Office of Naval Research Multidisciplinary University Research Initiative Project
Review Meeting, Thursday December 15th 2011
ONR Topic Chief: David Shifler

Tailoring of Atomic-Scale Interphase Complexions for Mechanism-Informed Material Design

Al-Mg Alloys

Grain Boundary Character Distribution in Senesitized Al-Mg Alloys

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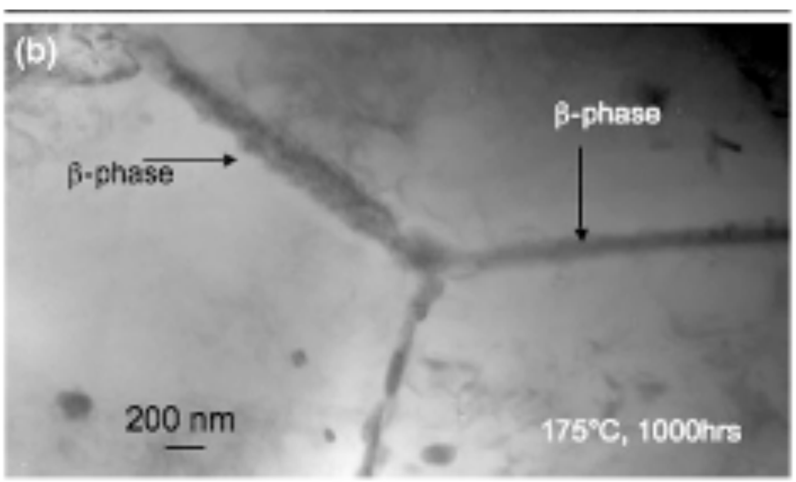
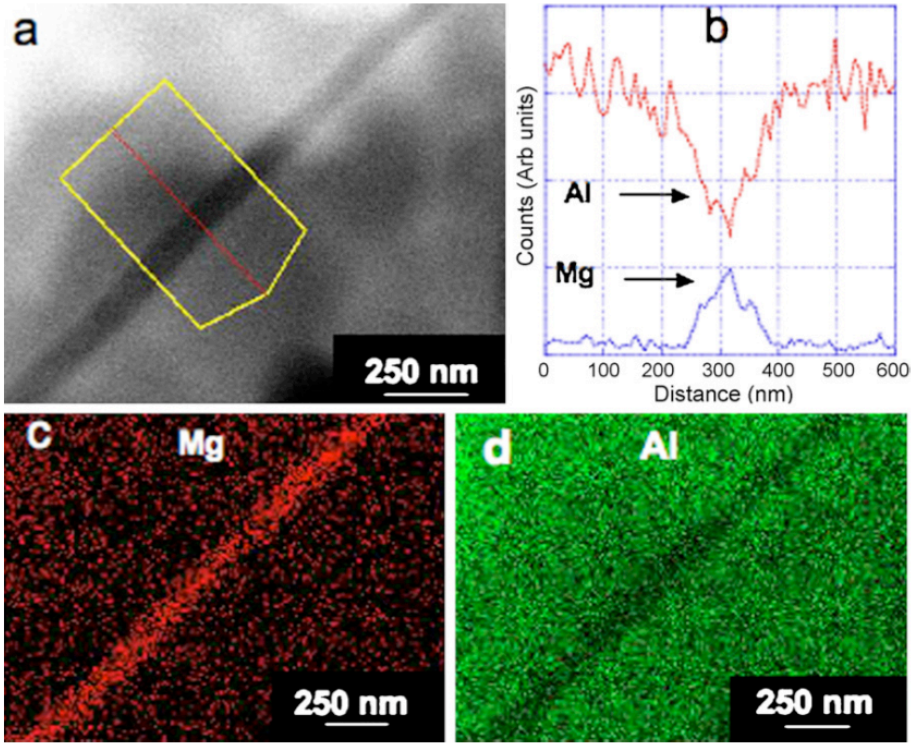
Sensitization in Al-Mg Alloys

- Sensitization: precipitation of beta phase (Al_3Mg_2)
- Prevalent in 5000-series Al alloys in service
- Greatly reduces lifetime - stress corrosion cracking



R. Goswami, et al, Met Trans A, 42A, 355 (2011)

R. Goswami et al. / Materials Science and Engineering A 527 (2010) 1089–1095



R. Goswami, et al, MSE A, 527, 1089 (2010)

Sensitization in Al-Mg alloys affects ship structures

4 DefenseNews December 13, 2010 ★

InBrief

Cracks Continue To Plague U.S. Cruisers

By CHRISTOPHER P. CAVAS

Barely a year after the U.S. Navy spent $40 million to fix the cruiser Port Royal after an embarrassing grounding, the ship is again out of action, back in a shipyard at Pearl Harbor, Hawaii. But this time it's not a damaged hull that's the problem. Rather, it's an issue that is plaguing all 22 cruisers in service: cracks in the aluminum superstructure.

The Port Royal was operating in the Pacific Northwest in September when sailors discovered new cracks in the superstructure, including on the 06 level, one of the highest decks in the ship. Most of the cracks that appear on the Ticonderoga-class cruisers are being repaired during regular overhauls, but in this case the damage was enough to send the ship home to Pearl Harbor for yet another extended repair period.

So far, the Navy has awarded $14 million to BAE Systems in Hawaii to fix the Port Royal. The work package will include repairs to the bulkheads and deck around two gas turbine intakes; fuel oil storage tank top repairs; superstructure crack repairs; and removal and replacement of aluminum decking and plating. The work is expected to be finished in February.

"We are dealing with a class-wide issue of superstructure structural issues," said Cmdr. Jason Salata, a spokesman for Naval Surface Forces in San Diego.

The Port Royal situation might be the worst case to date.

