缸盖蠕铁高温服役性能与损伤机制评价表征

Service properties and damage mechanisms of compacted graphite iron for cylinder head at high temperature

<u>庞建超</u>

邱 宇 邹成路 朱 刚 张孟枭 李守新 张哲峰

中国科学院金属研究所

2020年11月1日

jcpang@imr.ac.cn 15940017108(微信同号)

汇报提纲Contents

一、缸盖研究背景与主要工程问题

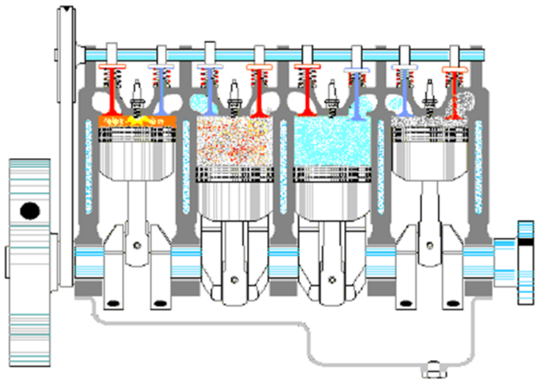
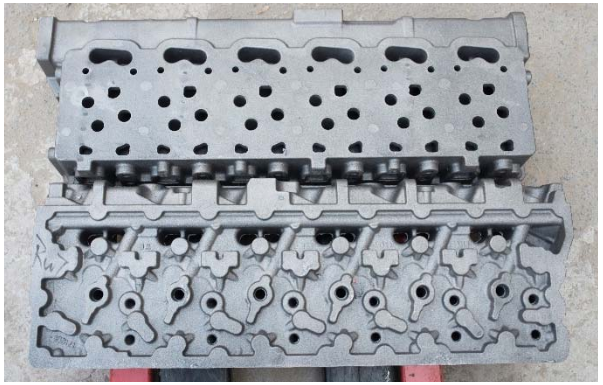
Research background and main engineering question

1. cylinder head for diesel engine

Application of diesel engine



Service condition of cylinder head

High-Temperature

High-Pressure

High-Speed

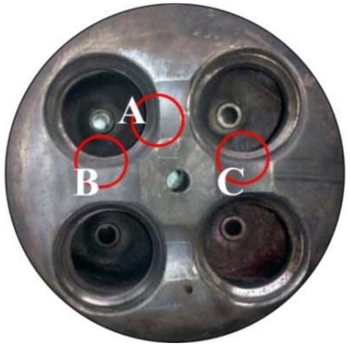
High-Efficient

High reliability   Service properties at high temperature

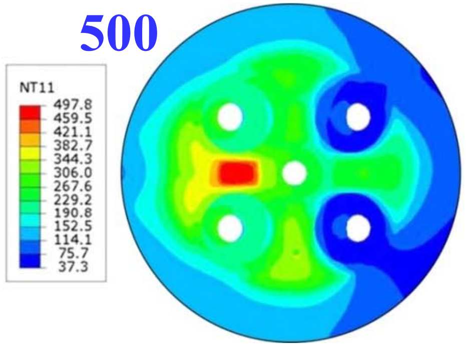
Silva, F. S., *Eng. Fail. Anal.* 2006;13:480. Information of Magna Powertrain.

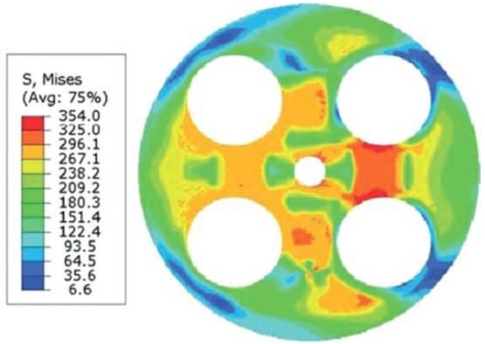
2. Service component and material requirement

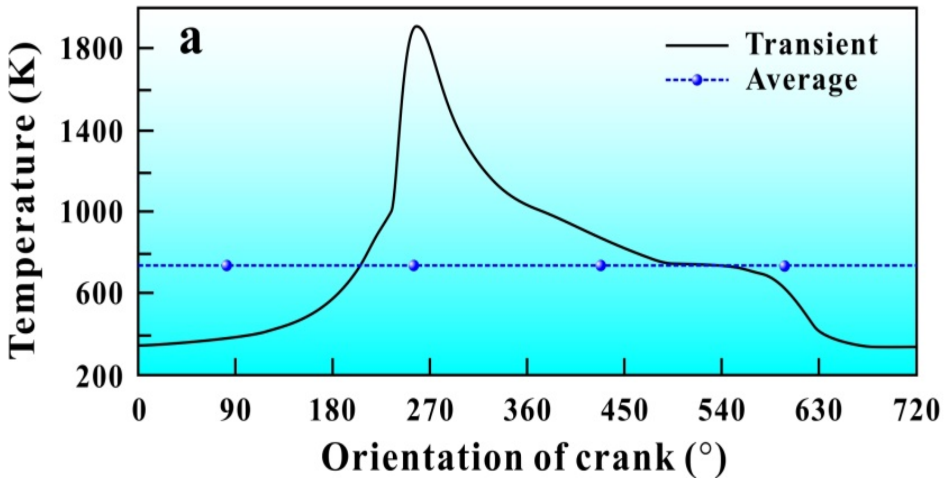
Cylinder head
(CGI)



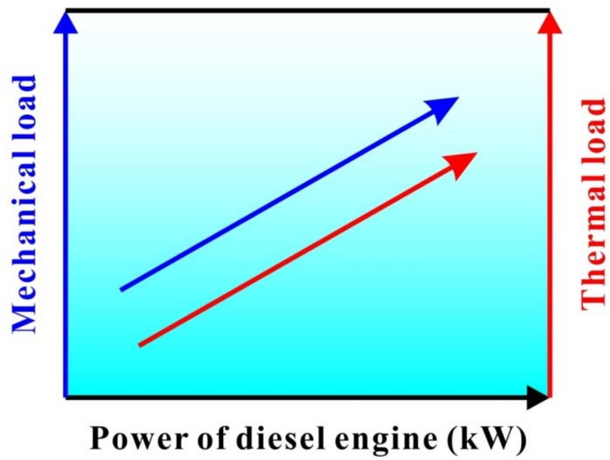
500







缸内燃气温度

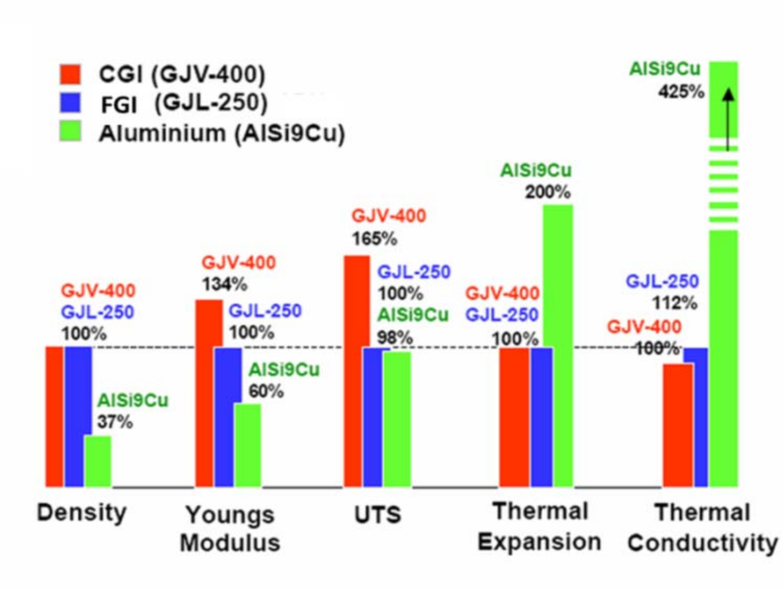


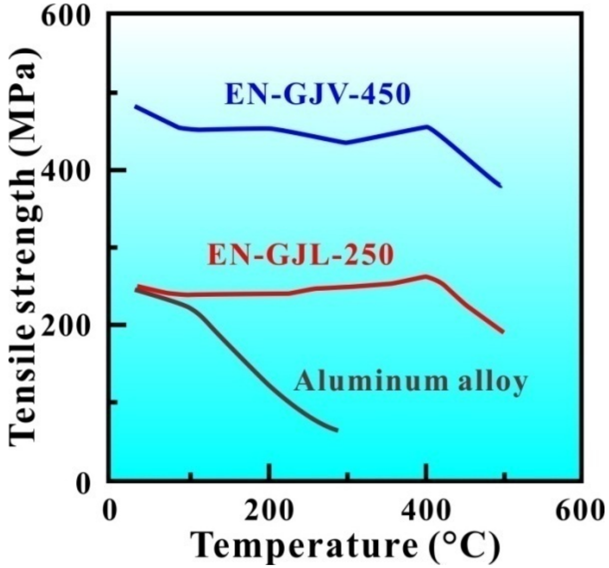
功率和机械热载荷的关系

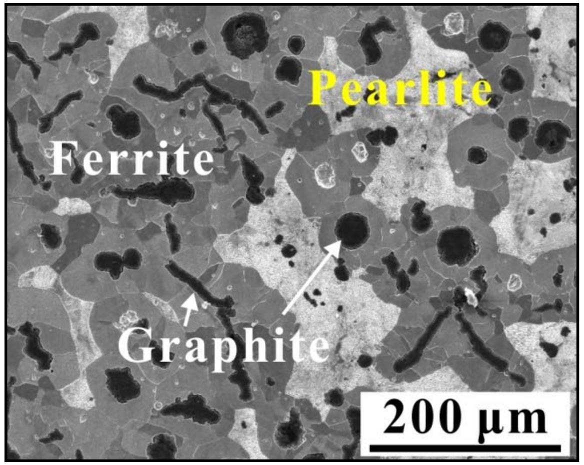
Complex harsh condition： Load & temperature

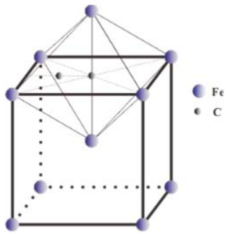
Zhang Q, et al. Eng. Fail. Anal.. 2013;34: 51. Guo B, et al. Adv. Mech. Eng. 2014;6: 862.

