Experiments supporting ICME of single crystal Ni-based turbine blades

"Integrating Computational Materials Science and Engineering"

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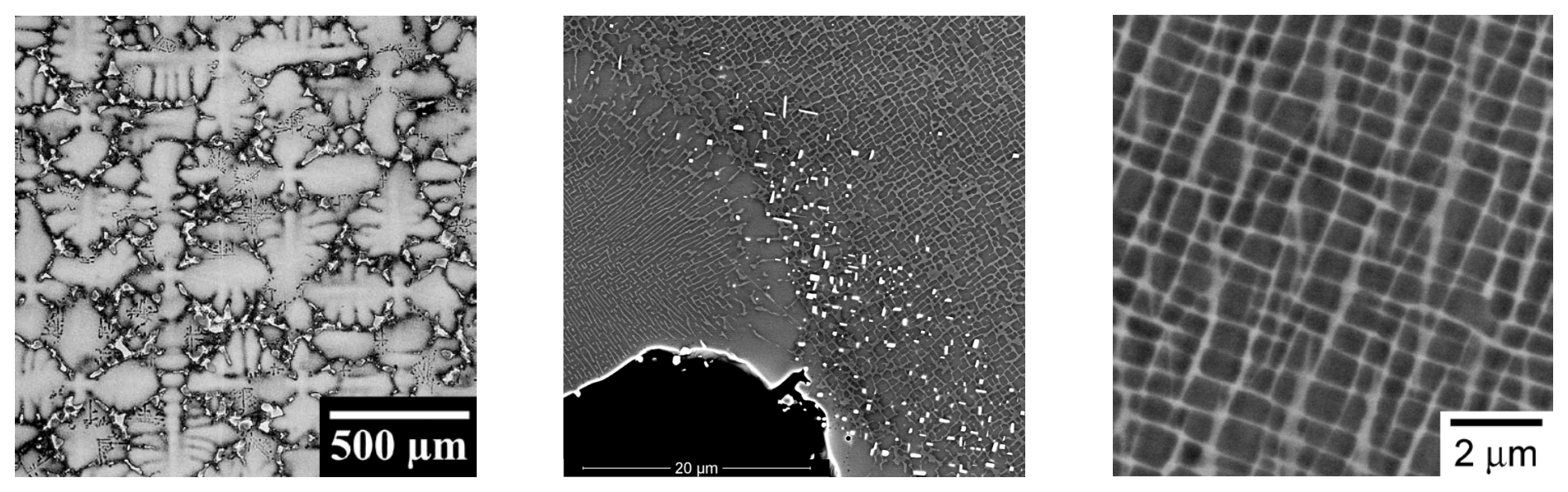

Introduction

As the geometrical complexity in turbine blade design increases (Fig.1), so does the demand for better materials and materials processing for sustaining performance in high temperature engine environments. For example, at a minimum, the turbine blade material must exhibit the following characteristics:

- *good castability* and *machinability*, *lightweight*,
- *high melting temperature*, *high creep resistance*,
- *oxidation resistance or coating compatible*,
- *resistant to thermal distortion/fatigue*,
- and *impact resistance*.

This requires knowledge of the 3D microstructure of the blade, its evolution in extreme environments, and how the material behaves when cast in the fine details of a modern high pressure turbine blade (Ref. 1).

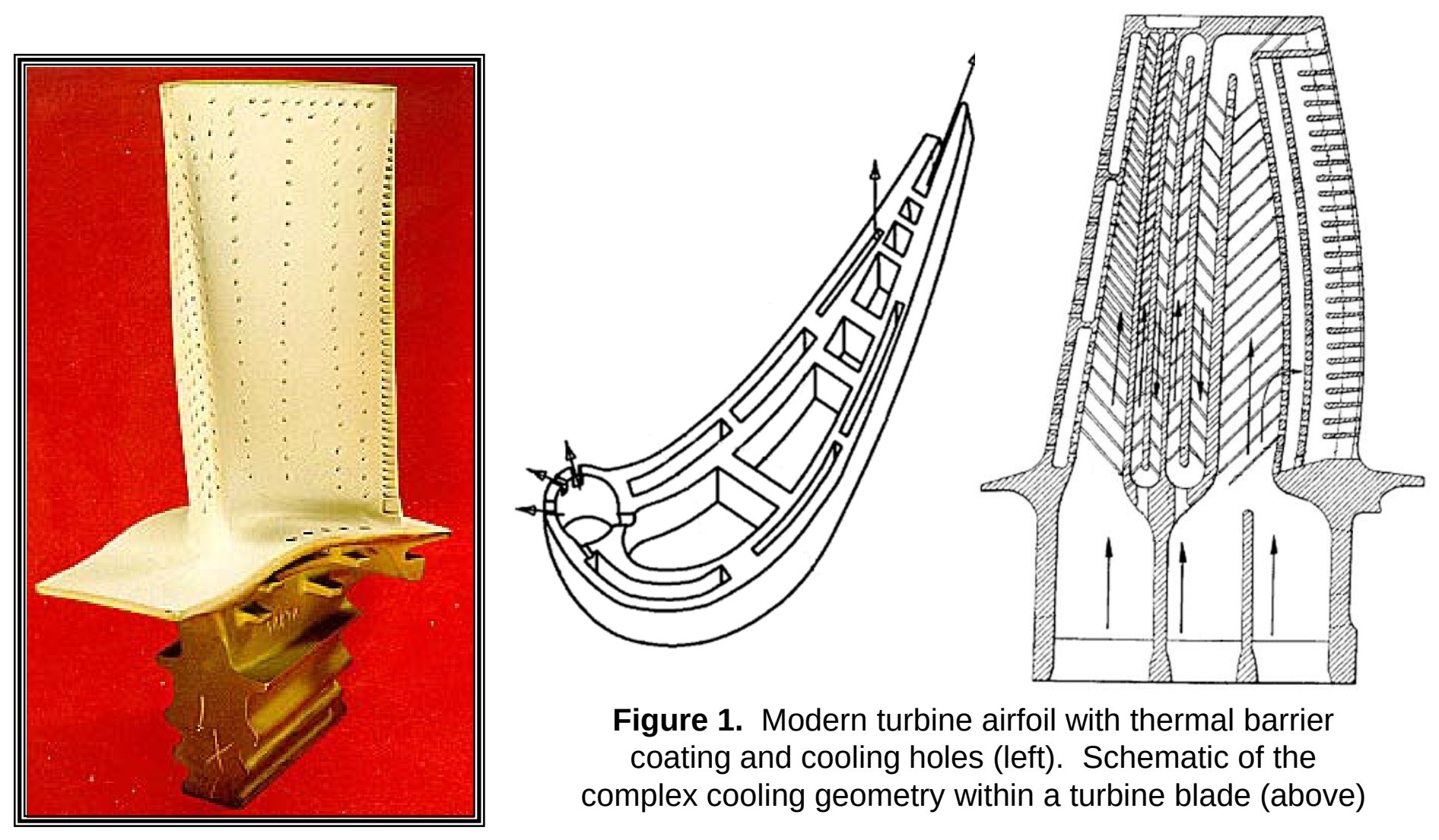

Figure 1. Modern turbine airfoil with thermal barrier coating and cooling holes (left). Schematic of the complex cooling geometry within a turbine blade (above)
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Objective & Experimental Approach

