

内燃机活塞铝硅合金疲劳寿命预测方法

Fatigue life prediction method of Al-Si piston alloy for internal combustion engine

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Shi Changxu Innovation Center for Advanced Materials

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研究背景

Research background



实验材料和方法

Experimental materials and methods



高温低周疲劳性能优化与寿命预测

High-temperature LCF property optimization and life prediction



热机疲劳损伤机制与寿命预测方法

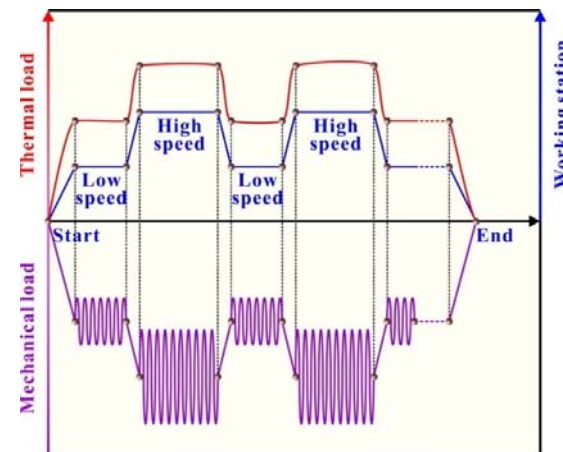
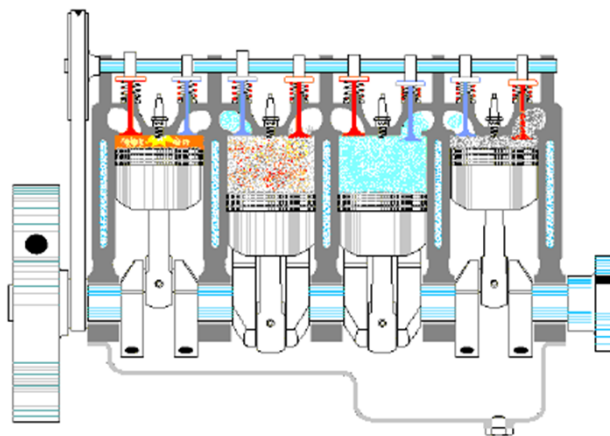
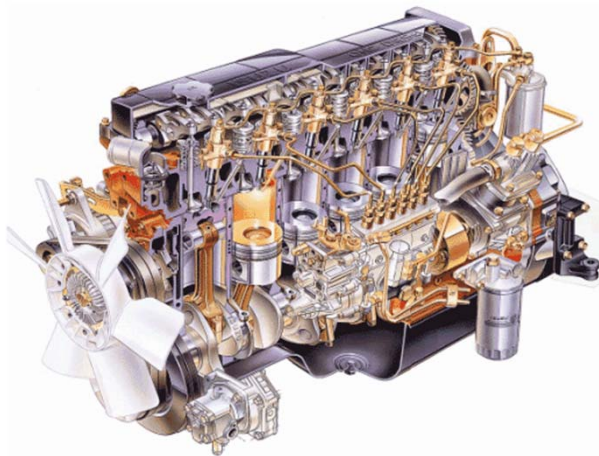
TMF damage mechanism and life prediction method



汇报小结

Summary

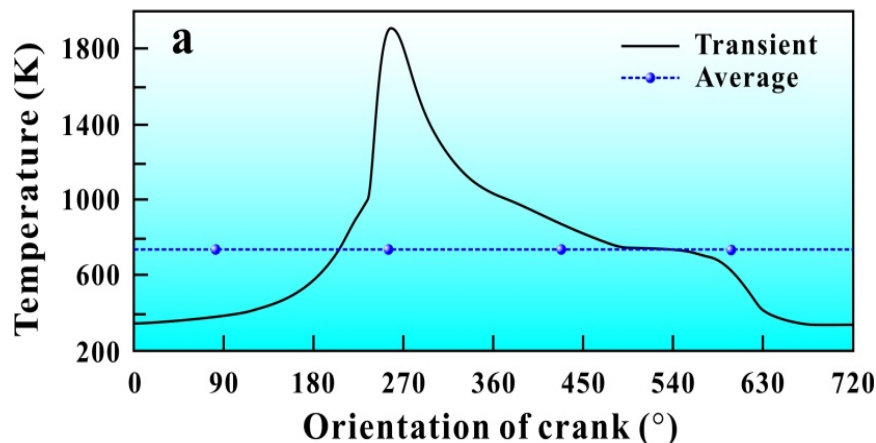
内燃机应用



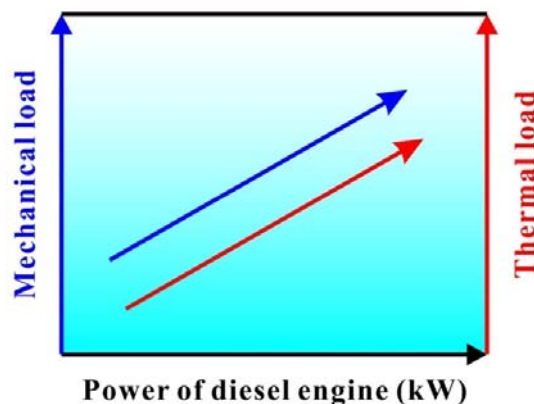
高效 高速 高温 高压

高可靠 长寿命 疲劳性能

活塞构件和性能分析



缸内燃气温度

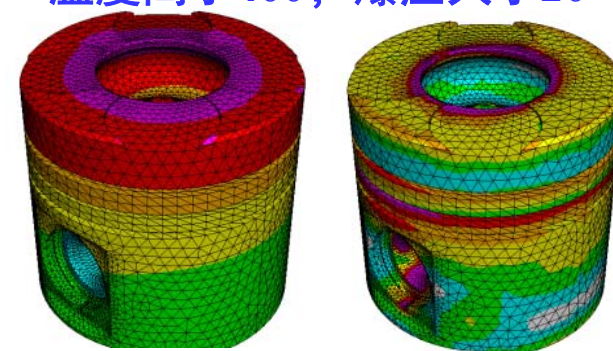


功率和机械热载荷的关系



典型构件失效分析

温度高于400；爆压大于20



温度应力仿真分析

材料要求

蠕变性能

高温强度

疲劳性能

铸造性能

密度重量

导热性能

线胀系数

经济性

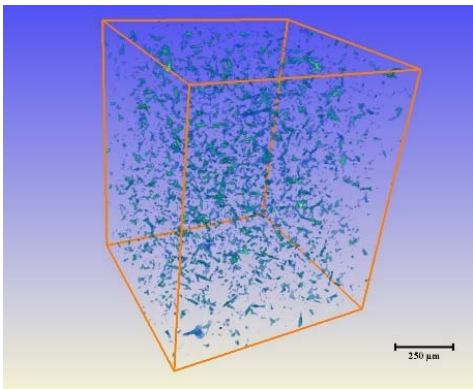
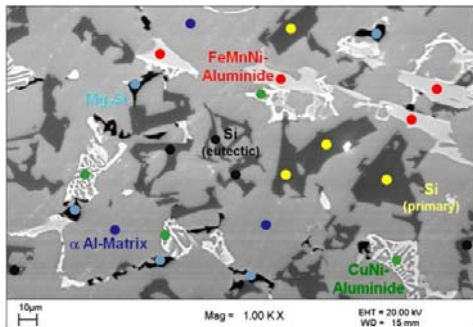
球墨铸铁

铸 钢

铝硅合金

复合材料

活塞构件材料微观组织



相名称	代号	晶体结构	E/GPa	热膨胀系数	显微硬度/GPa		析出温度 (°C)	稳定温度 (°C)
					25°C	350°C		
Al ₂ Cu	θ	四方	209.9	24.73	5.77	2.48	500	150~200
Mg ₂ Si	M	立方	80	28.95	5.63	1.77		
Al ₅ Cu ₂ Mg ₈ Si ₆	Q	六方	108.5	27.34	--	--	516	200~250
Al ₃ CuNi	δ	六方	205	23.52	10.45	6.46	517	350~400
Al ₇ Cu ₄ Ni	γ	三方	238.7	23.60	9.25	4.86	510	
Al ₃ Ni	ε	正方	245.8	24.60	5.95	3.54	542	
Al ₉ FeNi	T	单斜	235	26.17	7.71	5.83	545	
Al ₅ FeSi	β	单斜	189.6	--	--	--	560	

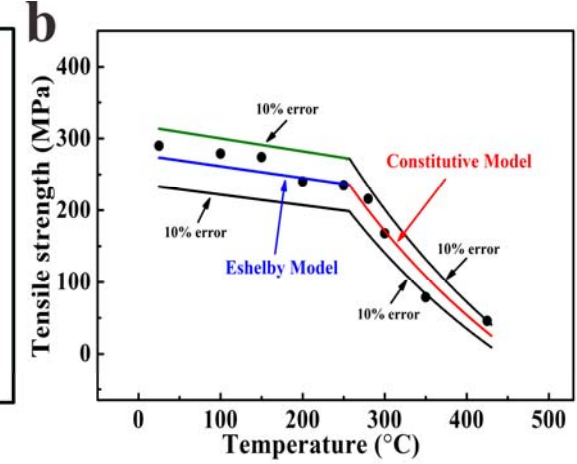
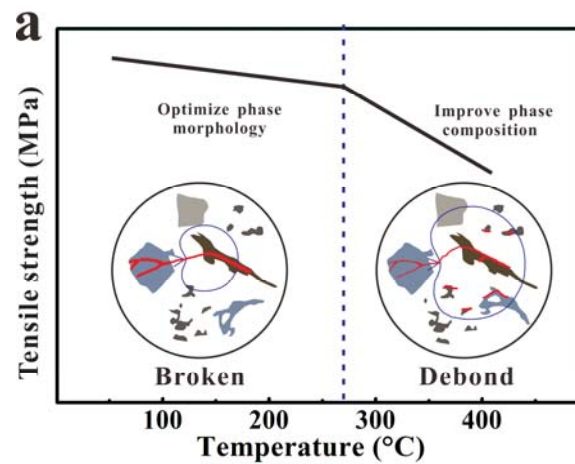
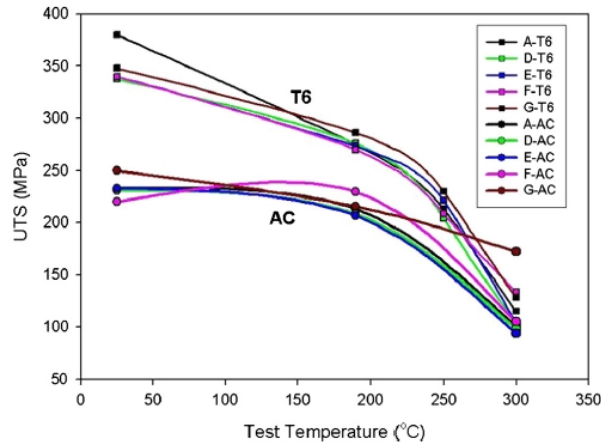
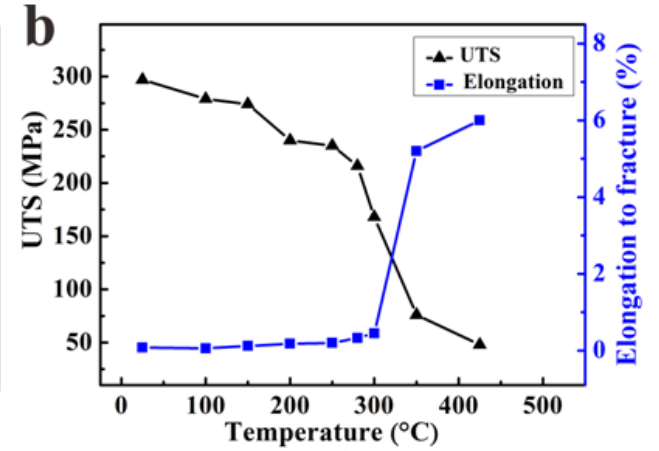
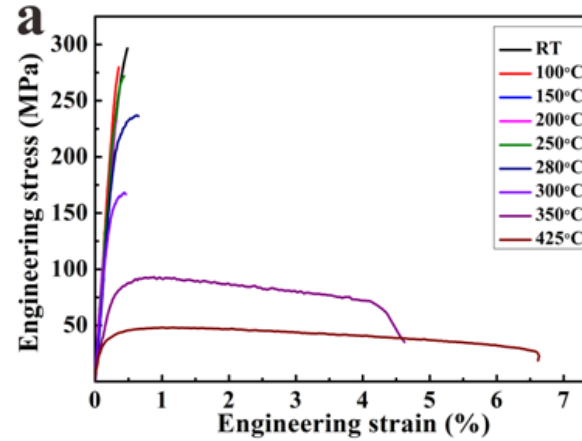
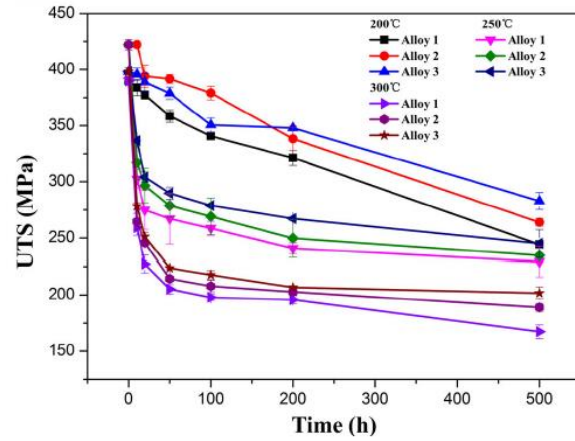
多种相