3. Material and microstructure

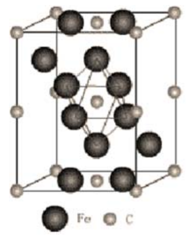








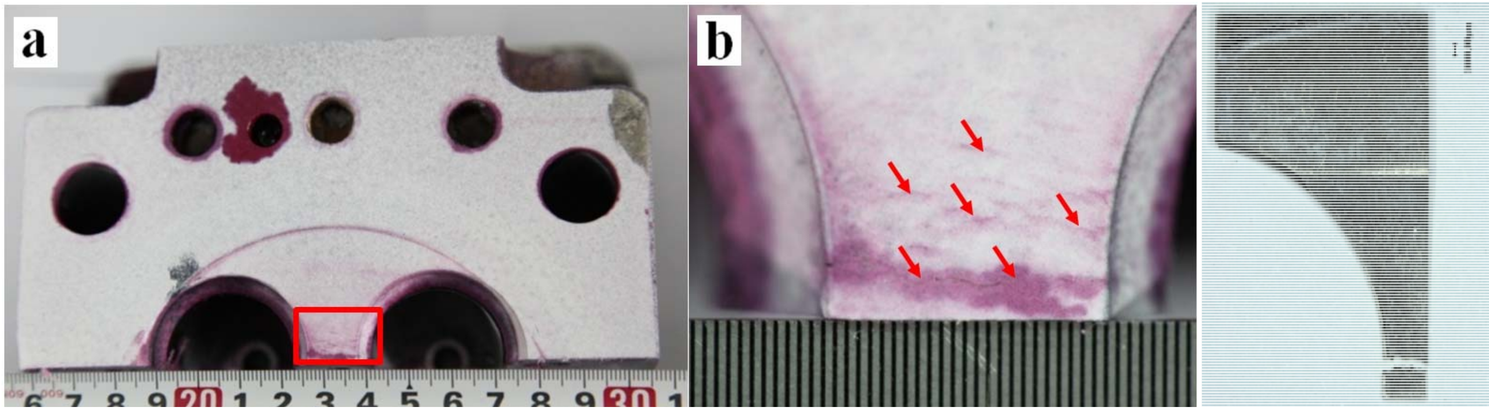
Elongation: ~ 50% **F**
Strength: 180~280 MPa
Hardness: HB 50~80

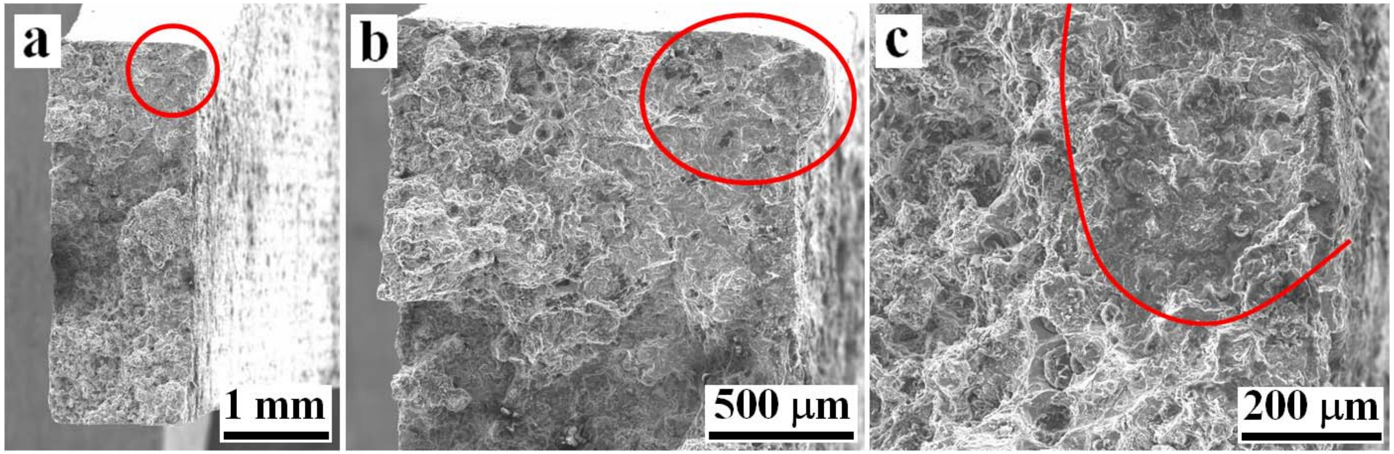


Elongation : ~ 0 **Fe_3C**
Strength : 35 MPa
Hardness : HB 800

Dawson S, *et al.* *AFS Trans*., 2004; 47: 1.

4. Failure mode at service conditions





Fatigue & oxidation

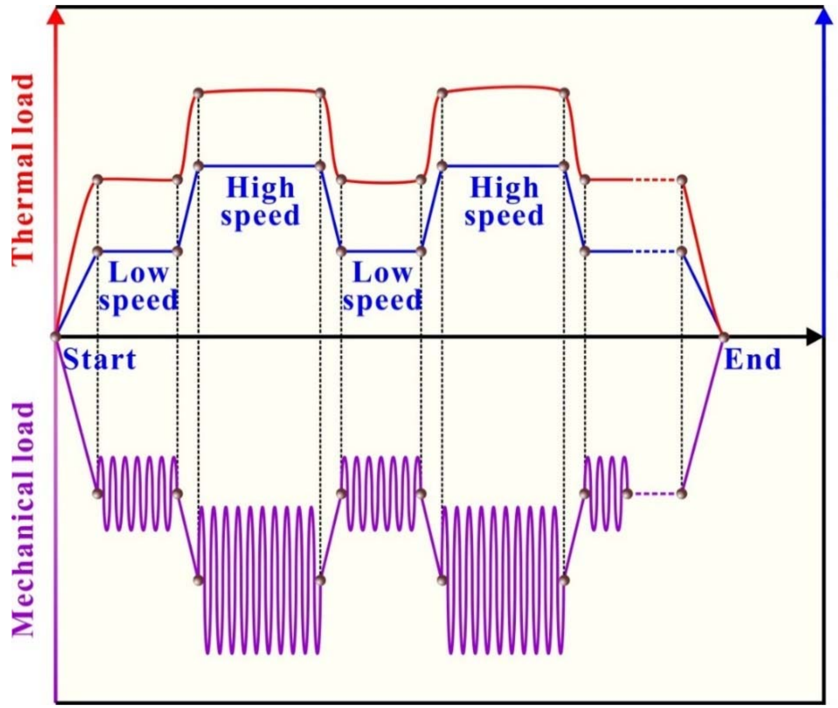
More failure less fatigue

Jing GX, Zhang MX, Qu S, Pang JC* *et al*, *Eng. Fail. Aanal.* 2018; 90: 36.