The objective of this research is to characterize the 3D microstructure in the turbine blade and couple this with critical mechanics experiments from the blade related to high temperature performance. The approach involves:

1. Obtaining etched optical images through serial sectioning a single crystal nickel-based superalloy (PWA 1484) turbine airfoil
2. Characterizing the 3D dendritic structure and eutectic particles and measuring microstructural statistics
3. Setting up techniques for critical high temperature mechanics experiments on specimens extracted from the blade related to high temperature performance, including:
   a) Milli-test apparatus for creep/fatigue at 1100°C
   b) In situ SEM tensile experiments

3D MICROSTRUCTURE CHARACTERIZATION

Multi-scale Microstructure Representation

Characterization is performed at multiple length scales using optical, SEM, and OIM methods to develop a descriptor-based microstructural representation. The goal is to couple microstructural heterogeneities to micromechanics 'damage' models for concurrent multi-scale FEM methods.

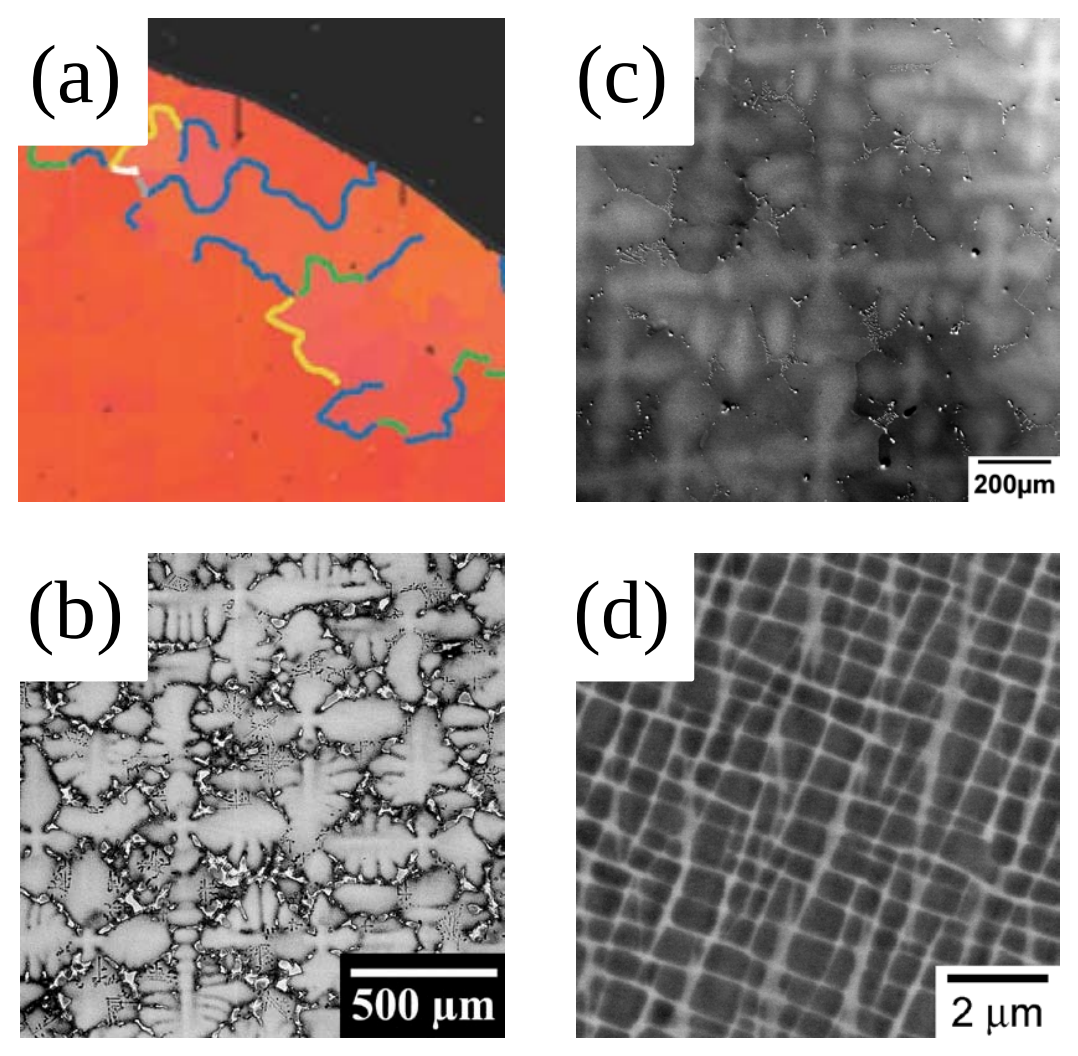
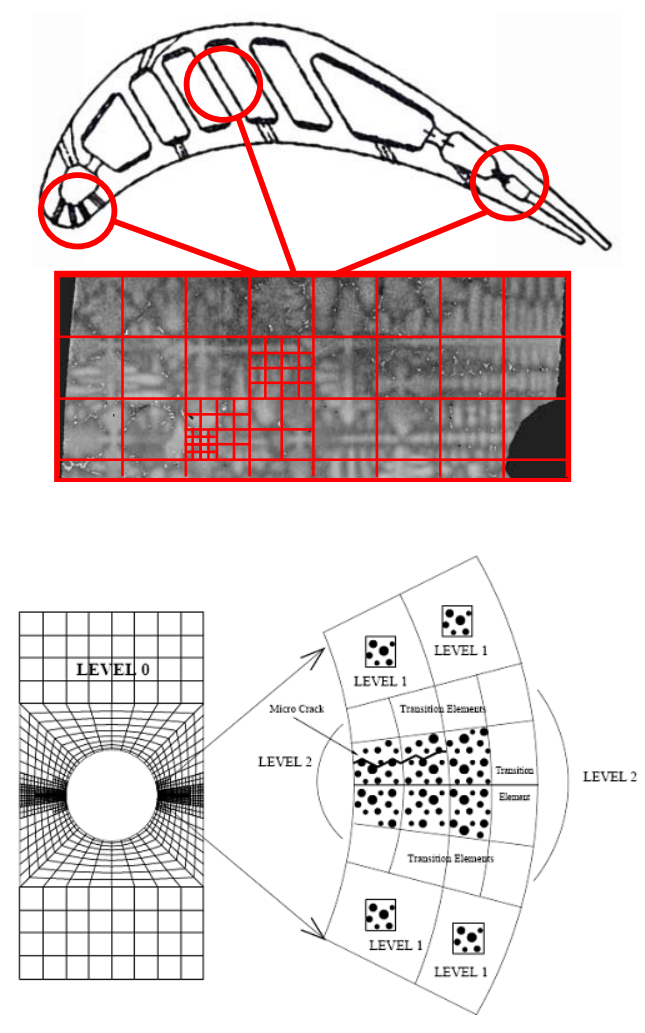


