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Creep, fatigue and environmental interactions and their effect on crack growth in superalloys

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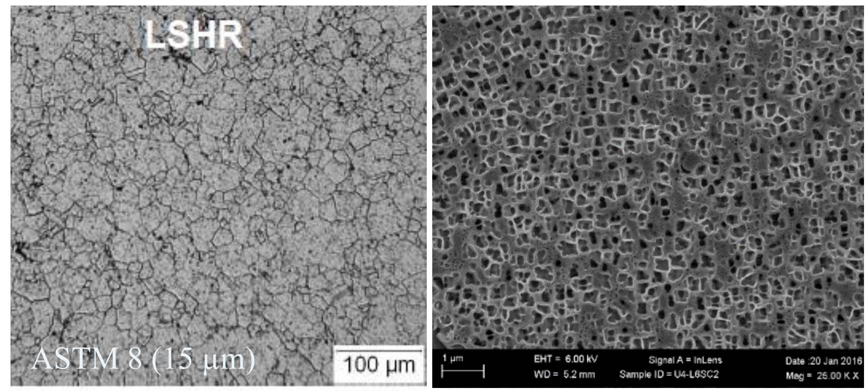
Presentation Overview

- Complex interactions of creep/fatigue/environment control dwell fatigue crack growth (DFCG) in superalloys.
- Crack tip stress relaxation during dwells significantly changes the crack driving force and influence DFCG.
- Linear Elastic Fracture Mechanics, Kmax, parameter unsuitable for correlating DFCG behavior due to extensive visco-plastic deformation.
- Magnitude of remaining crack tip axial stresses controls DFCG resistance due to the brittle-intergranular nature of the crack growth process.
- Proposed a new empirical parameter, Ksrf, which incorporates visco-plastic evolution of the magnitude of remaining crack tip stresses.
- Previous work performed at 704°C, extend the work to 760°C.

Experimental

Material: Low Solvus High Refractory (LSHR) P/M nickel-base disk alloy

Wt. %	Al	B	C	Co	Cr	Mo	Ni	Nb	Ta	Ti	W	Zr
LSHR	3.5	.03	.045	20.4	12.3	2.7	Bal.	1.5	1.5	3.5	4.3	0.05



Four Supersolvus Heat Treatments Evaluated

Condition	Cooling Rate (°C/min)	Aging Treatment	Thermal Exposure
FC+2SA	202°C/min	855°C/4 h +775°C/8h	None
SC+2SA	72°C/min	855°C/4 h +775°C/8h	None
FC+2SA+440	202°C/min	855°C/4 h +775°C/8h	815°C-440 h
SC+2SA+440	72°C/min	855°C/4 h +775°C/8h	815°C-440 h

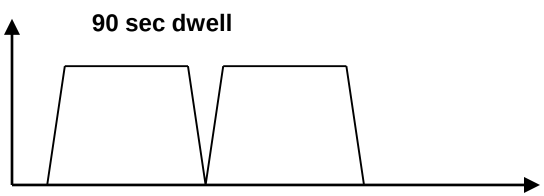
Testing performed at 704 °C and 760°C

Baseline FCG Testing:

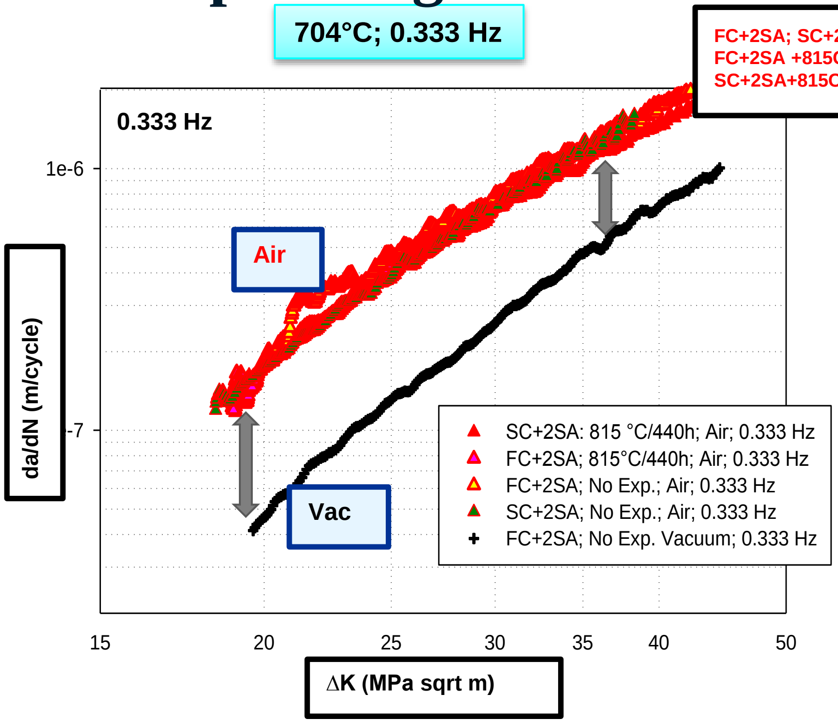
- Cyclic FCG in Air and Vacuum; 0.333 to 30 Hz
- Dwell FCG in Air and Vacuum; 90 sec hold at σ_{max}
- Specimen Geometry: Surface Flaw (KB bar)

