Slow Strain Rate Tensile Testing to Assess the Ability of Superalloys to Resist Environment-Assisted Intergranular Cracking

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Statement of Problem

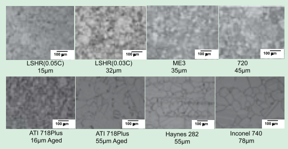
- Increased application temperatures of turbine disks in jet engines can activate dwell fatigue-environment interactions (Ref. 1 and 2).
- Intergranular crack initiation and propagation are often observed at 650 °C and higher, reducing life.
- Fatigue tests with dwells of stress on notched and precracked specimens are often used to study this, which is expensive and time consuming.
- Low-cost alternative tools are needed to more rapidly screen the susceptibility of varied disk superalloys to this cracking.
- Energy and petro-chemical industries utilize slow strain rate tensile tests (ASTM G129–06) to assess materials' resistance to intergranular cracking in corrosive environments (Ref. 3).
- Could such an approach be applied to assess the propensity for intergranular cracking of disk superalloys in air?

Objectives

- Evaluate the effects of varied disk alloy composition and microstructure on environment-assisted cracking at high temperature using tensile tests.
- Utilize uniform gage specimens to minimize cost and avoid complex competition at notches of inelastic hardening, creep, and stress relaxation, which all can influence cracking.
- Determine if variations of tensile strain rates and associated test durations of 10,000x influence propensity for intergranular cracking in air.

Materials Evaluated

- Powder metal (PM) and cast and wrought (CW) superalloys
- Recommended heat treatments shown and supplementary heat treatments also included
- Baseline grain sizes of 15 to 78 µm and supplementary grain sizes



Materials Evaluated

- PM and CW superalloys
- All strengthened by γ′ precipitates
- Cr: 12.3 to 24.31 wt%

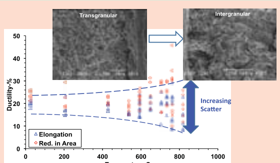
	Alloy - wt.%	Al	B	C	Co	Cr	Fe	Mn	Mo	Ni	Nb	O	S	Si	Ta	Ti	V	W	Zr
PM	LSHR (0.03C)	3.46	0.028	0.029	20.70	12.52	0.070		2.73	Bal.	1.45		<.001	0.030	1.60	3.50		4.33	0.049
PM	LSHR (0.05C)	3.54	0.027	0.045	20.40	12.30	0.068	0.001	2.71	Bal.	1.49	0.018	<.001	0.012	1.52	3.45	0.006	4.28	0.049
PM	ME3	3.40	0.025	0.050	20.70	12.8			3.80	Bal.	0.9		<.001		2.30	3.70		2.00	0.05
PM	Udimet 720	2.52	0.019	0.025	14.6	16.3	0.05		2.98	Bal.		0.001	<.001	<.010		5.05		1.31	0.03
CW	ATI 718Plus	1.45	0.002	0.022	8.88	17.94	9.36	0.05	2.66	Bal.	5.39	<.001	<.001	0.05		0.72	0.012	0.94	0.008
CW	Haynes 282	1.57	0.001	0.057	9.86	19.49	0.25	0.03	8.08	Bal.		<.001	<.001	0.04		1.96			
CW	Inconel 740	0.91		0.028	19.84	24.31	0.42	0.24	0.47	Bal.	1.95	<.001	<.001	0.48		1.67			0.02

Procedures

- Machined conventional uniform gage tensile specimens that were low stress ground, with gage sections then polished parallel to the loading direction for assessing potential surface cracking.
- Tensile tests were performed at 704 °C in air using a resistance heating furnace. Several comparative tests were also performed in vacuum:
  - "Fast" tensile tests were performed at an average strain rate of 0.7 s^{-1}: duration 0.1 to 0.32 s.
  - "Slow" tensile tests were performed at an average strain rate of 0.00008 s^{-1}: duration of 620 to 3320 s.
- Gage sides and fracture surfaces were then evaluated for intergranular cracking.

