

## Ceramic Inclusions In Powder Metallurgy Disk Alloys: Characterization And Modeling

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Powder metallurgy alloys are increasingly used in gas turbine engines, especially as the material chosen for turbine disks. Although powder metallurgy materials have many advantages over conventionally cast and wrought alloys (higher strength, higher temperature capability, etc.), they suffer from the rare occurrence of ceramic defects (inclusions) that arise from the powder atomization process. These inclusions can have potentially large detrimental effect on the durability of individual components. An inclusion in a high stress location can act as a site for premature crack initiation and thereby considerably reduce the fatigue life. Because these inclusions are exceedingly rare, they usually don't reveal themselves in the process of characterizing the material for a particular application (the cumulative volume of the test bars in a fatigue life characterization is typically on the order of a *single* actual component). Ceramic inclusions have, however, been found to be the root cause of a number of catastrophic engine failures. To investigate the effect of these inclusions in detail, we have undertaken a study where a known population of ceramic particles, whose composition and morphology are designed to mimic the "natural" inclusions, are added to the precursor powder. Surface connected inclusions have been found to have a particularly large detrimental effect on fatigue life, therefore the volume of ceramic "seeds" added is calculated to ensure that a minimum number will occur on the surface of the fatigue test bars. Because the ceramic inclusions are irregularly shaped and have a tendency to break up in the process of extrusion and forging, a method of calculating the probability of occurrence and expected intercepted surface and embedded cross-sectional areas were needed. We have developed a Monte Carlo simulation to determine the distributions of these parameters and have verified the simulated results with observations of ceramic inclusions found in macro slices from extrusions and forgings. The ultimate goal of this study will be to use probabilistic methods to determine the reliability detriment that can be attributed to these ceramic inclusions.



5<sup>th</sup> Annual FAA/Air Force/NASA/Navy Workshop on the  
Application of Probabilistic Methods to Gas Turbine Engines

*CERAMIC INCLUSIONS IN POWDER  
METALLURGY DISK ALLOYS:  
CHARACTERIZATION AND MODELING*

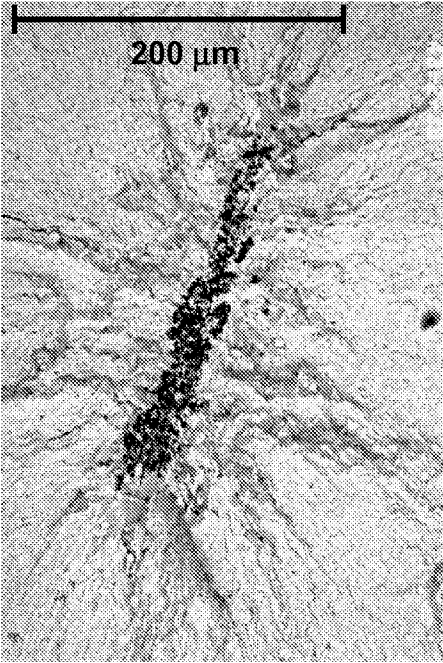
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Jack Telesman and Tim Gabb— NASA Glenn Research Center  
CPT Rob Barrie – US Army

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## Fatigue Crack from Inherent Ceramic Defect



- Inherent to powder process (unavoidable)
- Can cause significant life debit
- Large inclusions exceedingly rare
- Cost prohibitive to study the effect of naturally occurring inclusions on life



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## Scope of Work

- Develop life prediction methodology to account for effect of random defects in PM alloys
  - Seeding study (in progress)
    - Characterization of known populations of inclusions (seeds)
    - Characterize incubation of cracks from defects
    - Mapped back to natural inclusions in unseeded material
  - Modeling
    - Simulation of seed volumetric distribution to determine occurrence probability
    - Incubation model to match observed incubation life distributions

**Modeling Inputs Critical!**



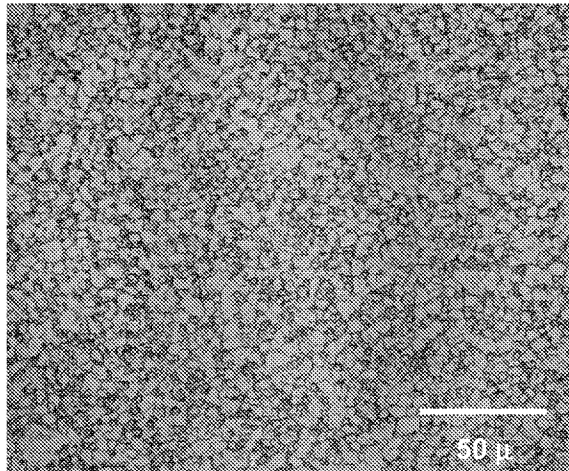
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# Material Parameters

**270 MESH PRODUCTION QUALITY UDIMET 720 POWDER FROM SPECIAL METALS**

## Processing Conditions

HIP  
EXTRUDE  
ISOFORGE  
SUBSOLVUS HEAT TREAT



Same conditions for both seeded and Unseeded material



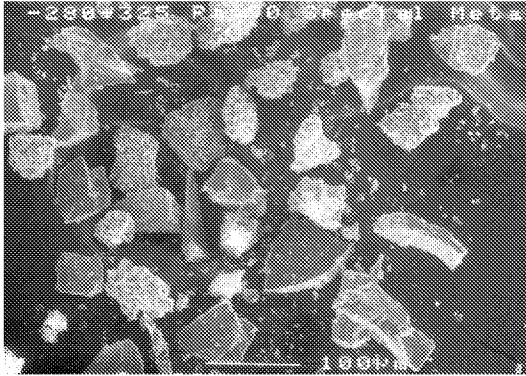
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# Seeding Parameters