Figure 2. Microstructure image at multiple scales with SEM & OIM. (a) Low angle boundaries between dendrites, (b) optical image of dendrite structure, (c,d) SEM images of pores, carbides and γ' precipitates.



Ghosh et al., Mech. Mater. (2007)

Figure 3. Potential FEM methodology for coupling microstructural descriptors with micromechanics damage models

Automated Dendrite Core Detection

After pre-processing the image to level the contrast and reduce noise, the dendrite structure is segmented and convoluted with a filter to identify dendrite core locations. Removing boundary effects and defining a penalty function for optimization is a key component for tuning the detection parameters (Ref. 3).

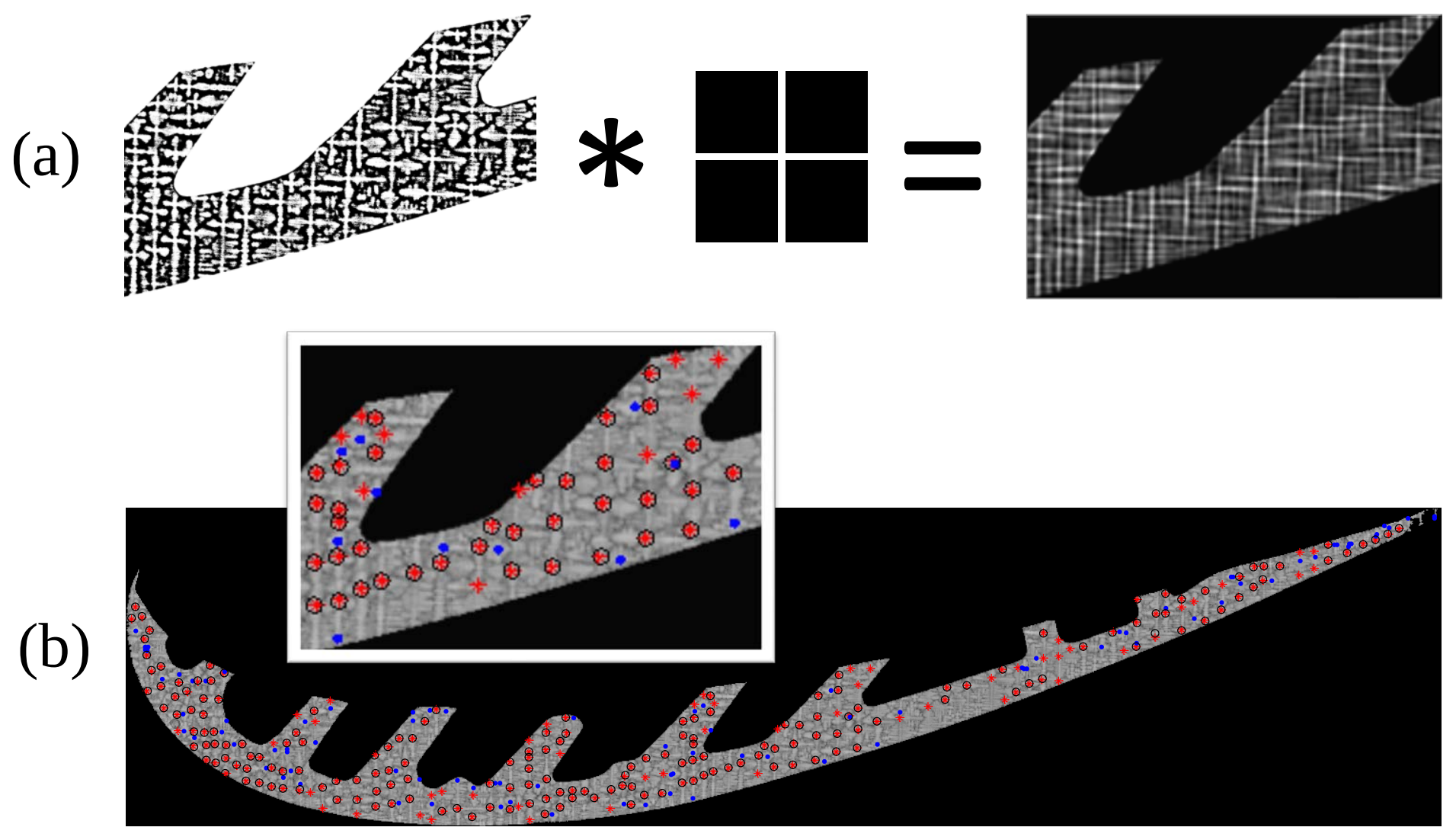


Figure 6. (a) Schematic showing the process of convolving a binary image of the dendrite structure with a "core detection" filter to highlight dendrite cores. (b) The dendrite structure with manually identified dendrite cores (red crosses), automated correctly (black circles) and incorrectly (blue circles) identified cores.

Experimental Methodology

A single crystal nickel-based superalloy turbine blade was sectioned, mounted with markers for positioning, and then iteratively polished, etched, and imaged for the dendritic structure and interdendritic defects, such as pores, carbides and eutectic particles (Ref. 2).