"Most of the issues are being dealt with when the ships come in for a regular availability," or overhaul, said one source familiar with the situation. "This is the first one I know of where we specifically went in for repairs." The work is necessary, the source added, "to restore structural integrity of the ship."

The problem, according to the Naval Sea Systems Command (NAVSEA), is the aluminum alloy used in the superstructure of the cruisers, which have steel hulls.

"There have been various degrees of crack repair on every CG [guided-missile cruiser] in the past year," said Chris Johnson, a NAVSEA spokesman in Washington. "The decking is the most prevalent cracking area due to exposure to elevated temperatures caused by solar absorption and exhaust temperatures."

More than 3,000 cracks have been found across the entire Ticonderoga class, which originally numbered 27 ships. Twenty-two of the ships remain in service. Port Royal, commissioned in 1994, is the newest.

Their superstructures are made of aluminum alloy 5456, a material used on numerous U.S. warships since 1958. The alloy, according to NAVSEA, relies on approximately 5 percent magnesium as an alloying element to develop strength. Over time, the magnesium leaches out of the material and forms a film, susceptible to stress-corrosion cracking in a marine environment.

NAVSEA has developed more than 17 alterations to deal with the cracks. In late 2008, the service began evaluating a different welding technique called Ultrasonic Impact Treatment (UIT). The Port Royal was one of the test ships for the new technique, Johnson said. □

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U.S. NAVY

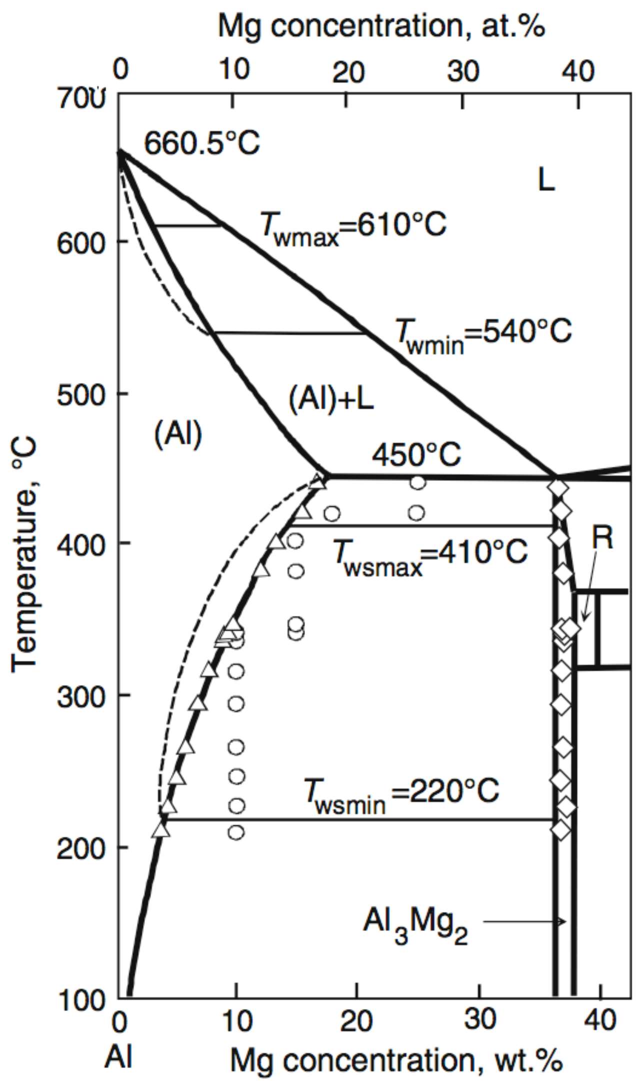
Sealing Cracks: The cruiser Port Royal being refloated at Pearl Harbor in September 2009 after repairs from a grounding. The U.S. ship is back in the shipyard because of a new series of cracks in its superstructure.

Sensitization can occur in-service over life of ship structures

Up to 80°C due to solar loading and other heat sources

Lead to intergranular corrosion and stress corrosion cracking

Earlier work on sensitization in Al-Mg alloys



- Sensitization is the result of precipiation of Al_3Mg_2 at the grain boundaries.[1]

- GBs with misorientations less than 20 ° do not nucelate Al_3Mg_2. [1]

- GBs with a (111) interface plane are more susceptible to Al_3Mg_2 precipitation. [1]

- A grain boundary wetting transition has been detected. [2]

- It has been suggested that GB phases may be found in the single phase solution field. [2]

1. A.J. Davenport et al. Mater Sci Forum 519–521 pp. 641-646 (2006).
2. B.B. Straumal et al. J Mater Sci (2010) 45:2057–2061.

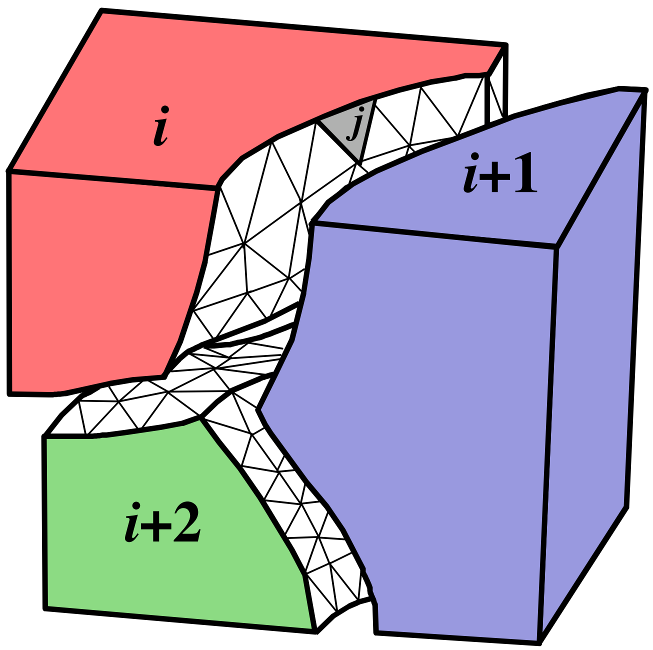
Objective and Status

Objective: Determine effect of Grain Boundary Crystallography and Chemistry on Sensitization in Al-Mg Alloys