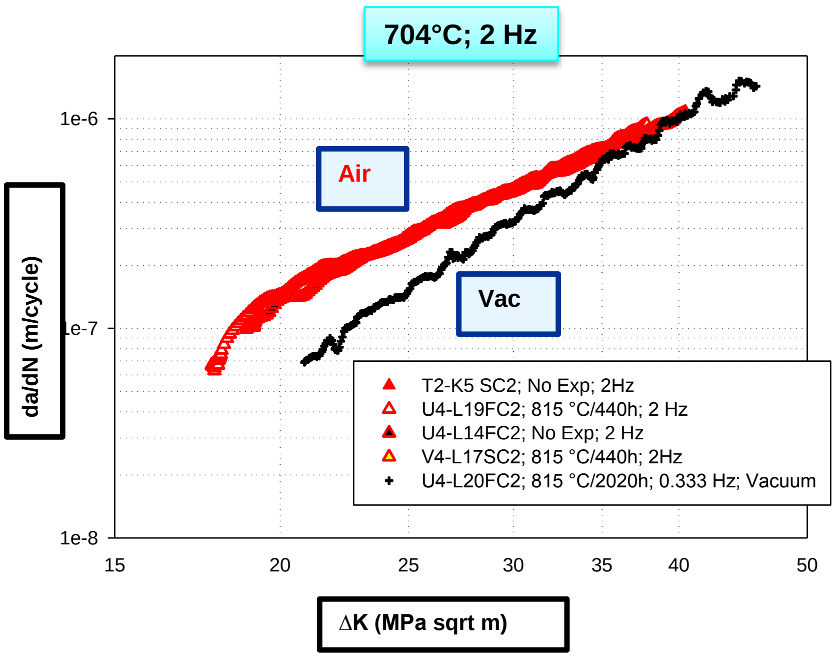
Baseline Stress Relaxation Testing:

- Strained to 1% total strain
- Stress relaxation measured for 100 h.
- Specimen: Cylindrical (4.05 mm diam.)



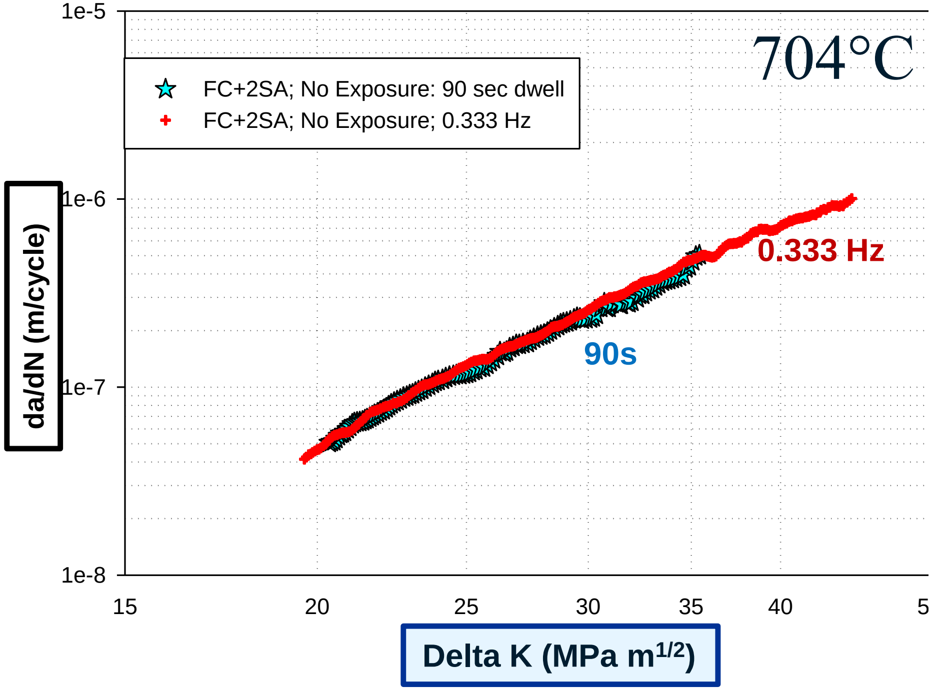
Separating Environmental Effects from Stress Relaxation



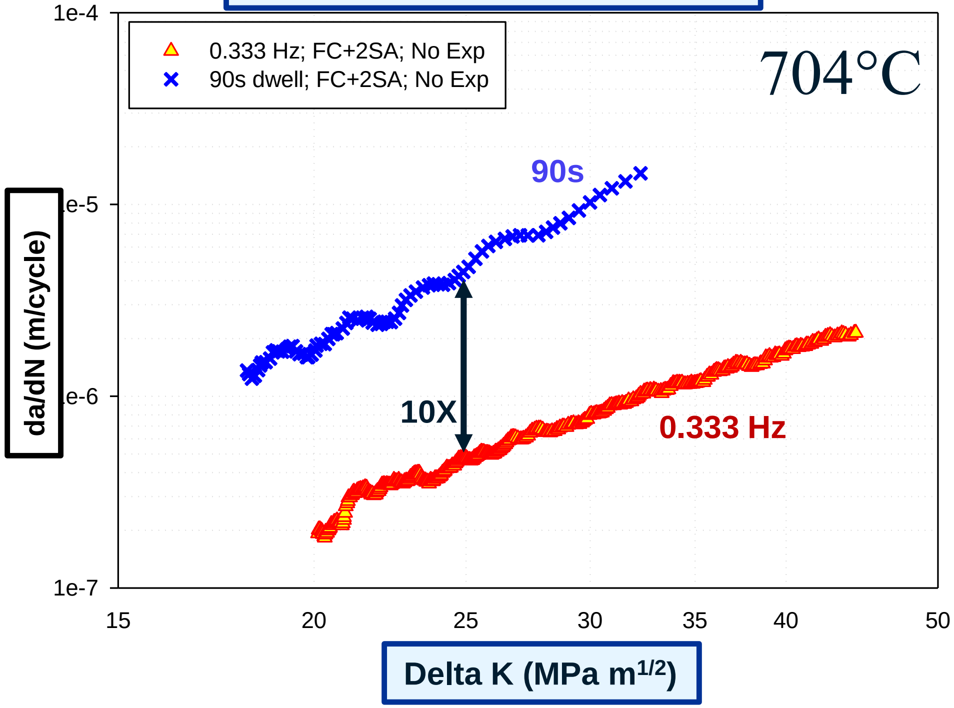


- All four conditions show faster cyclic FCGR in air than in vacuum – environmental debit.
- All conditions exhibited similar FCG resistance behavior but environmental effect is smaller at higher frequency.
- Assume these conditions posses similar *intrinsic* environmental resistance.
- Any differences in their dwell FCG resistance are then due to stress relaxation effects.