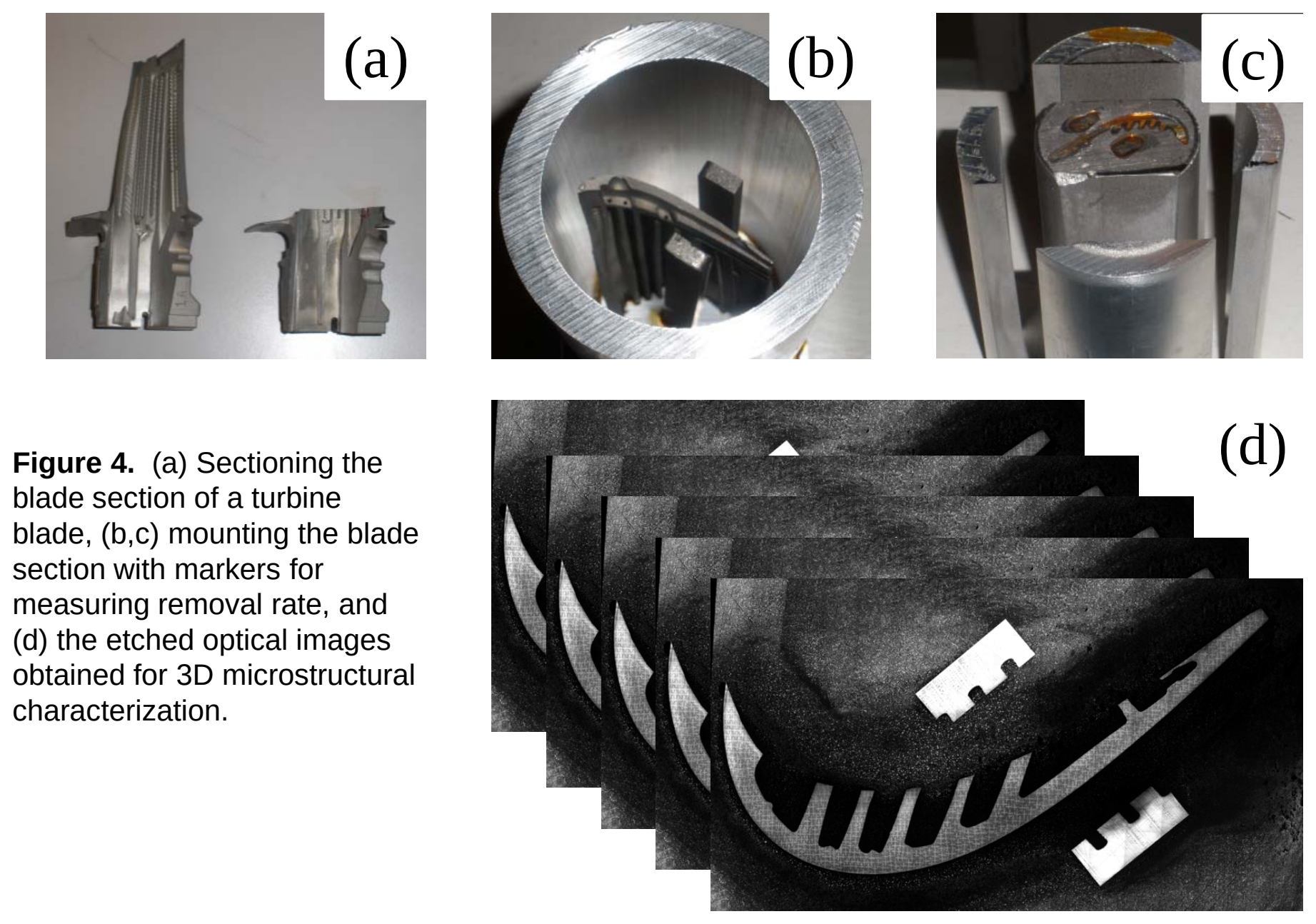


Figure 4. (a) Sectioning the blade section of a turbine blade, (b,c) mounting the blade section with markers for measuring removal rate, and (d) the etched optical images obtained for 3D microstructural characterization.

Automated Eutectic Particle Detection

For identifying interdendritic eutectic particles, a region growing technique is employed. The two important steps for this process are (i) using a localized filter for identifying seed points and (ii) automating the region growing algorithm with a criteria that stops growth at the particle interface.