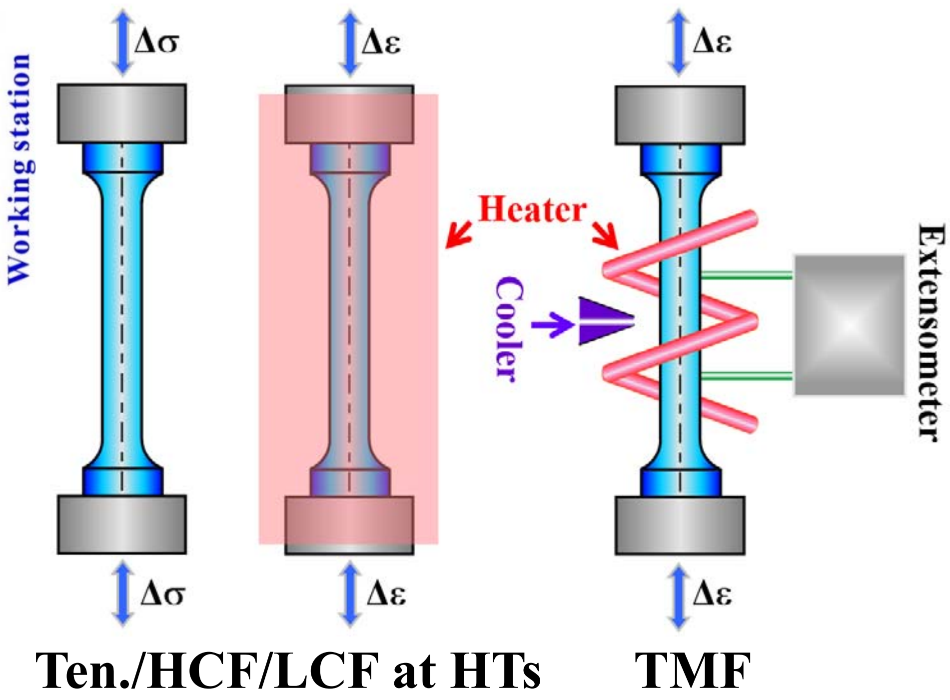
4. Failure mode at service conditions

热机疲劳：温度和机械载荷按一定相位变化

TMF: Temperature and mechanical load change with one phase



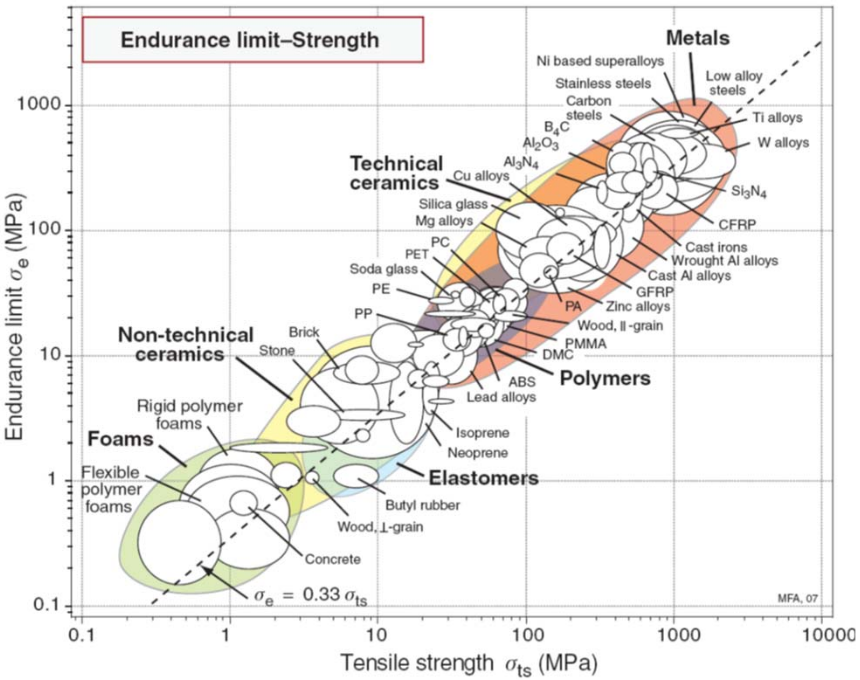
Sketch of load spectrum for cylinder head

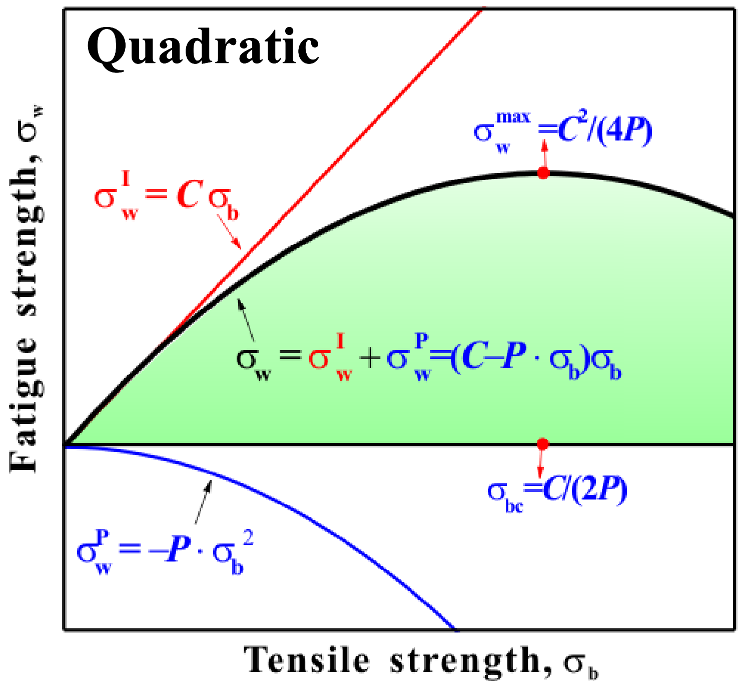


Heating and loading

Tensile at HTs	HCF at HTs	LCF at HTs	TMF
Tensile strength	HCF strength	LCF life	TMF life

5. Question of service property prediction





1870年 | $\sigma_w = m\sigma_b$

Whöler | m:0.4~0.5

Father of fatigue | Linear relation

$$\sigma_w = (C - P \times \sigma_b) \times \sigma_b$$

P: Process Defect

C: Intrinsic Defect

Materials Component

Pang JC *et al*, *Mater. Sci. Eng. A*, 2013; 564: 331; *Fatigue Fract. Eng. Mater. Struct.*, 2014; 37: 958.

5. Question of service property prediction

Basquin, 1910

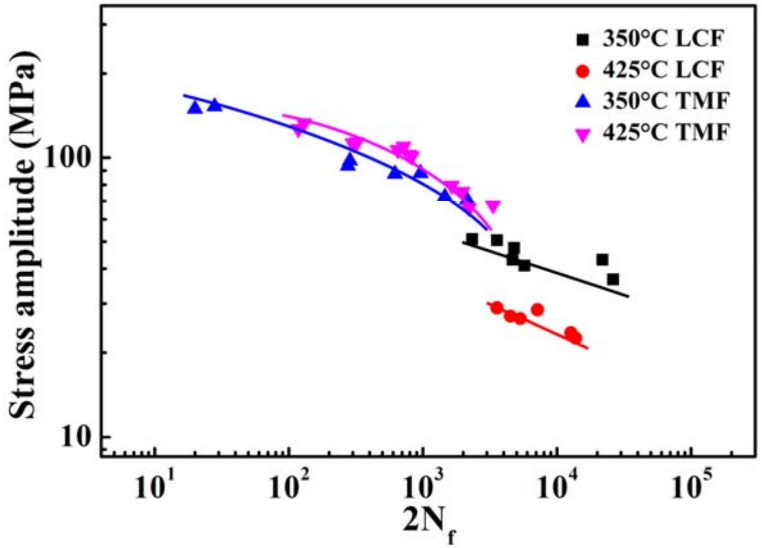
$$\sigma_a = \sigma_f (2N_f)^b$$

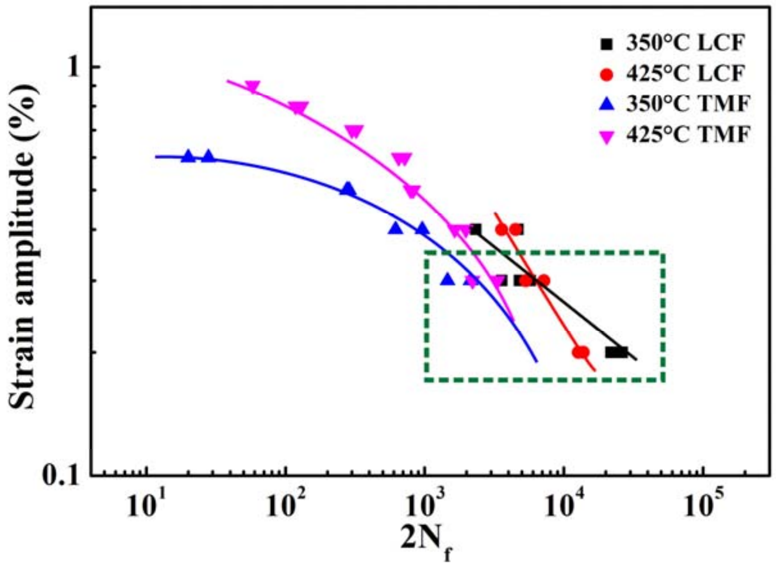
$$D_i = \frac{1}{N_f} = 2 \cdot (\frac{\sigma_a}{\sigma_f})^{-1/b}$$

Coffin & Manson, 1954

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

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

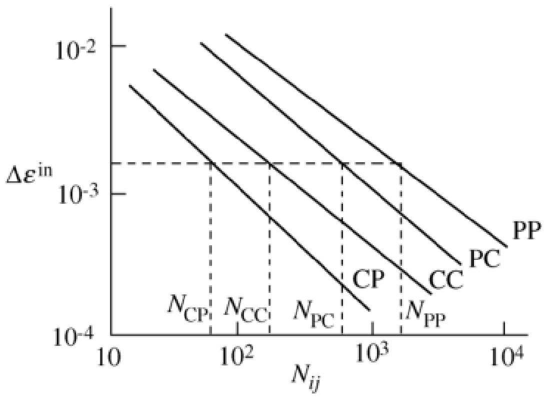




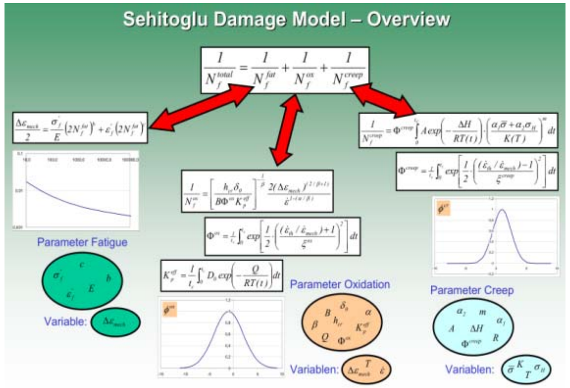
Thermal & force → **Typical model: Limited**

5. Question of service property prediction

SRP



Sehitoglu



Osttergren

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

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

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

Miller

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

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

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

Thermal & Force → **New model: Complex**

Coffin LF, *et al*. Proc. *Inst. Mech. Eng*. 1974;188:109. Neu RW, Sehitoglu H, *Metall. Mater. Trans. A*, 1998;20: 1755 . Miller MP, D.L. *et al. J. Eng. Mater. Technog*, 1992;114: 2346.