Vacuum: Cyclic vs Dwell

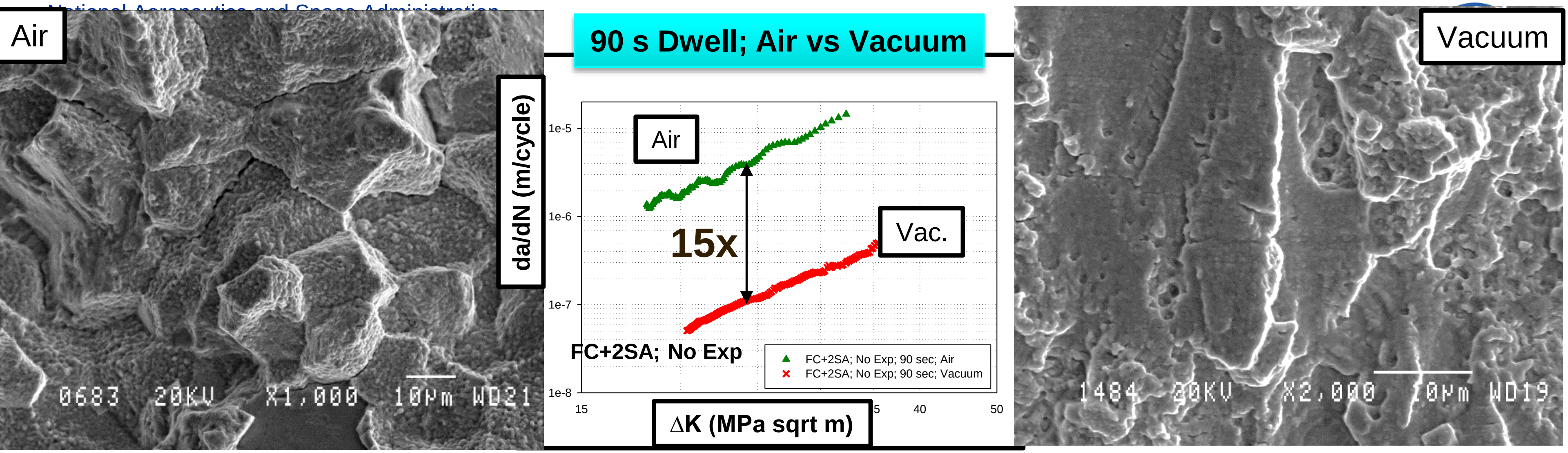


Air: Cyclic vs Dwell

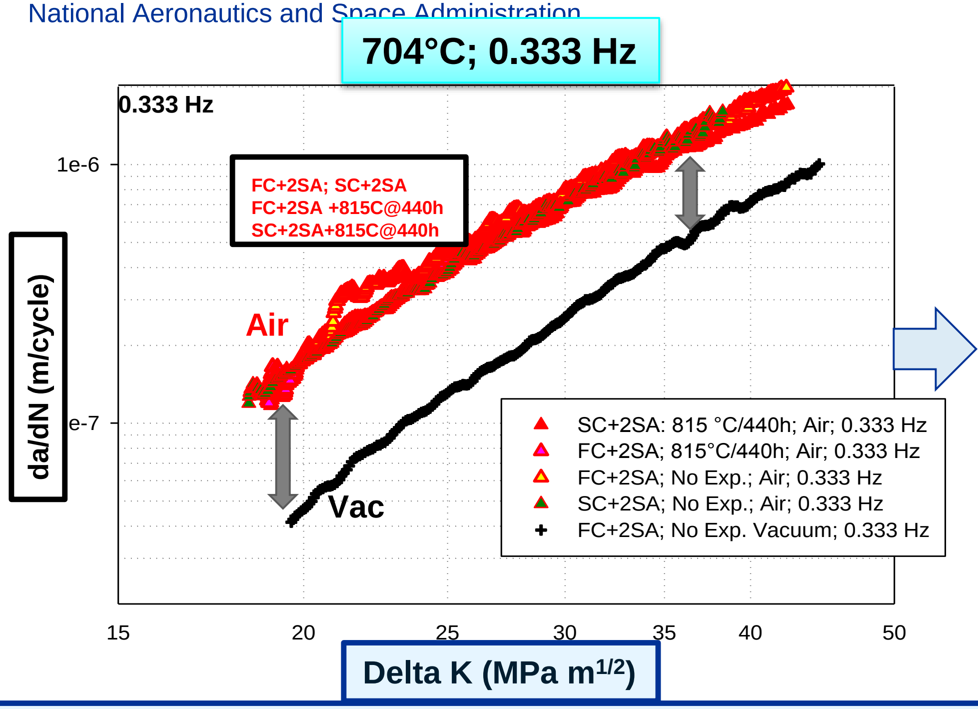


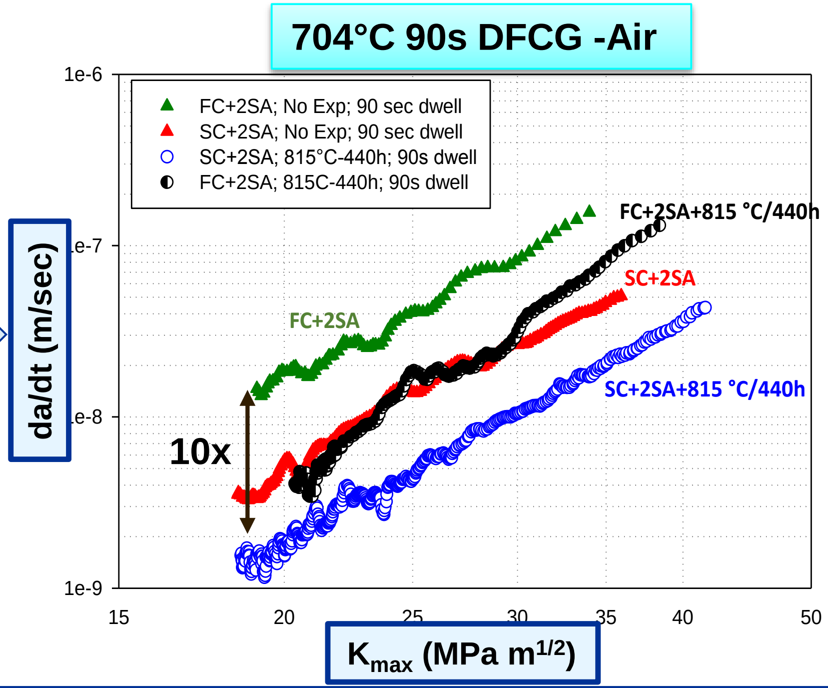
At 704°C:

- **90 sec dwell FCG rates in vacuum same as cyclic FCG in vacuum – *No Dwell Debit***
- ***Creep crack growth does not contribute towards dwell crack growth***
- **An order of magnitude increase in DFCG in air due to environmental damage**



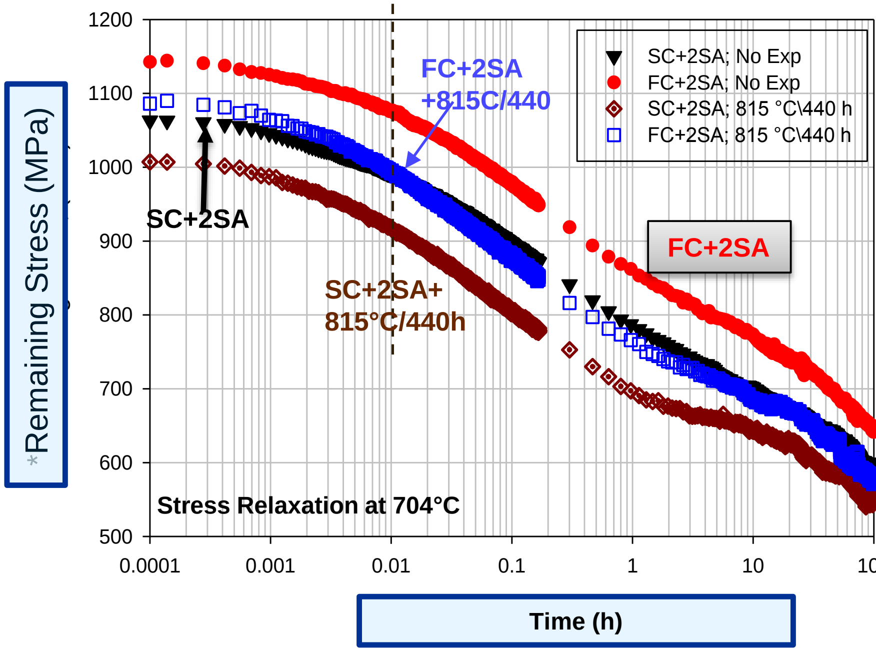
- **Brittle-intergranular failure mode was operative in air for 90 sec dwell.**
- **Only transgranular failure mode operative in vacuum. No evidence of grain boundary sliding or microvoid coalescence found (classical creep crack growth did not directly contribute to DFCG).**
- **Grain boundaries are strong! Cracks avoid growth along grain boundaries when environmental embrittlement or creep mechanisms are <u>not</u> operative.**

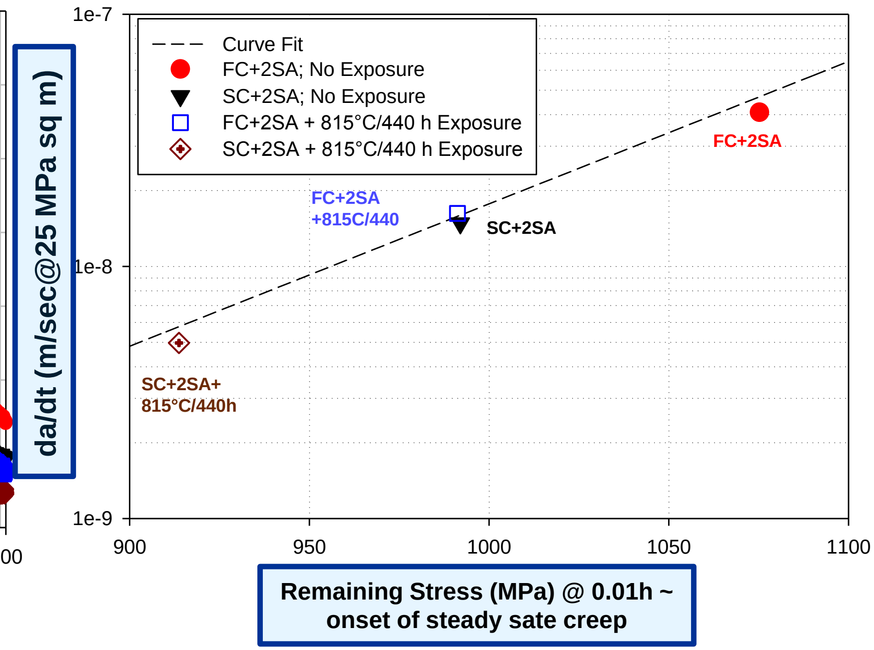




- **Four heat treatments: similar env. resistance → 10x difference in DFCG.**
- **"Creepier heat treatments" i.e. slower cooling rates and thermal exposures improve DFCG resistance.**
- **Environmental resistance similar – DFCG differences due to stress relaxation.**
- **LEFM Kmax parameter unsuitable for correlating visco-plastic influenced DFCG response.**

Relationship Between Stress Relaxation and DFCG





- Stress relaxation stresses decrease with slower cooling rates and ↑thermal exposure.