多尺度

热不稳定

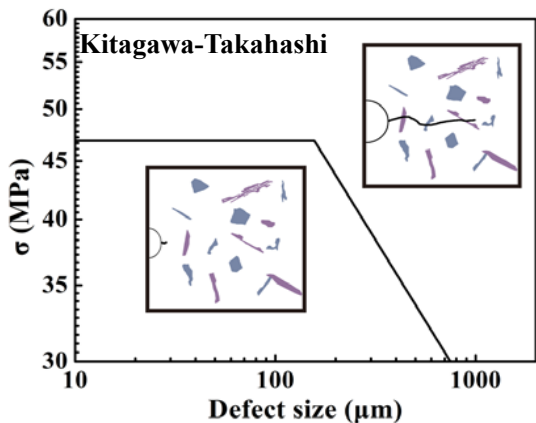
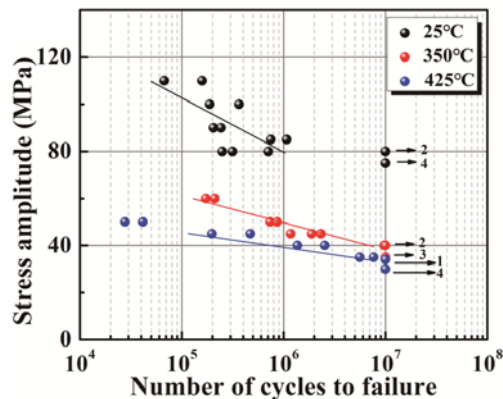
组织复杂可调控

铝硅材料拉伸行为与机制

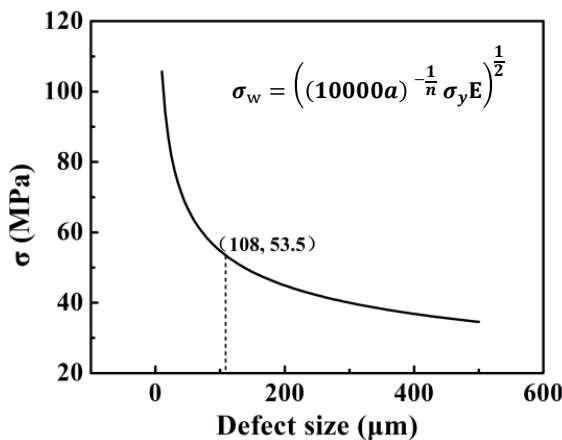
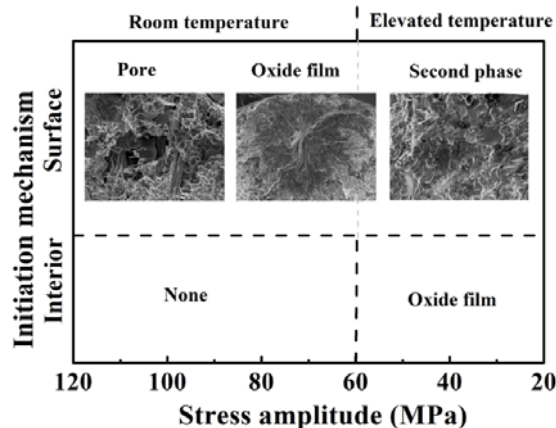


铝硅材料疲劳行为

不同温度高周疲劳

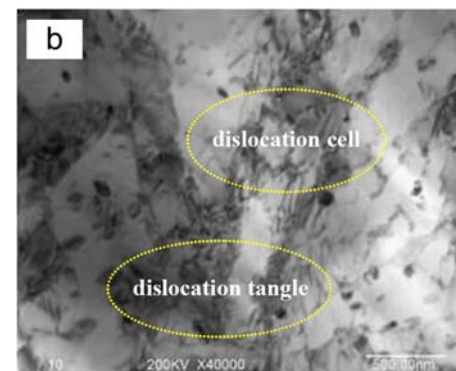
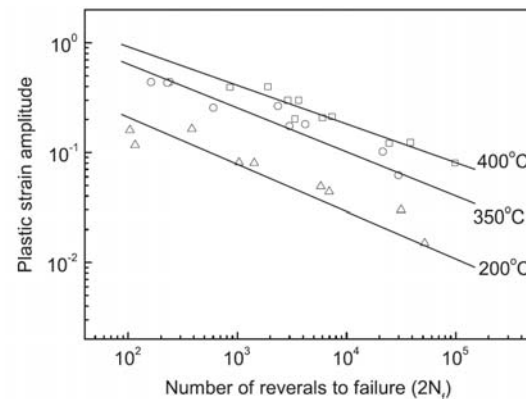


行为描述



机制分析

不同温度低周疲劳



复杂机制

简单方法

Basquin

$$\sigma_a = \sigma_f (2N_f)^b$$

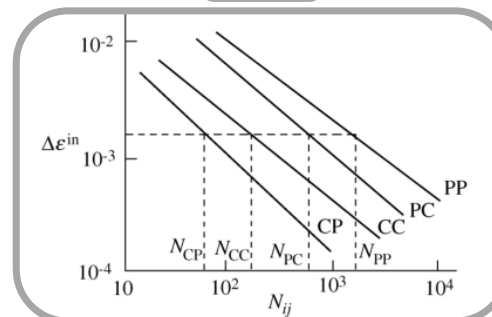
$$D_i = \frac{1}{N_f} = 2 \cdot \left(\frac{\sigma_a}{\sigma_f} \right)^{-1/b}$$

Coffin-Manson

$$\varepsilon_p = \varepsilon_f (2N_f)^c$$

$$D_i = \frac{1}{N_f} = 2 \cdot \left(\frac{\varepsilon_p}{\varepsilon_f} \right)^{-1/c}$$

SRP



Ostergren

$$\Delta W_T = \sigma_{\max} \cdot \Delta \varepsilon_p$$

$$N_f^\beta (\Delta W - \Delta W_0)^m = C$$

$$\sigma_{\max} \cdot \Delta \varepsilon_p \cdot N_f^\beta \cdot \nu^{\beta(k-1)} = C$$

Miller

$$\frac{da}{dN} = \left. \frac{da}{dN} \right|_{fatigue} + \left. \frac{da}{dN} \right|_{ox} + \left. \frac{da}{dN} \right|_{creep}$$

$$\left. \frac{da}{dN} \right|_{creep} = C_c \hat{C}^{mc} \left. \frac{da}{dN} \right|_{fatigue} = C_f \Delta J^{mf}$$

$$\left. \frac{da}{dN} \right|_{ox} = C_0 \Delta J^{m_0} \Delta t^{(1/2-\xi)}$$

Sehitoglu

$$\frac{1}{N_f} = \frac{1}{N_f^{fat}} + \frac{1}{N_f^{ox}} + \frac{1}{N_f^{creep}}$$

$$\frac{\Delta \varepsilon_{mech}}{2} = \frac{\sigma'_f}{E} (2N_f^{fat})^b + \varepsilon'_f (2N_f^{fat})^c$$

$$\frac{1}{N_f^{ox}} = \left[\frac{h_{cr} \delta_0}{B \Phi^{\alpha} K_p^{eff}} \right]^{-\frac{1}{\beta}} \frac{2(\Delta \varepsilon_{mech})^{(2/\beta+1)}}{\dot{\varepsilon}^{1-(\alpha-\beta)}}$$

疲劳测试尤其高温



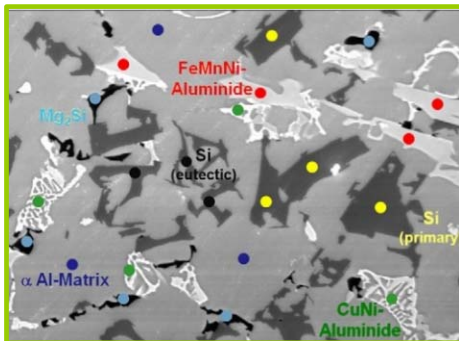
费时费力费钱还复杂

极端环境材料服役行为: 科学问题



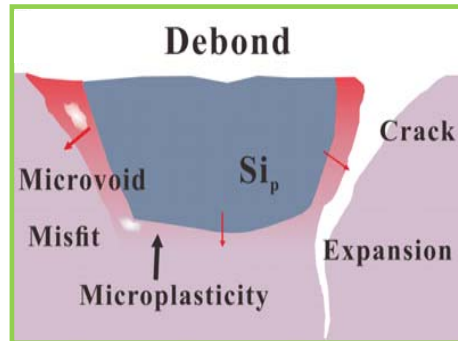
载荷环境复杂
因素多变化多

参数挑不准



微观组织复杂
多种相多尺度

机理理不清



损伤机制复杂
疲劳蠕变氧化

模型算不准

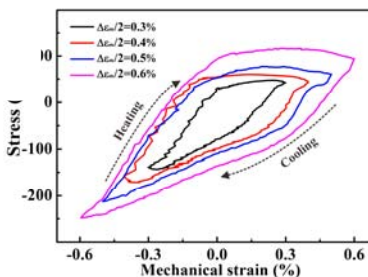
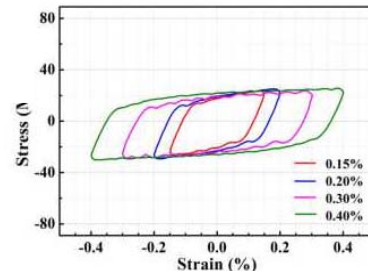
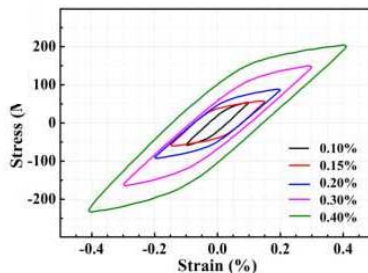
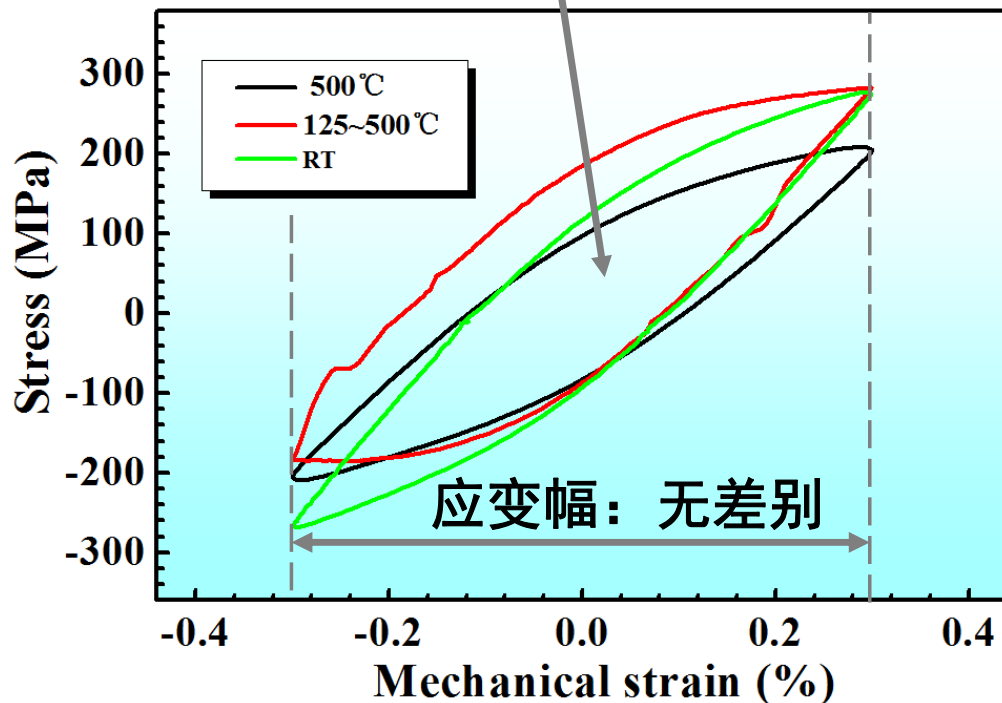
$$\frac{1}{N_f} = \frac{1}{N_f^{\text{fat}}} + \frac{1}{N_f^{\text{ox}}} + \frac{1}{N_f^{\text{creep}}}$$
$$\frac{\Delta \epsilon_{\text{mech}}}{2} = \frac{\sigma'_f}{E} (2N_f^{\text{fat}})^b + \epsilon'_f (2N_f^{\text{fat}})^c$$
$$\frac{1}{N_f^{\text{ox}}} = \left[\frac{h_{cr} \delta_0}{B \Phi^{\alpha} K_p^{\text{eff}}} \right]^{-\frac{1}{\beta}} \frac{2(\Delta \epsilon_{\text{mech}})^{(2/\beta+1)}}{\dot{\epsilon}^{1-(\alpha-\beta)}}$$

预测方法复杂
参数多成本高

方法用不好

科学问题: 合理简化、量化难测极端服役性能?