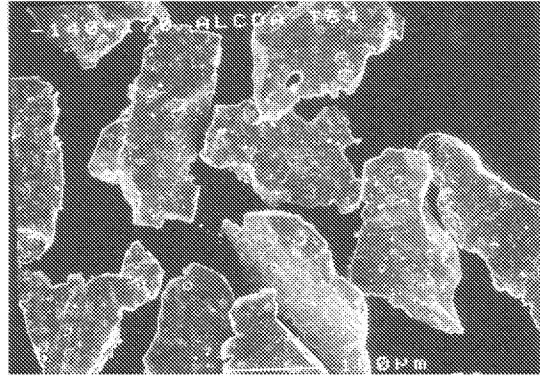
The seeds used were both alumina-rich

**Ram90**



- Used in the repair furnaces and crucibles
- -270+325 Mesh: A size distribution typical of production powder
- Type II : Soft
- Seeding Rate: 5300 seeds/in<sup>3</sup>

**Alcoa T64**



- Used as crucible material
- -140+170 mesh: Size distribution chosen to simulate a contamination event
- Type I : Hard
- Seeding Rate: 1140 seeds/in<sup>3</sup>

Seeding rates chosen to provide an acceptable number of surface connected inclusions



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## Seed Characterization Effect of Processing on Seeds

### **Seed size distributions were determined in situ:**

- Initial input size distribution of seeds (using image analysis)
- After Blending (Using the HLS process)
- After Extrusion (Using Metallography and image analysis)
- After Forging (Using Metallography and image analysis)
- After Machining LCF bars (Using SEM and image analysis)
- After Testing (Using SEM and image analysis)



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## Seed Characterization A Priori Seed Size Distributions

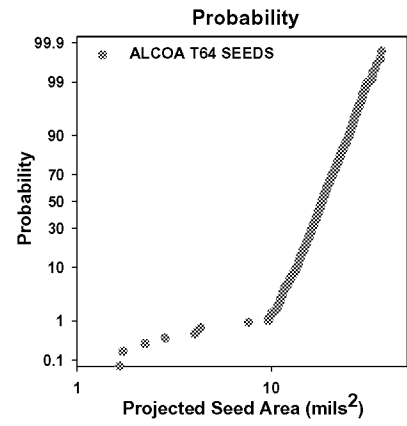
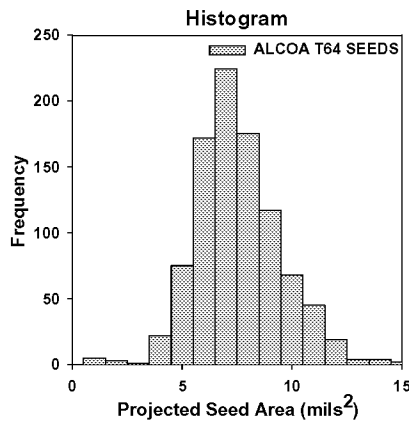
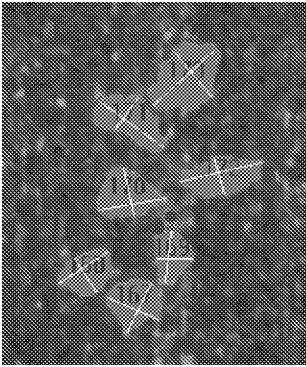


Image analysis used to determine: Projected Seed areas, Maximum Seed length, and Perpendicular Seed length



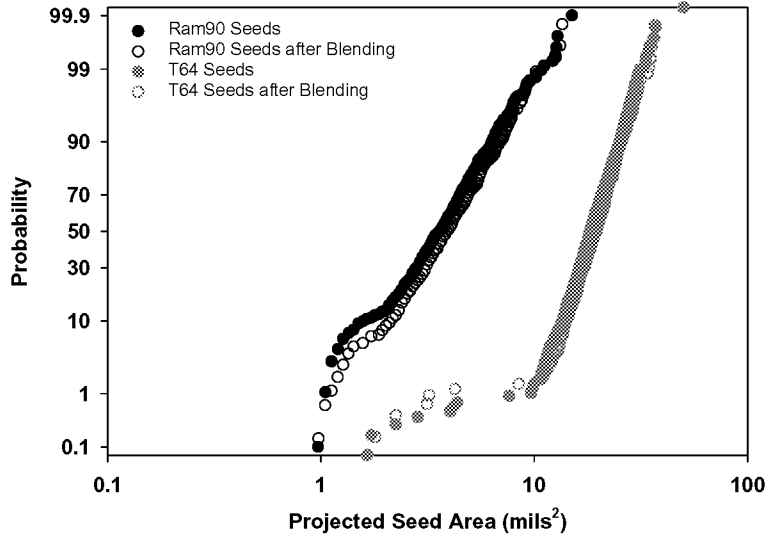
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## Seed Characterization After Blending