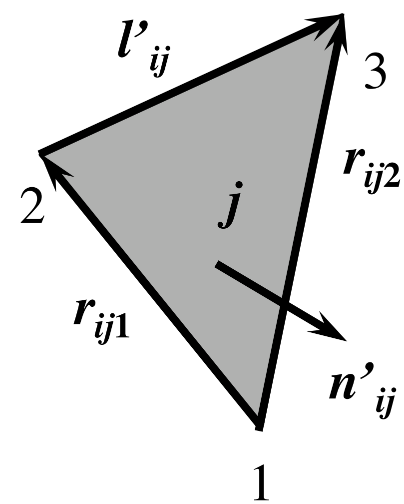
Status: The grain boundary crystallography of Al-Mg alloy 5083 has been calculated and compared to that of commerially pure Al.

Relative areas of different grain boundary types

Grain boundaries have five independent mesoscale parameters



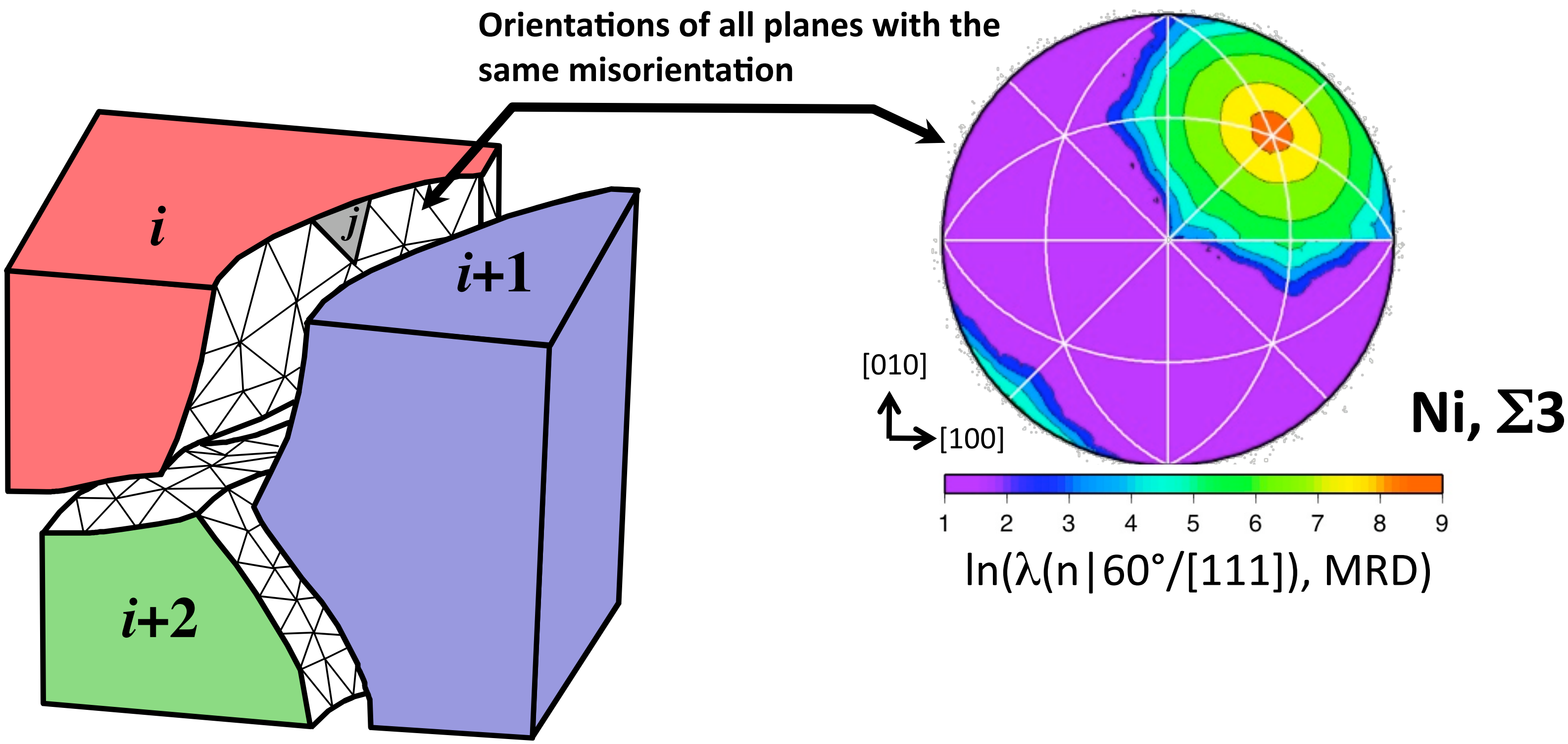
Three parameters for the misorientation: $\Delta g_{i,i+1}$



Two parameters for the grain boundary plane orientation: $\mathbf{n}_{ij}$

Rohrer et al. *Z. Metal.* **95** (2004) 197.