以滞回能为损伤参量：滞回环更全面



$$D = \frac{1}{N_f} = \left(\frac{W_a}{W_0} \right)^\beta$$

常温低周疲劳

模型发展 ↓ 损伤机制

高温低周疲劳

模型发展 ↓ 损伤机制

热机械疲劳

组织调控

损伤机制

预测模型

性能优化



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高温低周疲劳性能优化与寿命预测

High-temperature LCF property optimization and life prediction



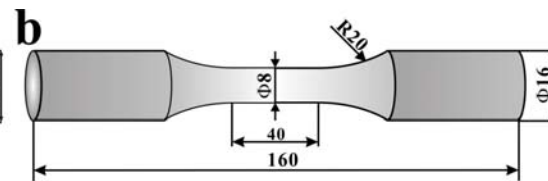
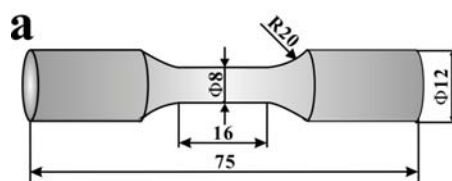
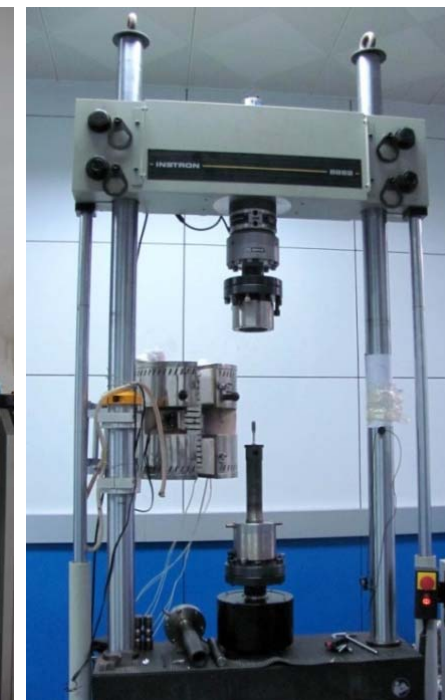
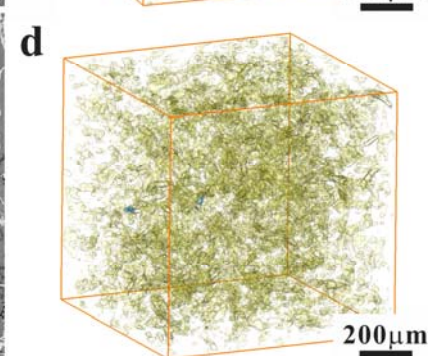
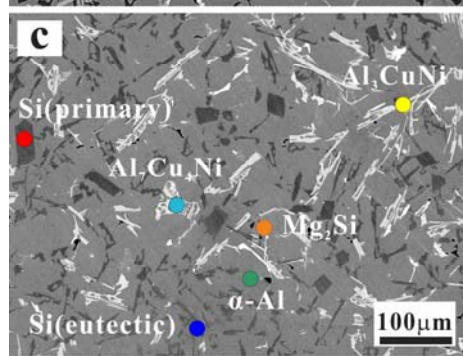
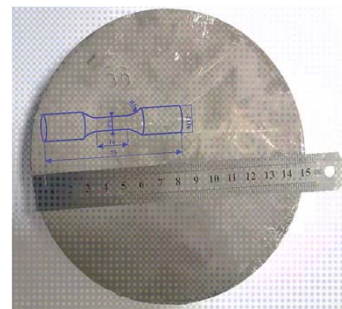
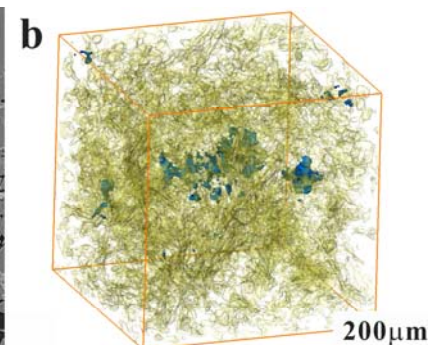
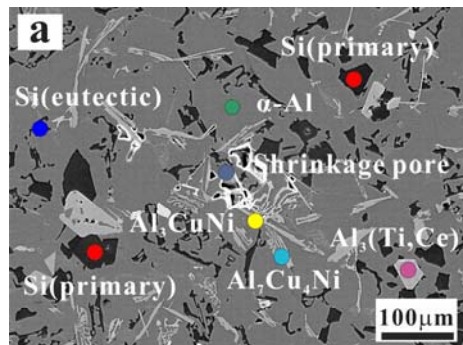
热机疲劳损伤机制与寿命预测方法

TMF damage mechanism and life prediction method



汇报小结

Summary



Unit: mm

低周疲劳速率: 1% /s (RT、280、350、425 °C)

热机械疲劳加热: 5 °/s (120-350、120-425 °C)



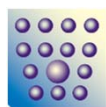
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热机疲劳损伤机制与寿命预测方法

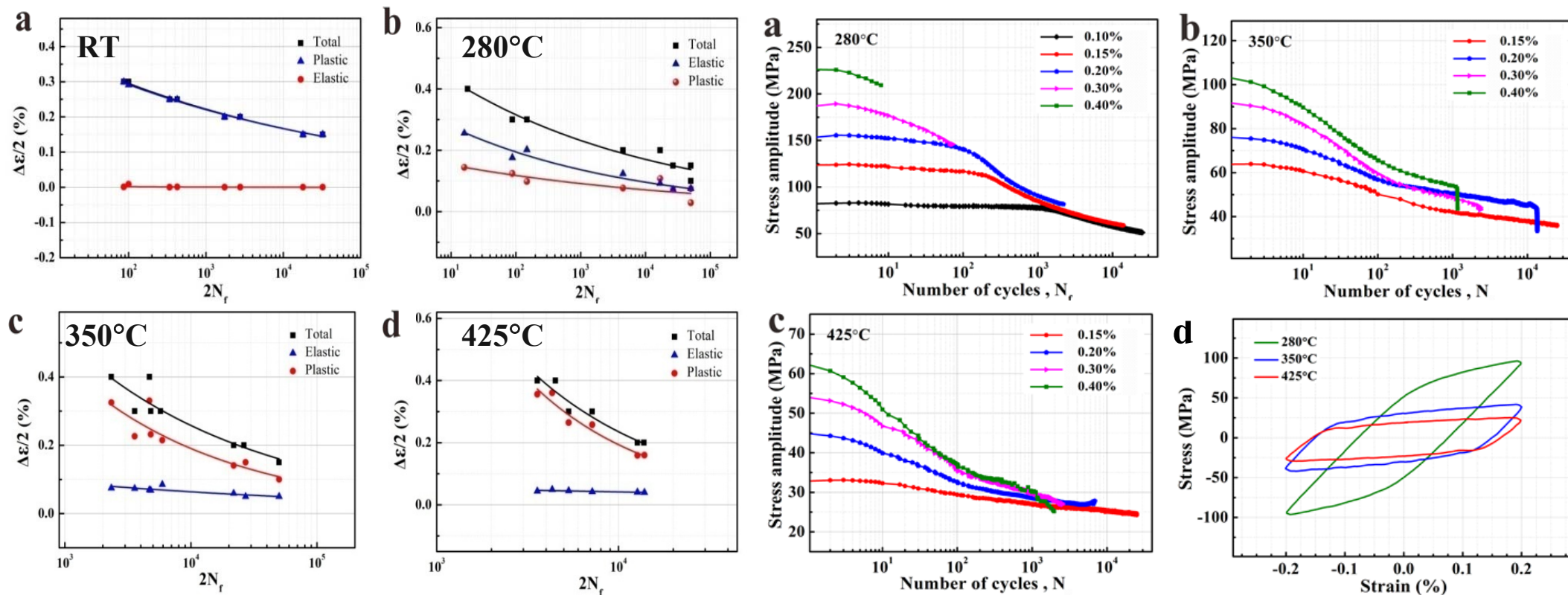
TMF damage mechanism and life prediction method