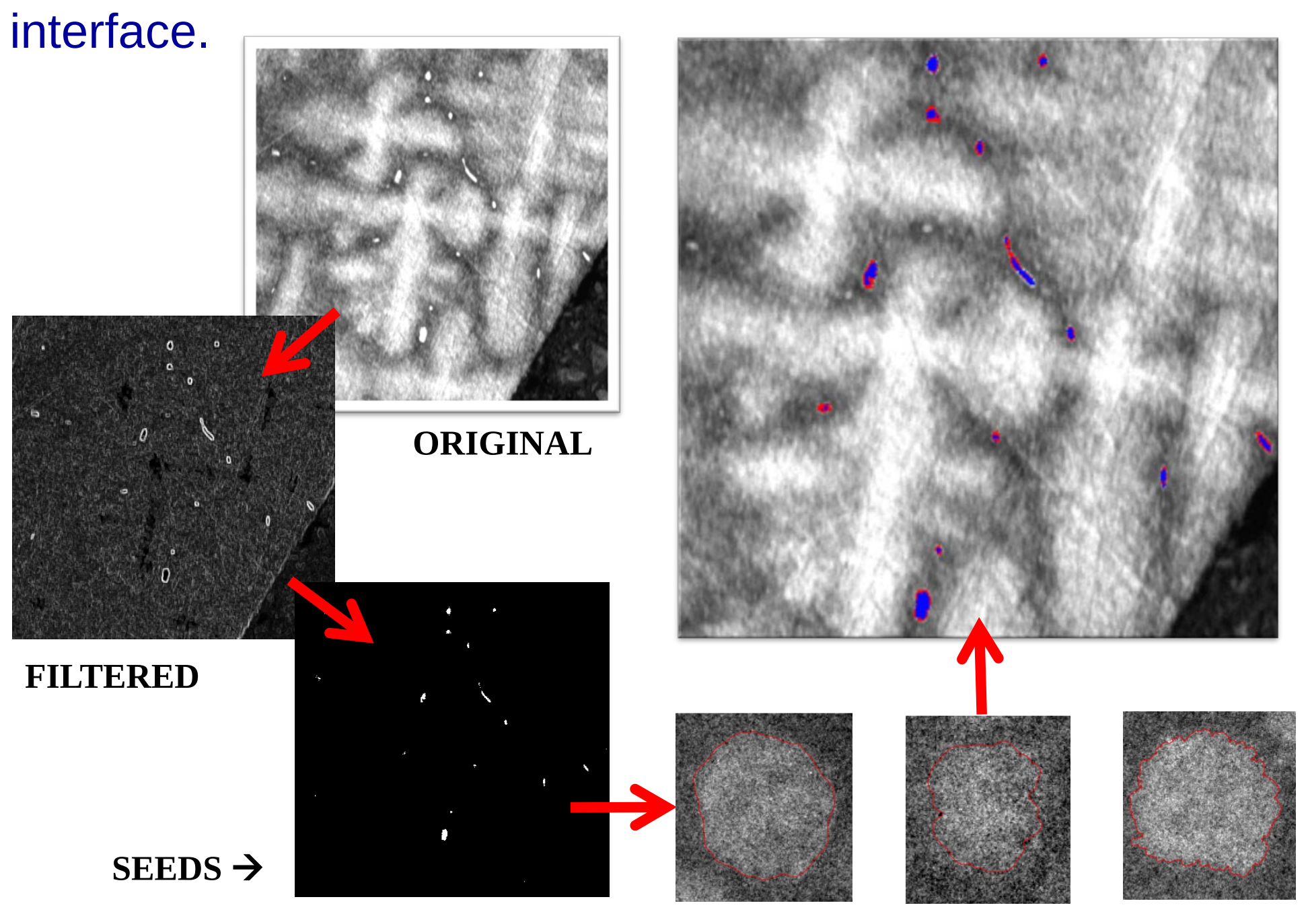


Figure 7. Schematic showing images for the eutectic particle detection. The original image is filtered to identify seed points for an automated region growing algorithm (used for EFTEM images in Ref. 4).

Image processing for microstructure feature identification

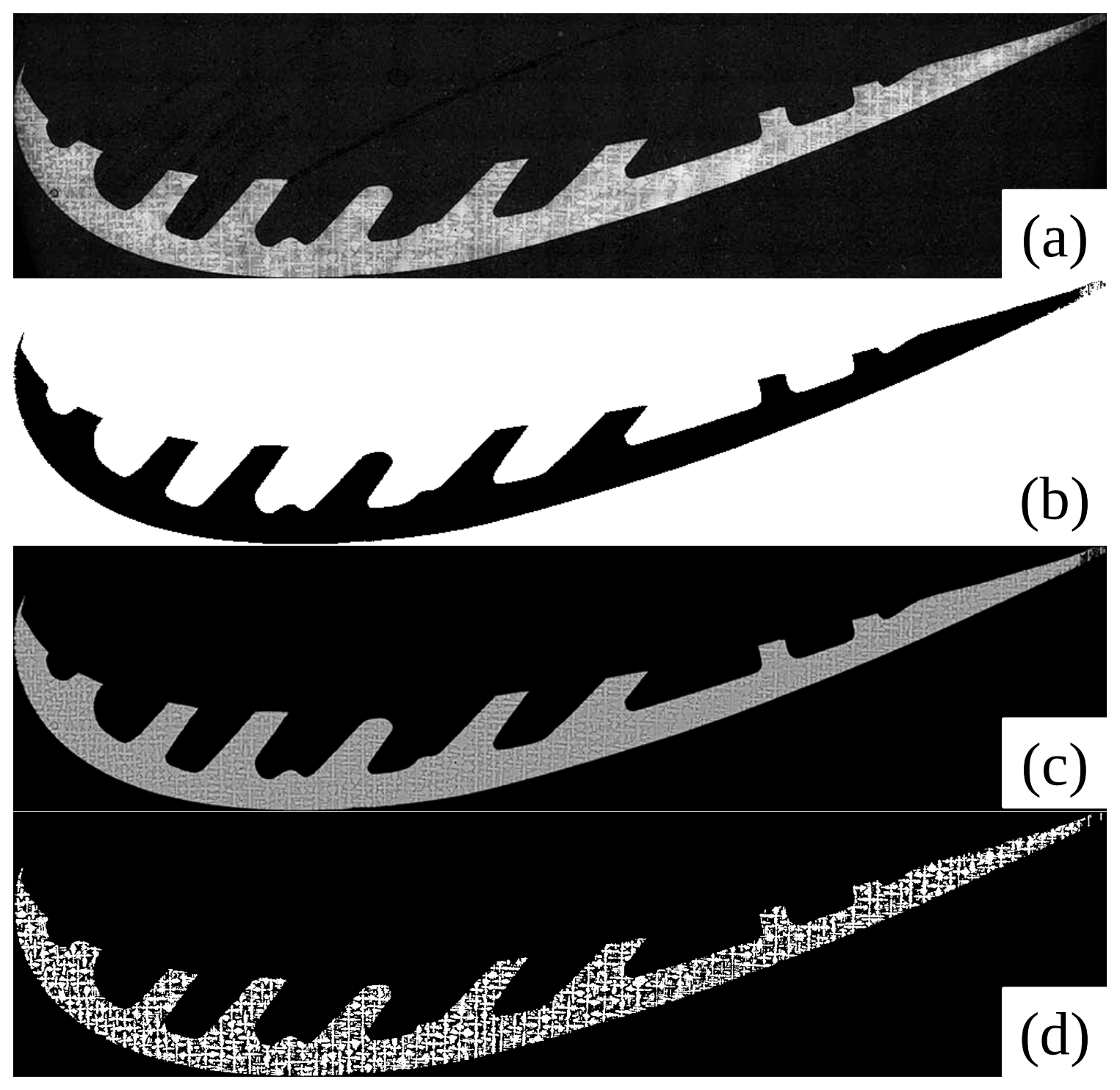


Figure 5. (a) Original image, (b) segmented mount binary image, (c) image after leveling contrast and denoising, and (d) segmented dendrite structure.

Microstructure Descriptors

Once relevant microstructure features have been identified, microstructure descriptors can be correlated with microstructure-sensitive properties to help describe phenomenological relationships between processing and properties, which can then be to integrate computational materials models.

