Theory of Tin Whisker Growth
"The End Game"

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iNEMI Tin Whisker Workshop at ECTC

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Updated 2007 to match published paper

History – Growth Mechanisms

- **Dislocation Theories**
  - **Growth at the Tip**
    - **1952 Peach – Dislocation Mechanism**
    - **1976 Linborg – 2 Stage Dislocation Mechanism**

1954 – Koonce and Arnold clearly showed whiskers grow from base – refuting these theories

  - **Growth at the Base**
    - **1953 Frank and Eshelby – Rotating Edge Dislocation Pinned to a Screw Dislocation, Climb and Glide**
    - **1956 J. Franks - Dislocation Glide**
    - **1957 Amelinckx et. al. – Helical Dislocations**

History – Growth Mechanisms (2)

- **1957 G.S Baker**
  - **Observations Not Consistent or Compatible with dislocation mechanisms of whisker growth**
- **1958 Smith and Rundle – X Ray Investigation of Whiskers**
  - **Several Crystallographic Orientations**
  - **No evidence of screw dislocations**
- **1958 Ellis**
  - **Not all Whisker Grow Axes were low-indice glide plane directions**
    - **Dislocation theory Could Not Rationalize non-glide plane whisker growth directions**
- **2003 Lebret et.al**
  - **Whiskers axes noted in non-slip directions → Dislocation mechanisms are not applicable**

History - Recrystallization

- **Recrystallization – General Statements without Model**
  - **1958 Ellis**
    - **Another mechanism (other than dislocation theory) would be necessary → Recrystallization**
  - **1963 Glazunova and Kudryavtsev**
    - **Tin Whiskers are a distinct form of Recrystallization**
  - **1980 T. Kakeshita, et al.**
    - **Whiskers grow on recyrstallized grains**

A New Theory/Model of Whisker Growth

Initial and Necessary Conditions

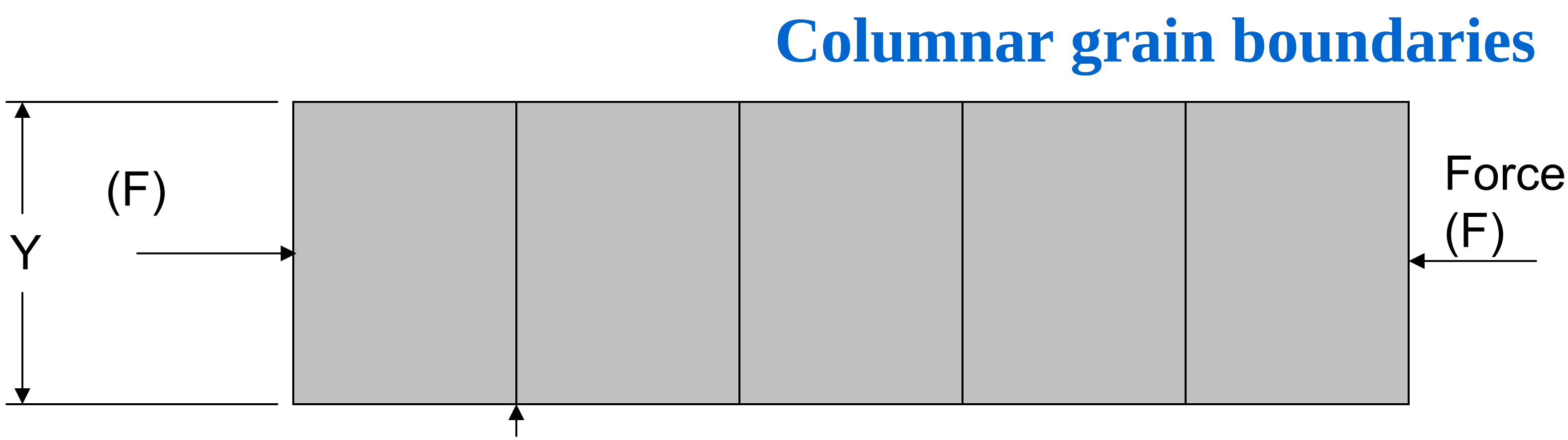
- **Lowering of the energy of the system is <u>required</u>, but not necessarily each atom. Lowering the energy state of each atom would be a plus**
  - **In this theory the atoms at the whisker grain boundary at the base of the whisker are shown to be (on average) at lower energy levels (compressive stress levels) than surrounding areas – this aids the movement of Sn atoms without requiring that they go to a higher energy state**
  - **The base of the whisker is the grain boundary interface of the whisker with other whisker grains – not the surface of the tin deposit in the area of the whisker grain**
- **There must be vacancies at the whisker grain boundary at the base – otherwise, Sn atoms cannot move there.**
  - **Grain Boundaries are always high vacancy sites with a low degree of order and atom packing density that may act as a source or sink for vacancies**

Regardless of any tin whisker theory specifics – I believe that these two statements must be true

- **Additionally – for this theory, the <u>driving force is compressive stress</u>**

Simplified 2D Example on Matte Tin

Simplified 2D picture of tin grains as plated (I did this in 2D to simplify it and make the math clearer)



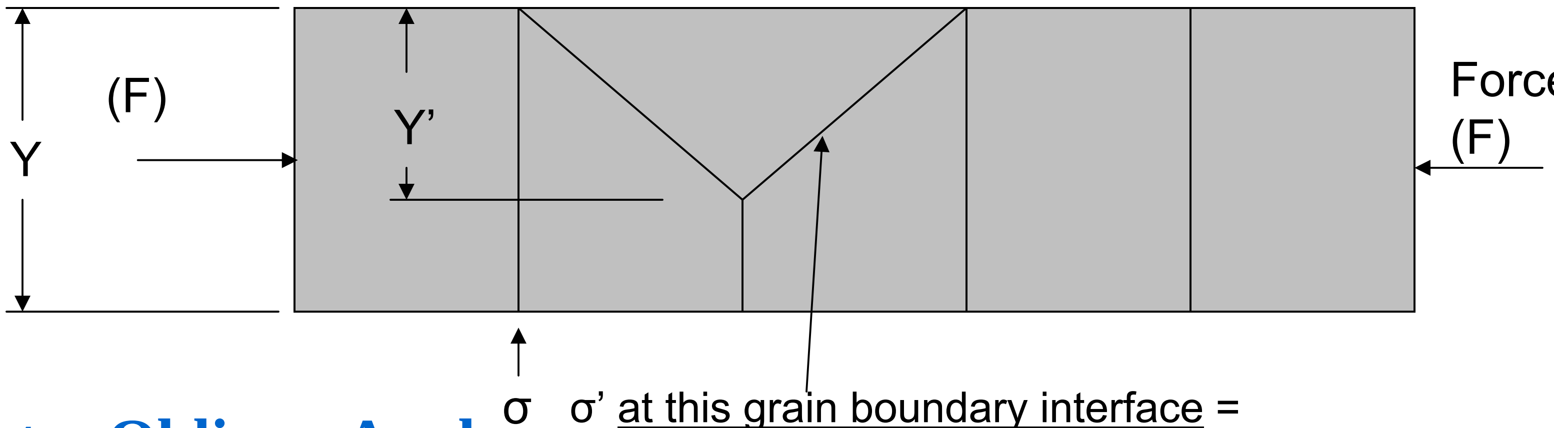
σ at the grain boundary interfaces = F/A
where A = Area
In this 2D simplification A = Y (or at any given dimension in Y = Y' – since units are "per dimension" – Units could be lbs/in^2 or N/m^2 – simplified in 2D to Lbs/in or N/m)

Stress σ = compressive Stress in the tin layer – resulting from the force (F)
- Source of this force can be many items (mechanical, ΔCTE, intermetallic growth, etc.)

*Recrystallization is Necessary

Simplified 2D after recrystallization forming grain with shape
Similar to the below. Note – for this simplification I used a 45º angle but this is not critical – some, non-vertical angle is however. 45º makes X and Y equal making the math simple
Note: FIB cross-sections have routinely identified this non-vertical angle at the base of the whisker grain.