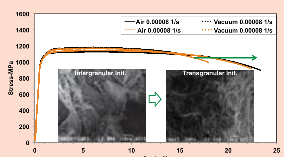
Tensile Tests Can Activate Intergranular Cracking in Air: e.g., ME3

- Conventional tensile tests—ASTM E21–09 (0.00008 → 0.0008 s^{-1})



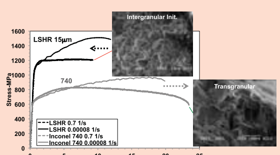
Tensile Response Changed With Environment: e.g., ME3

- ME3 had increased elongation and elimination of intergranular surface cracking in vacuum

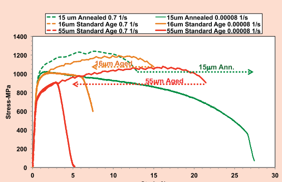


Tensile Response Changed With Strain Rate: e.g., LSHR(0.05C), Inconel 740

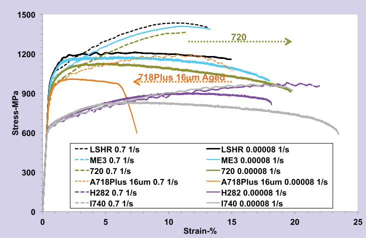
- Decreased strain rate (0.7 → 0.00008 1/s) reduced strength, and also could affect elongation and encourage intergranular cracking



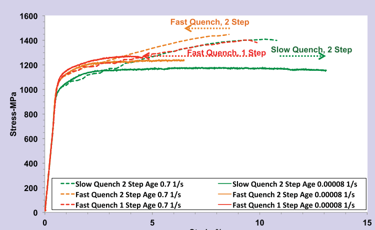
Varied Microstructure Influenced This Changed Strain Response: e.g., 718Plus



Comparison of the Superalloys With Their Recommended Heat Treatments



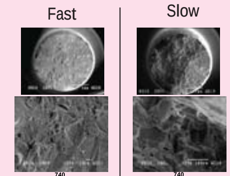
Comparison for Varied Quench, Aging Heat Treatments: LSHR(0.03C) at 32 µm



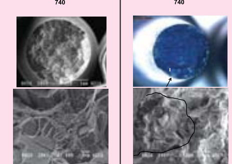
Failure Modes Progressively Changed

Fast | Slow

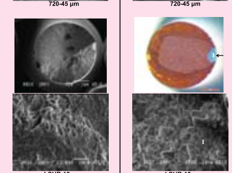
No Intergranular Cracking: 718Plus Annealed, Inconel 740



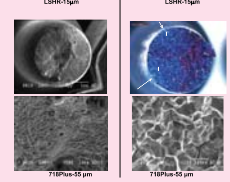
Noncritical Intergranular Cracking: H282, 720-45 µm



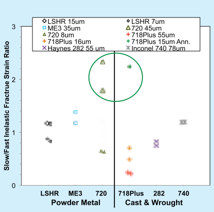
Intergranular Cracking Initiating Failure: LSHR, ME3, 720-8 µm



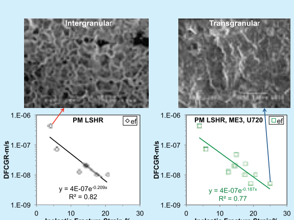
Intergranular Failure: 718Plus-16 µm, 55 µm



Slow/Fast Tensile Strain Ratios Varied



Tensile vs. Dwell Fatigue Crack Growth



Summary of Results

- Tensile tests at fast versus slow strain rates were used to compare the effects of varied alloy composition and heat treatment on environment-assisted cracking of several PM and CW superalloys.
  - Intergranular surface cracking occurred in air for many of the alloys in slow strain rate tensile tests.
- More extensive intergranular surface cracking occurred for specimens having lower inelastic fracture strains.
  - This occurred for materials and heat treatment conditions having high dwell fatigue crack growth rates.

Conclusions

- Fast versus slow strain rate tensile testing can discriminate the air environment-controlled failure mode responses of powder metal (PM) and cast and wrought (CW) superalloys.
  - Response can vary with strain rate, environment, composition, and microstructure.
- The ductility of PM and CW superalloys can be limited at low tensile strain rates, due to air environment-assisted intergranular surface cracking.
  - Inelastic fracture strains can correlate with dwell fatigue crack growth rates.
- A material's sensitivity to air environment-controlled intergranular cracking can be screened using this test methodology, as a one low-cost, first-tier screening tool.

References

1. A. Pineau, S. D. Antolovich, "High Temperature Fatigue of Nickel-Base Superalloys-A Review With Special Emphasis on Deformation Modes and Oxidation," Engineering Failure Analysis, Vol. 17, 2009, pp. 2668-2697.

2. D. A. Woodford, "Gas Phase Embrittlement and Time Dependent Cracking of Nickel Based Superalloys," Energy Materials, Vol. 1, No. 1, 2006, pp. 59-79.

3. ASTM G129-00(2013), "Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking," ASTM Book of Standards, Vol. 03.02, 2013.

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