汇报小结

Summary

低周疲劳性能与寿命预测模型

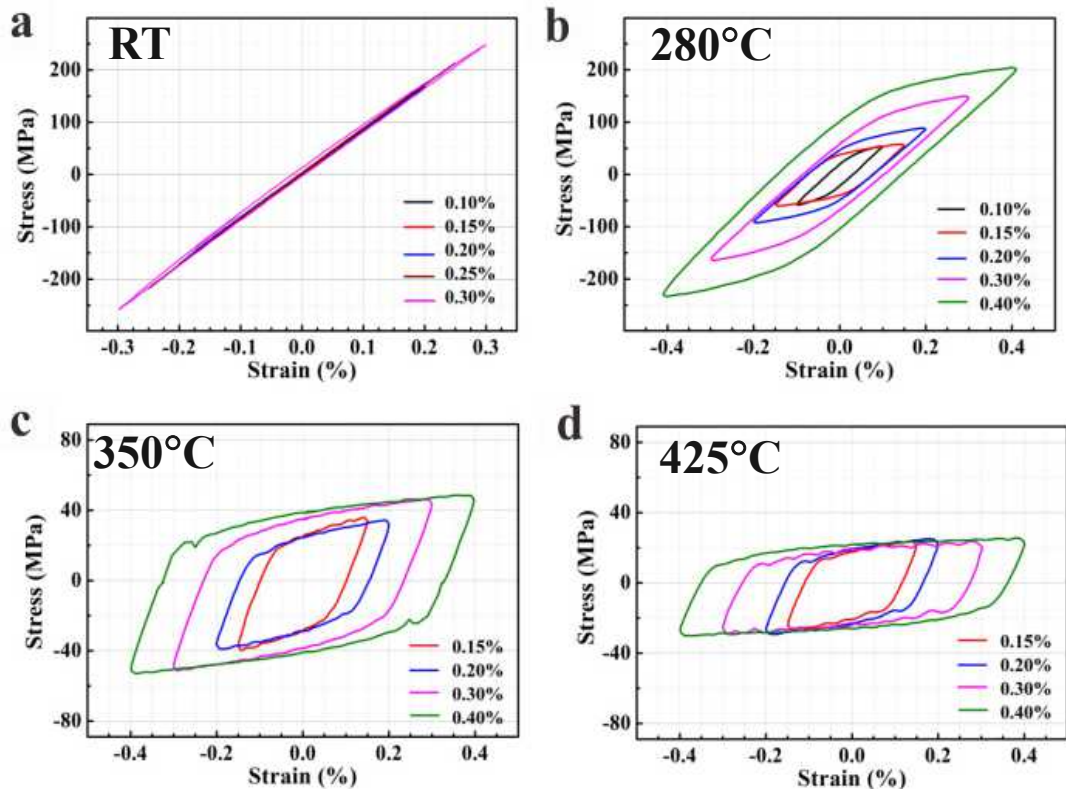


不同应变疲劳寿命曲线

不同应变疲劳寿命曲线

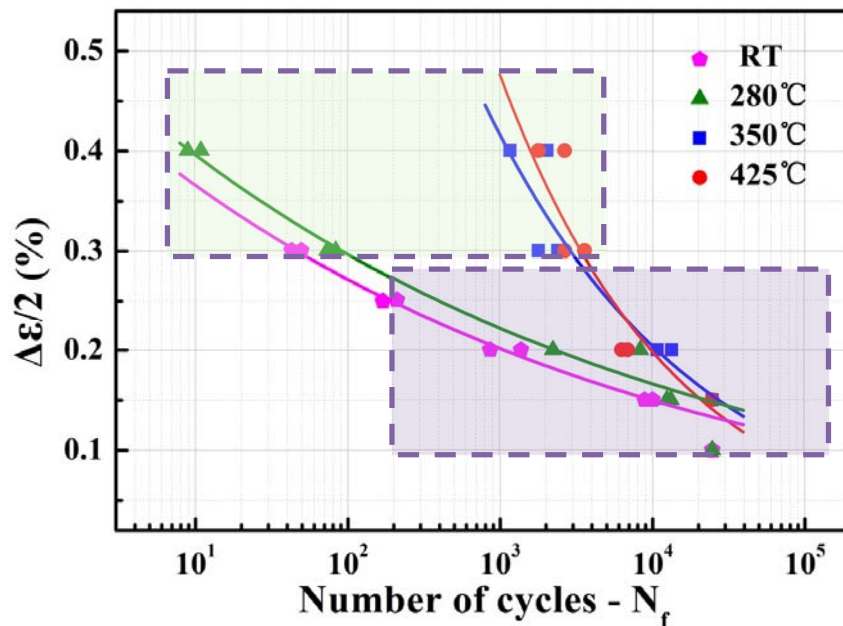
循环硬化能力随温度升高而降低

低周疲劳性能与寿命预测模型



不同温度滞回环

疲劳寿命随温度的变化趋势不同

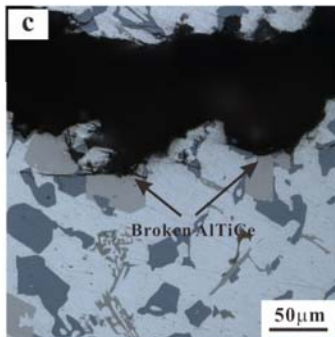
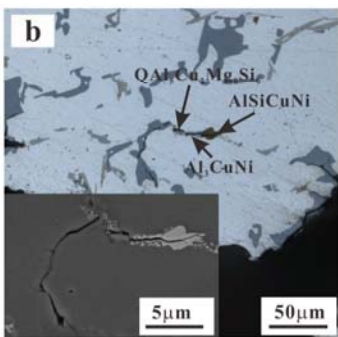
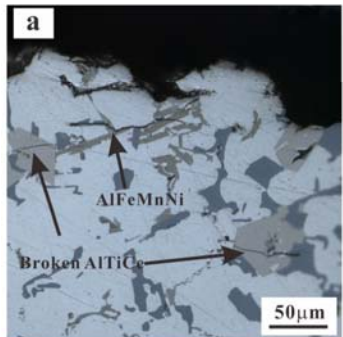


不同温度应变寿命曲线

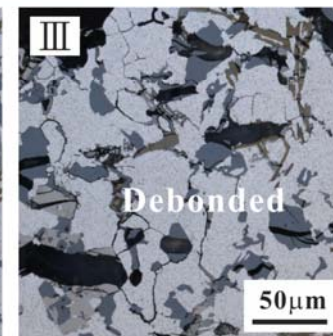
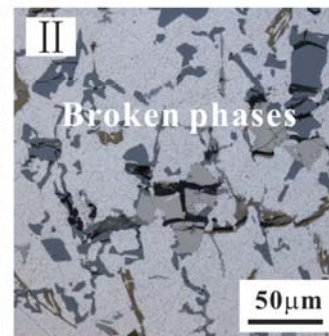
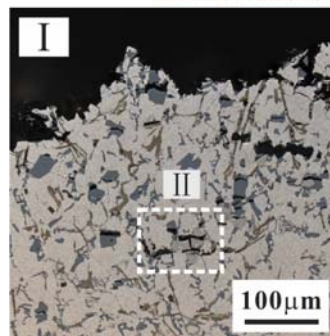
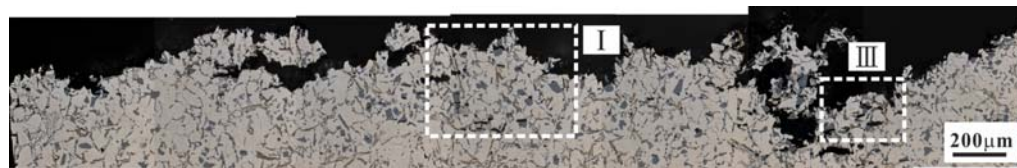
高应变：疲劳寿命随温度升而增加

低应变：寿命随温度升高有所降低

疲劳寿命随温度的变化趋势不同



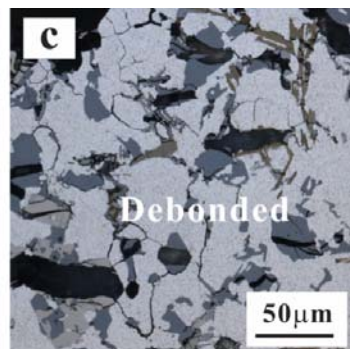
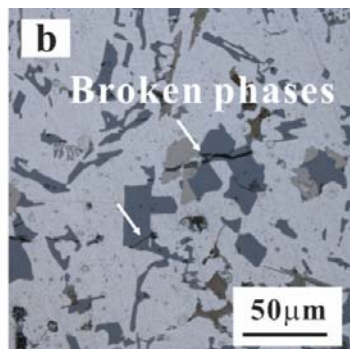
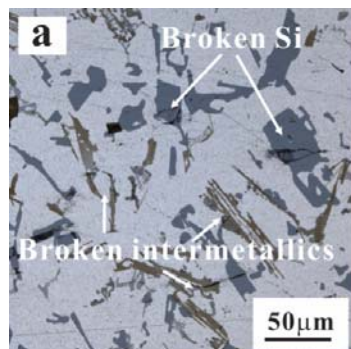
疲劳裂纹扩展和损伤形貌(室温-0.2%)



疲劳裂纹扩展和损伤形貌(425°C-0.2%)

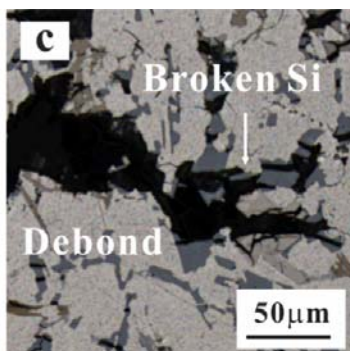
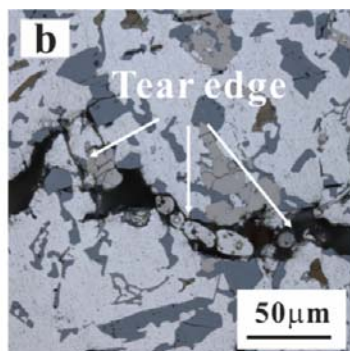
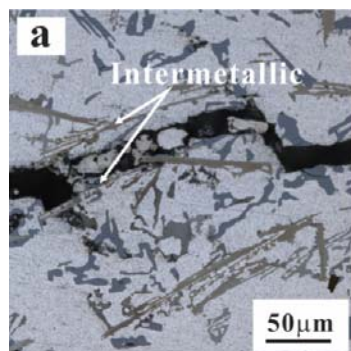
初生硅聚集区开裂 金属间化合物加速扩展, 高温损伤明显

疲劳开裂



损伤程度增加

裂纹扩展

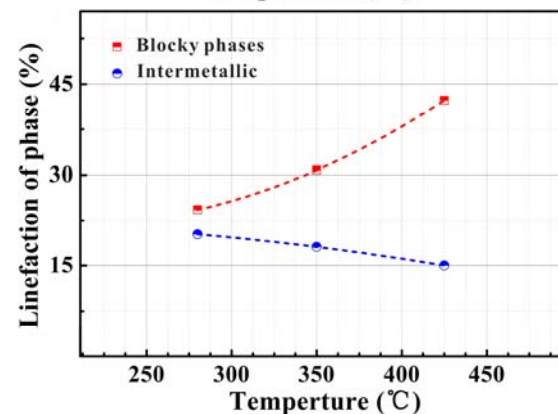
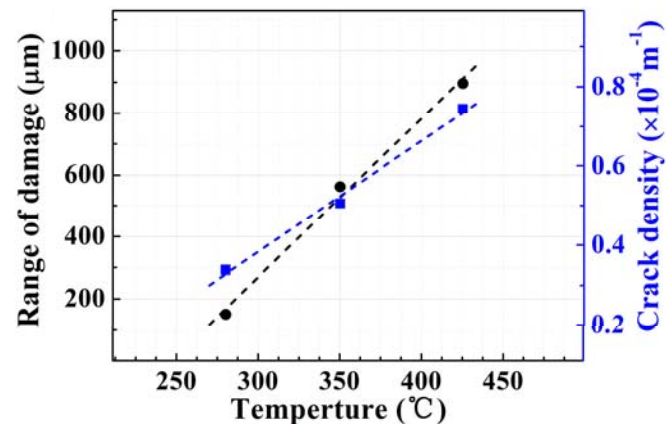


阻力增加

RT

350 °C

425 °C



初生硅开裂，温度升高开裂的倾向降低；室温优先从片状相扩展；425°C出现相脱沾沿晶扩展

低周疲劳性能与寿命预测模型

$$\varepsilon_a = \varepsilon_e + \varepsilon_p = \frac{\sigma'_f}{E} (2N)^b + \varepsilon'_f (2N)^c$$

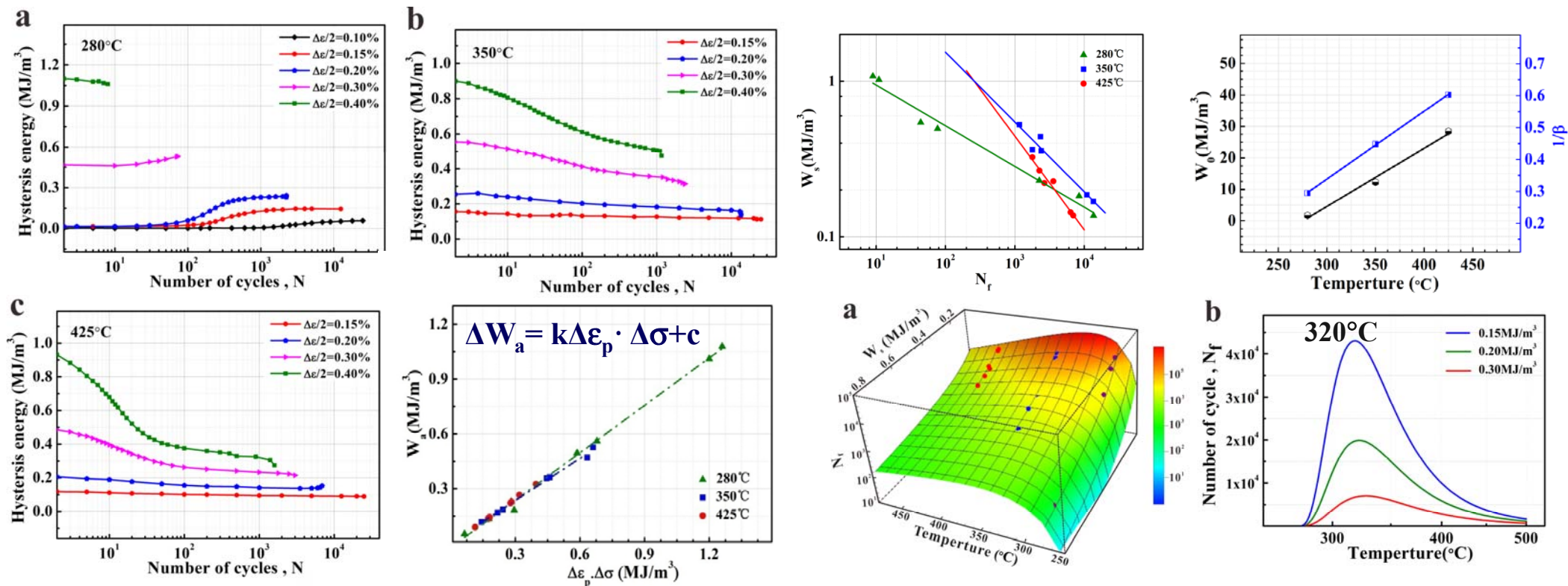
其中 σ'_f 为疲劳强度系数， b 为疲劳强度指数； ε'_f 疲劳延性系数， c 为疲劳延性系数