***The angled grain boundary suggests but does not prove recrystallization. They could be plated as such.**



σ' at this grain boundary interface =

F/A where A= $\sqrt{2}$*Y'

Thus σ'= σ/1.414

Or most importantly, stress is lower at this grain boundary than it is at the vertical grain boundaries σ'< σ

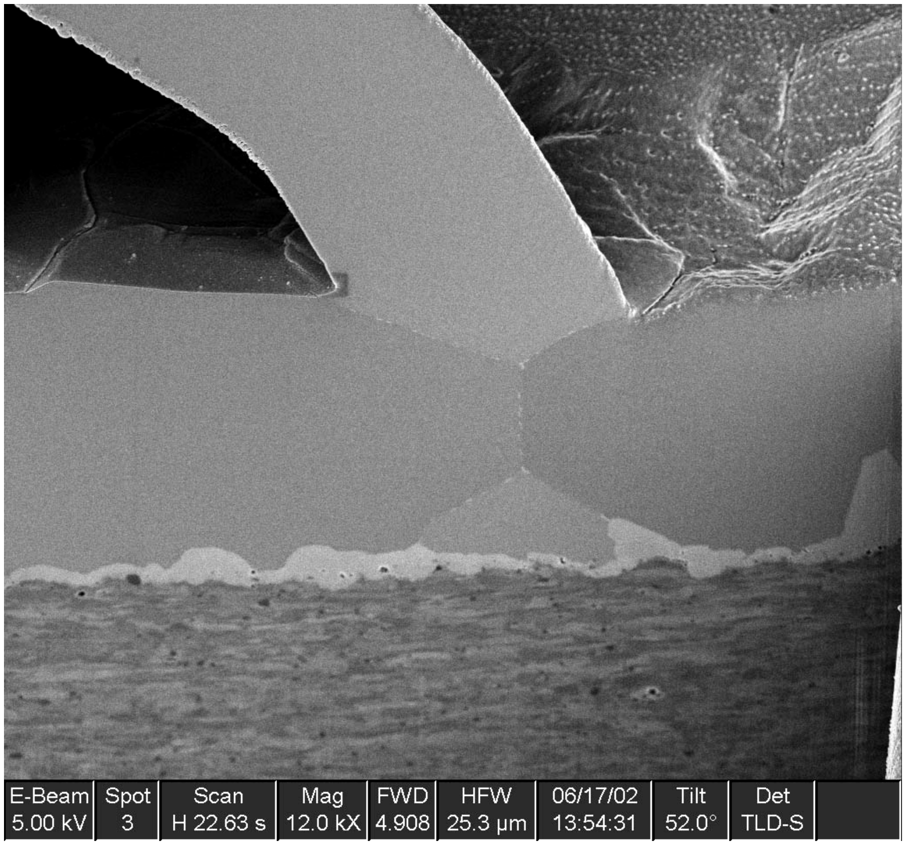
This is the source of the stress gradient in the grain boundaries

Creates Oblique Angle Grain Boundaries that result in lower stress areas

Note: *Not a specific grain orientation*

Typical Tin Whisker Grain

Matte Tin

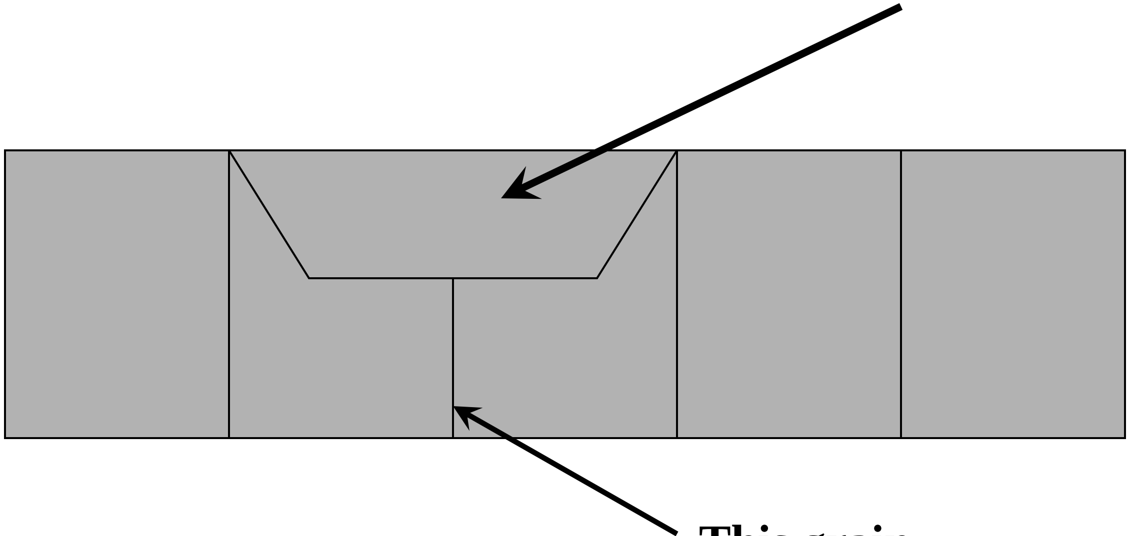


Notice the oblique angle grain boundaries as noted on the previous slide. This is typical of FIB cross-sections of whiskers

Image courtesy of N. Vo , Motorola

Oblique Grain Boundaries

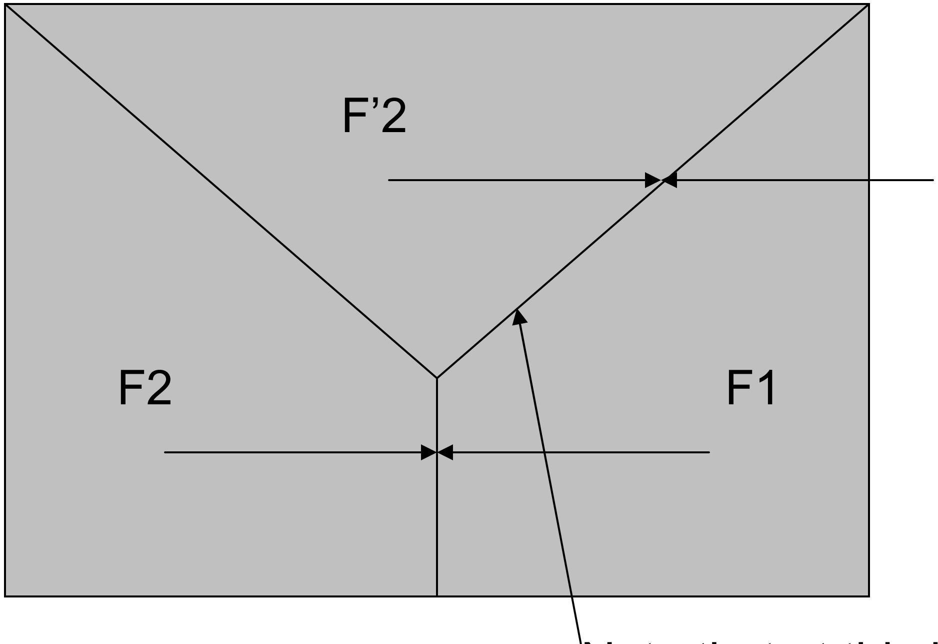
Shape shown is just representative - could also be grain boundaries that look similar to below



This grain boundary not necessary?

This is just an example. Different features won't necessarily prevent whisker growth, but they may result in slower growth, or a less desirable whisker site.

The Grain Boundary is Key



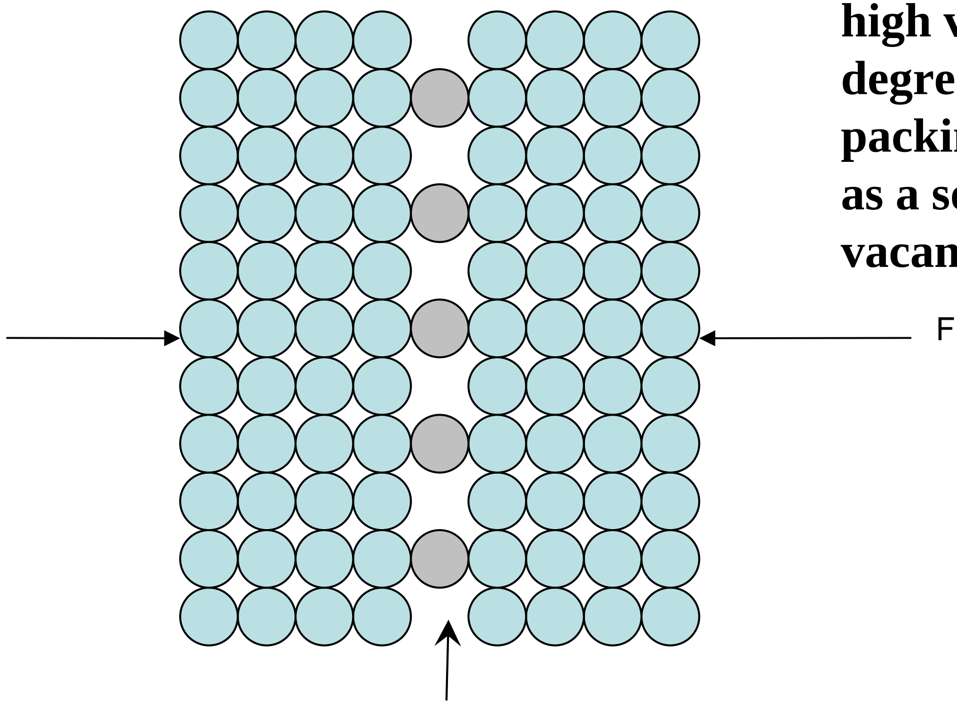
F1 = F2
F'1 = F'2

Projected stress on the angled grain boundary has a smaller compressive component than the surrounding area

Note that at this interface the force on both sides of the grain boundary is still the same (Macro-stress).
Only the stress on the grain boundary (Micro-stress) is different due to the larger area that the force is acting upon