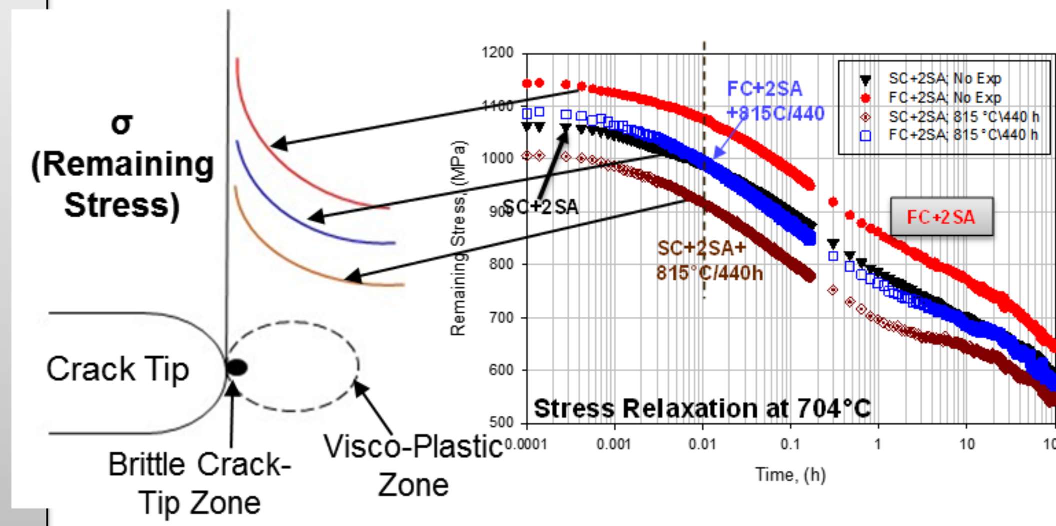
- Remaining stresses closely correlate with dwell fatigue crack growth
Yet… Classical creep propagation mechanisms DO NOT contribute to crack growth

- **Why is magnitude of remaining stresses important? What governs the relationship?**

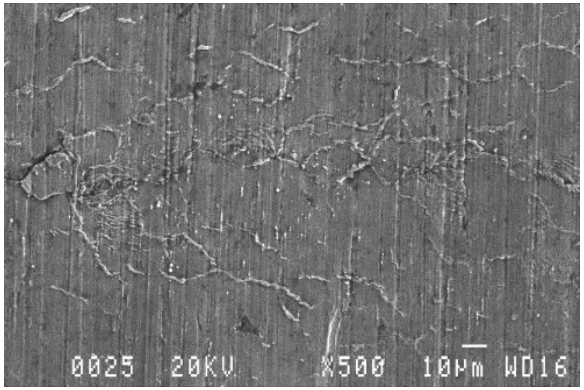
*Remaining Stress = Relaxation Stress

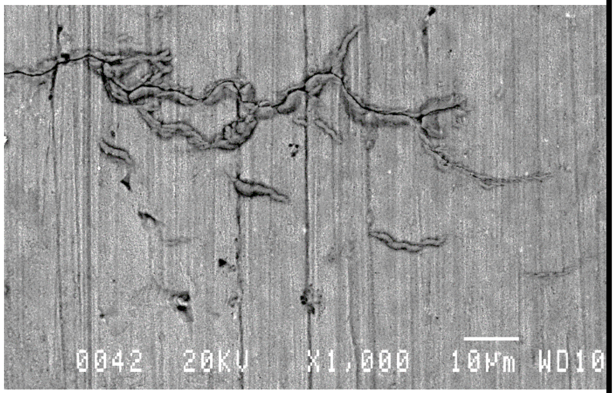
DFCG Failure Mechanism

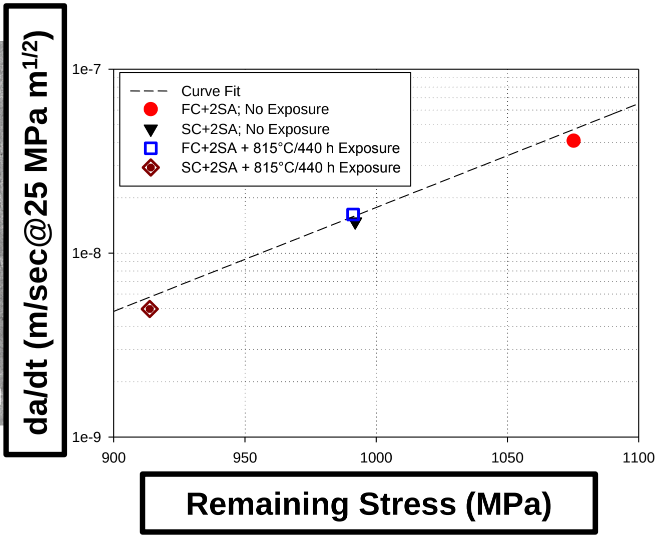
- Cracks grow through brittle-intergranular process controlled by crack tip tensile stress
- Magnitude of crack tip tensile stress controls DFCG propagation rates
- Stress relaxation behavior sets the magnitude of crack tip tensile stresses
- Strong, yet indirect relationship between stress relaxation and DFCG behavior