温度/°C	模型参数				E (GPa)
	σ'_f (MPa)	ε'_f (10^{-3})	b	c	
RT	410	0.18	-0.121	-0.415	81
280°C	282	1.96	-0.154	-0.111	72
350°C	179	38.3	-0.153	-0.323	68
420°C	76	676.1	-0.113	-0.636	64

随着温度的升高， σ'_f 降低， ε'_f 迅速升高， b 和 c 没有关系

Basquin&Manson-Coffin模型

低周疲劳性能与寿命预测模型



$$N_f = (W_0/W_s)^{1/\beta}$$

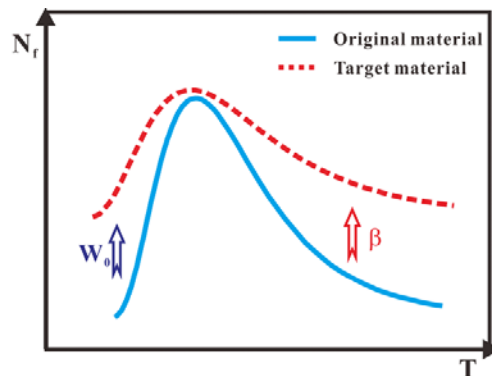
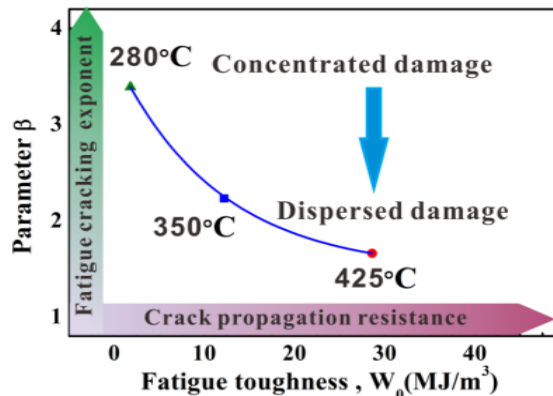
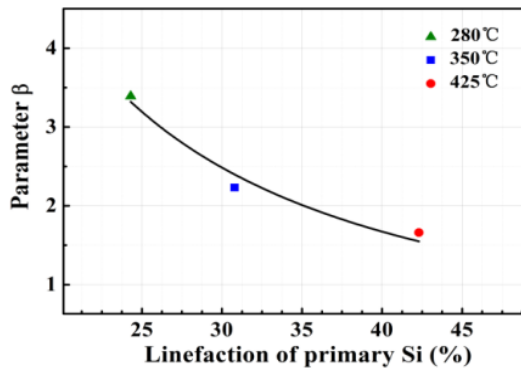
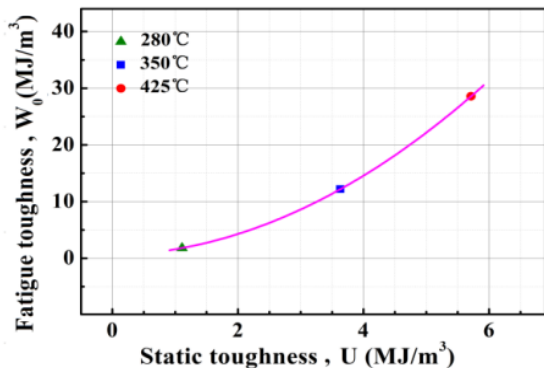
能量模型