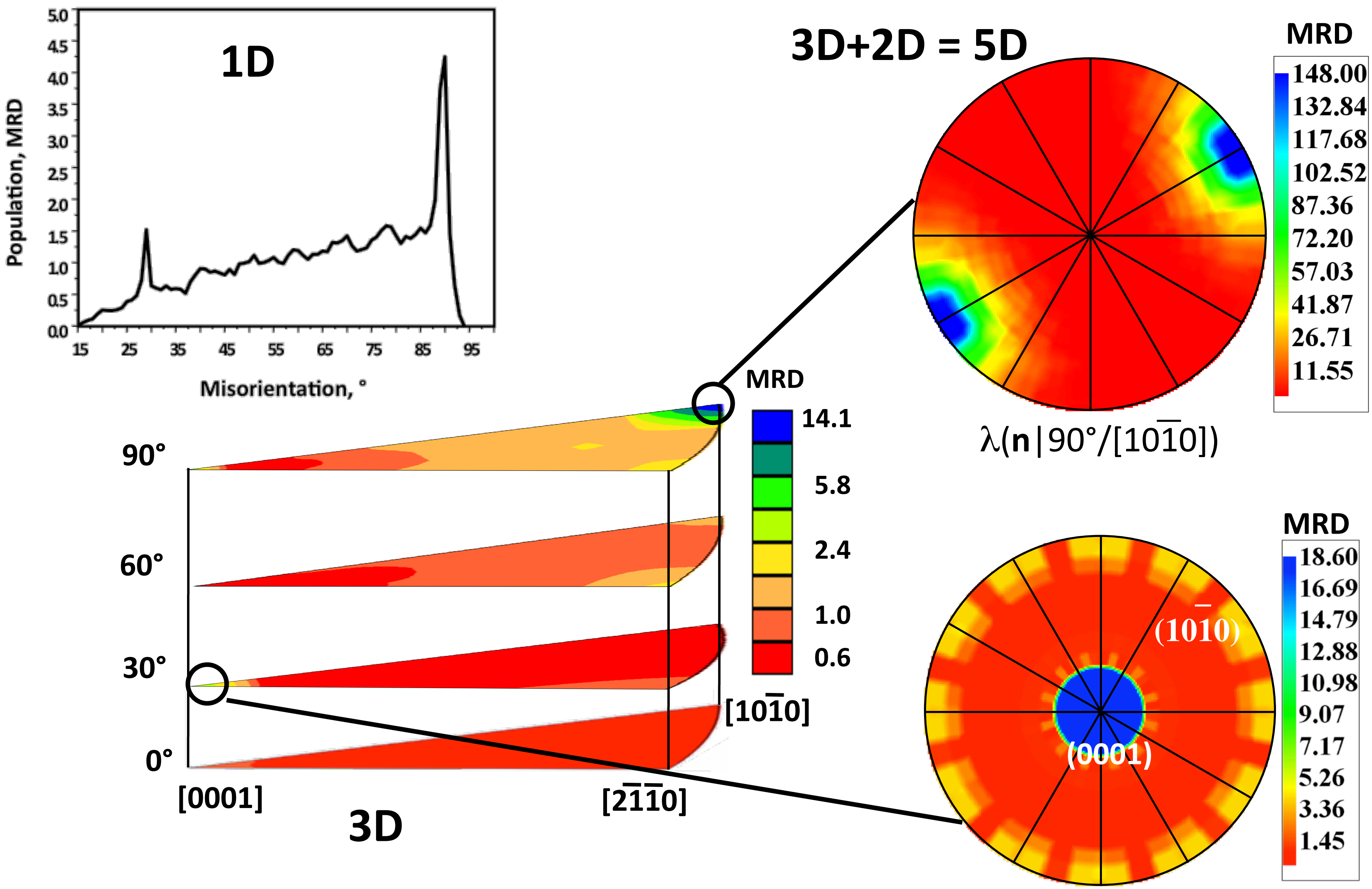
Grain Boundary Character Distribution



The grain boundary character distribution (GBCD), $\lambda(\Delta g,\mathbf{n})$, is the relative areas of GB distinguished by misorientation and plane orientation.

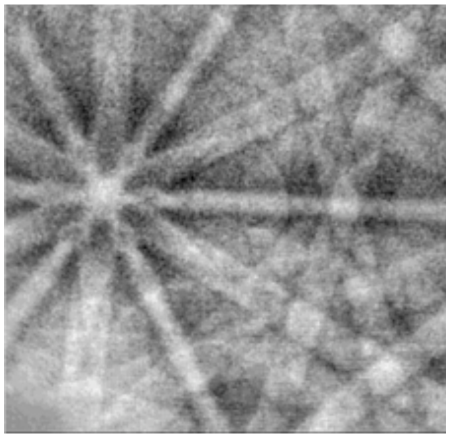
Li et al., *Acta Mater.* **57** (2009) 4304