Embrittled crack tip region – Interrupted 90s dwell tests

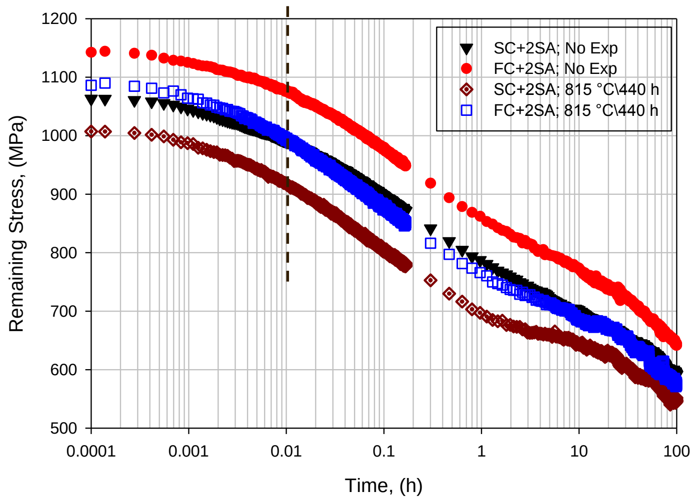






New Empirical Parameter for Modeling Dwell Crack Growth in Air

Approach: Use stress relaxation results to simulate and normalize the differences in the crack tip tensile stresses under visco-plastic conditions



$$Ksrf = Kmax/SRF$$

K_{srf}* – modified stress intensity factor normalized by *SRF

K_{max}* – *Applied LEFM stress intensity factor during dwells

$$SRF = (\sigma_0/\sigma_m)^4$$

SRF= stress relaxation factor

σ_o= remaining stress at the onset of steady state creep (highest remaining stress condition)

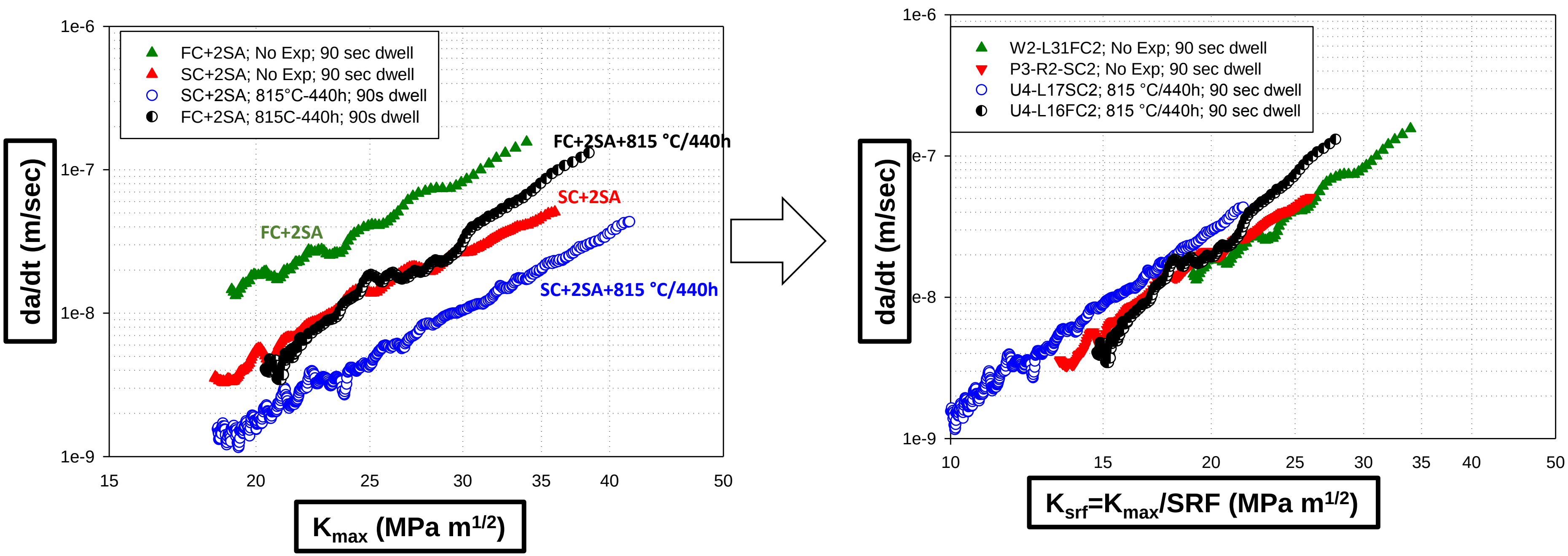
σ_m= remaining stress for other conditions – onset of steady state creep

$$\dot{\varepsilon} = A\sigma^{n1}t^m + B\sigma^{n2}$$

n2= 4 (steady state creep component per the relaxation fit)

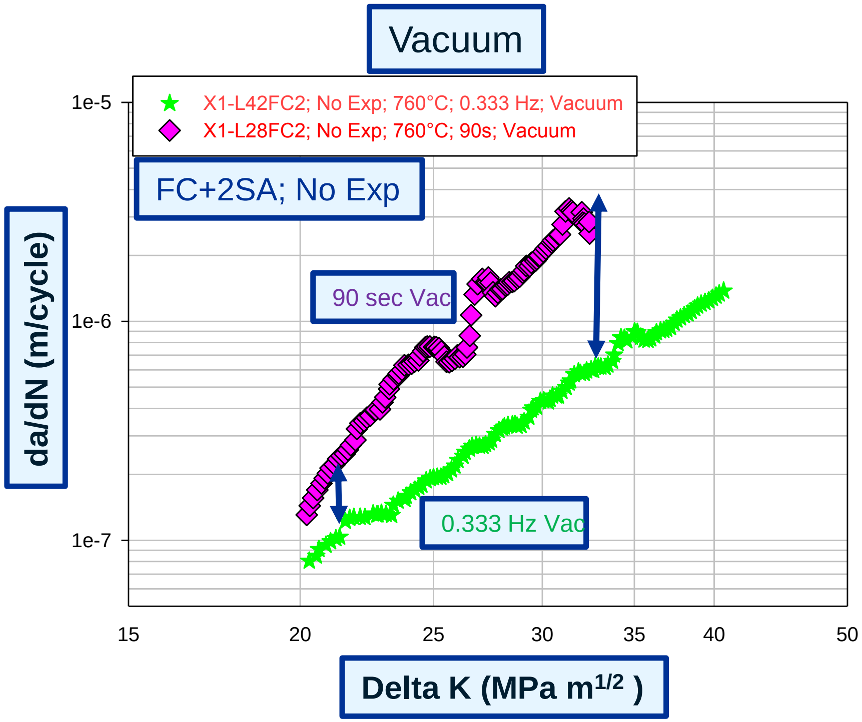
New Empirical Parameter for Modeling Dwell Crack Growth in Air