6. Simplified and quantified service properties at HTs

Microstructure characteristic

Tensile strength → Fatigue strength

LCF at HTs → TMF

Thermal & Force

Fatigue & Creep & Oxidation

Complex conditions

How to reasonably simplify and quantify the three damages

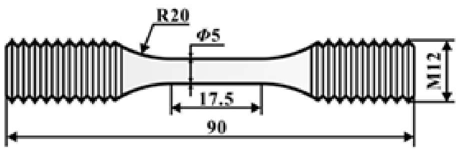
Macroscopic properties

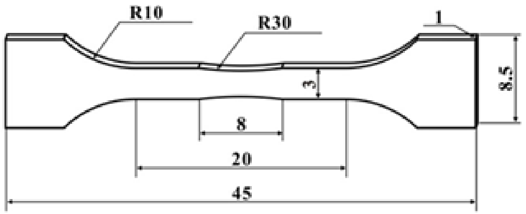
Microscopic damage

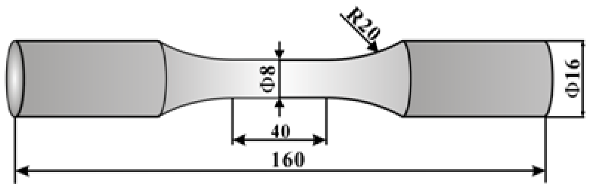
Systematic research

Experimental methods









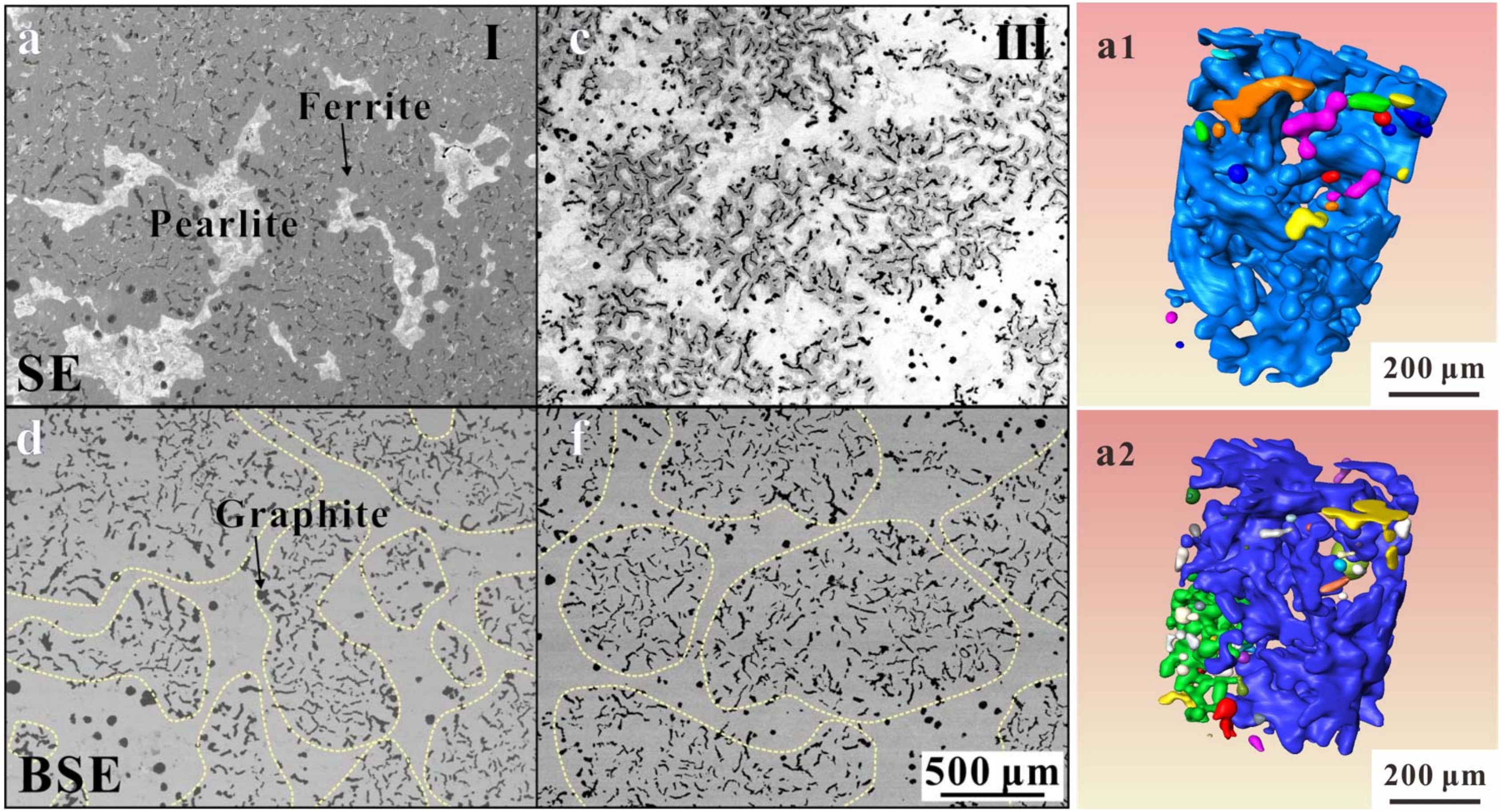
Ten./ LCF ratio : 10^{-2}/s\ 10^{-4}/s

TMF Tem.: 25~400, 25~500 ˚C

FS: Staircase 5 Pairs 1×10^{7}

HCF/LCF Tem.: 25, 400, 500 ˚C

Microstructures of samples

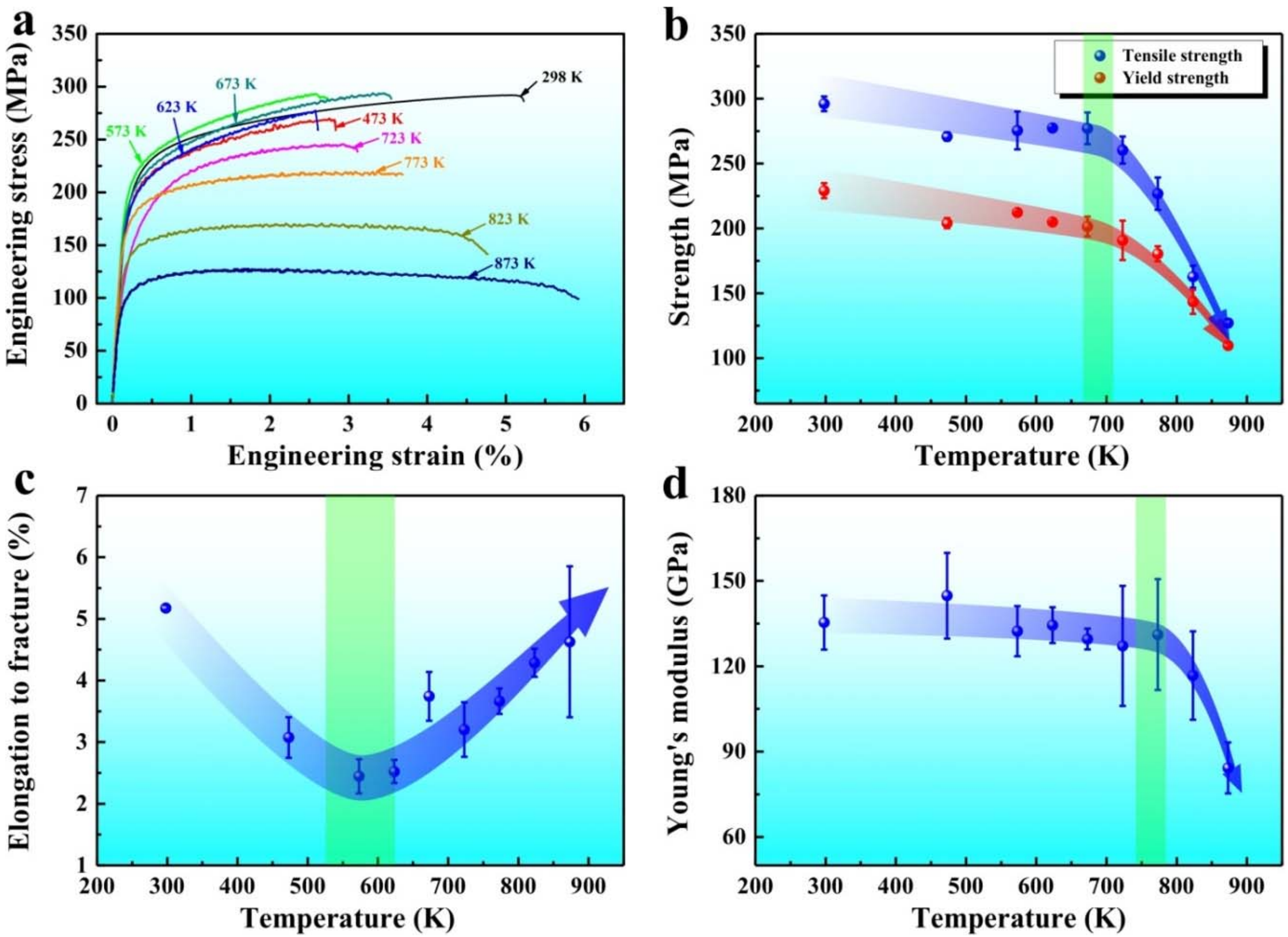


F:10%~60% P:15%~80% G:~10% VG:60%~90%

Recognition of traditional materials: composite

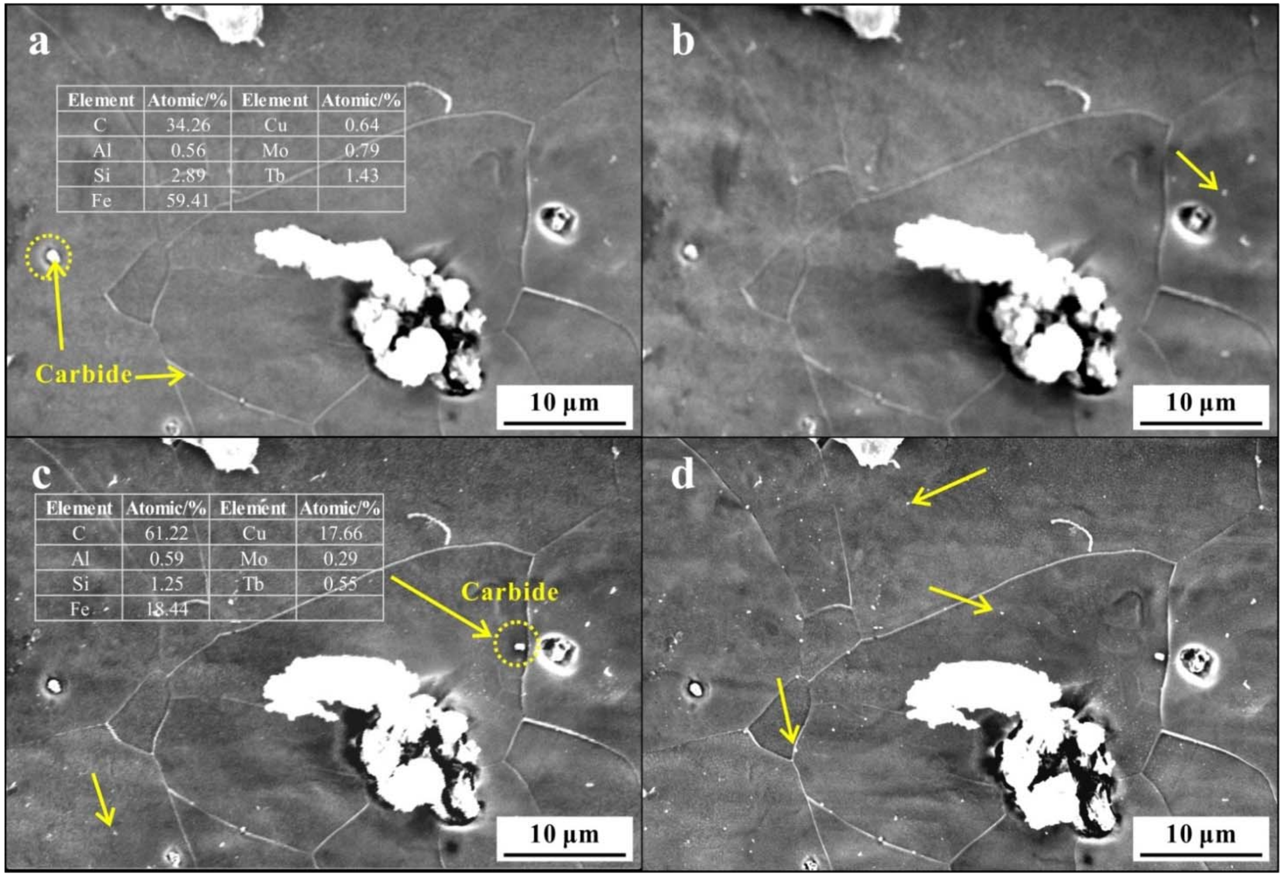
二、拉伸损伤机制与性能定量表征
Tensile damage mechanism and property characterization

1. Tensile properties of CGI



Qiu Y, Pang JC*, *et al*. *Mater. Sci. Eng. A* 2016; 667: 290.

