Effects of Low-Angle Boundaries on the Properties of CMSX-4 Single Crystal Superalloy

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Low Angle Boundaries (LABs) occur in single crystal superalloy turbine blades. LABs are the result of an additional misoriented grain forming in the casting which can cause a decrease in mechanical and high temperature properties of the blade. Howmet cast several CMSX-4 slabs with varying degrees of primary and secondary misorientation to determine trends between LAB severity and tensile, stress rupture, corrosion and oxidation properties. Through testing and observation, an increase in the degree of total misorientation led to a slight downward trend in tensile properties, no discernible trend for stress rupture life and no preferential attack of the LABs during hot corrosion or oxidation.

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Project Background

Turbine Efficiency

Higher operating temperatures in turbine engines increase efficiency while simultaneously demanding materials capable of withstanding highly corrosive and large stress environments.

Low Angle Boundaries

Low Angle Boundaries (LABs) are spurious grains in a single crystal with a misorientation of less than 15° from the primary grain growth direction. Previous studies have shown that properties decrease with an increasing LAB angle.

LAB in CMSX-4

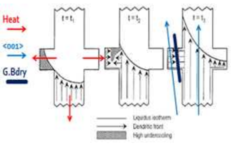
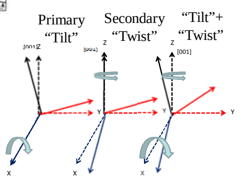


Image adapted from R.E. Napolitano and R.J. Schaefer, J. of Materials Science 35 (2000) p 1641-1659

Possible mechanism for LAB formation during cooling.



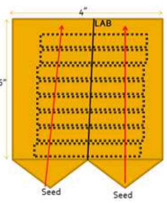
Tilt is the misorientation of the primary dendrite growth direction. Twist is a secondary rotation about the primary dendritic arms. Previous studies have only looked at the effects of primary (tilt) misorientation on properties.

Project Goal:

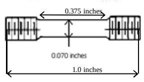
To characterize the effects of low angle boundaries on CMSX-4 mechanical properties including secondary (twist) misorientationl.

Experimental Procedure

Bicrystal slabs of CMSX-4 (composition below) with different misorientations varying the tilt and twist were cast using seed crystals (right). The misorientations are shown below. Mechanical test bars were cut transverse to the LAB – shown in the schematic to the right. Elemental composition o f CMSX-4 is shown below.



Cr	Co	Mo	Re	W	Al	Ti	Ta	Hf	Ni
6.5	9	0.6	3	6	5.6	1	6.5	0.1	Bal



Total misorientation calculated assuming it approximately followed a Pythagorean trend

Slab	Tilt	Twist	Total
K 1-3	3.1	1.7	3.5
E 1-2	5.9	3.4	6.8
L 1-2	6.1	0.7	6.1
F 1-2	8.0	5.3	9.6
D 1-2	8.1	6.8	10.6

Elevated temperature tensile and stress rupture testing under the conditions below were conducted using three specimens per condition.

Elevated Temperature Tensile 871°C (1600°F)
Low-Temp Stress Rupture 871°C (1600°F) 606 MPa (88 ksi)
High-Temp Stress Rupture 1093°C (2000°F) 148 MPa (21.5 ksi)

Hot Corrosion and Oxidation Testing

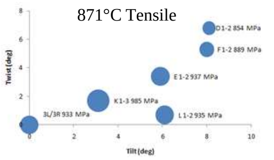
Scrap pieces from the test slabs were cut to contain a LAB and type II corrosion testing was performed. A 0.7 wt% Na_2SO_4 salt solution was sprayed to a density of 0.075 mg/cm^2. Samples were placed in a furnace at 700°C in an atmosphere of SO_2 catalyzed to SO_3 gas. Samples ran for a total of 125 h in 50 h cycles with salt resprayed after each cycle.

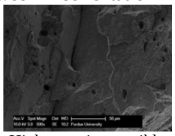
Additional samples were cut from the slabs for oxidation testing. Samples were polished to a 6μm finish and placed into a furnace preheated to 1000°C for 24 and 120hrs.

Results

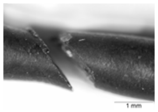
Tensile

The first graph isolates tilt and twist and shows the 0.2% offset yield strength. Due to inseparable variables the rest of the data is plotted as total misorientation. The second plot shows total misorientation versus the 0.2% offset yield and ultimate tensile strengths. The secondary axis shows the slight downward relationship between misorientation and percent elongation.