Explaining the Grain Boundary Diffusion

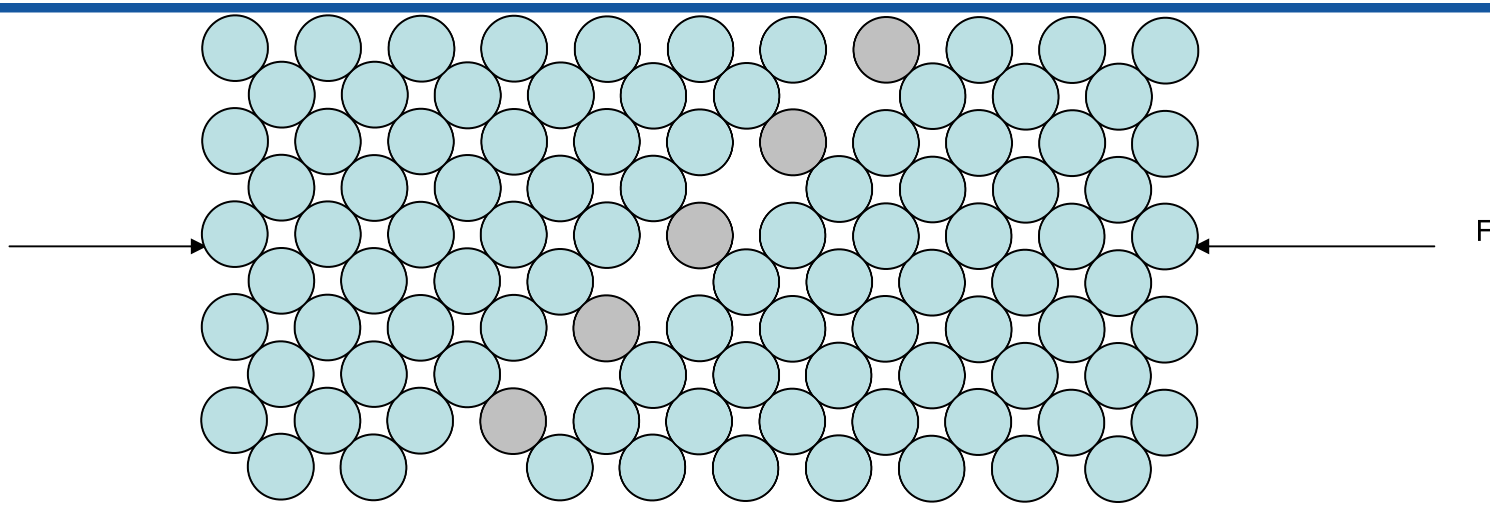
Grain Boundaries are always high vacancy sites with a low degree of order and atom packing density that may act as a source or sink for vacancies



Simplified Representation of a Vertical Grain Boundary

In this simplified representation, stress on the individual atoms in the grain boundary is clearly 2x the stress on the individual atoms in the adjacent tin grains.

Stress on an Oblique Angle Grain Boundary



Simplified Representation of the Grain Boundary Rotated to a 45º Angle

Stress on the atoms in the grain boundaries is exactly equal to the stress on the atoms in the vertical grain boundary of the previous page divided by 1.414 = 70% of the stress of the atoms in the vertical grain boundary.

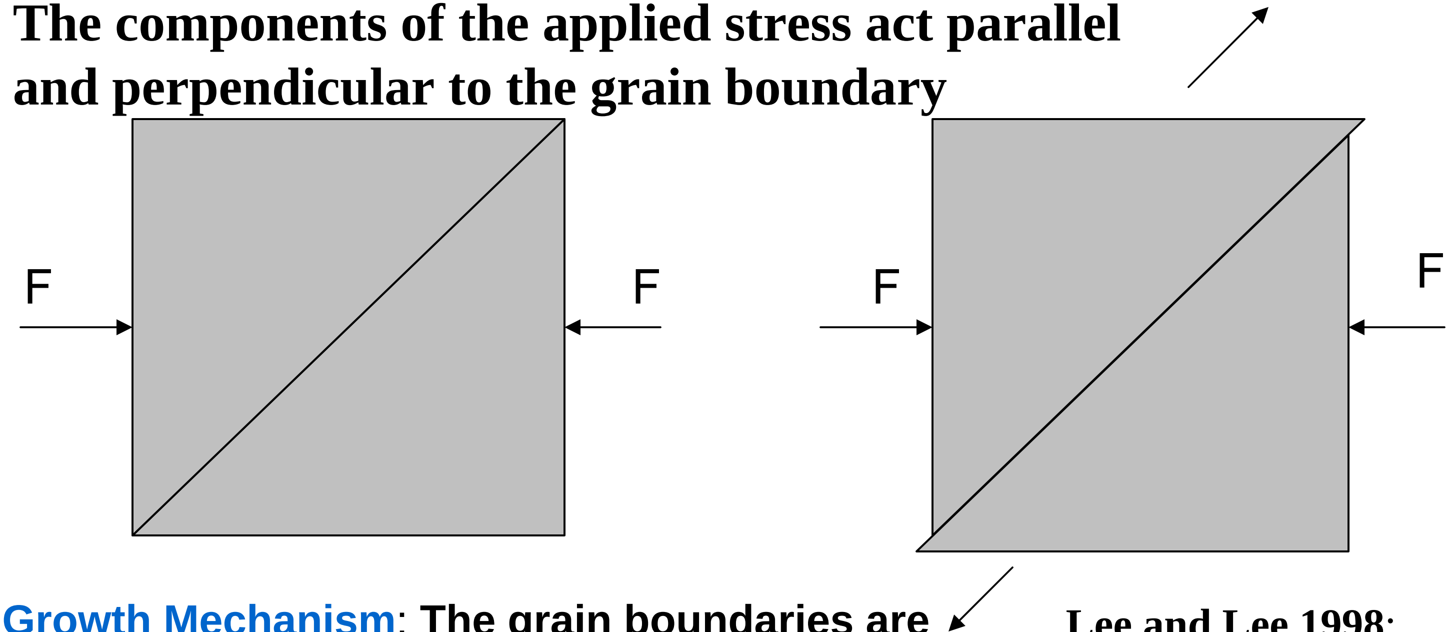
→This is the source of the stress gradient and this is what drives Sn atom diffusion to oblique angle grain boundaries.

As the angle is increased, the reduction in stress on the individual atoms in the grain boundary increases.

For these oblique angle grain boundaries, the stress on the individual grain boundary atoms is higher than the stress on the bulk Sn grain atoms. Thus Sn atoms will naturally want to move into the lattice structure of a Sn grain (lower stress) if a site is available.

Another Look At The Angled Grain Boundary

The components of the applied stress act parallel and perpendicular to the grain boundary



Key Growth Mechanism: **The grain boundaries are not fixed – <u>grain boundary sliding (creep) will occur</u> along the angular grain boundary**.

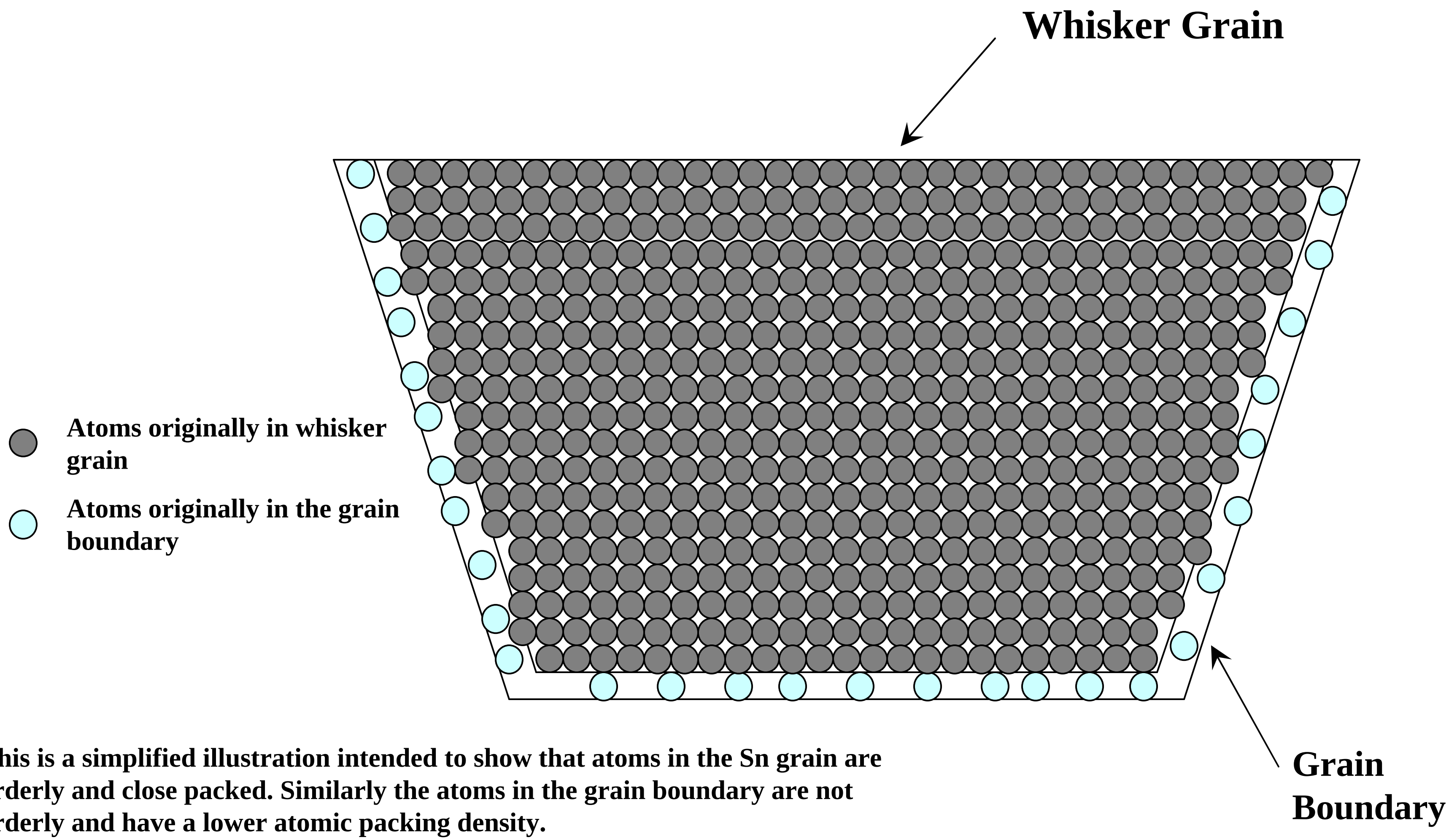
Tin at room temp >0.6 Tmp → creep mechanisms are known to occur