$$W_0 = aT + b$$

$$1/\beta = mT + n$$

$$N_f = \left[\frac{(aT+b)}{W_s} \right]^{\frac{1}{mT+n}}$$

低周疲劳性能优化与模型推广



β 疲劳开裂指数，表征疲劳微裂纹萌生。初生Si相、 α -Al界面开裂。

参数意义

W_0 疲劳韧度表征裂纹扩展，细化共晶Si、金属间化合物，提高塑性

初生Si和共晶Si

控制初生Si含量

细化Si骨架

α -Al基体

弥散析出微纳
米高温稳定相

引入高温稳定
强化粒子

金属化合物

调整物相构成

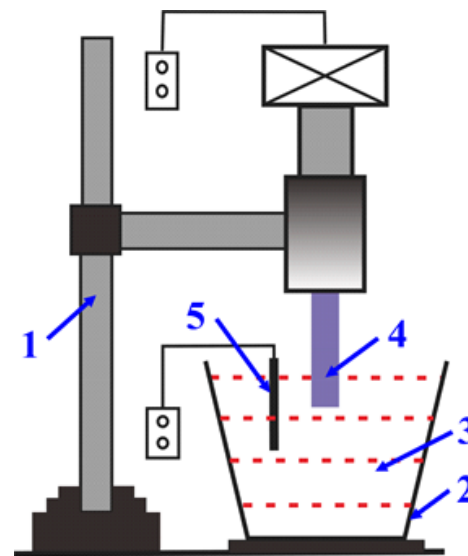
细化物相尺寸

熔体处理

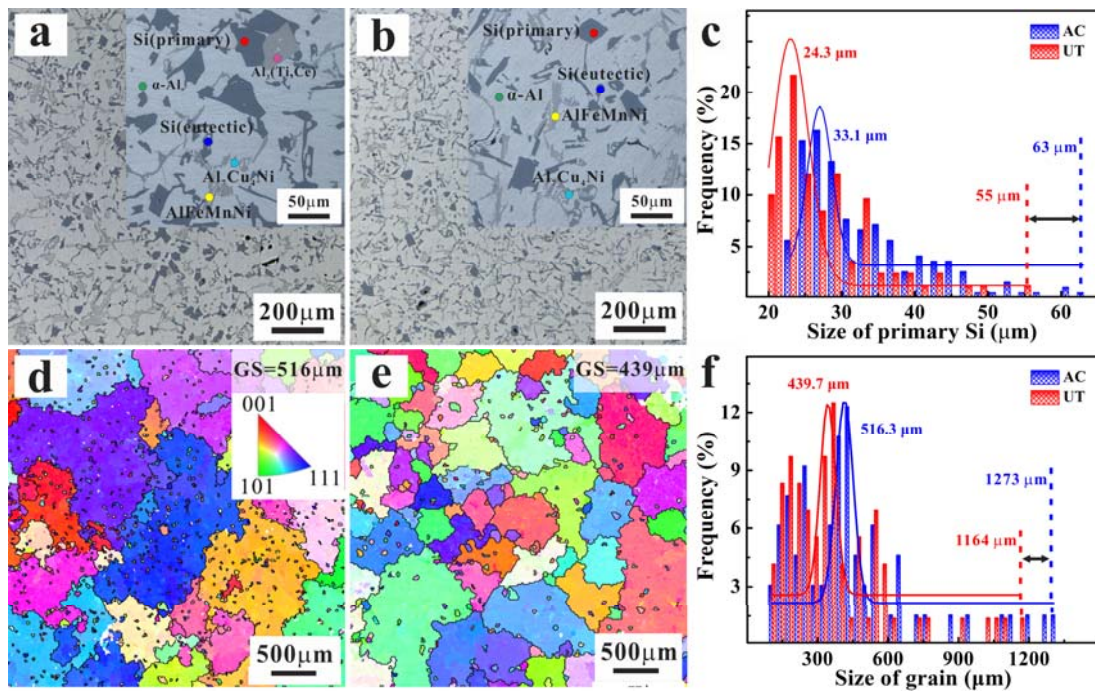
凝固处理

热处理

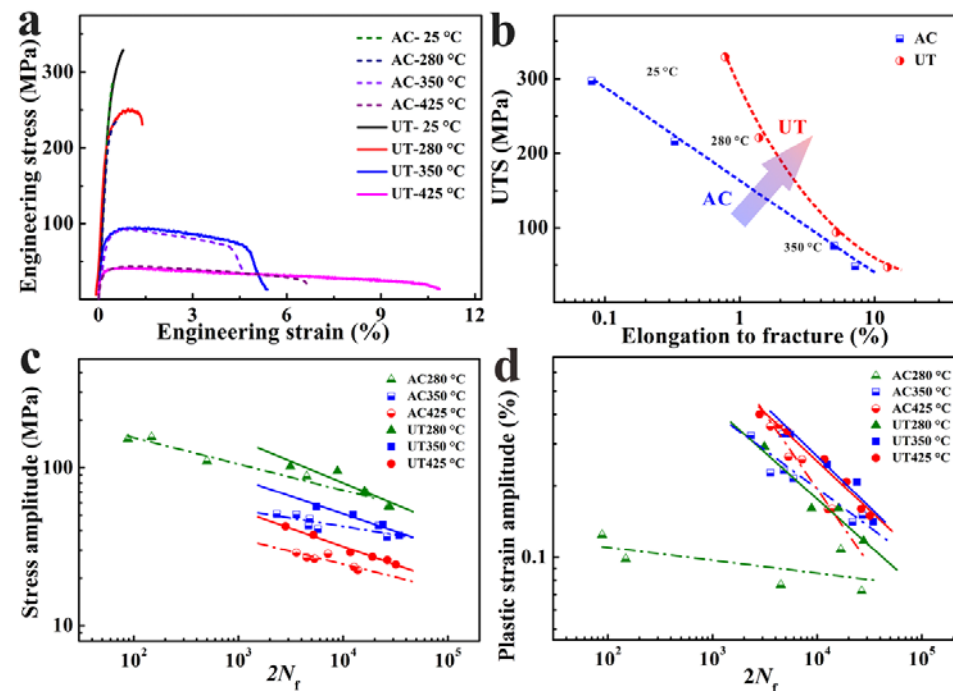
超声处理



组织调控思路



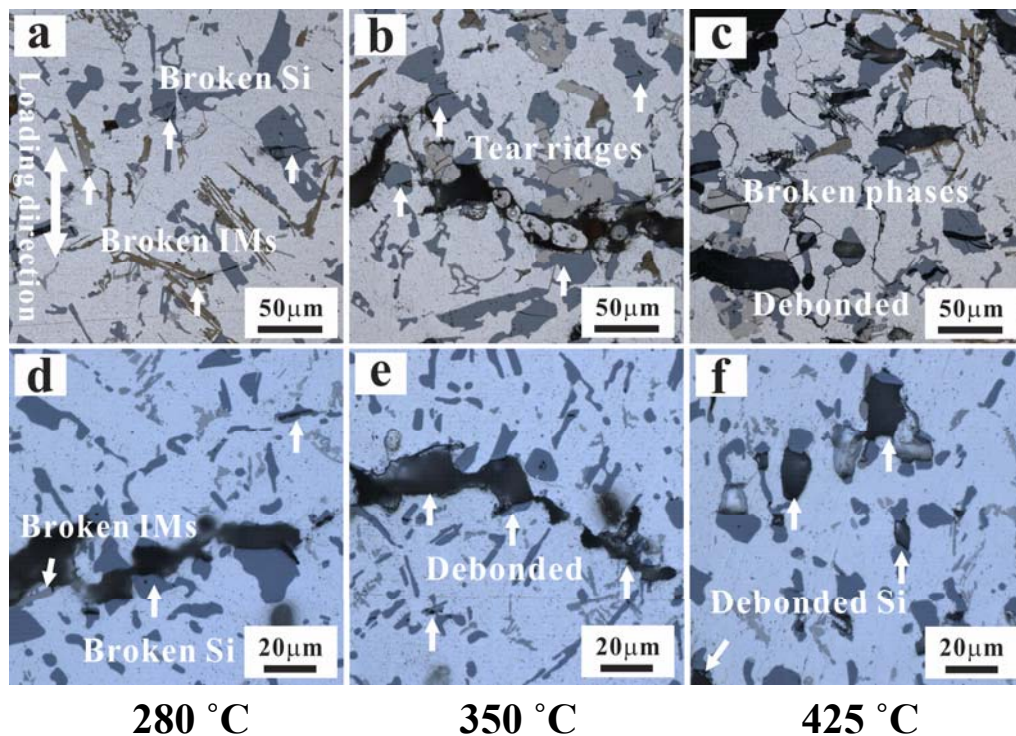
基体组织、初生硅和金属间化合物明显细化



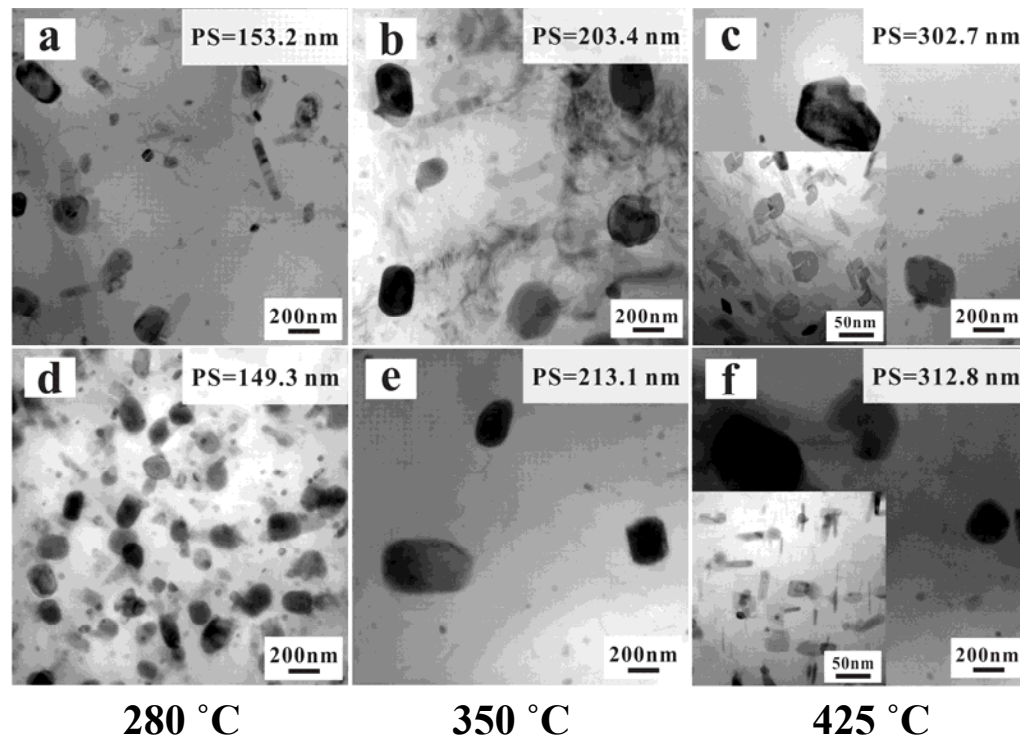
力学性能明显提高

A
C

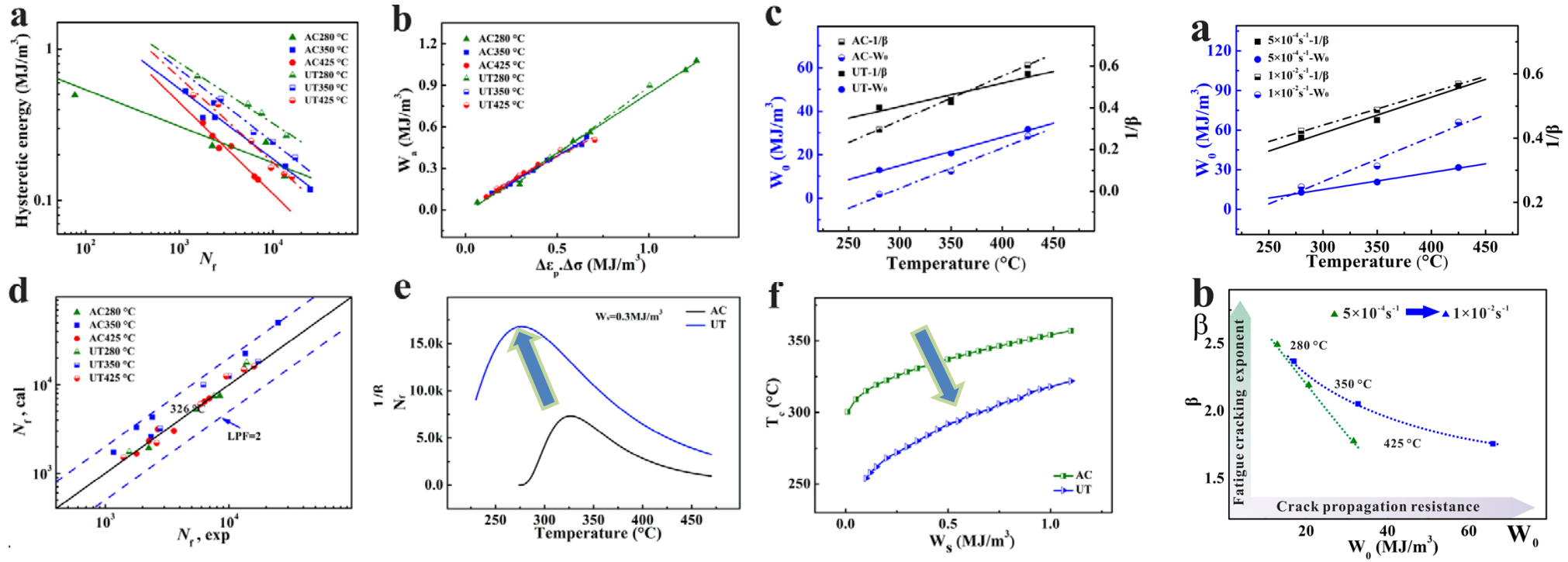
U
T



低周微观机制



析出相尺寸变化



超声处理前后寿命预测

不同应变速率



研究背景

Research background



实验材料和方法

Experimental materials and methods



高温低周疲劳性能优化与寿命预测

High-temperature LCF property optimization and life prediction



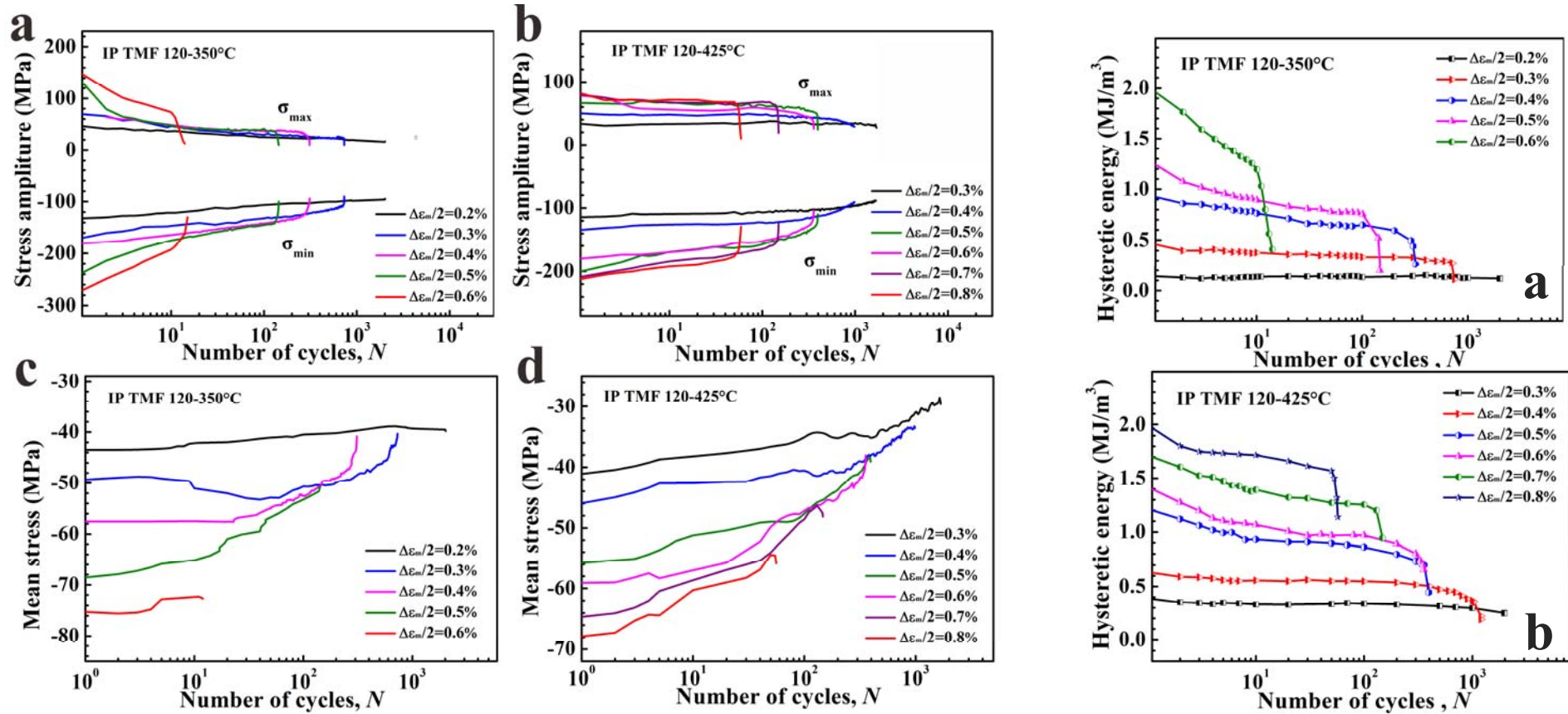
热机疲劳损伤机制与寿命预测方法

TMF damage mechanism and life prediction method

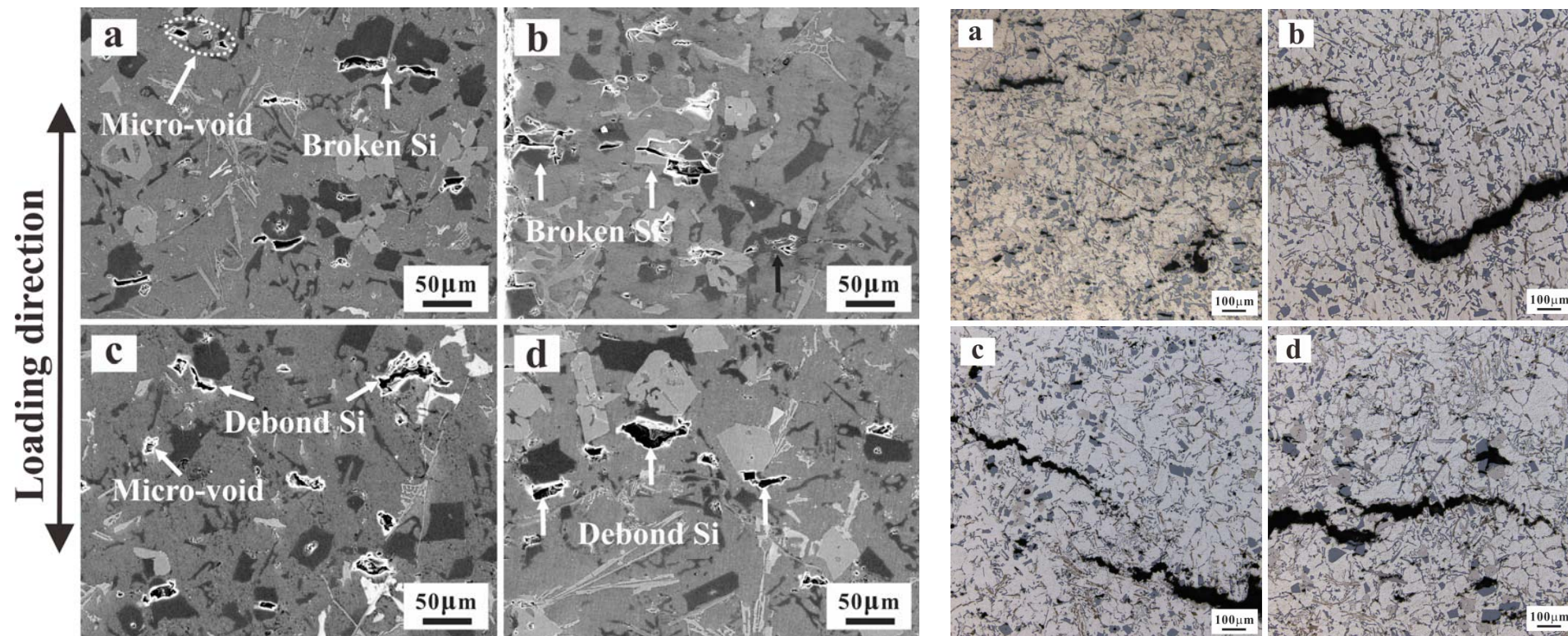


汇报小结

Summary



疲劳循环变形行为

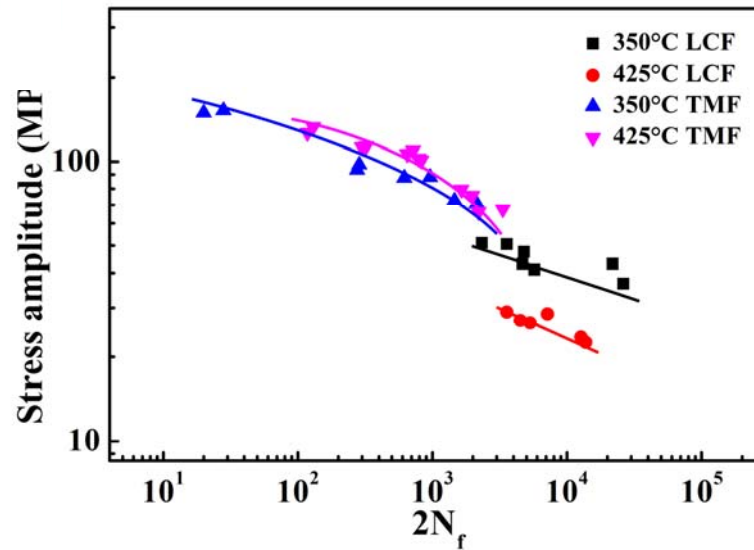


损伤演变: 120-350 °C: a (0.3%) ; b (0.6%) 120-425 °C: c (0.3%); d (0.6%)