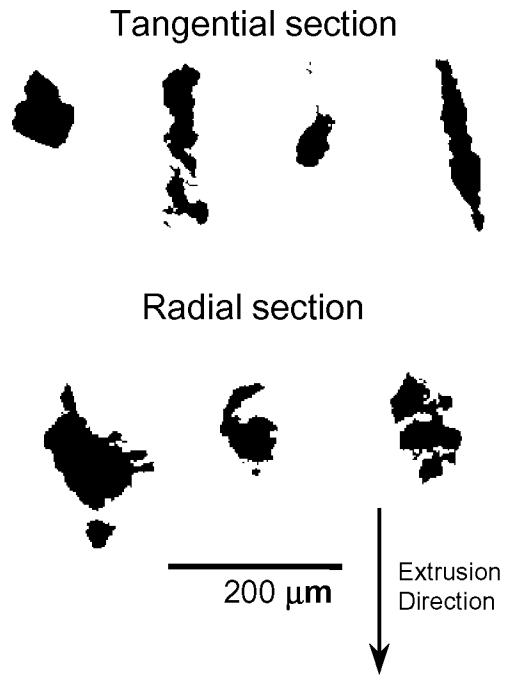
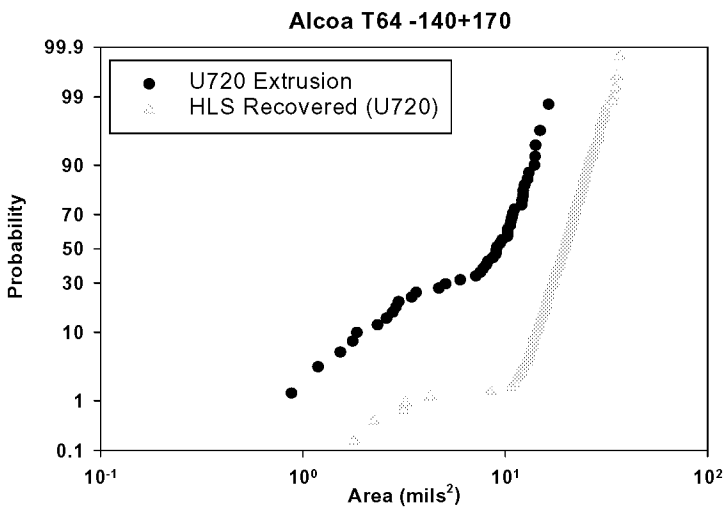
After seeding and blending the powder, the HLS process was used to recover the seeds



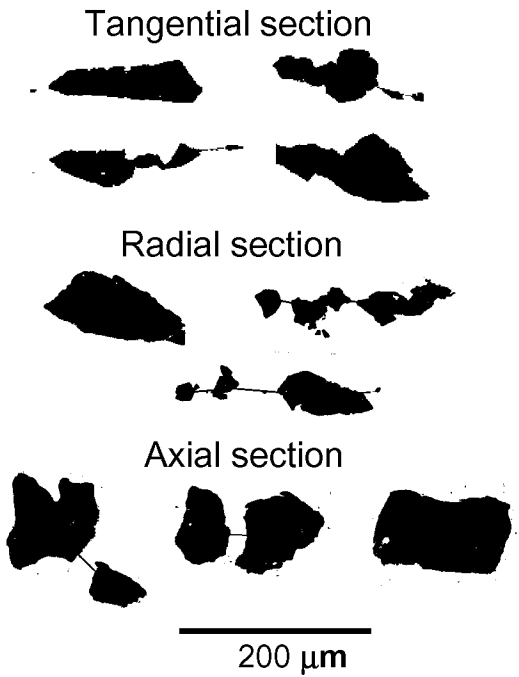
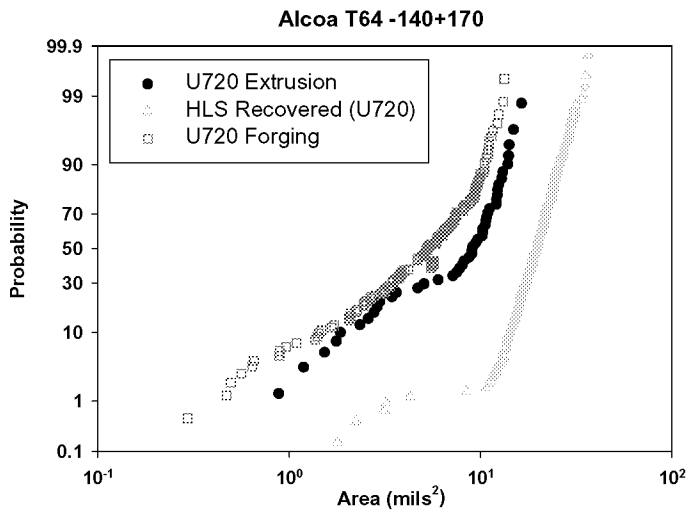
**Blending had negligible effect on the seed size distribution**

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# Seed Characterization After Extrusion