There is lower atomic packing density in the grain boundaries. Without this, there would be no difference in the stress states between a grain boundary and a bulk tin grain

Lee and Lee 1998:
"The biaxial compressive stress gives rise to <u>strains normal to the film plane,</u> which are <u>dependent on the tin grain orientations."</u>

Stress-assisted diffusion, another creep mechanism that can be used to accommodate gb sliding, has been proposed as a whisker growth mechanism by others - Tu, Lindborg

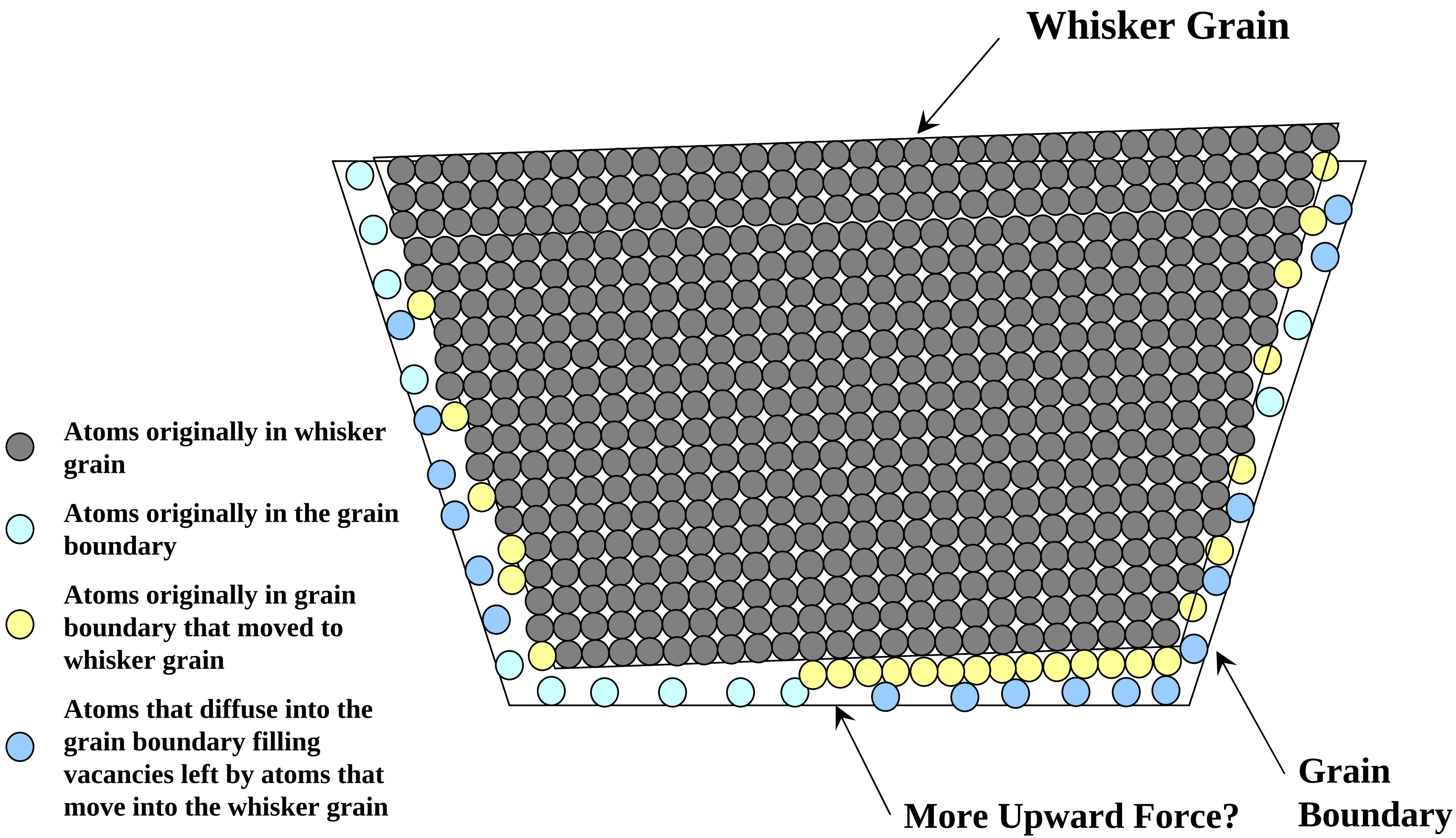
The Atomic Level of the Whisker Grain



This is a simplified illustration intended to show that atoms in the Sn grain are orderly and close packed. Similarly the atoms in the grain boundary are not orderly and have a lower atomic packing density.

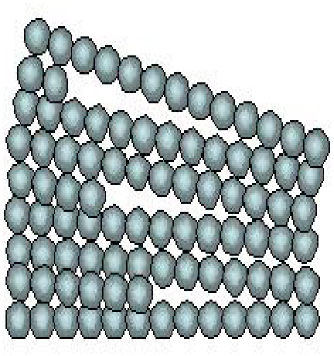
The Atomic Level of the Whisker Grain

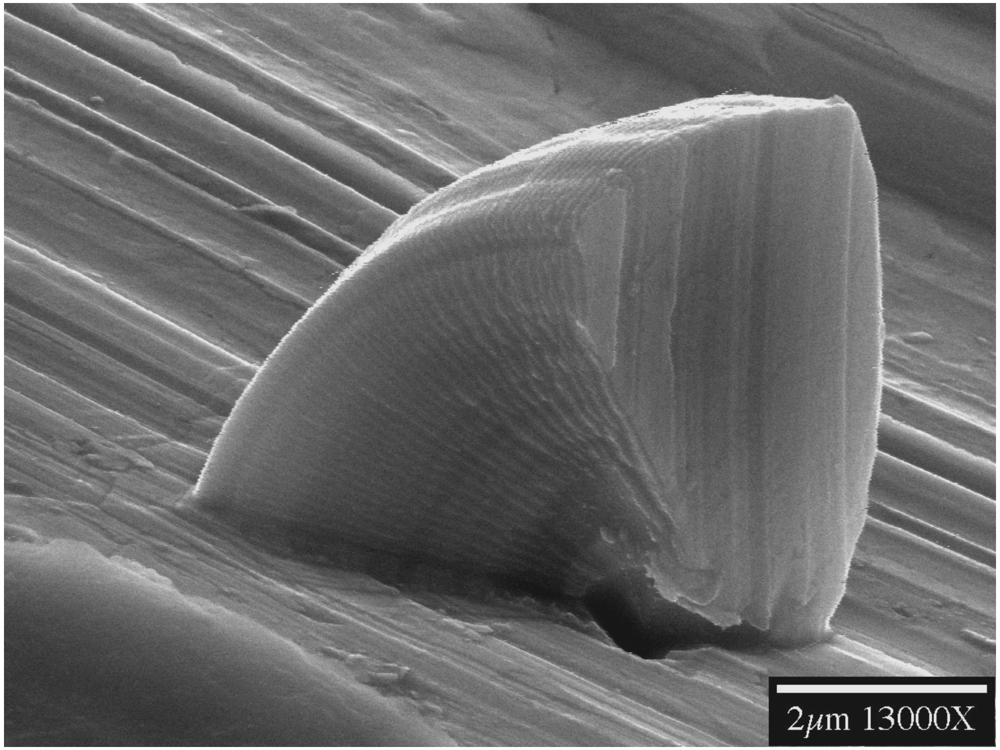
Example of one grain boundary slip 1 atom distance