In situ ferrite evolution

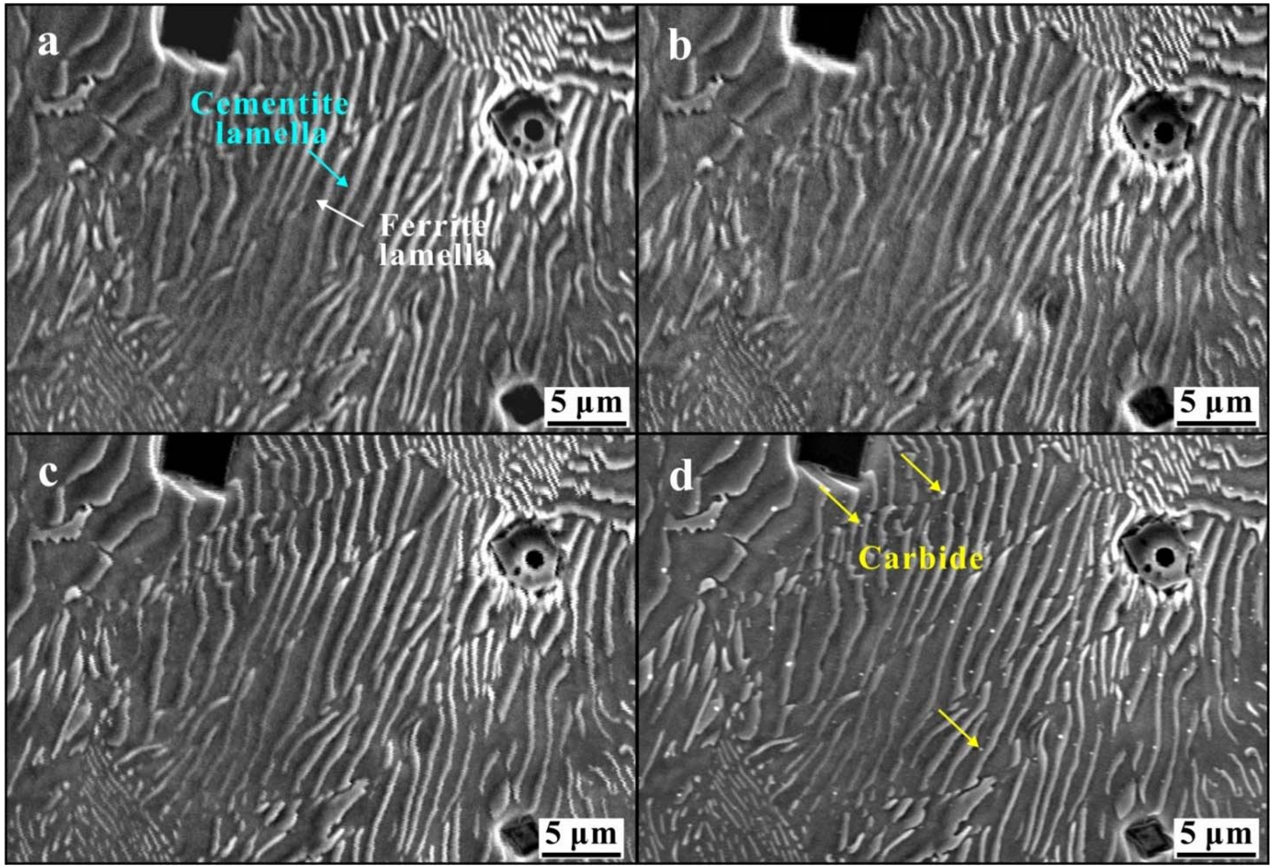


(a) 25˚C; (b) 200˚C; (c) 400˚C; (d) 600˚C

Carbon diffusion   Carbide formation

2. Tensile mechanism of CGI

In situ pearlite evolution

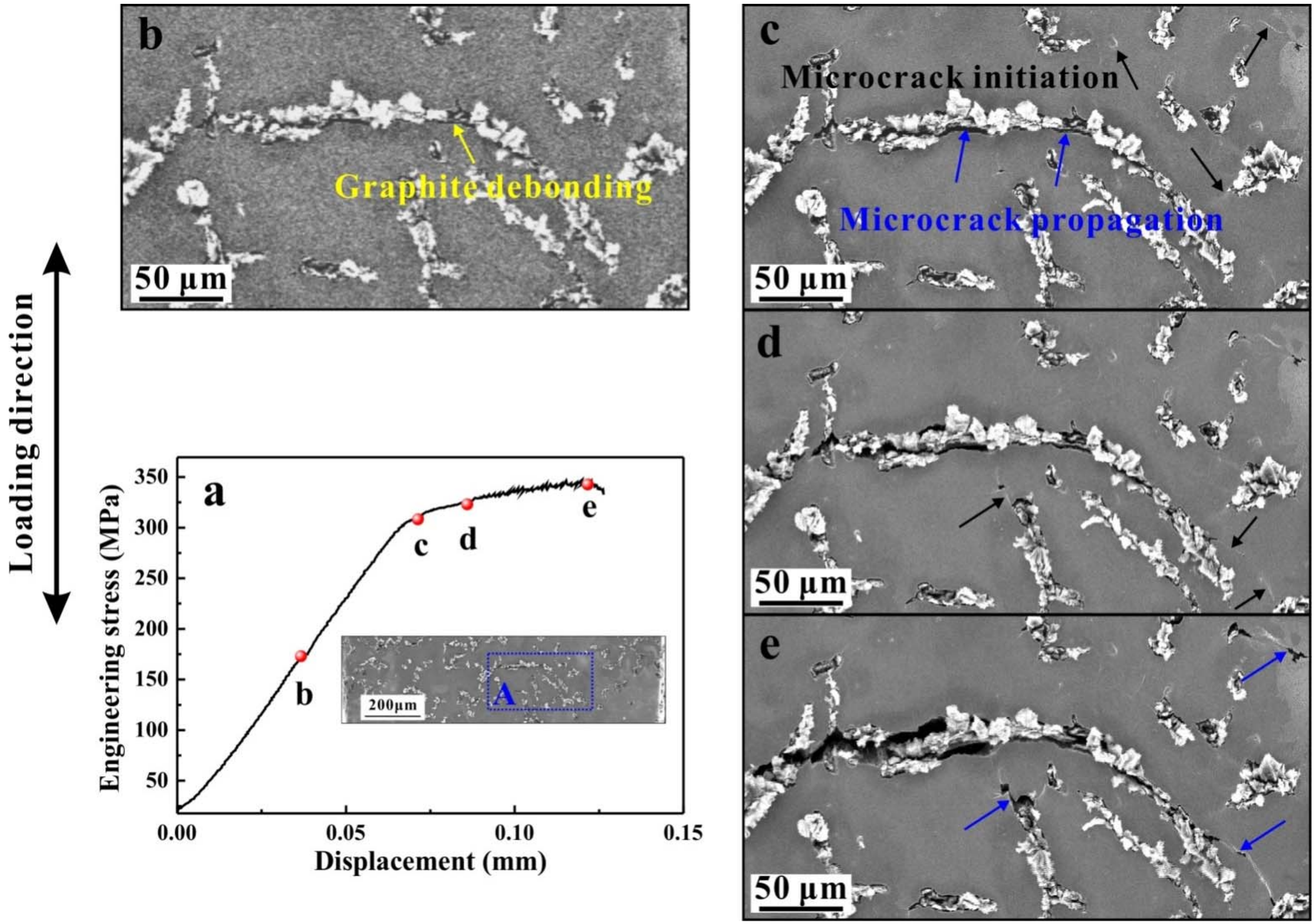


(a) 25˚C; (b) 200˚C; (c) 400˚C; (d) 600˚C

Carbon diffusion   Carbide formation

2. Tensile mechanism of CGI

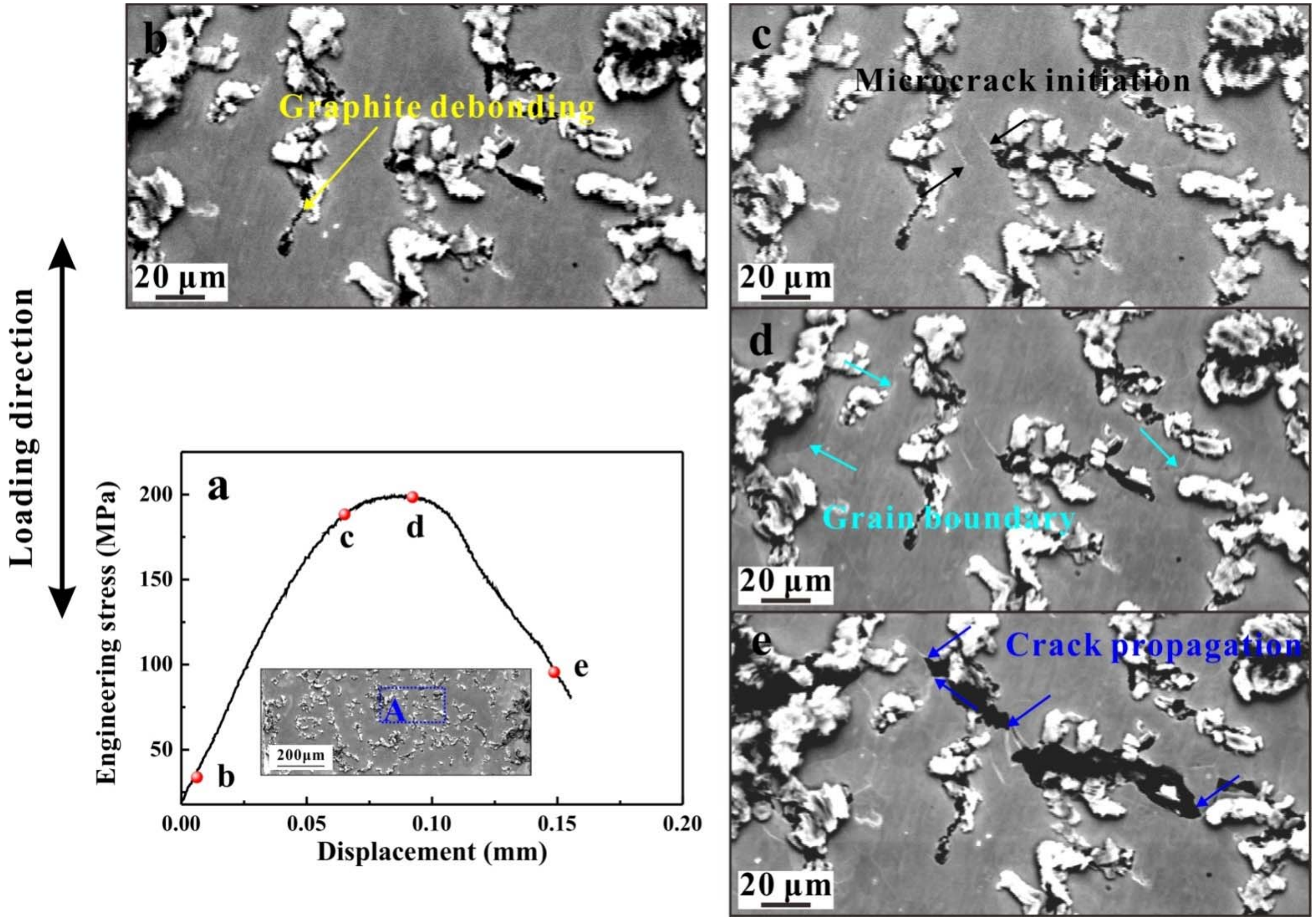
In situ analysis at RT