Multi-dimensional GBCD representations

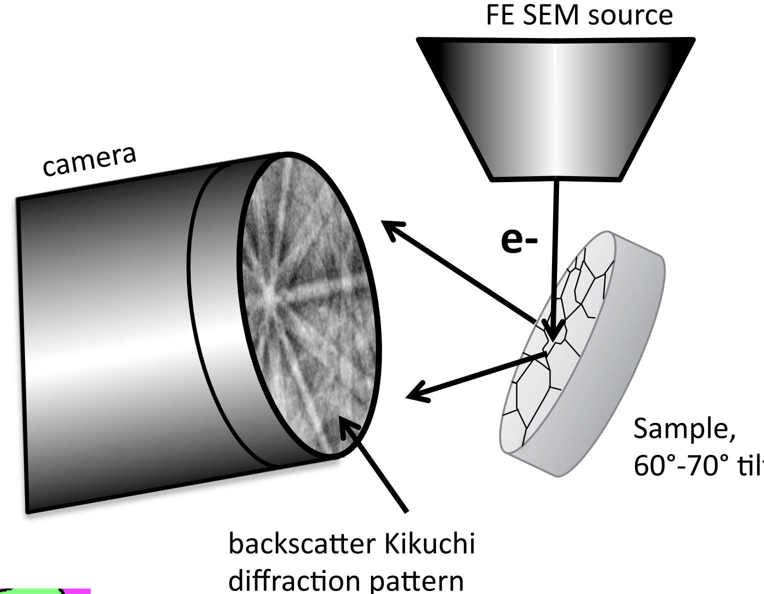


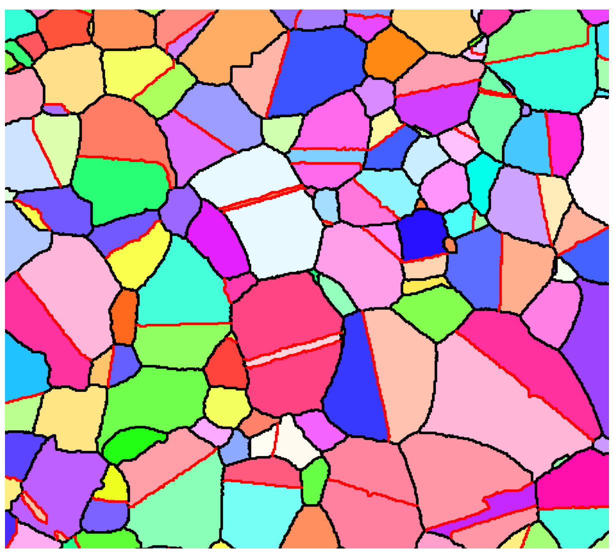
WC: Kim et al., *J. Am. Ceram. Soc.*, **91** (2007) 1001

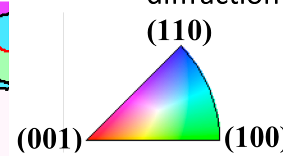
All Measurements Based on Orientation Mapping in the SEM



Electron backscattered diffraction pattern, indexed by computer







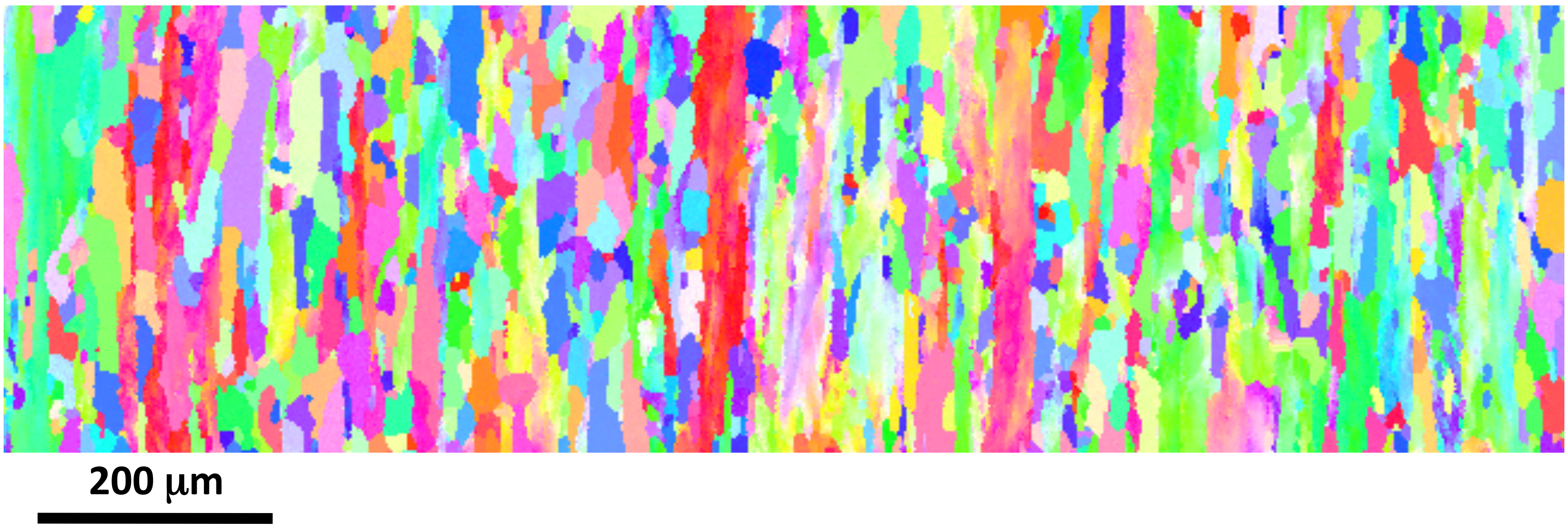
Inverse pole figure map (TiO_2) displays accumulated orientations.

100μm

GB inclination must be measured by serial sectioning or determined by stereology.