If One Grain Boundary is Pinned

Curved tin crystal
-Partial layers added
-Dislocations expected

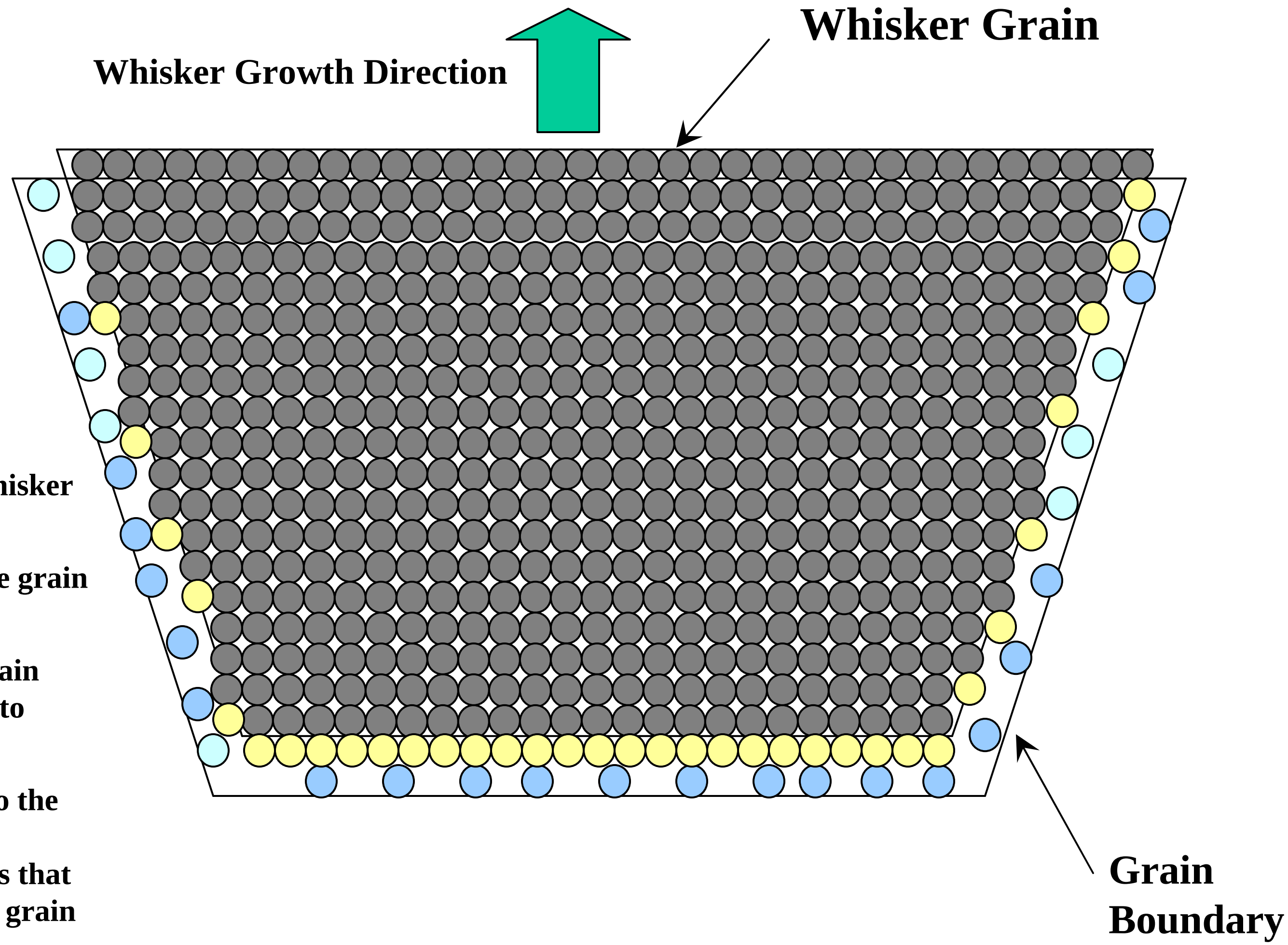




Slide Pictures and Illustrations from Peter Bush, iNEMI Tin Whisker Workshop at ECTC, 2004

The Atomic Level of the Whisker Grain

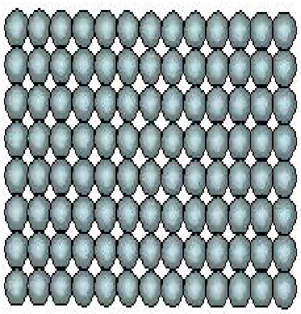
Now another 1 atom grain boundary slip - on the left

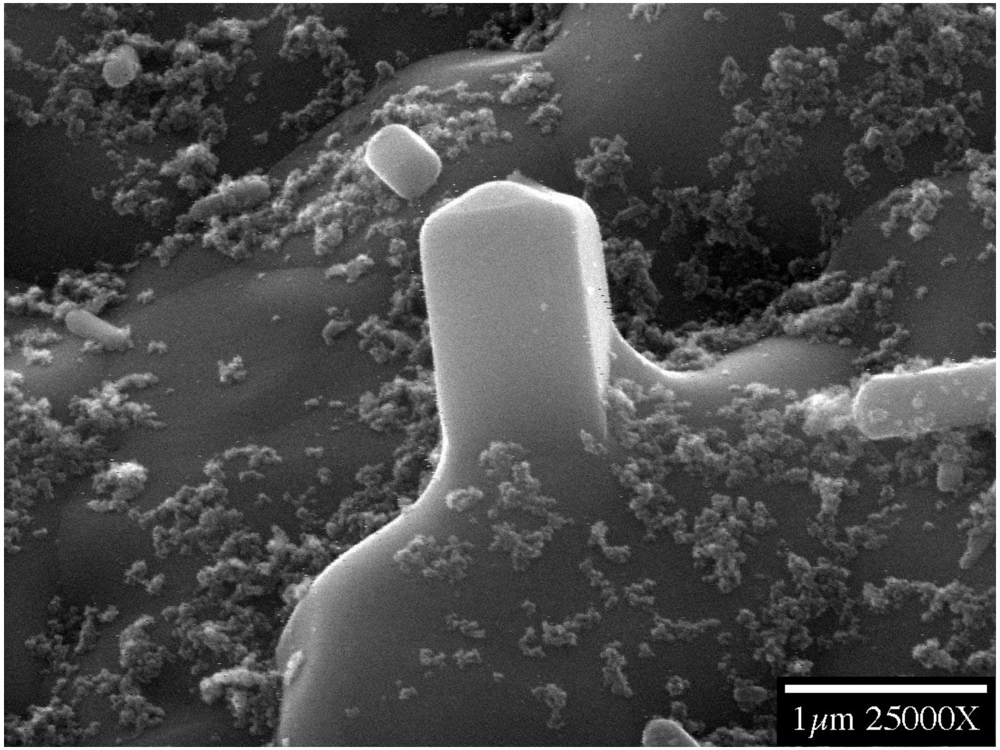


- Atoms originally in whisker grain
- Atoms originally in the grain boundary
- Atoms originally in grain boundary that moved to whisker grain
- Atoms that diffuse into the grain boundary filling vacancies left by atoms that move into the whisker grain

Uniform growth Direction

Near perfect tin crystal





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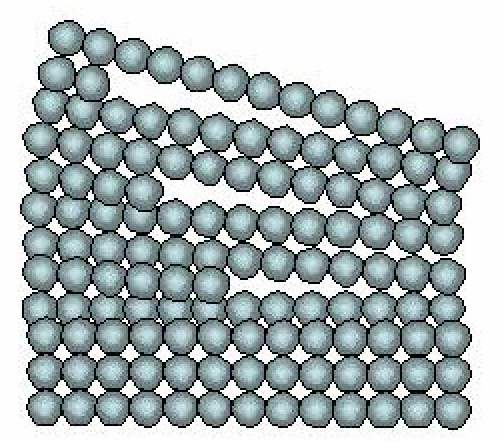
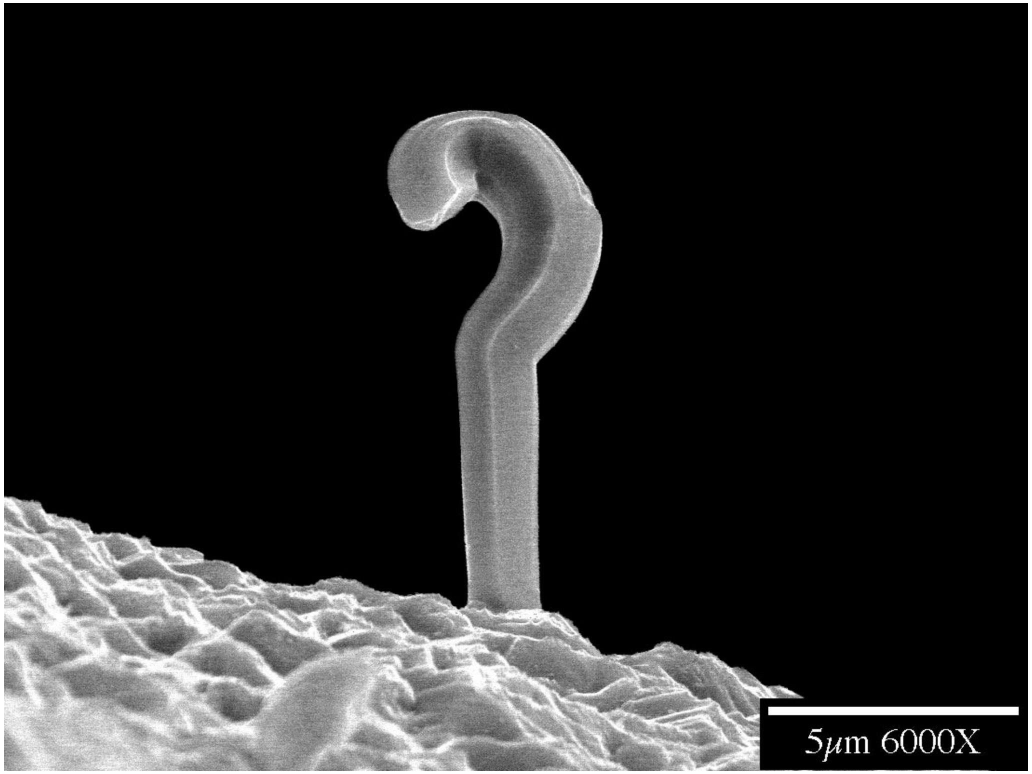
When slip is non-uniform