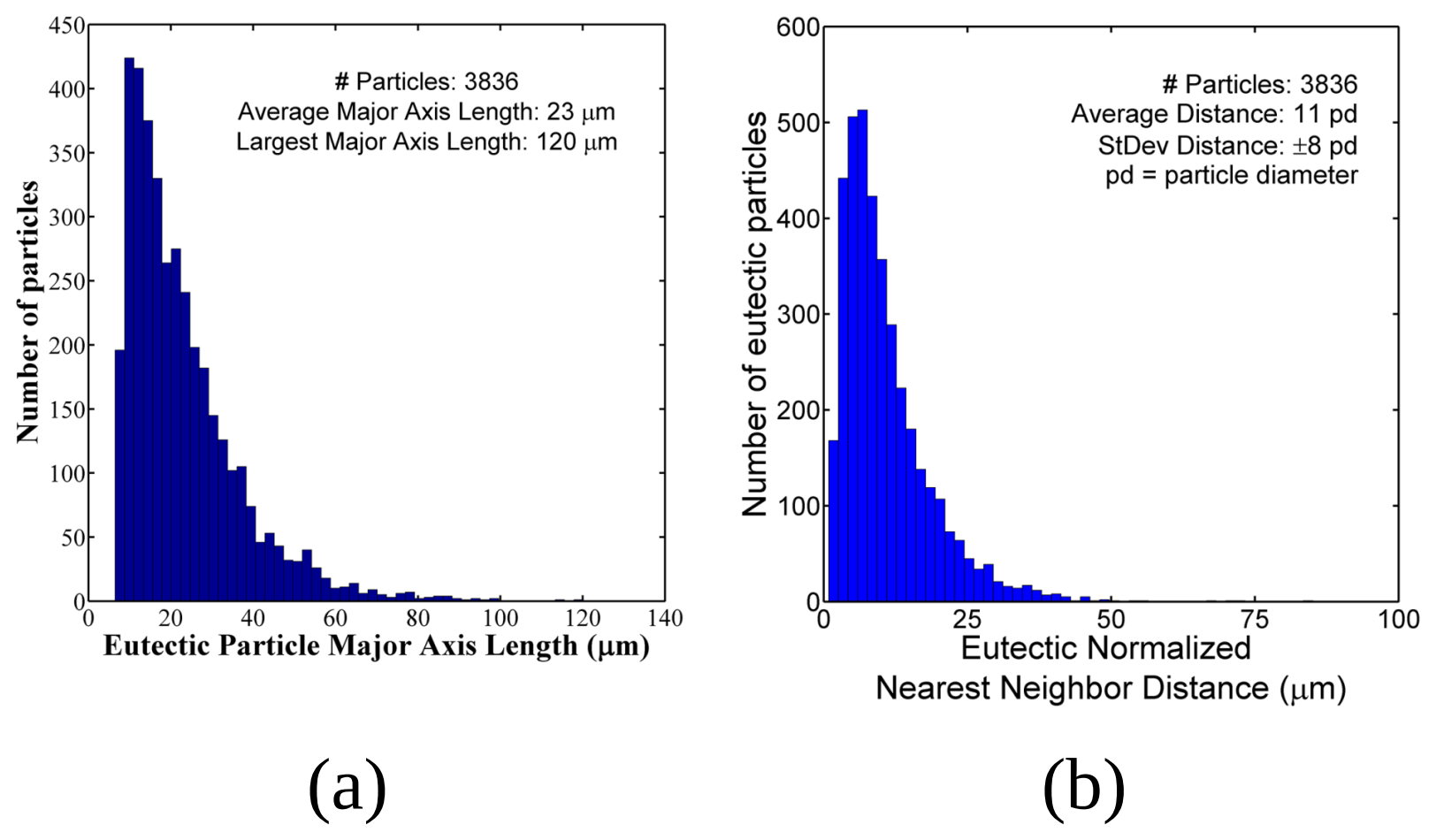


Figure 8. (a) Histogram of the major axis length from 3836 eutectic particles from 15 successive slices spaced 10 µm apart, and (b) the histogram of nearest neighbor distances for these eutectic particles normalized by the equivalent particle diameter.

HIGH TEMPERATURE DAMAGE MECHANICS

High temperature mechanics of miniature specimens

What is the variability in high temperature properties of specimens from an as-processed blade? How do these compare to properties taken from a bulk slab material? Here, miniature specimens with dimensions influenced by the blade geometry are used in a test frame designed to test specimens at 1100°C in creep and fatigue. There are a number of challenges in designing the experimental technique for this - setup is currently ongoing.

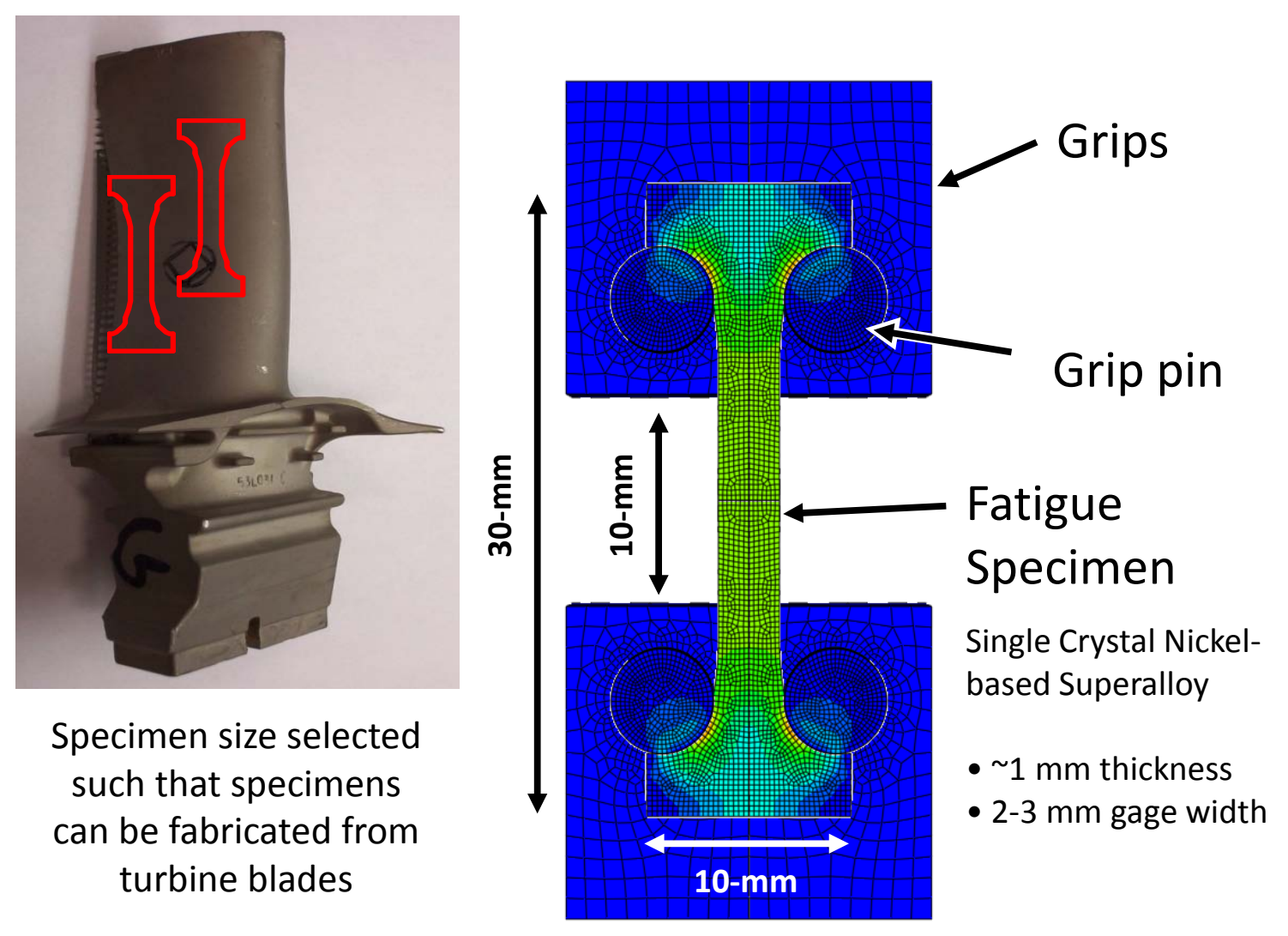


Figure 8. Miniature specimen dimensions and grip design for high temperature creep and fatigue experiments.