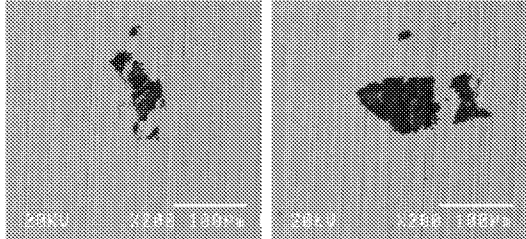
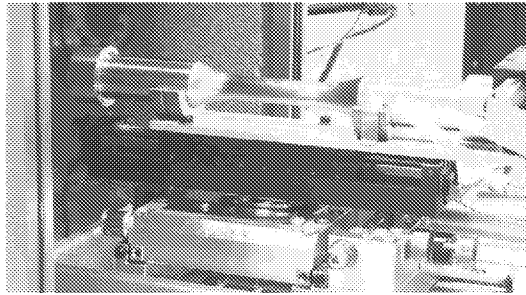
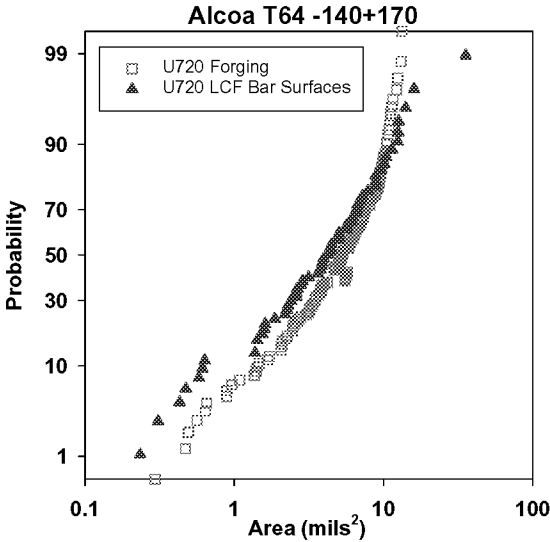
# Seed Characterization After Forging



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# Seed Characterization: LCF Bar Surfaces

## SEM Rotary Stage



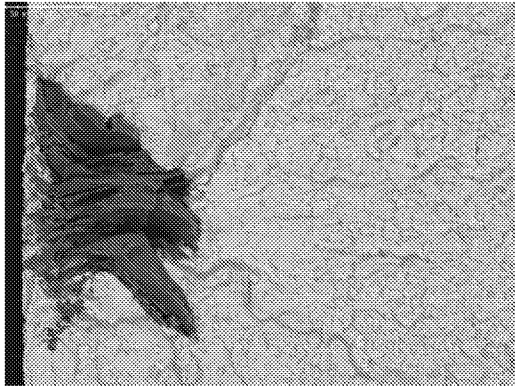
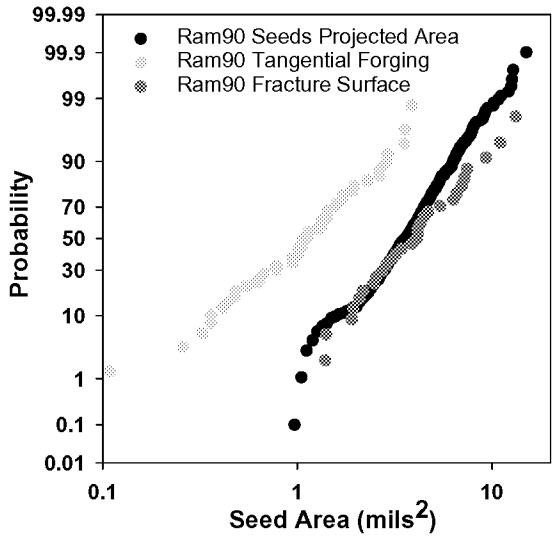
- Interrupted Testing
- Crack initiation and incubation



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## Seed Characterization Fractography



- All specimens thus far failed from seeds
- Most initiation sites were on the surface
- Most seeds causing failure seemed to have the bulk of their volume within the specimen
- As expected their size distribution is large



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## Simulation of Inclusion Spatial Distribution

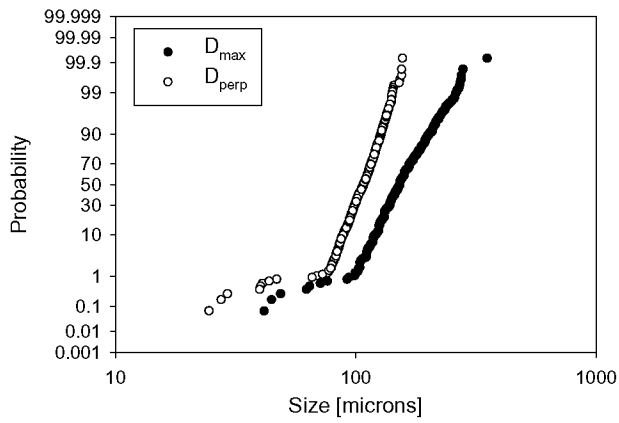
- Assumptions:
  - Inclusions are randomly distributed in the volume (Poisson distributed)
  - Inclusions can be modeled as ellipsoidal particles
  - Ellipsoids may have preferred orientations
  - Inclusion size distribution can be modeled by three correlated log-normal distributions (max, min seed dimensions and assumed third dimension)
- Random Variables:
  - Number of inclusions in specimen volume (Poisson distribution)
  - **x**, **y**, and **z** coordinates (uniform distributions)
  - **a**, **b**, and **c** inclusion dimensions (correlated log-normal distributions)
  - Inclusion rotations:  $\phi$ ,  $\theta$ , and  $\psi$  (correlated normal distributions)