Curved and straight crystal
-Partial layer addition changed to complete layer
-Dislocation-free straight section





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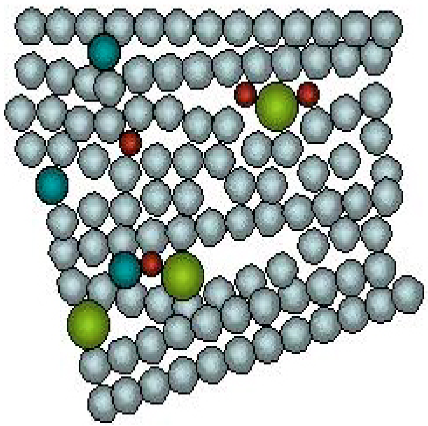
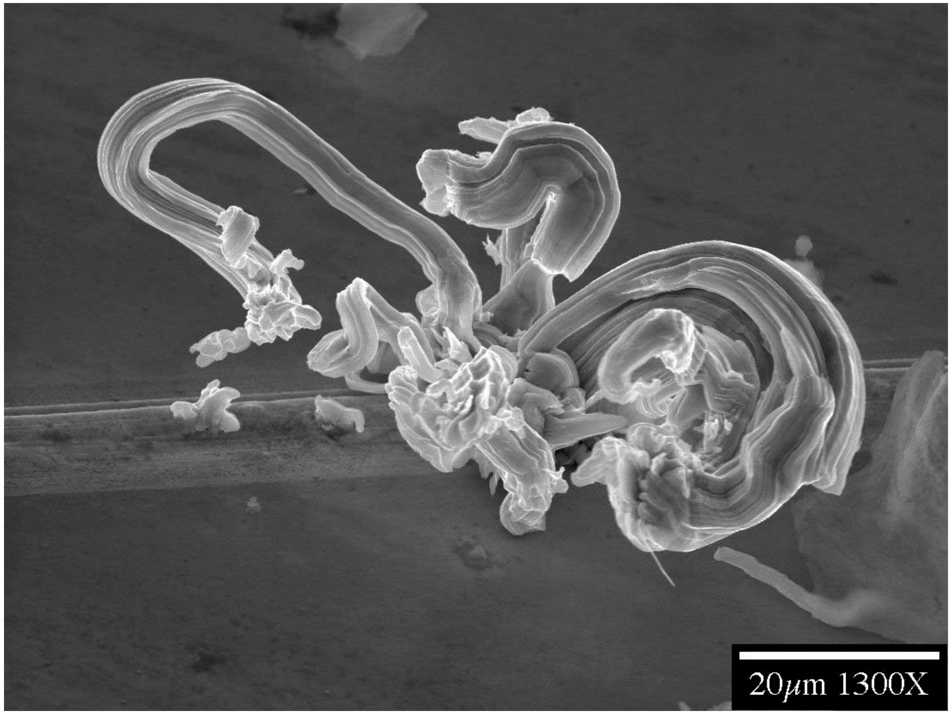
Impurities in the Whisker

Very imperfect tin crystal
-Possible incorporation
of impurities causing
lattice distortion





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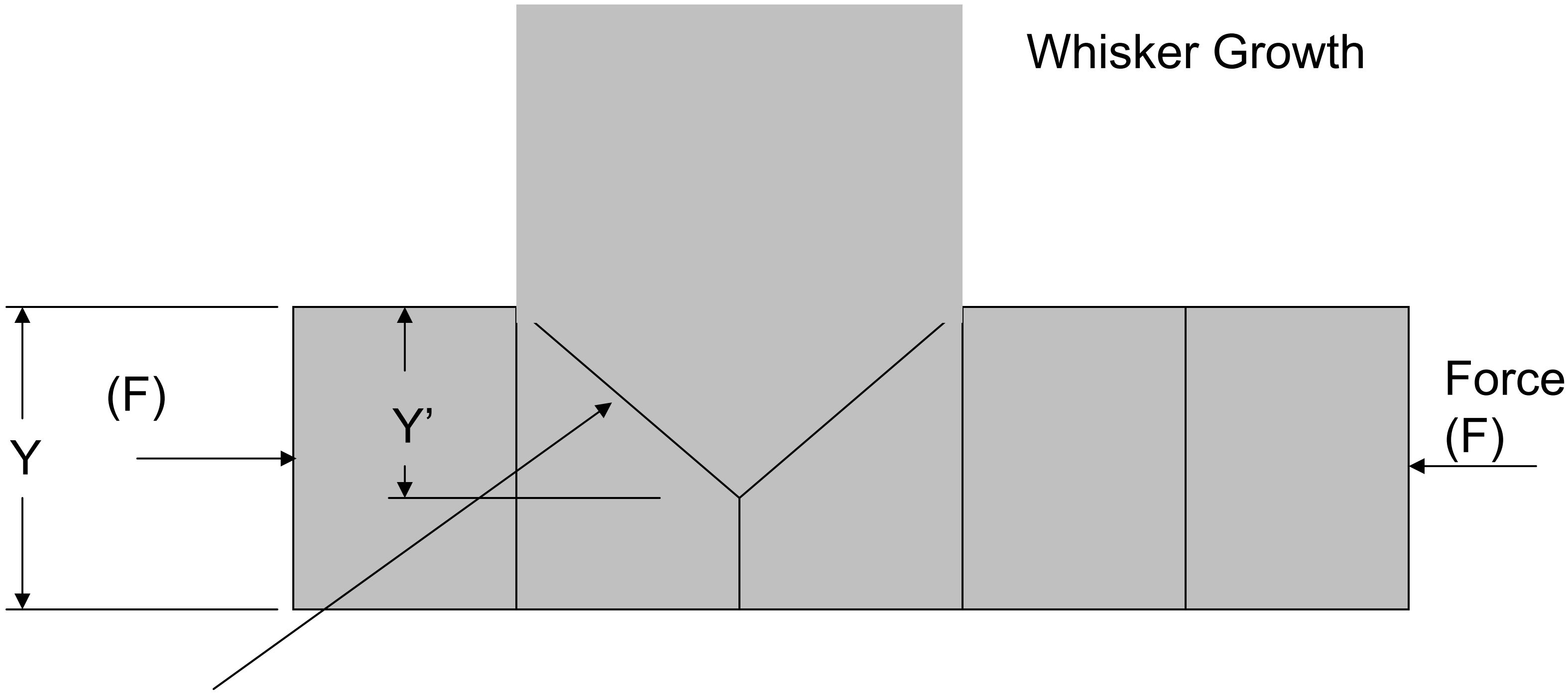
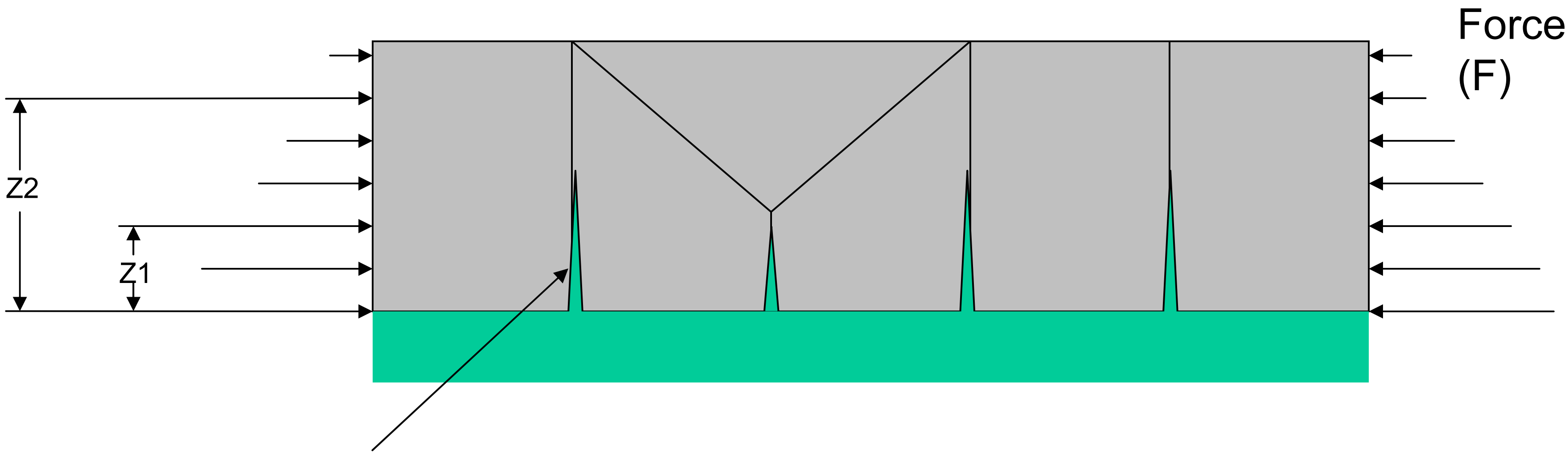
Summary of Whisker Growth



The Force (F') at this grain boundary interface results in "micro motion" with both a vertical and horizontal component (due to the angle that the force is acting upon the surface) This causes grain boundary sliding (creep). The grain boundary sliding results in vacancies in the Sn lattice at the base of the whisker. Diffusion of Sn atoms to the lower stress grain boundary, which now has vacancies, from the higher stress grain boundaries now occurs. Sn atoms move to the base of the tin crystal resulting in whisker growth.