Al-Mg Alloy 5083

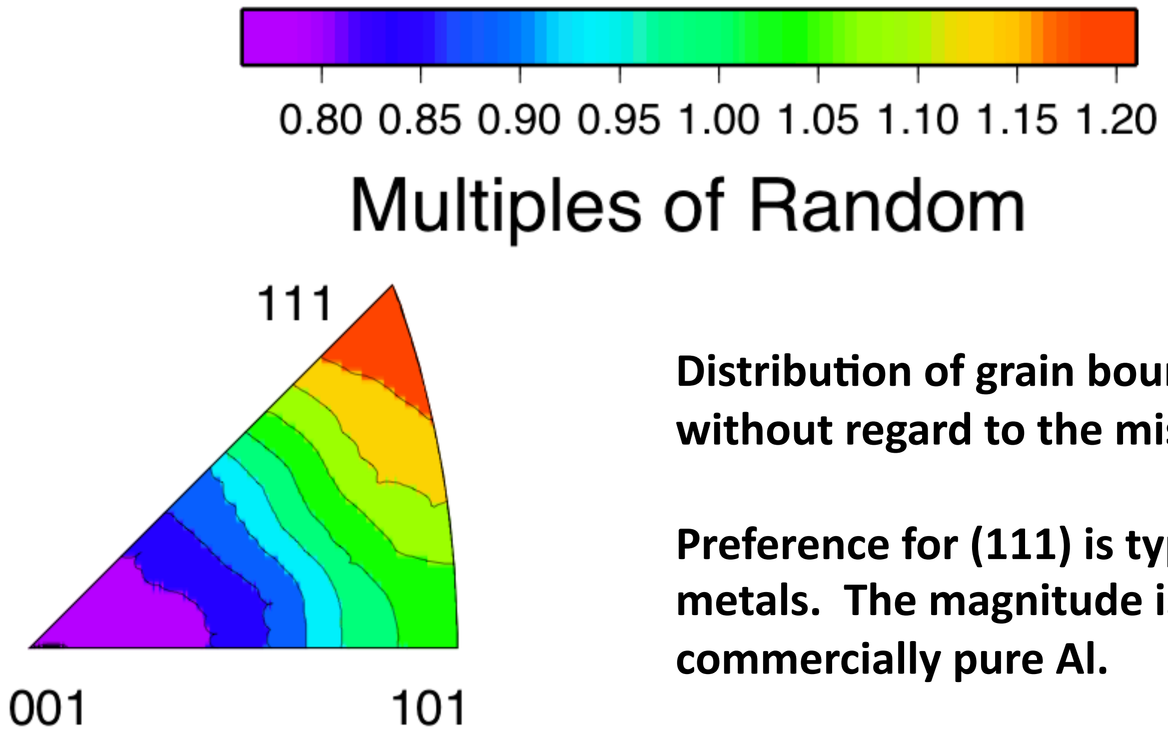
Section of the orientation map



Orientation map recorded at NRL, microstructures analyzed at Carnegie Mellon

38,118 grain boundary line segments extracted

Al-Mg Alloy 5083, Grain Boundary Plane Distribution

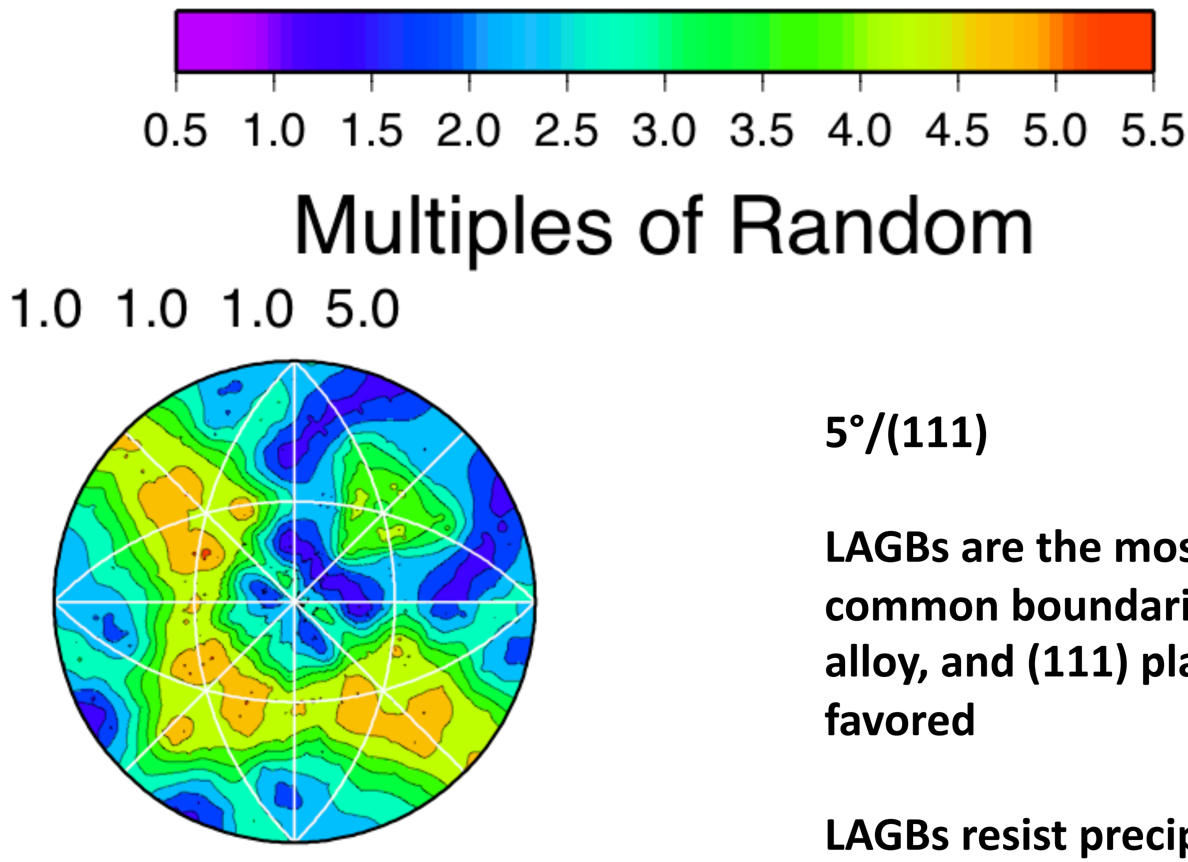


Distribution of grain boundary planes, without regard to the misorientation.

Preference for (111) is typical for fcc metals. The magnitude is comparable to commercially pure Al.