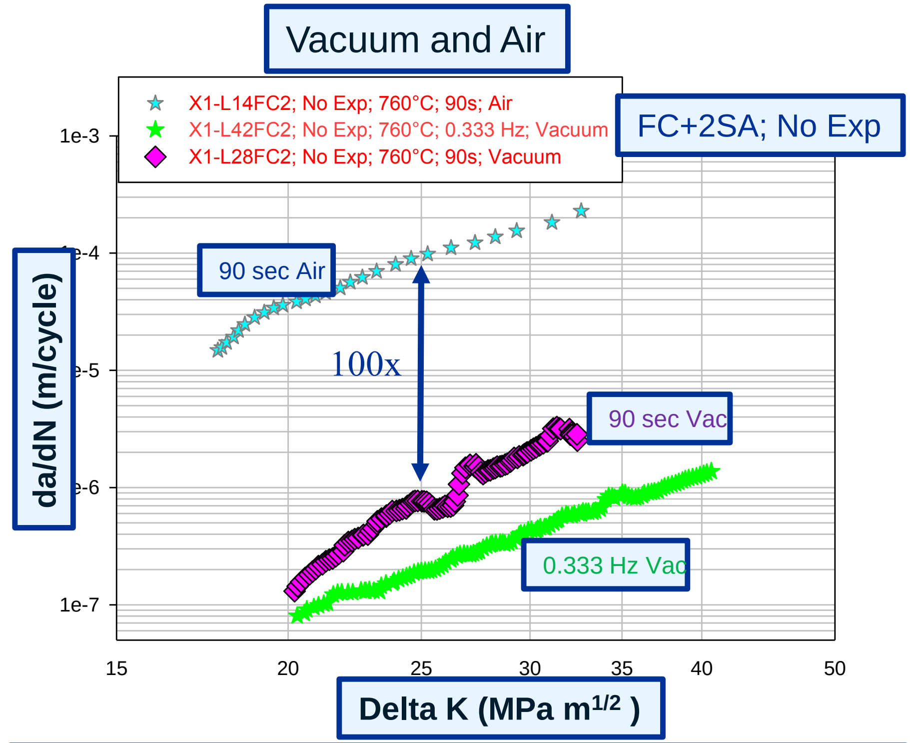
Plots of da/dt vs K_{max} and K_{srf} : 704°C



• New Ksrf parameter able to compensate for a 10x spread in DFCG rates using standard LEFM parameter.

DFCG in Vacuum and Air – Behavior at 760°C



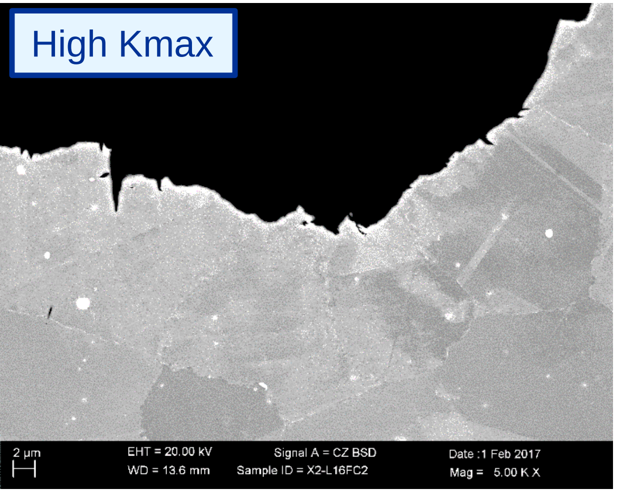


- In contrast to 704°C, creep crack growth occurs in vacuum at 760°C
- More significant at high ΔK → increase in crack tip plasticity

- DFCG in air 100x faster than in vacuum.
- Environmental degradation is predominant…. Ksrf approach may still be applicable.

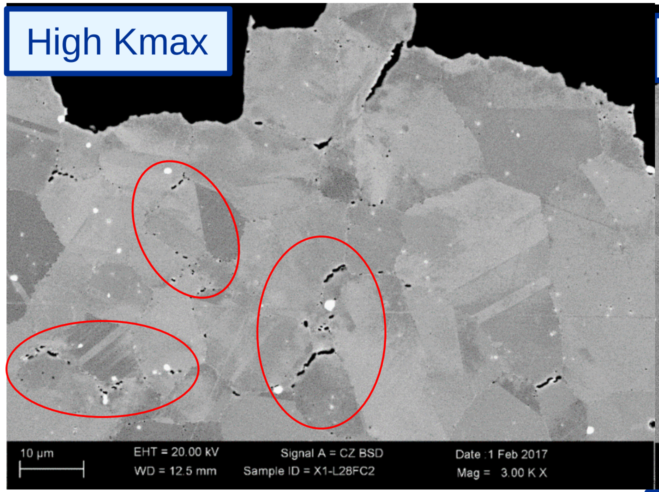
Comparison of Microstructural Damage Mechanisms

704°C – 90 sec; Vacuum



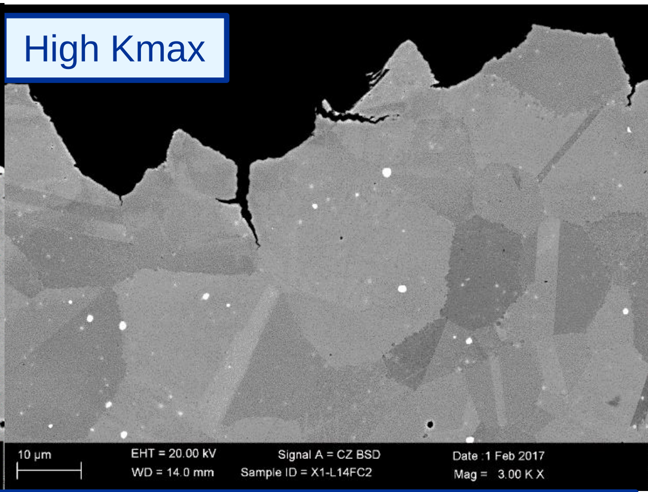
- Lower T. ; DFCG=Cyc FCG;
- No evidence of creep damage
- Transgranular failure mode