Sn on a Cu Substrate

Looking at this closer - on a Cu substrate
Force is "like" a hydrostatic force (although not as uniform a variation) – in other words, Greater near the substrate interface as such the stress on the vertical grain boundary also varies from the substrate Interface to the surface.

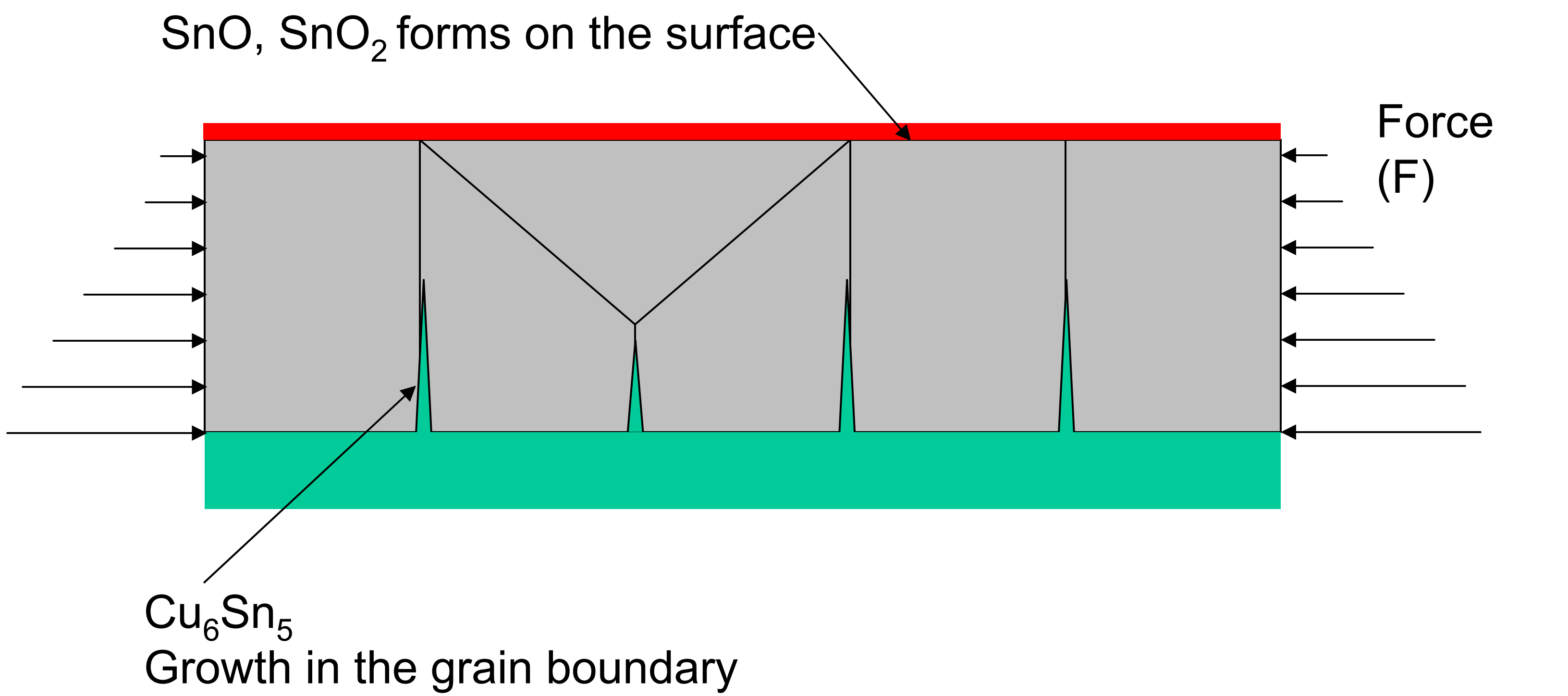


Cu_6Sn_5
Growth in the grain boundary

On the vertical grain boundaries σ @ Z1 is > σ @ Z2
Thus the energy state of the grain boundary is less, near the surface. IF Sn atoms had a place to go (vacancies) they would preferentially move toward the surface.
However….

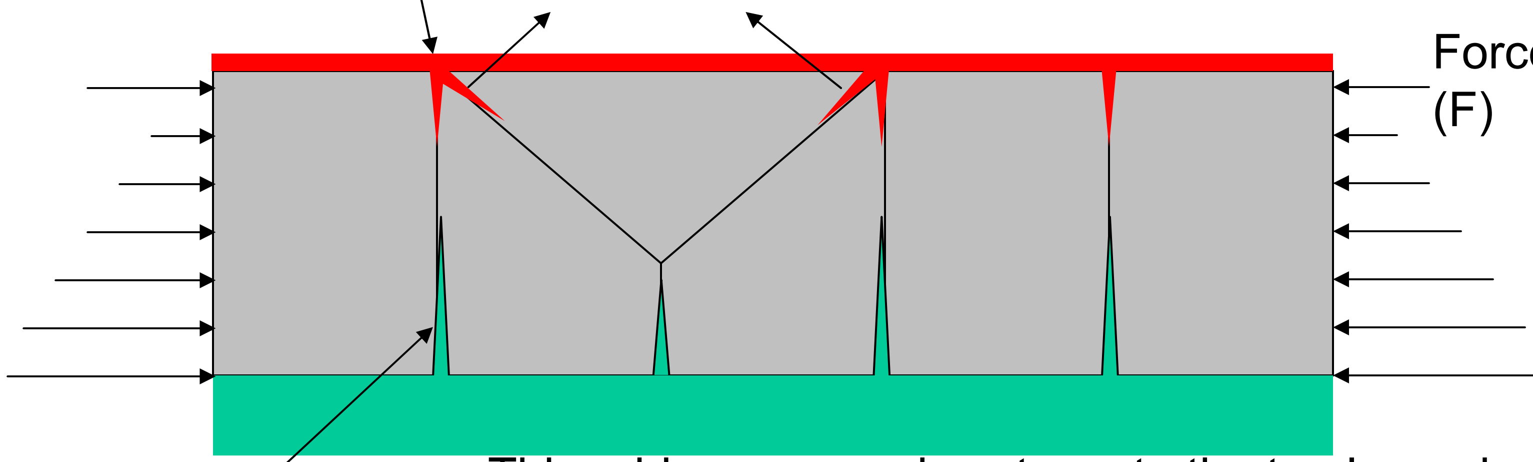
Oxide Effect

Surface is not really flat and uniform – simplified for illustration only



Oxide largely eliminates surface vacancies and also constrains the plating so some compression could be maintained near the surface

Stress from Oxide



This adds compressive stress to the top layer due to SnO and SnO_2 molar volume being > than the Sn it replaces. This changes the shape of the Force profile (similar to vectors above) AND potentially adds a "lifting" force at the angled grain boundaries (the whisker grain), which further reduces the stress state at the base of the whisker grain. It also makes it likely that the oxide layer at the grain boundary interface to the whisker grain will crack.