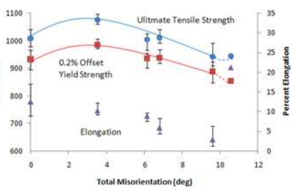




High porosity possible failure mechanism

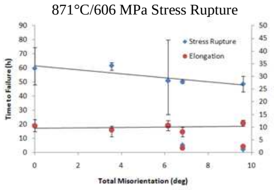


E 1-2 sample showing fracture near a 45° angle along the most favorable slip plane.

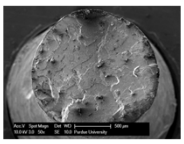


Stress Rupture

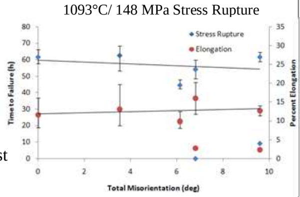
The graphs show stress rupture lifetime versus total misorientation for each condition with only a small downward trend for the 871°C/606 MPa test and no significant trend for the 1093°C/148 MPa test. The lone points are tests that failed at much shorter lives and are not included in the average life.



F 1-2 sample showing interdendritic failure.

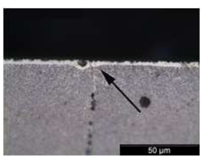


3R showing a smooth fracture surface in contrast to the interdendritic morphology



Hot Corrosion and Oxidation

Hot corrosion specimen (E 1-2) showing the intersection of a LAB with the surface exposed to salt with scale thickness of 31.2 μm; the arrow points to the intersection. No preferential attack can be observed.



Oxidation specimen (F 1-2) showing the intersection of a LAB and the oxidized surface with scale of 3.1 μm. There is no apparent preferential attack of the material at the boundary.

Discussion

Tensile

Tensile properties decreased as a near linear function of grain boundary total misorientation, which follows trends previously observed[1,2] for low-angle boundaries. The elevated tensile test exhibited a 50 MPa drop in ultimate tensile strength, a 0.2% offset yield strength at the greatest misorientation, and elongation generally decreased with increasing LAB misorientation. Previous studies[1,2] indicate that a significant decrease in mechanical properties occur with greater than 9-10° of misorientation of the LAB.

The effects of tilt versus twist could not be independently quantified due to the absence of control slabs increasing one misorientation direction without a secondary misorientation present. Study of the fracture surface indicates the specimens did not fracture at the LAB.

Stress Rupture

There is no discernible trend in the stress rupture data with respect to increasing misorientation. It may be noted that there is not a significant decrease in properties but more investigation may be necessary. Studies[1] have shown that creep properties follow a downward trend similar to the tensile properties; however, this was not replicated with these tests. Similar to tensile fracture, stress rupture fracture surfaces are not preferential to the LAB.

Hot Corrosion and Oxidation

No preferential attack of the LAB was observed in either oxidation or corrosion tests. The specimens tested developed a uniform scale with no apparent attack specific to the low angle grain boundary. This result, along with further testing, may eliminate the theory of corrosive attack at the boundaries as a possible mode of failure for turbine blades.

Future Work

Additional test slabs and data are needed to draw more definite conclusions regarding the observed trends. In each condition, a maximum of only three data points were collected. More samples and tests would contribute to a larger statistical sampling and a more accurate standard deviation. Fatigue testing may also be performed to analyze the effects of LABs on single crystal CMSX-4 properties.

Future slabs can be cast with negligible twist and increasing tilt and vice versa to quantify independently their effects. Also, the slabs could be hot isostatic pressed to reduce the possible porosity effects on the properties. Smaller slabs would reduce the probability of additional casting defects.

References

1) Shah, Dilip and Cetel, Alan. "Evaluation of PWA1483 for Large Single Crystal IGT Blade Applications." Pratt & Whitney. Hartford, CT. 2010.
2) J.R. Li, J.Q. Zhao, S.Z. Liu, & M. Han. "Effects of Low Angle Boundaries on the Mechanical Properties of Single Crystal Superalloy DD6." National Key Laboratory of Advanced High Temperature Structural Materials & the Beijing Institute of Aeronautical Materials. Beijing, China. 2008.