These are the boundaries that are most susceptible to precipitation

Al-Mg Alloy 5083, Grain Boundary Plane Distribution for Low Angle Grain Boundaries

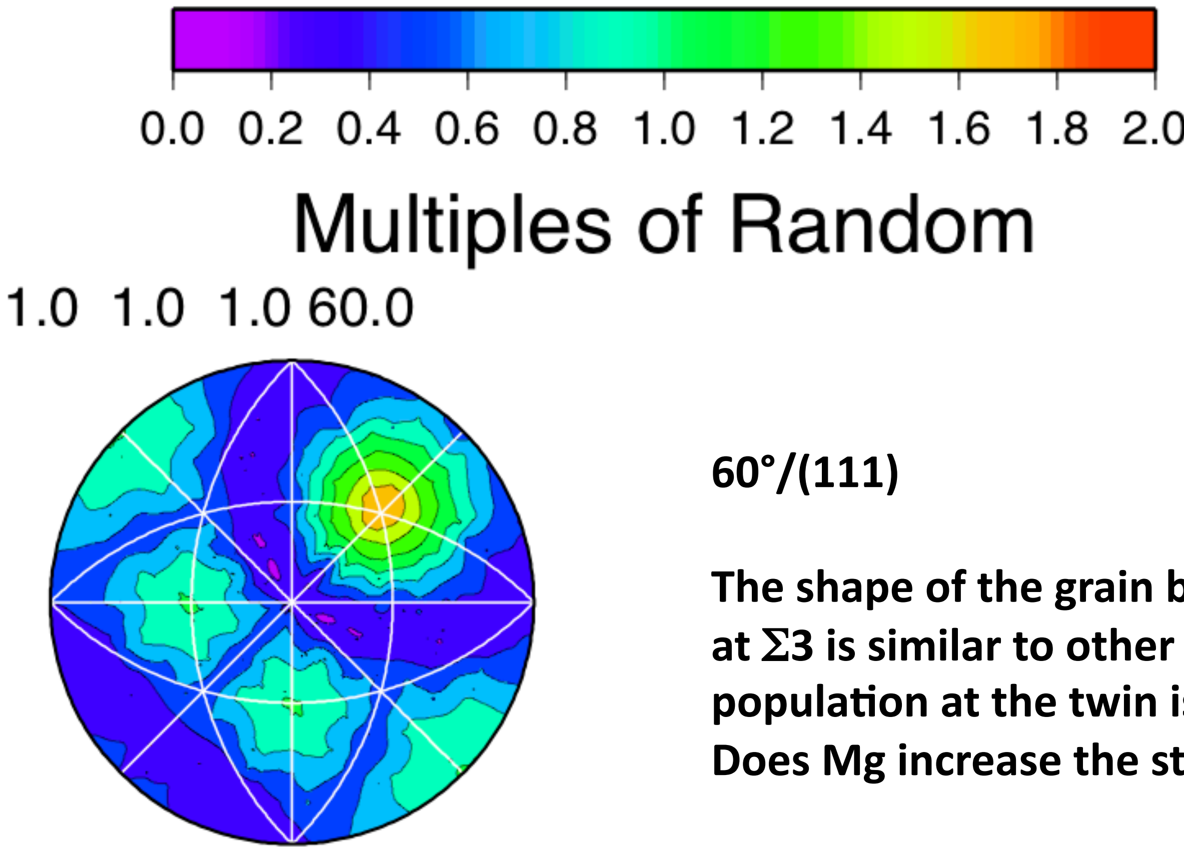


5°/(111)