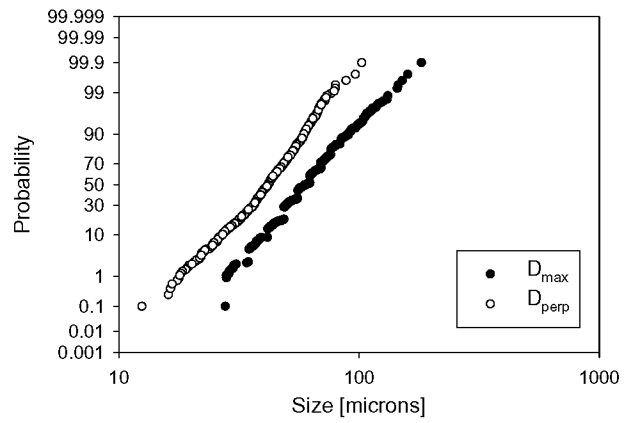
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# Seed Size Distributions

Alcoa T64 -140+170 Seeds



Ram90 -270+325 Seeds



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## Methodology

- Generate Poisson distributed number of inclusions
- Generate for each particle:
  - x, y, and z coordinate from uniform distributions
  - a, b, and c dimensions from correlated log-normal distributions
  - $\phi$ ,  $\theta$ , and  $\psi$  rotations from correlated normal distributions
- Determine, for each inclusion
  - intersects specimen surface?
    - calculate intercepted area
  - interferes with other inclusions?

Entire process repeated to determine distribution of expected surface intercepts, areas, etc.





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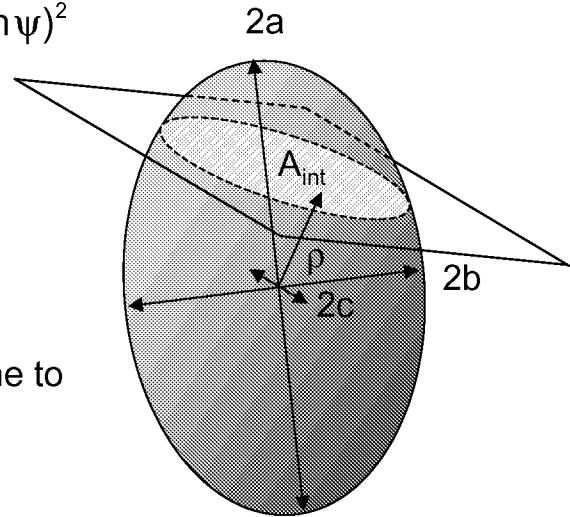
## Intercepted Area Solution for 3D Ellipsoid

$$\begin{aligned} \Phi &= a^2(-\sin\phi\cos\theta\sin\psi + \cos\phi\cos\psi)^2 \\ &+ b^2(-\sin\phi\cos\theta\cos\psi - \cos\phi\sin\psi)^2 \\ &+ c^2(\sin\phi\sin\theta)^2 \end{aligned}$$

$$A_{\text{int}} = \pi abc \frac{\Phi - \rho^2}{[\Phi]^{3/2}} = \pi abc \frac{1 - \rho^2/\Phi}{\sqrt{\Phi}}$$

Where:

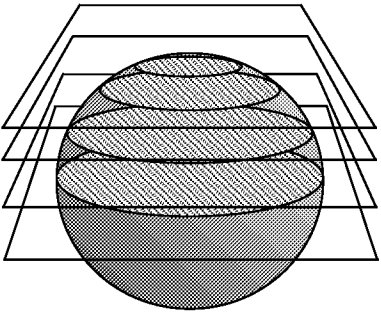
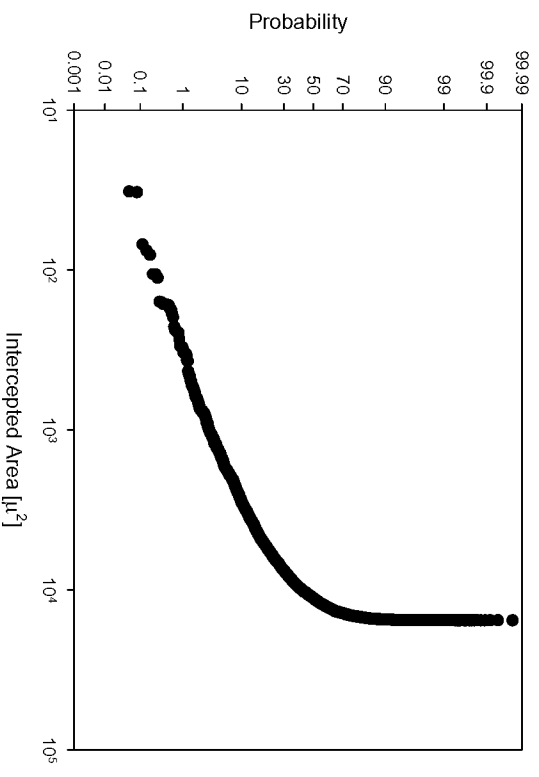
- $\rho$  = distance from sectioning plane to centroid
- a, b, c = ellipsoid dimensions
- $\phi, \theta, \psi$  = rotation angles