Graphite crack   **Slipping in ferrite**

2. Tensile mechanism of CGI

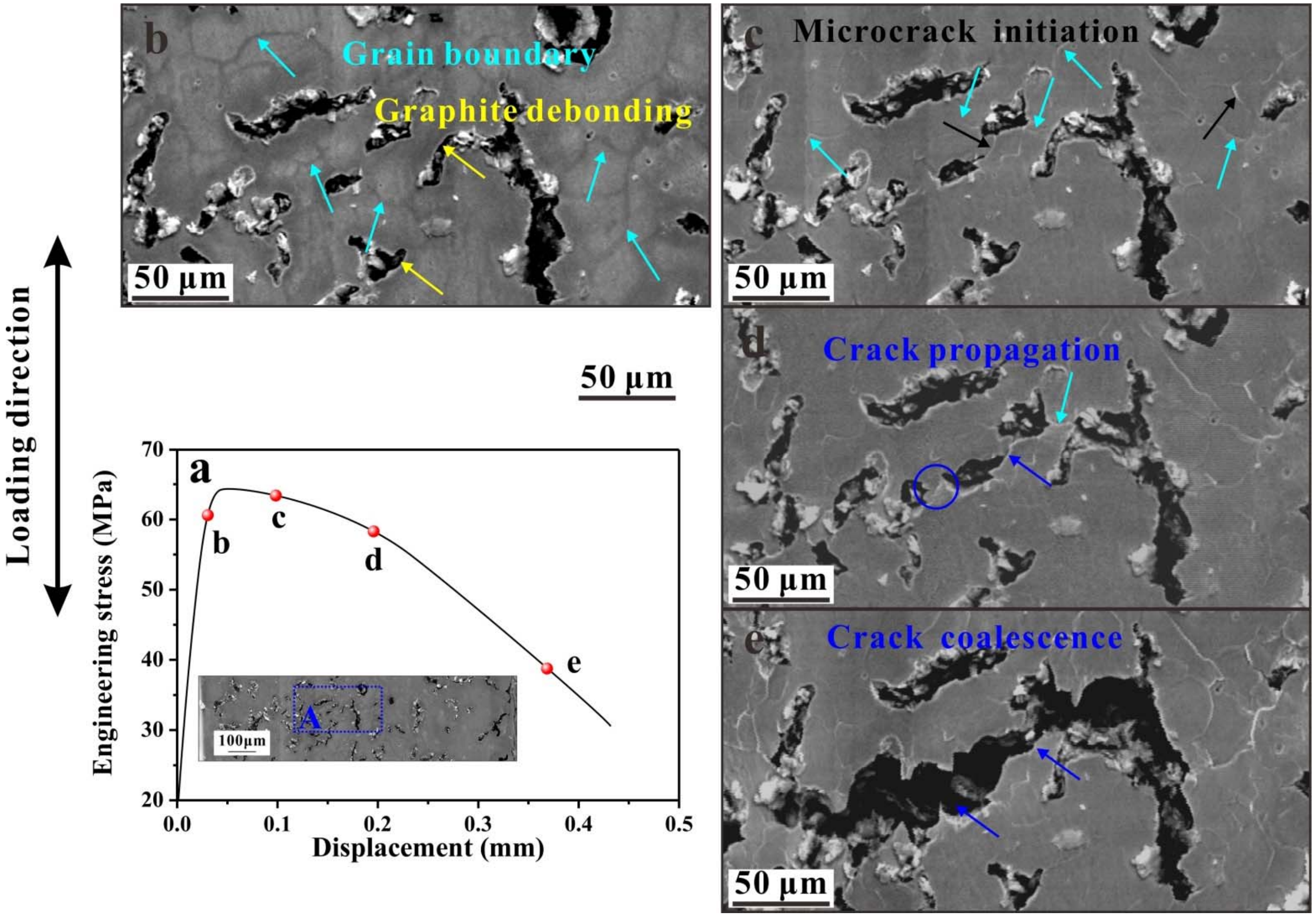
In situ analysis at 450 ˚C



Inner slipping GB sliding

2. Tensile mechanism of CGI

In situ analysis at 600 °C



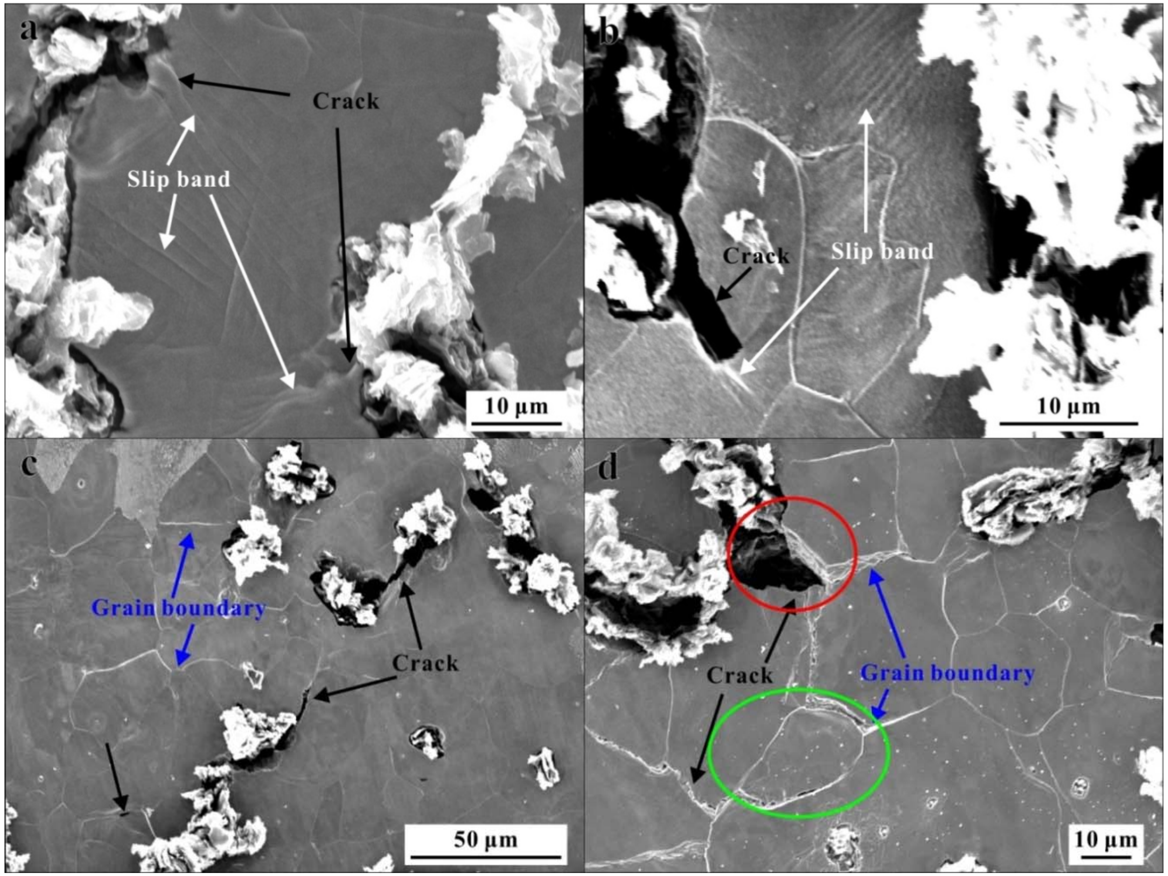
GB sliding in ferrite

2. Tensile mechanism of CGI

Ferrite analysis after fracture

Slipping

Slipping



Sliding

Sliding

(a) 25°C; (b) and (c) 450°C; (d) 550°C