LAGBs are the most common boundaries in the alloy, and (111) planes are favored

LAGBs resist preciptation

Al-Mg Alloy 5083, Grain Boundary Plane Distribution for Σ3 Grain Boundaries

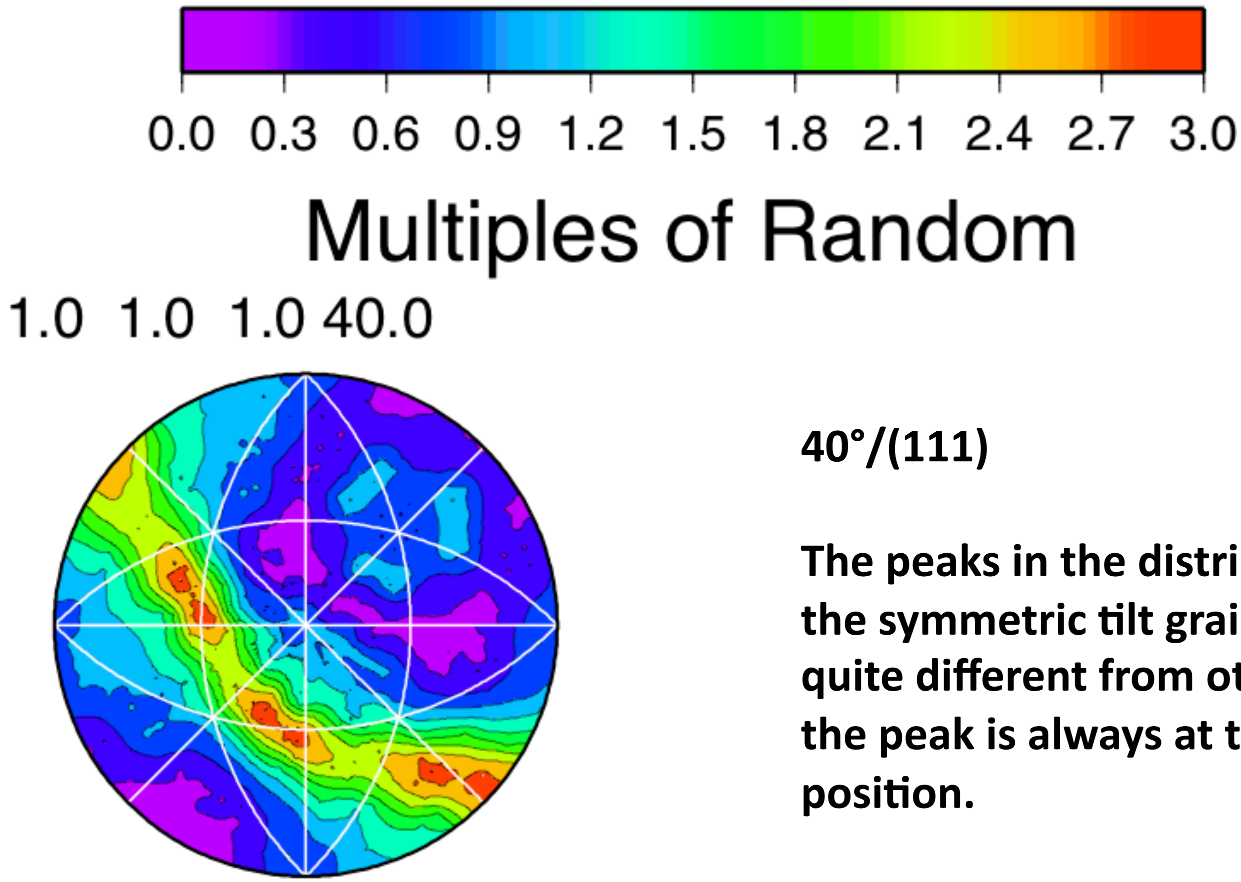


60°/(111)

The shape of the grain boundary plane distribution at Σ3 is similar to other fcc metals, but the population at the twin is the lowest I've ever seen. Does Mg increase the stacking fault energy in Al?

{111} twist GBs are the best sites for Al_3Mg_2 nucleation

Al-Mg Alloy 5083, Grain Boundary Plane Distribution for Σ7 Grain Boundaries

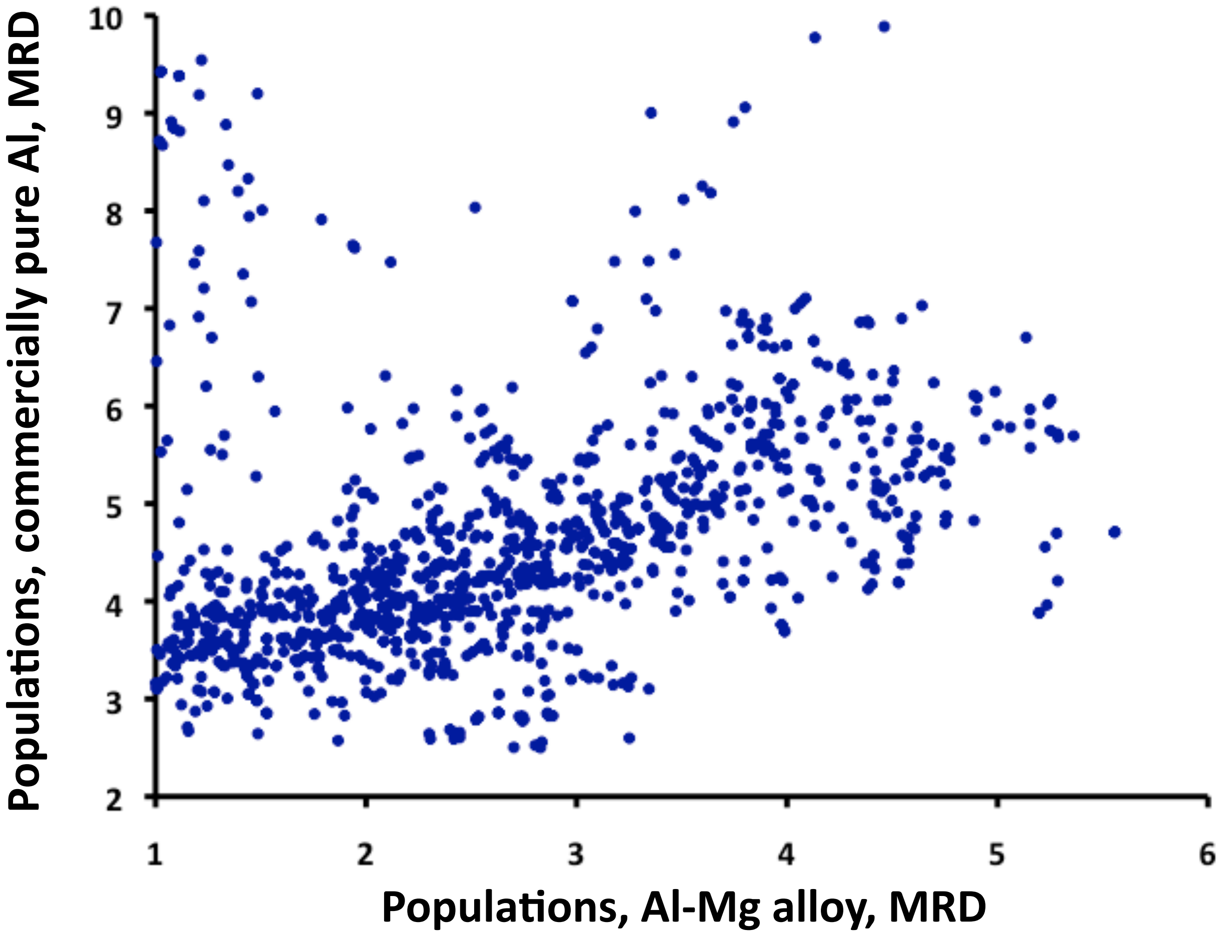


40°/(111)

The peaks in the distribution are very near the symmetric tilt grain boundaries. This is quite different from other fcc metals where the peak is always at the pure twist position.

{111} twist GBs are the best sites for Al_3Mg_2 nucleation

GB plane distribution in Al-Mg Alloy 5083 is only weakly correlated with Al 1050.



Each point is a single grain boundary type, and the position is determined by the population in cp Al 1050 and Al 5083

Summary and Recommendations

The grain boundary plane distribution of AA 5083 has some characterisrics in common with commercial purity Al, but there are many differences.

Low misorientation angle grain boundaries are very common.

{111} twist boundaries are relatively rare compared to other fcc materials.

Complete study the grain Grain Boundary Character Distribution, collect data from oblique sections for comparison.

Correlate with ongoing 3D atom probe tomography studies at NRL