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# Intercepted Area Distribution – Uniform Spheres

Uniform Spheres  
 -140+170 Seed Average Diameter



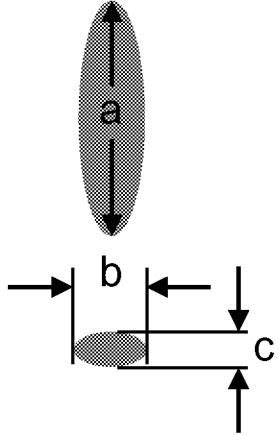
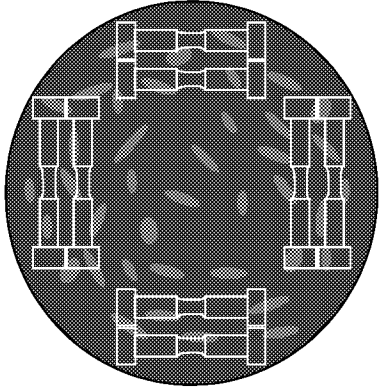
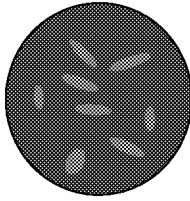
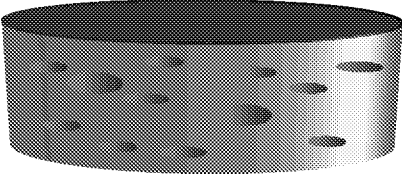
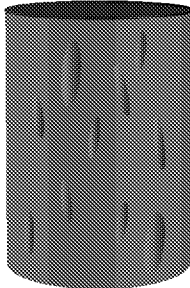
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# Model Inputs: Seed Orientations

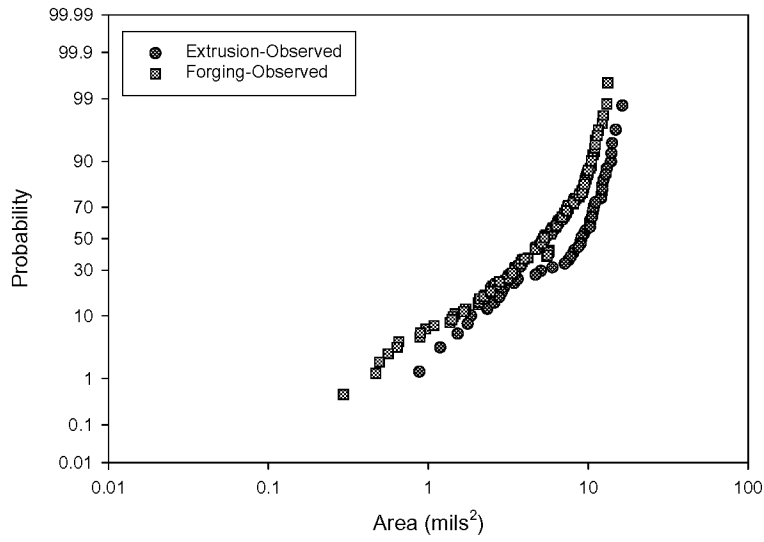
Extrusion

Forging



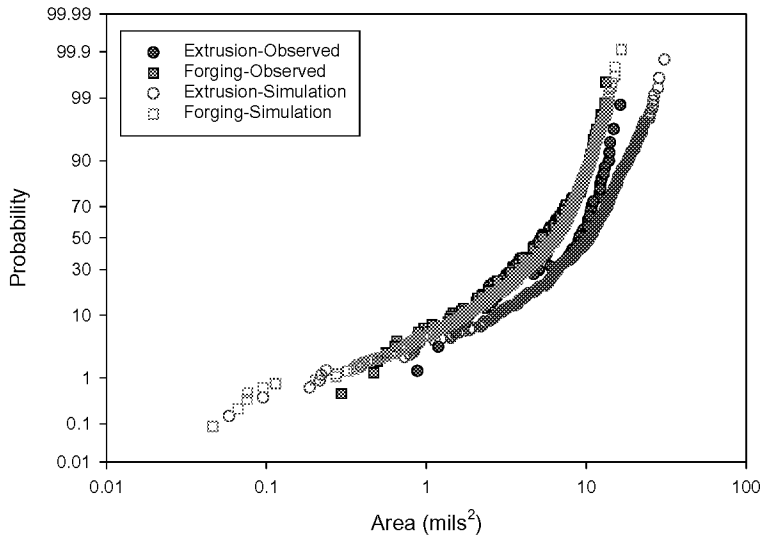
# Intercepted Surface Area

Area Comparison of Tangential Orientations  
Extrusion and Forging - Observed  
Alcoa T64 -140+170



# Intercepted Surface Area

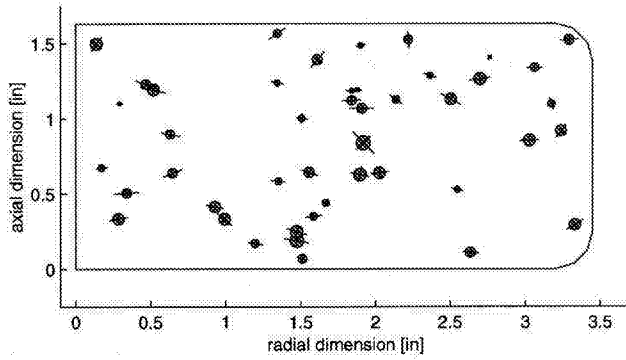
Area Comparison of Tangential Orientations  
Extrusion and Forging - Observed vs. Simulated  
Alcoa T64 -140+170