Molar Vol. (cc/gm-mol)

Cu	Sn	Cu6Sn5	SnO2	hydrated SnO2
7	16	118	21	36

Thus – humidity increases stress and diffusion rates

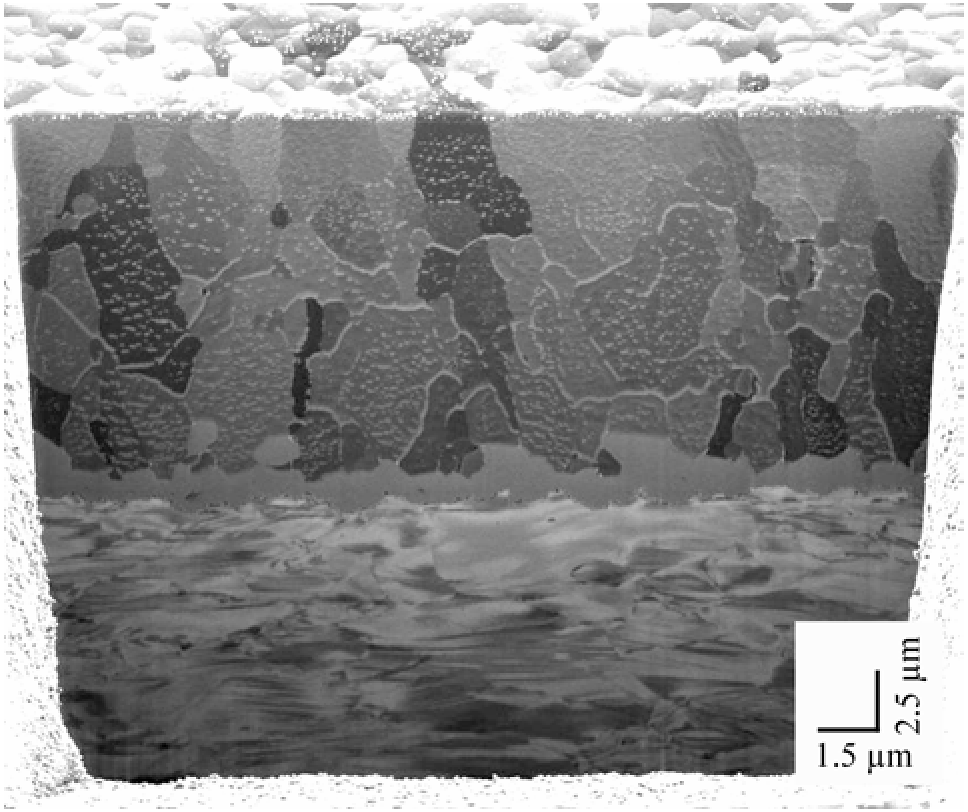
Fisher's Criteria for Whisker Model

- The mechanism must produce a single crystal
  - Yes!
- The mechanism must explain a linear growth rate
  - Yes!
- The mechanism must rationalize the observed induction periods for spontaneous growth
  - Recrystallization Event
  - Stress buildup
- The mechanism should be capable of rationalizing the sudden termination of whisker growth at the end of a period of extremely high and constant growth rate
  - Stress relief and/or whisker grain boundary pinning

Other Things this Model Explains

- **Why thinner platings are more prone to tin whisker growth**
- **The shape influence whisker grains - since every one we've ever seen is a oblique angle grain boundary – but crystal orientations vary**
- **The impact of oxide layer and humidity - and even meshes somewhat with the "cracked oxide" theory**
- **Why tin atoms move to the whisker grain boundary**
- **The uniform dimension growth – as atoms are added not just at the base – but at all grain boundaries as vacancies in the lattice occur**
- **Why SnPb works to mitigate whiskers**
  - **Lots of oblique angle grain boundaries (see next page)**

SnPb Microstructure



SEM Image SnPb - NIST

SnPb has also been theorized to work in prevention of whiskers by substitutional diffusion of a large atom or addition of a soft phase that can cushion the Sn grains from high compressive stress

Based on this theory of tin whisker growth, the SnPb grain structure does not support significant tin whisker growth

Lots of horizontal grain boundaries

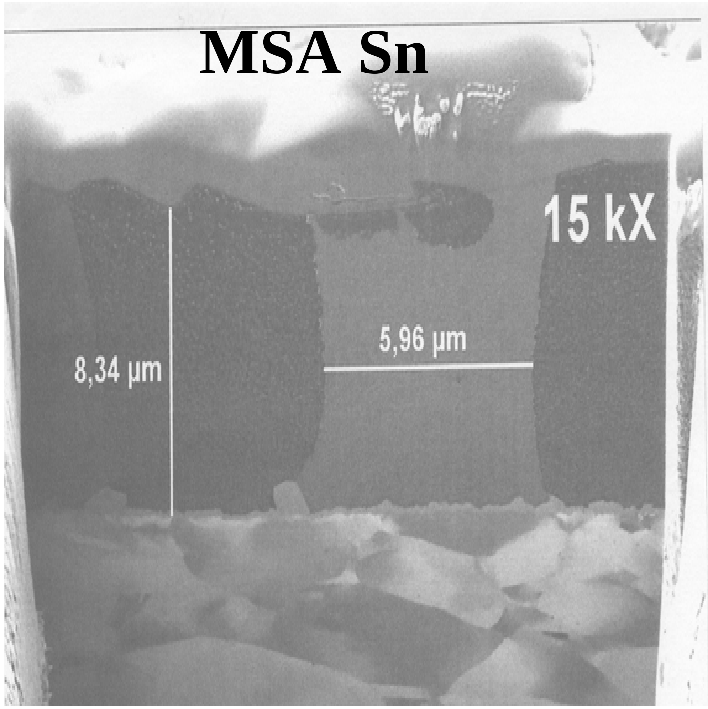
Almost an equiaxial grain structure. Not a columnar grain structure

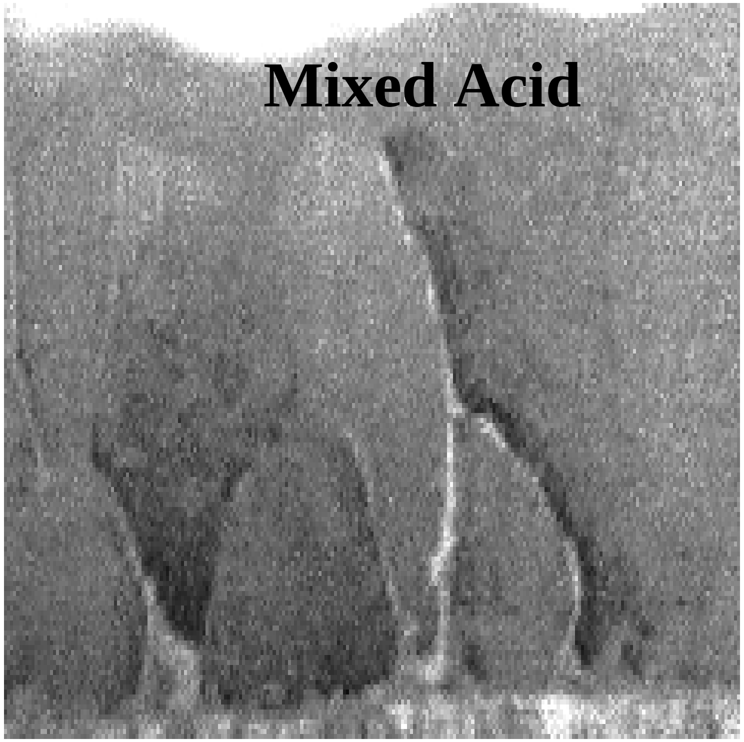
Other Things this Model Explains (2)

- **Why larger grains are less prone to whisker growth***
  - **Less grain boundary for growth of intermetallics and oxides (less stress)**
  - **Larger grain boundary areas for the individual whisker grain – takes more stress to cause grain boundary sliding and more tin atom diffusion to result in whisker growth**
  - **Reflowed Sn results in much larger (~10X grain sizes if distinguishable at all) It also explains why it might not work (breaking up of grains at edges etc.)**

*C. Xu, Y. Zhang, C. Fan, and J. Abys, "Understanding Whisker Phenomenon: The Driving Force for Whisker Formation", CircuiTree, pp. 94-105, April 2002.

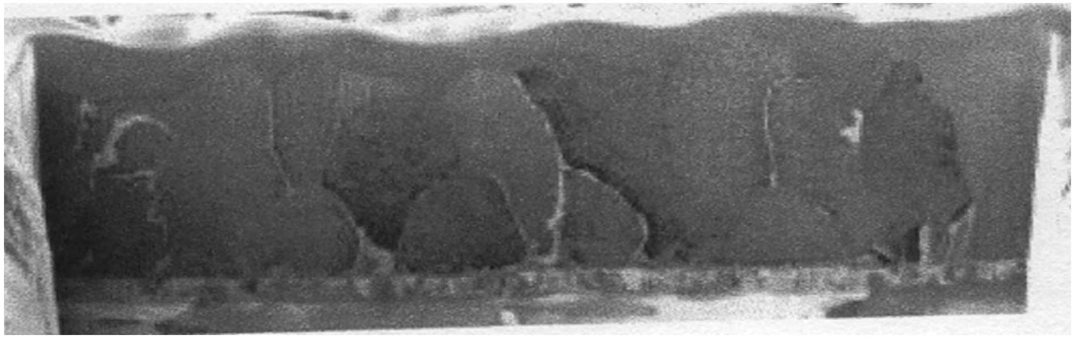
Matte Tin Grain Structures





Vertical Grain boundaries. No place to relieve stresses

Preventing Tin Whiskers on Sn Finishes



SEM Image: Technic Inc.

Today's mitigation practices focus on preventing/minimizing stress build-up (Ni underlayer, annealing etc.) which cannot account for all sources of stress.

Can a Sn finish be plated with sufficient <u>horizontal grain boundaries</u> PLUS large grain sizes (and low as-plated stress)? **(Example above comes "close" with ~1µm grain sizes and has been claimed to be whisker free. Shetty (Technic) explains the performance of this bath based on dispersed intermetallic stresses)**

See Rohm-Hass ST380!

This allows a mechanism to relieve stress buildup – regardless of the source (based on this theory) and thus prevent whisker growth.

Acknowledgements

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of Hewlett-Packard

who first proposed grain boundary sliding as a possible key mechanism in Tin Whisker growth

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