The challenges of high temperature testing of miniature specimens

- **Heat?** Induction heater & butterfly coil design augmented with flux concentrator for localized heating

- **Measure & Control T?** Pyrometer correlated to thermocouple temperature in "hot" zone

- **Measure Strain?** High Temperature LVDT Extensometer Strain Measurement

- **Grip Design?** Ni-based superalloy grips, pin loaded

- **Alignment?** Special alignment specimen with small strain gauges along with an anti-rotation device

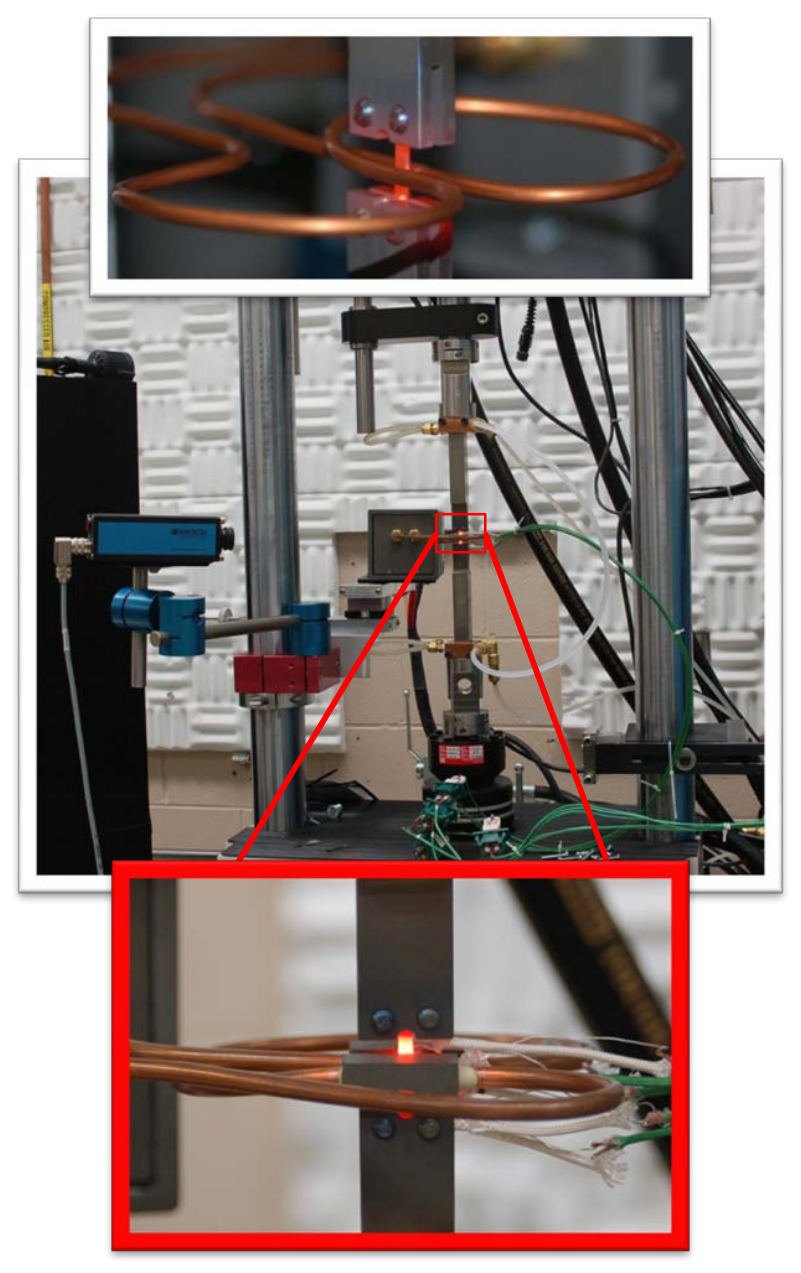


Figure 8. The challenges of high temperature testing of miniature specimens. Images show the butterfly coil design (top), the test frame (middle), and the coil design with the flux concentrator (bottom).

Local strain behaviour via *in situ* SEM tensile experiments

In situ SEM tensile experiments were designed to correlate localized strain behavior at the surface with crystallographic-based parameters (Ref. 5), such as the Schmid factor. While this experiment was run on a polycrystal, microstructure-property relationships in experiments of this ilk may be important for understanding damage nucleation in superalloys at high temperatures.