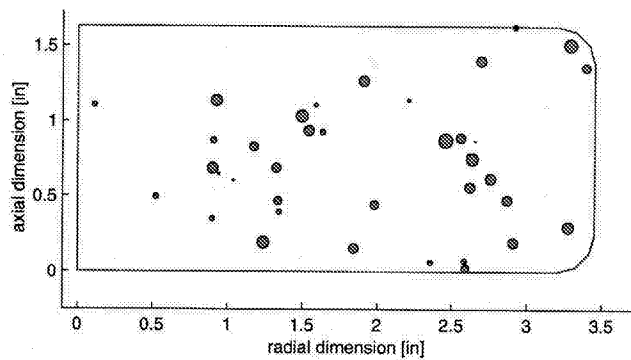
## Model Comparisons Seed Maps for Alcoa T64 Forging Chord Slices

**Actual Metallographic Observations**



Average # of Intercepts: 43  
Mean Area/Seed [mils<sup>2</sup>]: 5.74  
Area/Seed SD [mils<sup>2</sup>]: 3.35

**Prediction**



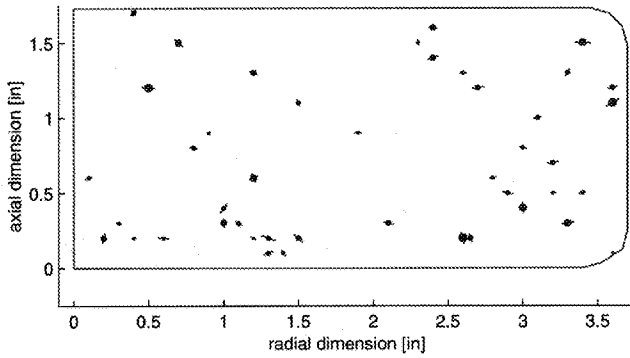
Average # of Intercepts: 38.4  
Mean Area/Seed [mils<sup>2</sup>]: 6.38  
Area/Seed SD [mils<sup>2</sup>]: 3.17



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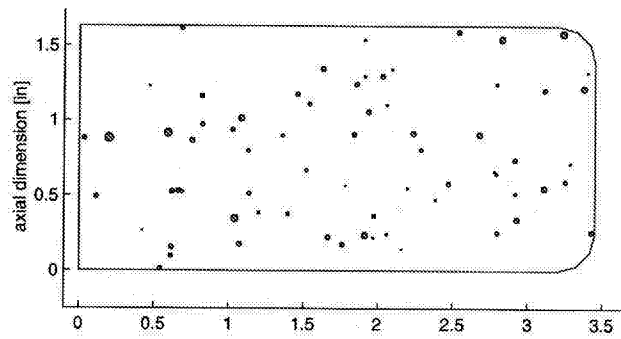
## Model Comparisons Seed Maps for Ram90 Forging Chord Slices

**Actual Metallographic Observations**



# of Intercepts: 45  
Mean Area/Seed [mils<sup>2</sup>]: 1.35  
Area/Seed SD [mils<sup>2</sup>]: 0.94

**Prediction**



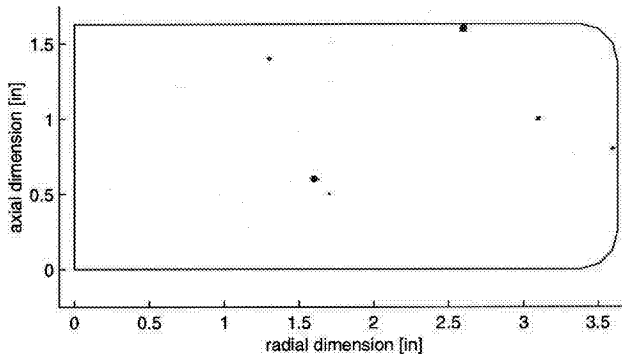
Average # of Intercepts: 75.4  
Mean Area/Seed [mils<sup>2</sup>]: 1.18  
Area/Seed SD [mils<sup>2</sup>]: 0.85



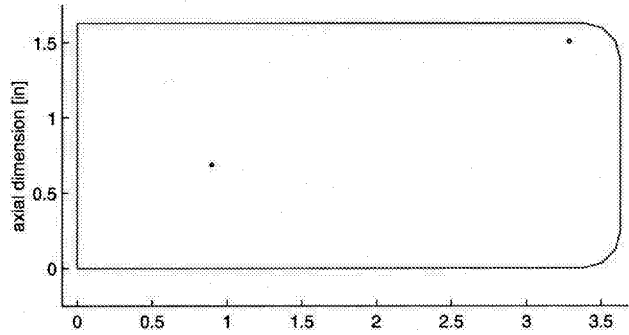
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## Model Comparisons Inclusion Maps for Unseeded Forging Chord Slices