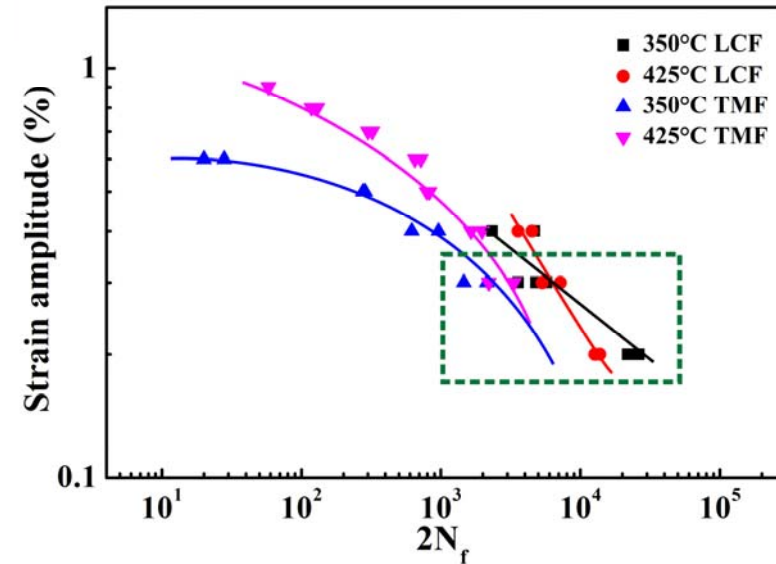
长寿命 高温 多损伤

疲劳寿命预测方法

S-N曲线
(Basquin公式)



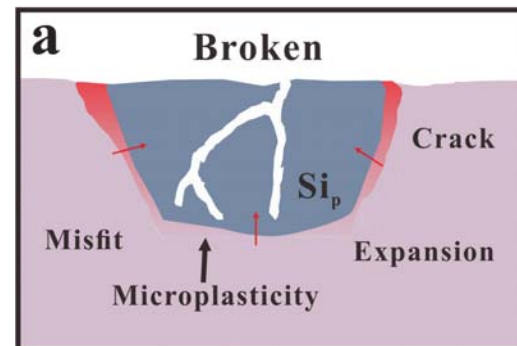
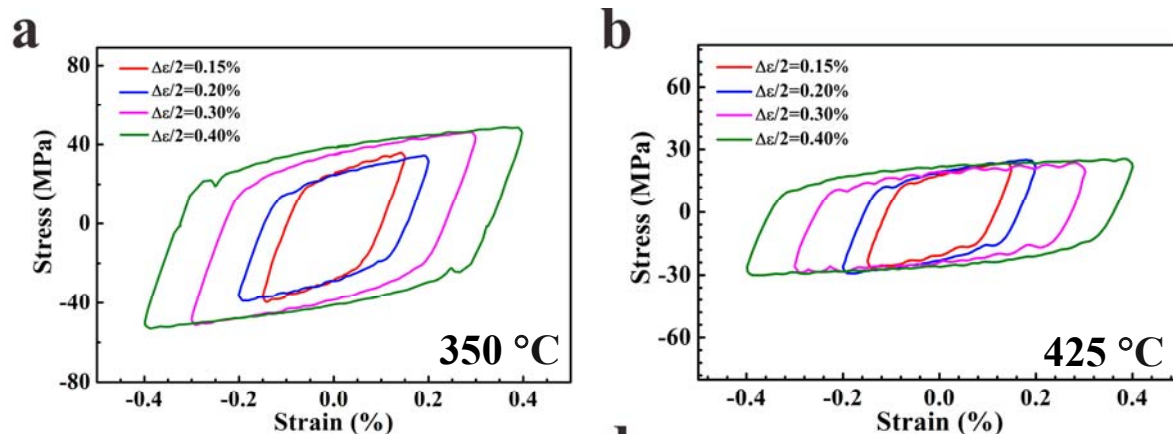
ϵ -N曲线
(Coffin-Manson公式)



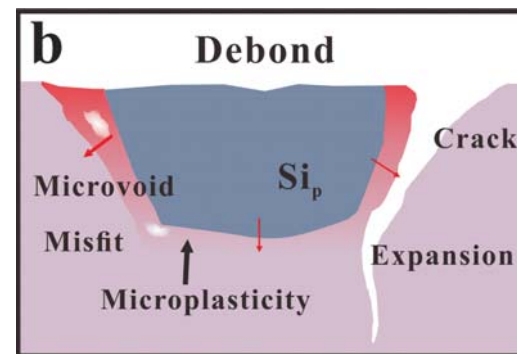
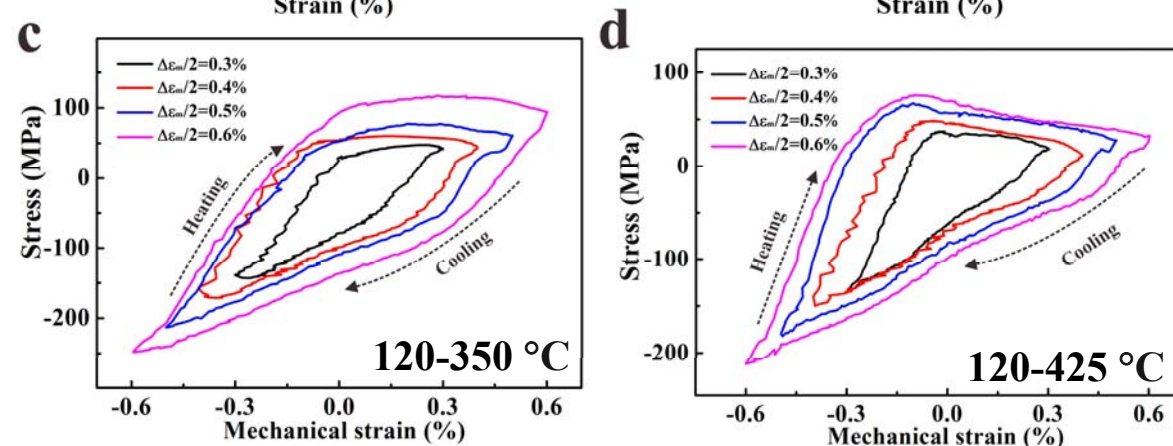
热机械疲劳寿命趋势偏离经典疲劳模型线性关系

热机疲劳性能与机制

低周疲劳

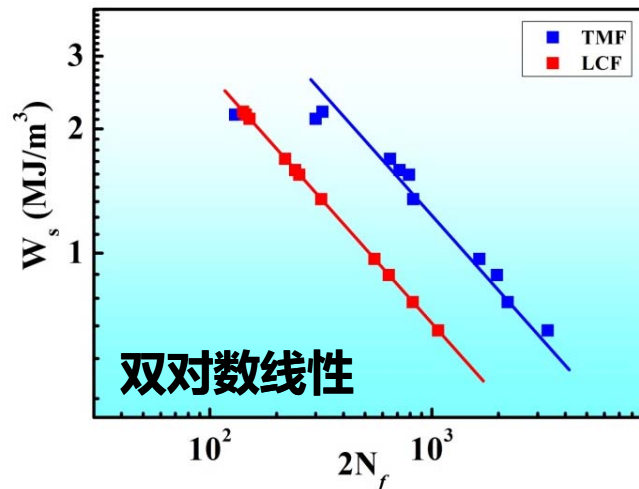
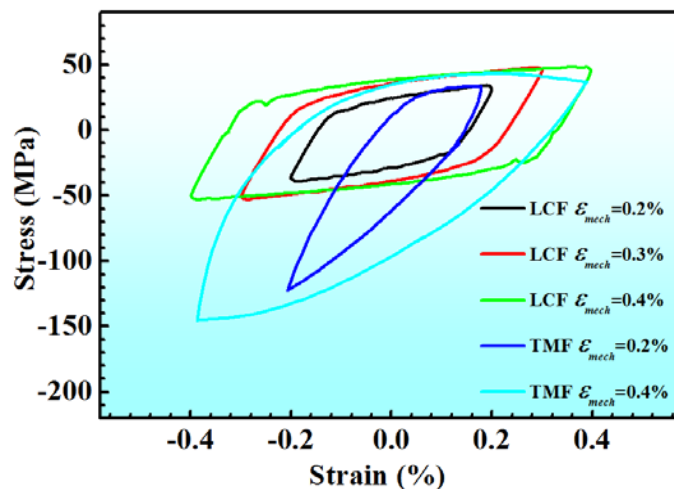