2. Tensile mechanism of CGI

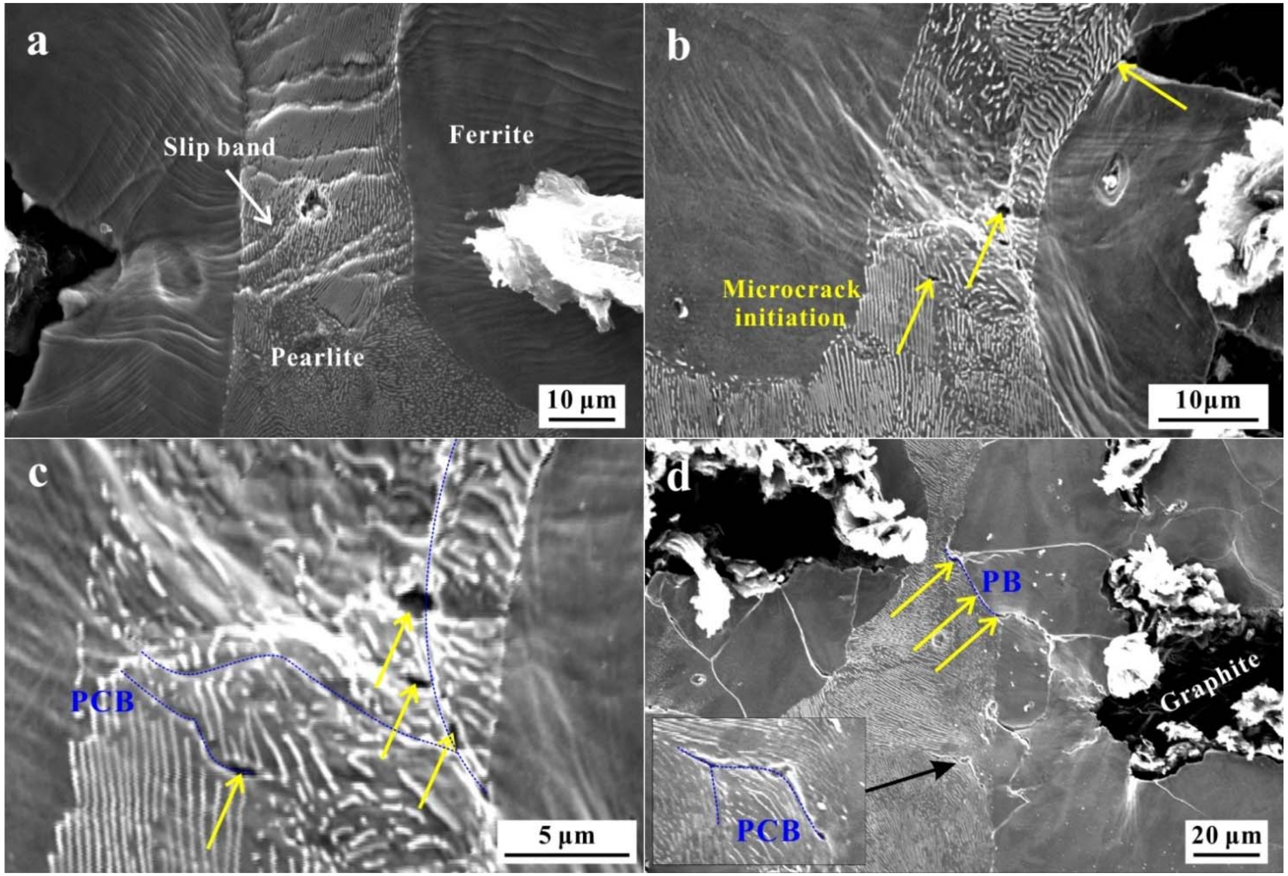
Pearlite analysis after fracture

Slipping

Cracking

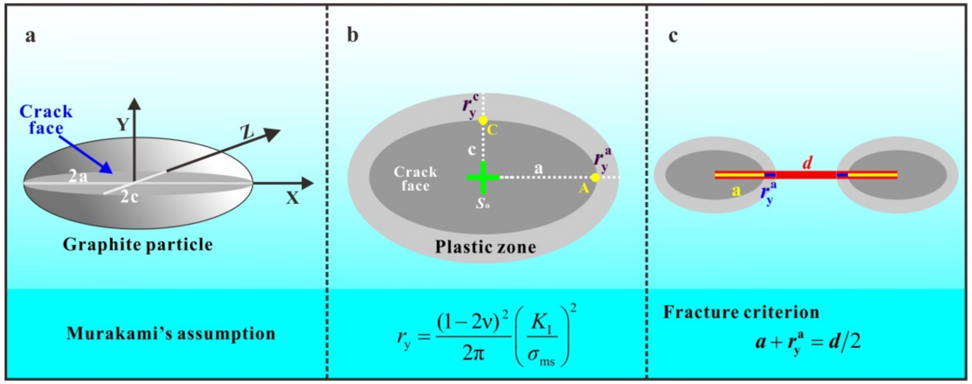
microvoid

Cracked PB



(a) 25˚C; (b) and (c) 450˚C; (d) 550˚C

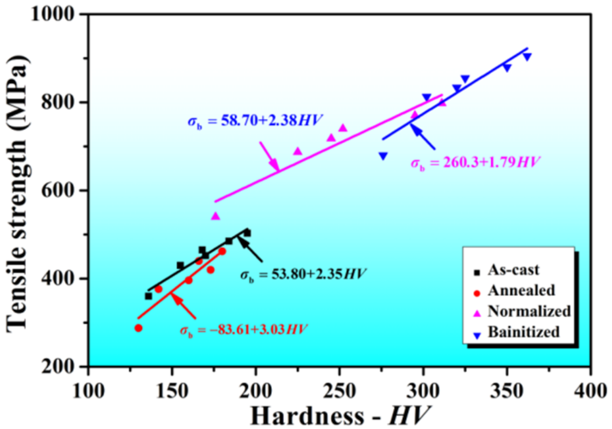
Murakami ' hypothesis



TS of CGI and YS of matrix

$$\sigma_b = \frac{\sqrt{6}\sigma_{ms}}{Y_a}\sqrt{\alpha - 1},$$

$$\alpha = \frac{d}{2a}$$



Takeo Yokobori (T< 450°C)

