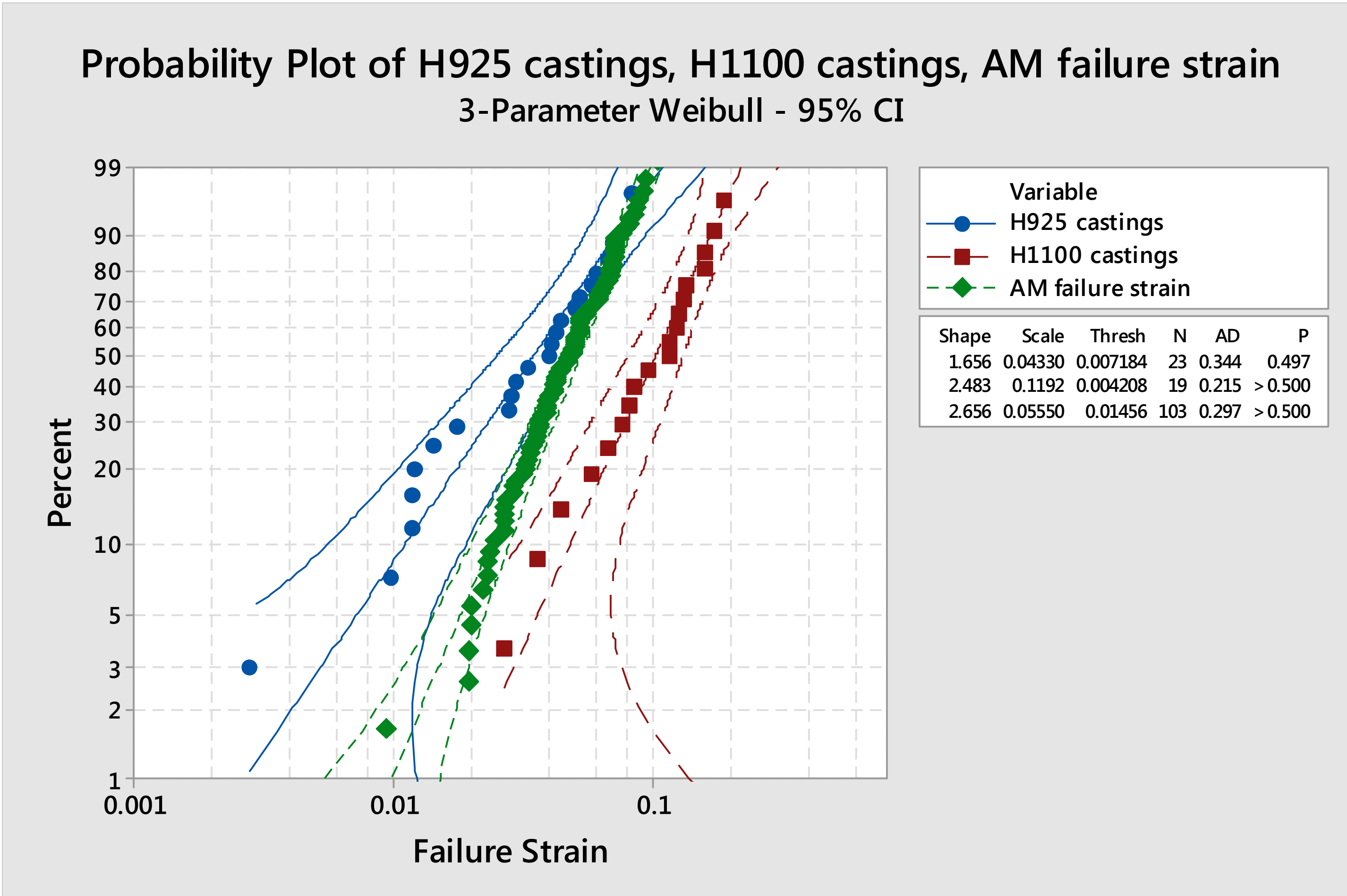
Comparison to Additive manufactured (AM) PH17-4 Stainless Steel



Shape	Scale	N	AD	P
2.099	0.05208	23	0.300	>0.250
2.603	0.1238	19	0.206	>0.250
3.470	0.07105	103	0.538	0.181

103 samples of AM material (laser powder bed processed), H900 heat treat

- Weibull shape parameter (slope) is actually higher for the AM material, i.e. tighter distribution, but overall ductility range is similar to castings with defect-controlled failure strain. Suggests that defects, e.g. porosity, also control the ductility of AM material.
- Highest ductility ("defect-free" samples) of castings and AM material is similar.