热机械疲劳



低周与热机疲劳循环变形行与机制相似

热机疲劳快速预测方法



基于微观机制以高温低周疲劳替代热机械疲劳降低成本

高温低周疲劳 ✓

温度恒定，频率较快，时间短成本低。

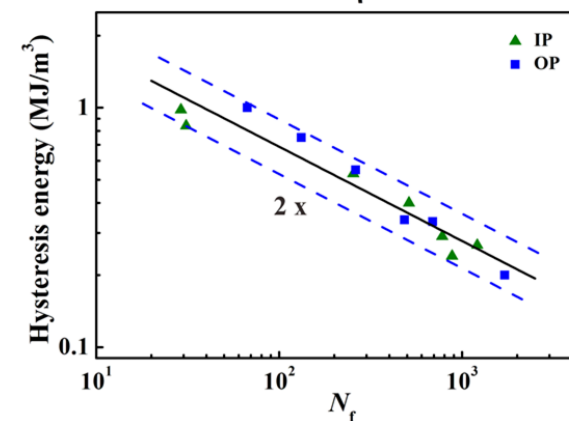
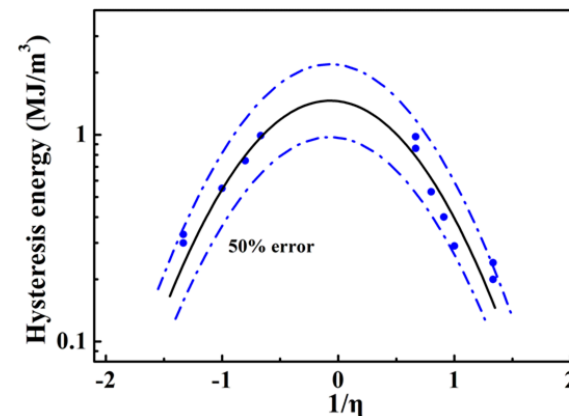
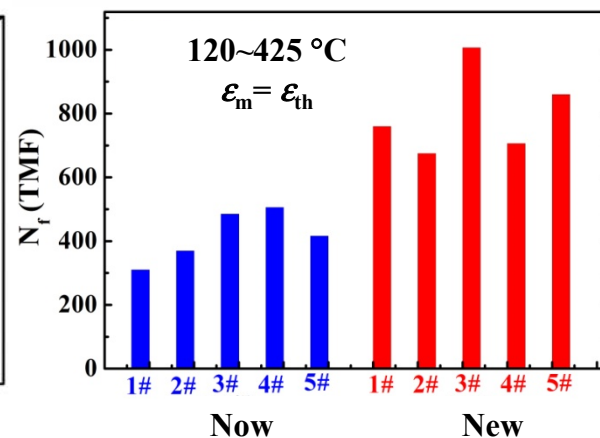
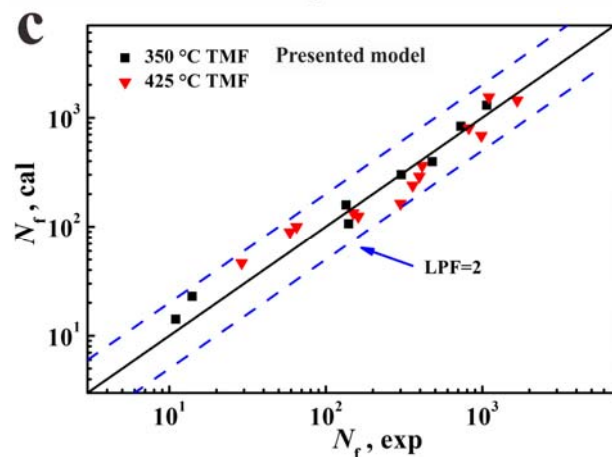
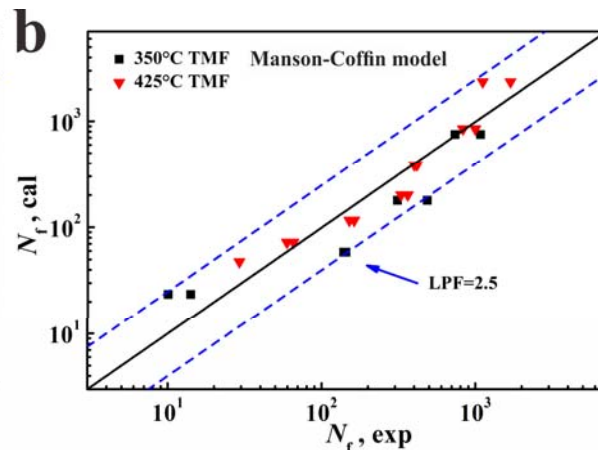
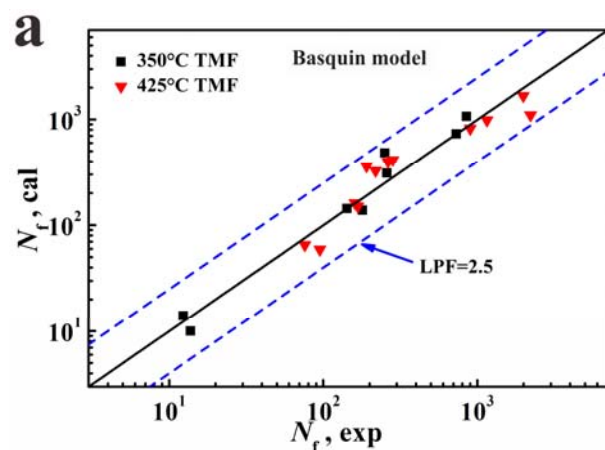
疲劳、蠕变

指数修正

热机械疲劳 ✗

温度循环，频率低，难度大，成本很高。

热机疲劳性能与机制



热机疲劳快速预测方法

$$N_f = \left(\frac{W_s^{TMF}}{W_0^{LCF}} \right)^{-\beta_{LCF}} \left(\frac{\dot{\epsilon}_{LCF}}{\dot{\epsilon}_{TMF}} \right)^{(1-r)}$$

$$N_f = (W_0 / (A \exp(\gamma \eta^{-2}) + B))^\beta$$

约束比 η =机械/热应变

热机疲劳快速预测方法推广

Abaqus高温疲劳寿命预测插件
— □ ×

室温环境
高温环境

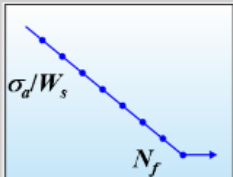
疲劳理论

高周疲劳:

$$\sigma_a = \sigma'_f (2N_f)^b$$

低周疲劳:

$$w_s = w_\theta (N_f)^\beta$$



输入参数

σ'_f	b	w_θ	β	K
A	M	N	C	D
K'	n'	γ	F	G

疲劳分析结果

odb导入

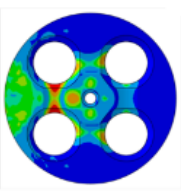
计算分析

数据统计

可视输出

Life/hours

9.80×10¹³
 2.45×10⁶
 1.53×10⁵
 1.11×10⁵
 7.35×10⁴
 4.08×10⁴
 1.40×10⁴
 3.24×10³



有限元模型选择

应力: MPa 载荷: N 温度: °C 长度: mm	▼ 分析步 Initial ☐ Bolt-1 ☐ Bolt-2 ☒ Warm up ☐ Full load ☐ Cool down ☒ Idle load	▼ 集合 ☐ All ☐ ASSEMBLY ☐ Cylinder body-1 ☐ Cylinder bolt-1 ☒ Cylinder head-1
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能量法软件



研究背景

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高温低周疲劳性能优化与寿命预测

High-temperature LCF property optimization and life prediction



热机疲劳损伤机制与寿命预测方法

TMF damage mechanism and life prediction method



汇报小结

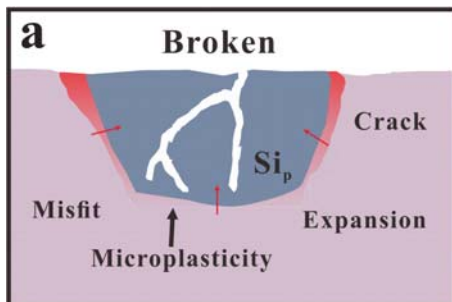
Summary

损伤机制

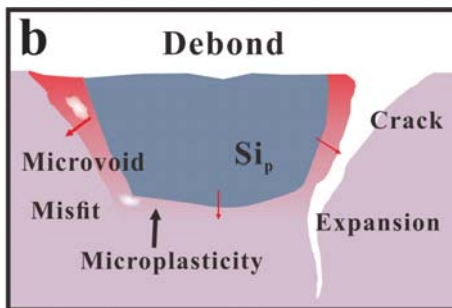


预测模型

疲劳-蠕变机制



W_0 疲劳韧度
表征裂纹扩展,
细化共晶Si、
金属间化合物,
提高塑性。



β 疲劳开裂指
数,表征疲劳
微裂纹萌生。
初生Si相、 α -
Al界面开裂。

疲劳寿命

$$W_{a,TMF} = A + K \epsilon_{mech} + W_{a,LCF}$$

高温低周疲劳

$$N_f = [(aT + b) / W_s]^{1/mT+n}$$

热机械疲劳

$$N_f = \dot{\epsilon}^{1-r} \cdot (W_0 / W_s)^{1/\beta}$$

机制
相似

服役
寿命

服役 温度

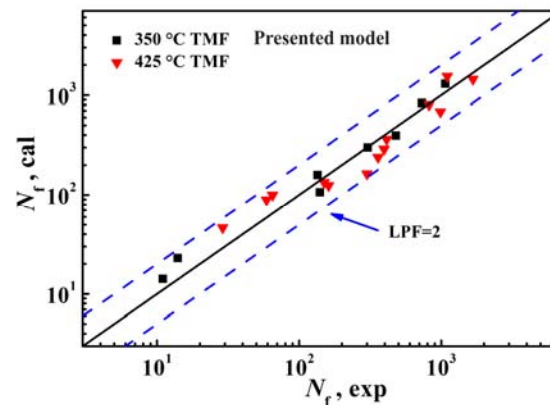
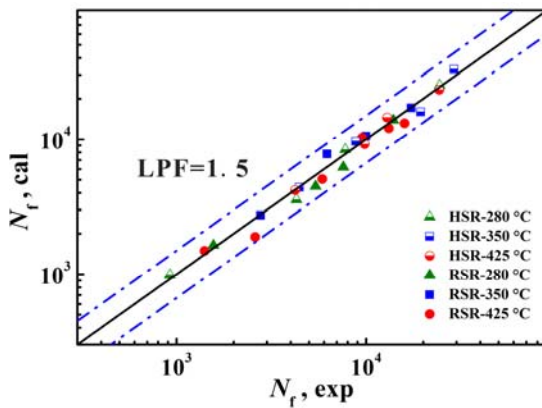
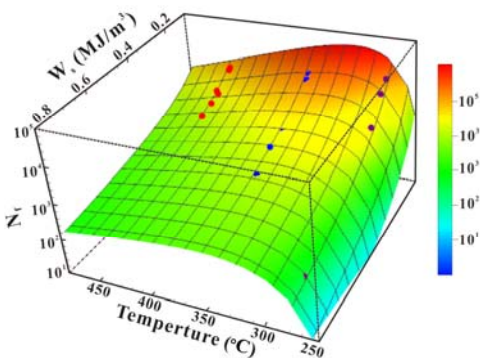
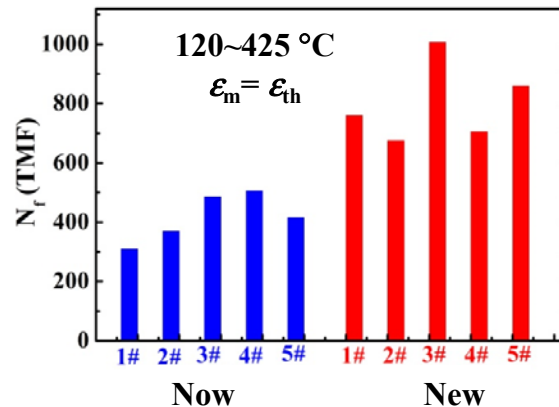
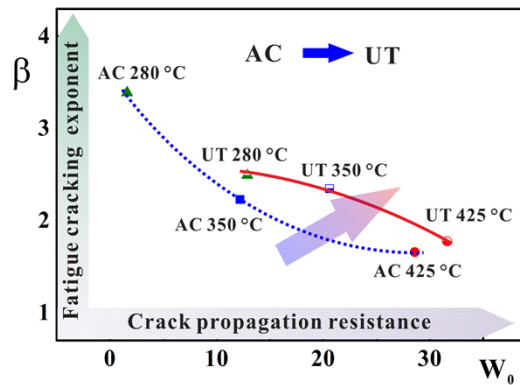
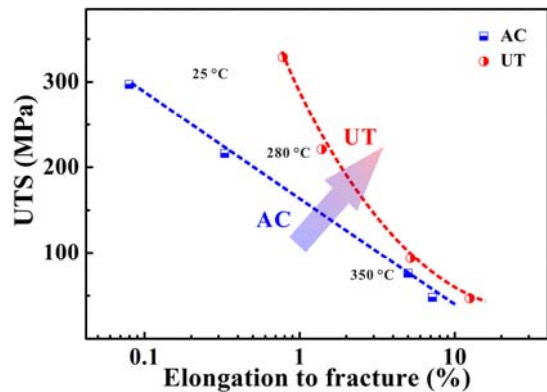
常温低周疲劳

$$N_f = (W_0 / W_s)^{1/\beta}$$

载荷 温度

服役构件疲劳

$$N_f = (W_0 / (A \exp(\gamma \eta^{-2}) + B))^{\beta}$$



简单准确

多种因素

方案优化

推广应用

静态性能 疲劳行为 损伤机制 性能预测 温度效应 性能优化

1. Wang M, Pang JC*, *et al*, *Mater. Sci. Eng. A* 2017; 704:480.
2. Wang M, Pang JC*, *et al*, *Mater. Sci. Eng. A* 2018; 715:62.
3. Wang M, Pang JC*, *et al*, *Adv. Eng. Mater.* 2018;20:201700610.
4. Liu HQ, Pang JC*, *et al*, *Adv. Eng. Mater.* 2018;20: 201700972.
5. Wang M, Pang JC*, *et al*, *Mater. Sci. Eng. A* 2019; 759:797.
6. Wang M, Pang JC*, *et al*, *Int. J. Fatigue* 2019; 127:268.
7. Liu HQ, Pang JC*, *et al*, *Fatigue Fract. Eng. Mater. Struct.*, 2019; 42:2372.
8. Wang M, Pang JC*, *et al*, *J. Mater. Res. Technol.* 2019; 8:4556.
9. Liu HQ, Pang JC*, *et al*, *Mater. Charact.* 2020; 159:110032.
10. Wang M, Pang JC*, *et al*, *Mater. Sci. Eng. A*. 2020; 783: 139279.
11. Liu HQ, Pang JC*, *et al*, *Mater. Sci. Eng. A*. 2021; 824: 141762.
12. Wang M, Pang JC*, *et al*, *Materials*. 2022; 15: 7113.

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