**Actual Metallographic Observations**



**Prediction**



# of Intercepts: 6  
Mean Area/Seed [mils<sup>2</sup>]: 1.02  
Area/Seed SD [mils<sup>2</sup>]: 1.0

Average # of Intercepts: 0.42  
Mean Area/Seed [mils<sup>2</sup>]: 0.2  
Area/Seed SD [mils<sup>2</sup>]: 0.02

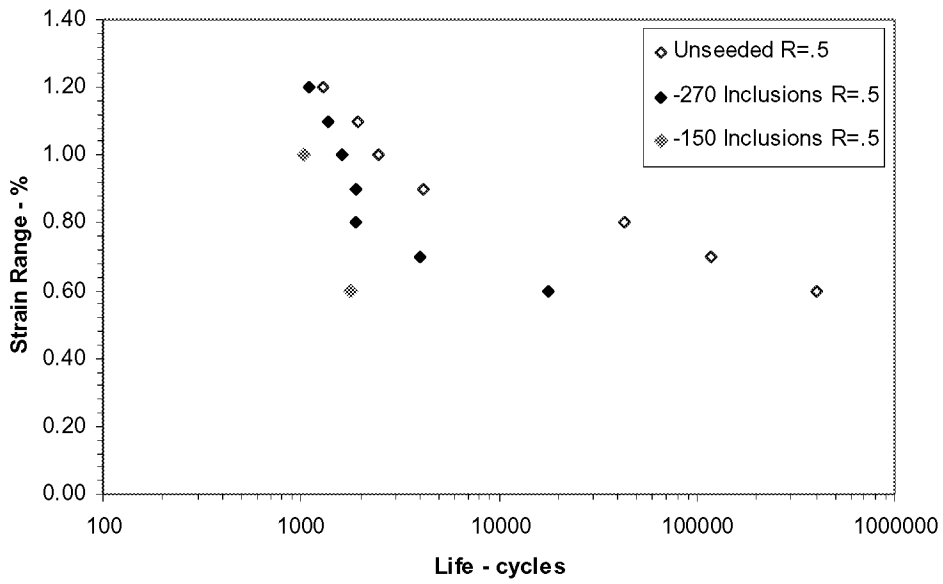






# Preliminary LCF Results

LCF Life at 1200°F, R = 0.5



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## Summary

- Seeding study underway to characterize effect of ceramic inclusions on part life
- Monte-Carlo Simulation Model adequately estimates occurrence rate and intercepted area distributions of seeded inclusions
- Preliminary LCF results promising
- Ultimate goal: determine effect of naturally occurring ceramic inclusions on component reliability



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## Material Parameters

**270 MESH PRODUCTION QUALITY UDIMET 720 POWDER FROM SPECIAL METALS**

### Processing Conditions

Same conditions for both seeded and unseeded material

**HIP:** 2025F / 15Ksi / 3hrs / cleaned to 9" dia

**EXTRUDE:** 5hr presoak / 2019F / 6:1 ratio  
3.5" dia x 6.5"-7.0" mults

**ISOFORGE:** 1.5hr presoak / 2000F / 0.1 in/in/min  
75% upset / final thickness 1.6"

### Heat treat Conditions

**SUB SOLVUS SOLUTION:** 2050F / 3Hrs / DOQ

**AGING:** 1400F / 8Hrs / AC  
1200F / 24Hrs / AC

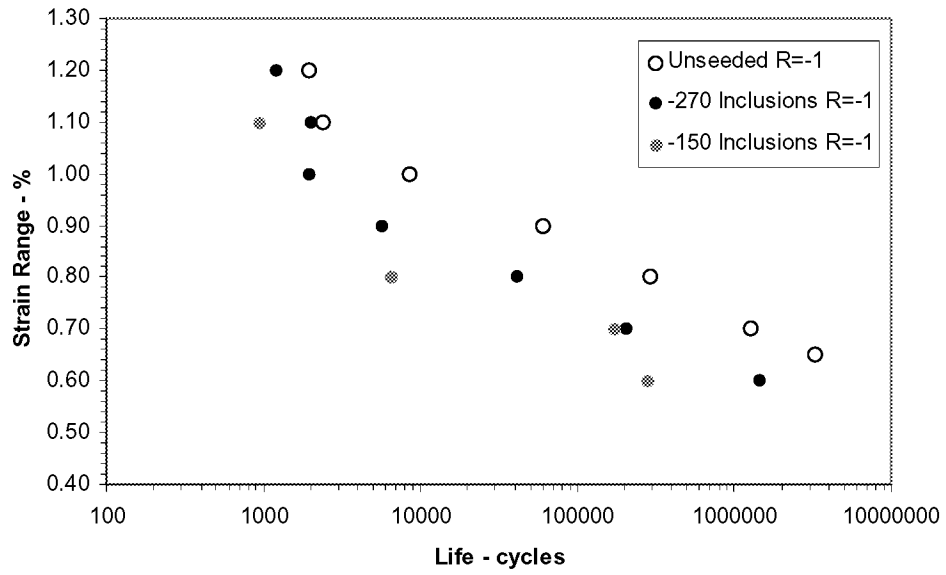


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# Preliminary LCF Results

## LCF Life at 1200°F



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# Preliminary LCF Results

## LCF Life at 1200°F