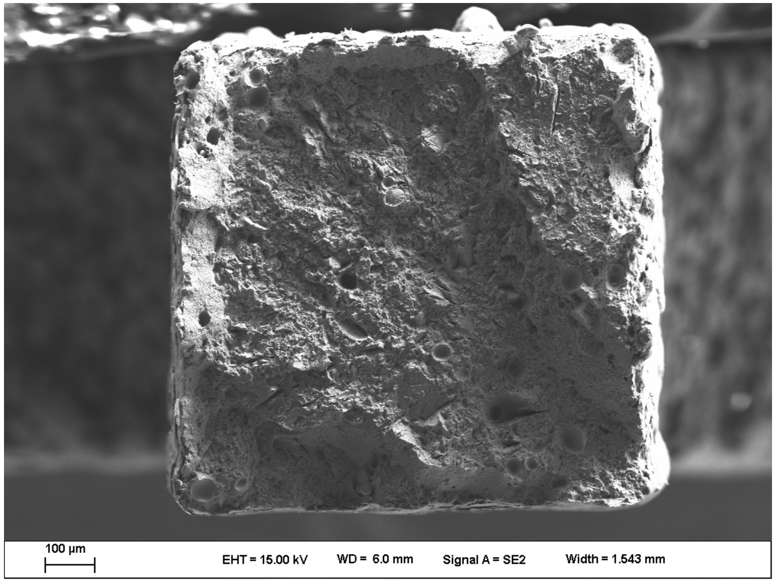

Probability Plot of H925 castings, H1100 castings, AM failure strain
3-Parameter Weibull - 95% CI
Percent
99
90
80
70
60
50
40
30
20
10
5
3
2
1
0.001
0.01
0.1
Failure Strain
Variable
H925 castings
H1100 castings
AM failure strain
Shape Scale Thresh N AD P
1.656 0.04330 0.007184 23 0.344 0.497
2.483 0.1192 0.004208 19 0.215 >0.500
2.656 0.05550 0.01456 103 0.297 >0.500

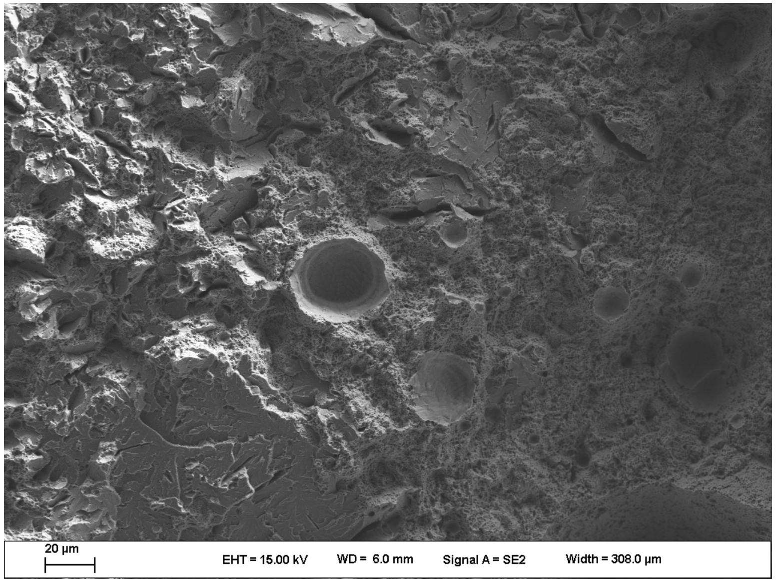
AM Fracture Surfaces

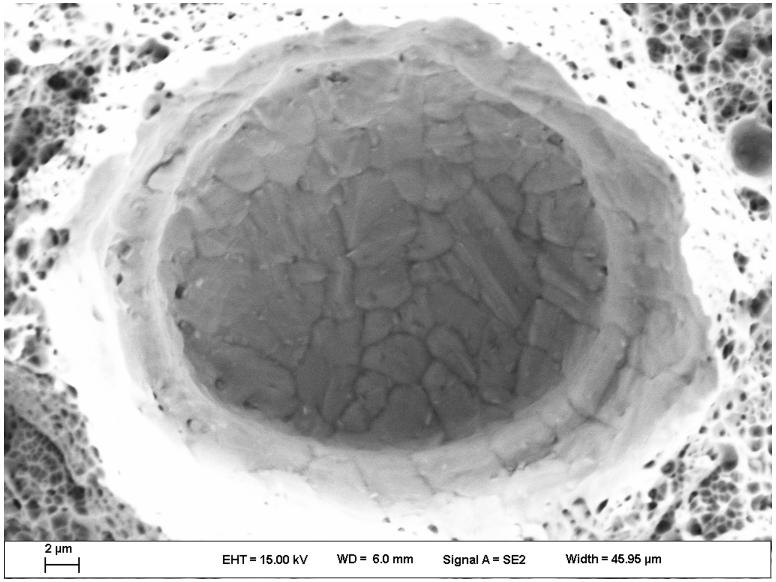
- Many defects found on AM fractures surfaces from samples with low measured ductility. Spherical defects related to original powder particles?