760°C – 90 sec; Vacuum



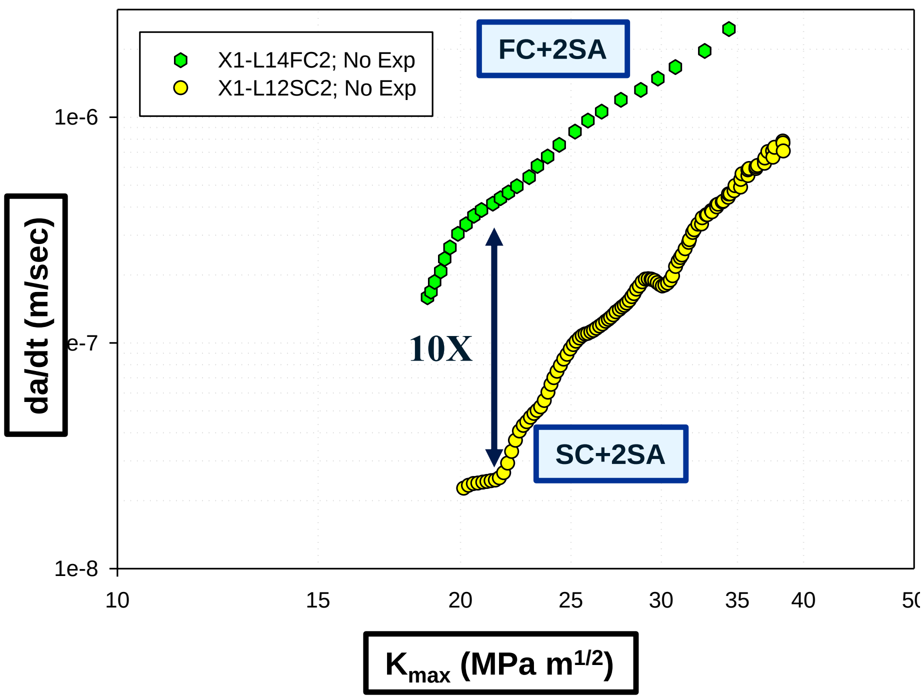
- High Temp; DFCG > CFCG
- Slow DFCG
- Grain boundary creep cavitation

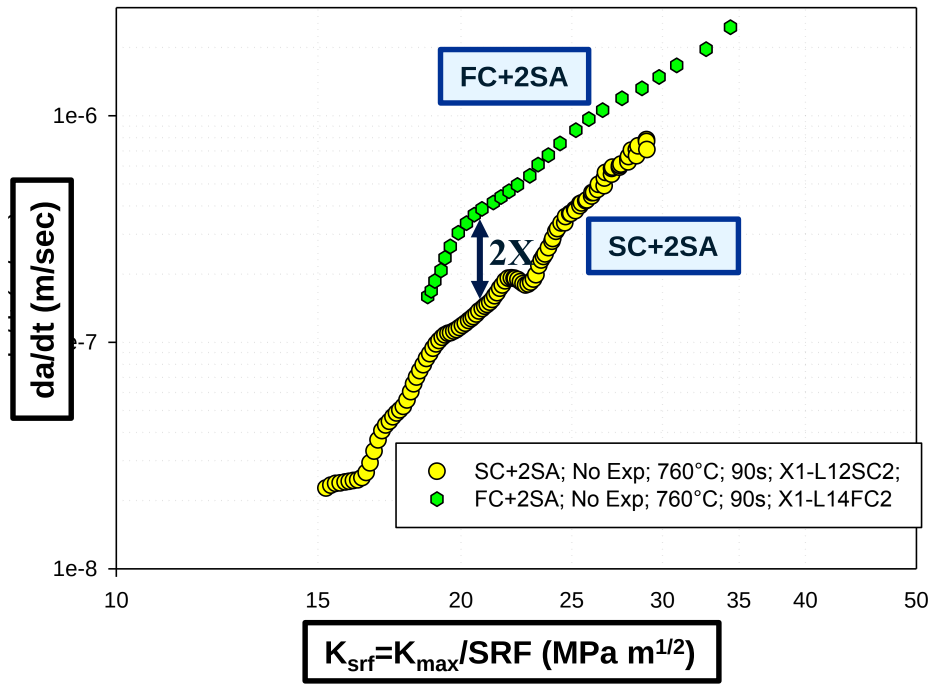
760°C – 90 sec; Air



- High T; DFCG>>CFCG
- Fast DFCG
- Environmentally induced intergr. failure mode dominant
- Inadequate time for creep cavitation

760°C DFCG; K_{max} vs K_{srf}





- Identical methodology used to calculate K_{srf} as at 704°C
- K_{srf} correlated DFCG within 2X for FC+2SA and SC+2SA (no exposures)

- Other two conditions experienced likely specimen mixup at the vendor…No agreement between stress relaxation repeats, sorting out the issues…

Conclusions

- **A new empirical parameter, Ksrf, proposed to correlate DFCG in superalloys.**

- **The new parameter modifies LEFM_Kmax parameter by accounting for differences in visco-plastic evolution of the magnitude of remaining crack tip axial stresses.**

- **Magnitude of remaining crack tip axial stresses controls DFCG resistance due to the brittle-intergranular nature of the crack growth process.**

- **The parameter works well at 704°C and looks promising even at 760°C.**

- **Creep crack growth mechanisms are active at 760°C but are still considerably lower than the environmentally induced DFCG debit.**

Acknowledgment

Special acknowledgment to Mr. Andrew Ring for his excellence and diligence in performing a multitude of complex mechanical testing.