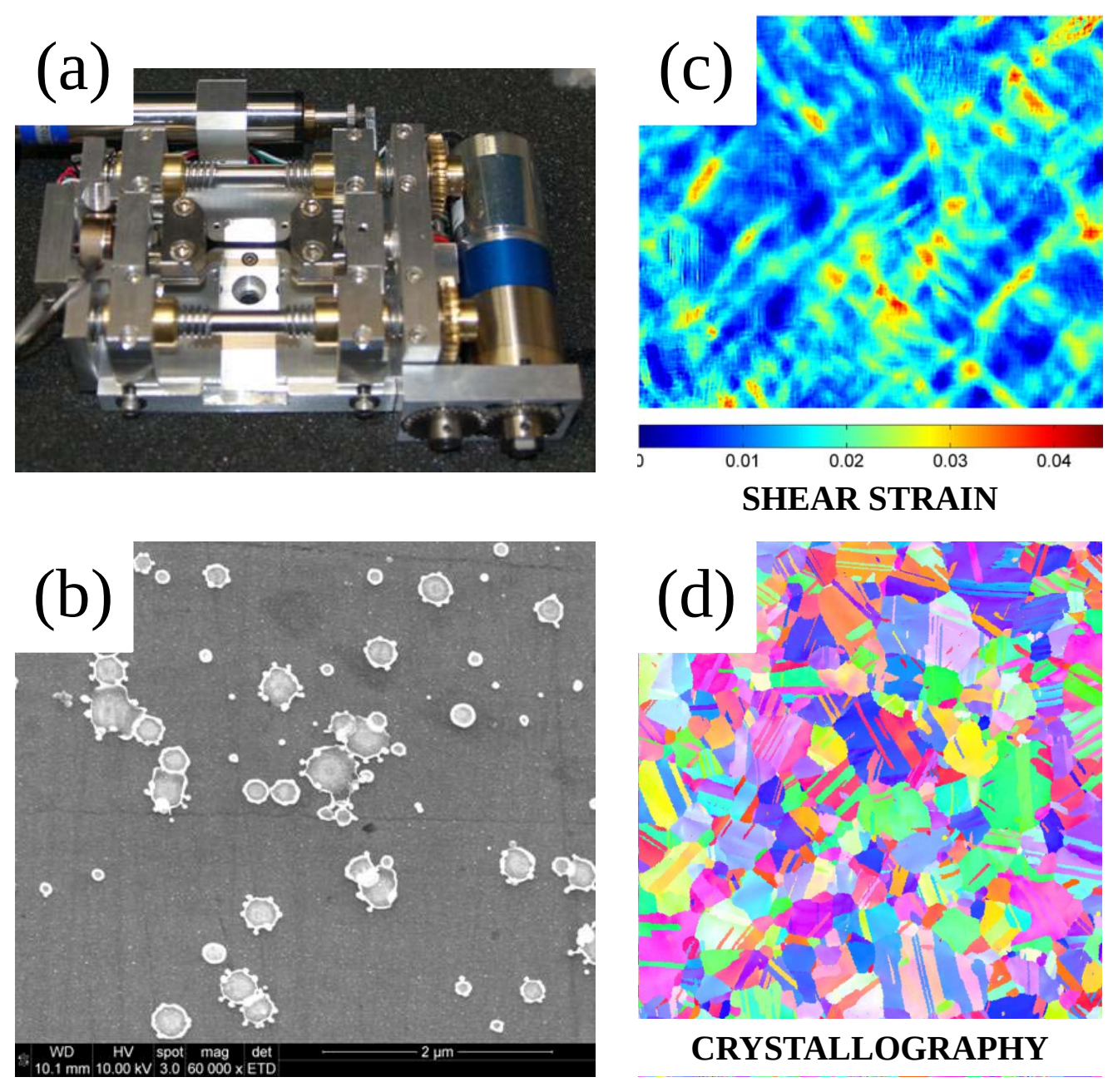


Figure 9. (a) In situ SEM tensile stage, (b) laser ablated platinum nanoparticles for digital image correlation, (c) shear strain contour map, and (d) EBSD pole figure.

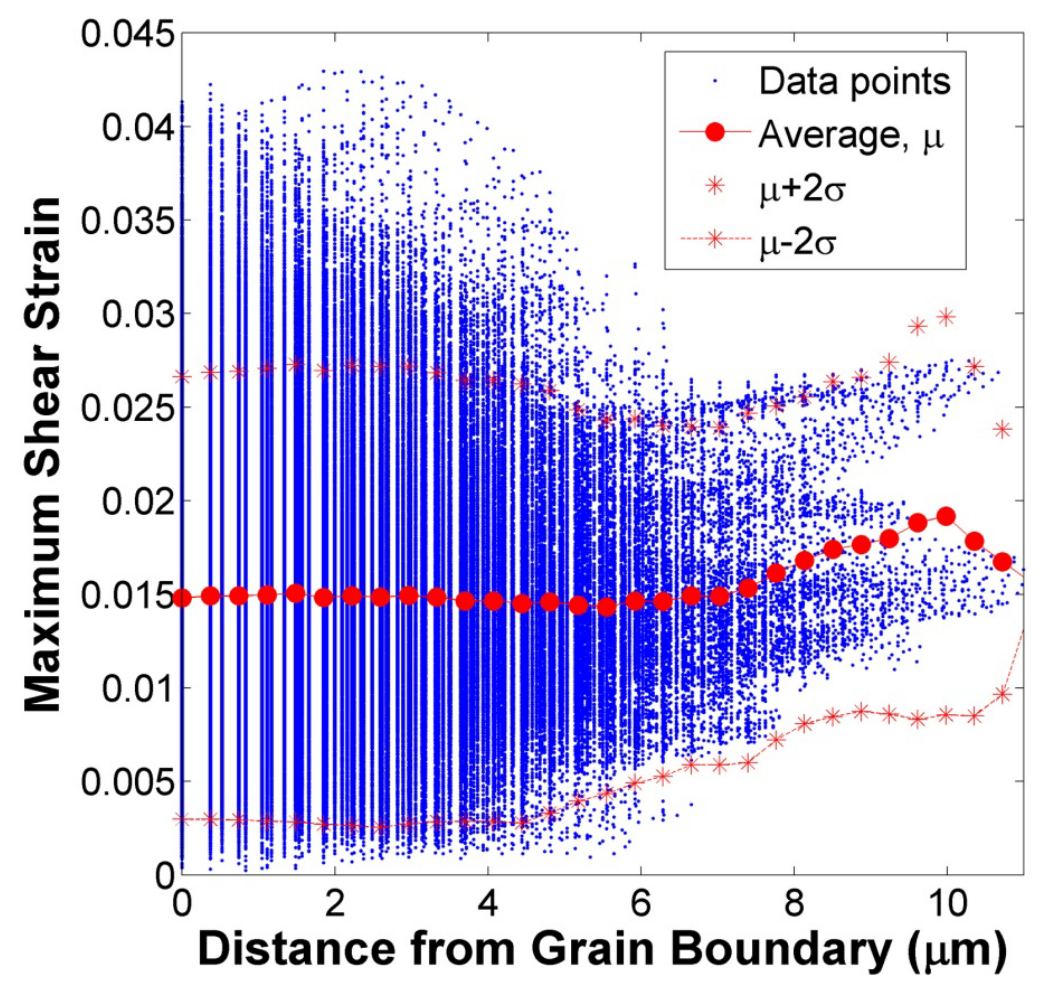


Figure 10. Maximum shear strain as a function of distance from the grain boundary.

Conclusion

Property and design constraints on next generation turbine blades will require tailoring properties and microstructure for different regions of the component. Information on 3D characterization and local properties are necessary to advance the integrated engineering of these highly engineered devices. Characterization and representation techniques are being developed to address these issues combined with small scale mechanical testing (creep and fatigue) to assess properties at the scale of the component features.

References

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