- Defects appear different than those found on bulk cast material.

Note also: surface finish effects are very important for AM samples



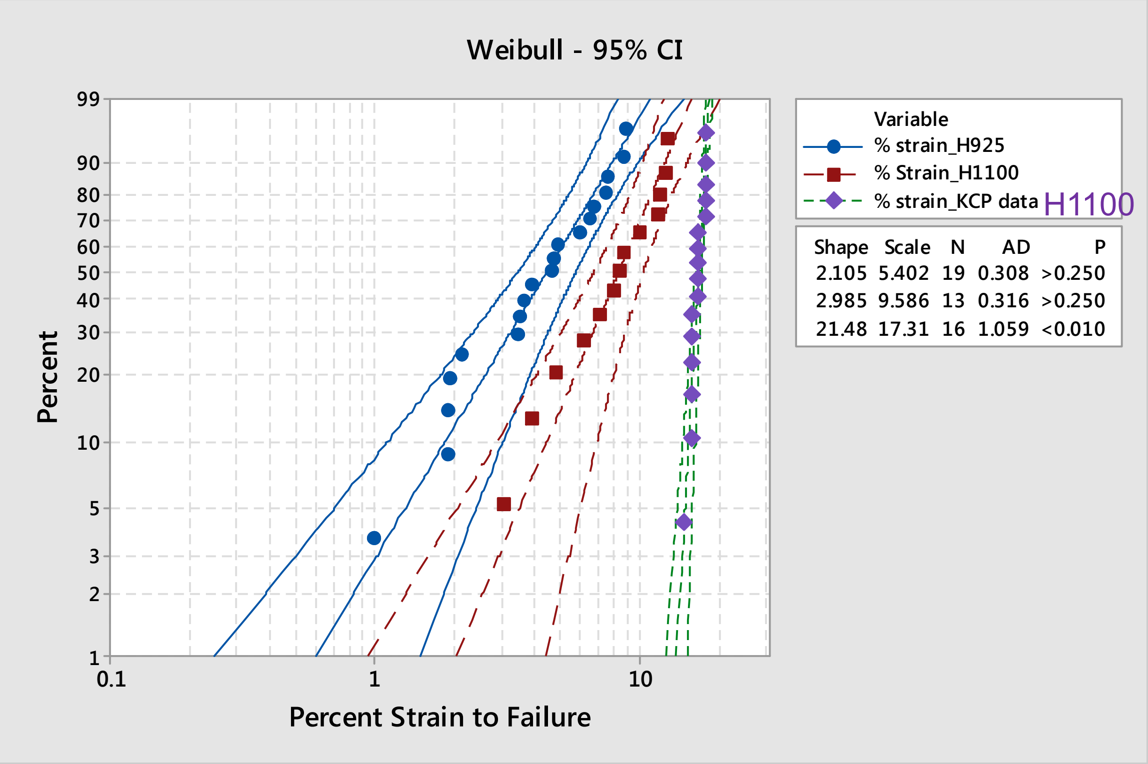




But, castings can be produced without defects

- While casting porosity clearly affects ductility, that doesn't mean all castings contain porosity. We can produce largely defect-free castings through careful control of process parameters (liquid metal fill, gate and risering, etc.), and depending on the cast part geometry.
- Can we develop techniques to control/reduce defects in AM material?

Tests on a different batch of separately cast 0.25 in. diameter round bars. Heat treated to H1100



Shape	Scale	N	AD	P
2.105	5.402	19	0.308	>0.250
2.985	9.586	13	0.316	>0.250
21.48	17.31	16	1.059	<0.010

Summary

- Defects, such as casting porosity, negatively affect the tensile ductility of PH17-4 stainless steel castings. The results can be quantified with an "Index of defect susceptibility" and a critical strain approach developed by Cáceres e al. for other alloys.

- Weibull statistical analysis can also be applied to evaluate the failure strain of PH17-4 castings. Choice of 2-parameter vs. 3-parameter Weibull affects the detailed distribution results.

- Comparison to AM powder-bed processed material shows that AM material has similar range of failure strains, also likely controlled by processing defects.