Dislocation pinning-unpinning

$$\frac{\sigma_{ms}}{\sigma_{ms}^0} = \left(\frac{\dot{\varepsilon}E\omega_0}{mkT\sigma_{ms}^0}\right)^{mkT}$$

Strength and temperature:

$$\sigma_b = \sigma_0 \exp(-BT)\cdot\exp(AT\ln T)$$

Vacancy diffusion (GB) (T> 450°C)

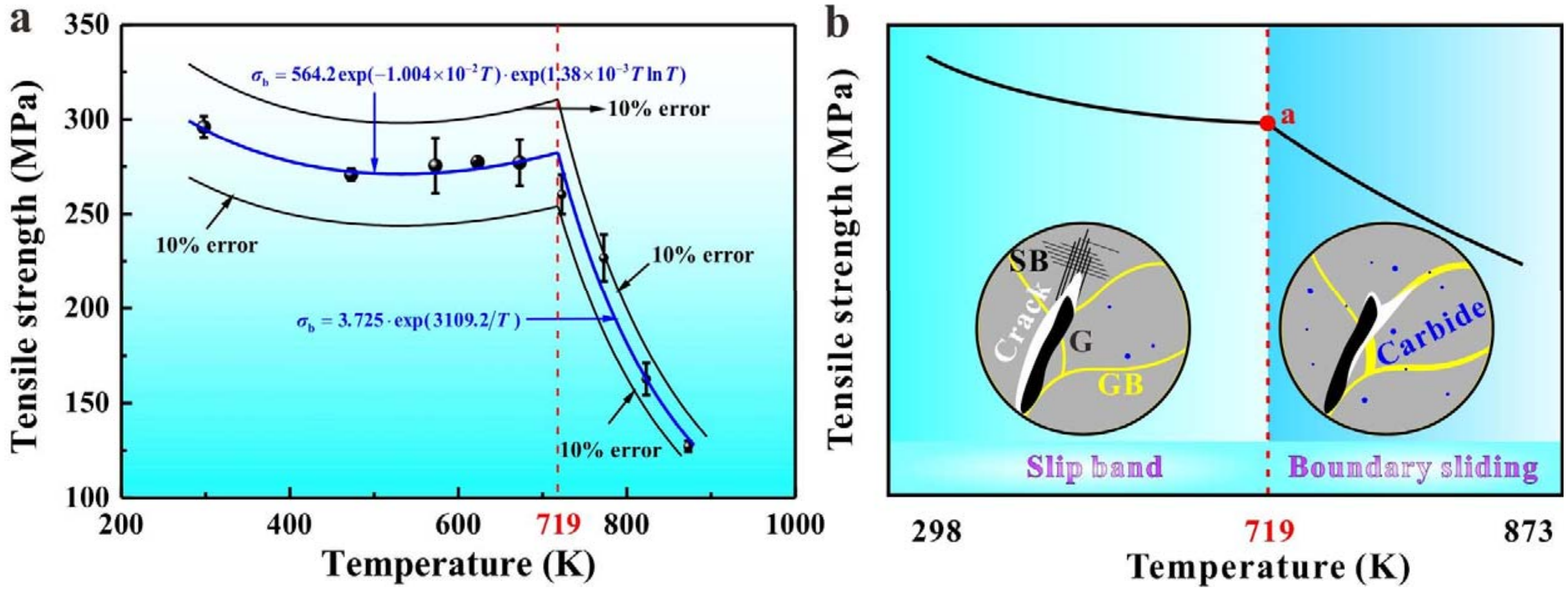
$$\tau_c = \tau_0 \exp(\frac{Q}{RT}) \quad \sigma_b = \frac{\tau_c}{\mathrm{con}(\bar{\theta})\sin(\bar{\theta})}(1-\frac{\Delta l_0}{l_0})$$

Strength and temperature:

$$\sigma_b = \sigma_0 \exp(\frac{Q}{RT})$$

Kogoh S, *et al*. *J. Mater. Sci.* 1992 27: 4323. Qiu Y, Pang JC*, *et al*. *Mater. Sci. Eng. A* 2016; 664: 75.

4. Brief summary



Tensile strength (a) and mechanism (b) evolutions of CGI with temperature

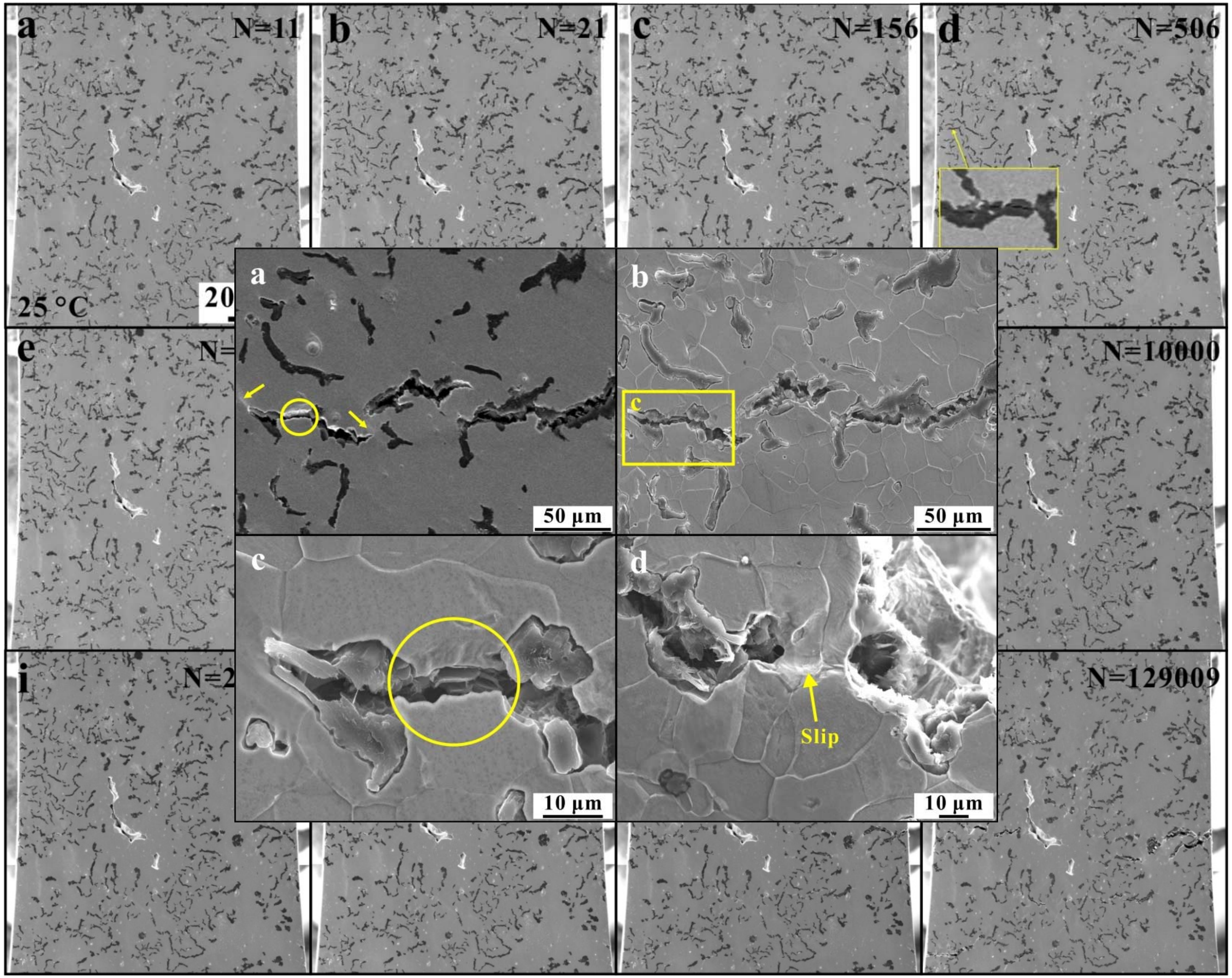
三、高温疲劳损伤机制与强度预测

Fatigue damage mechanism and strength prediction

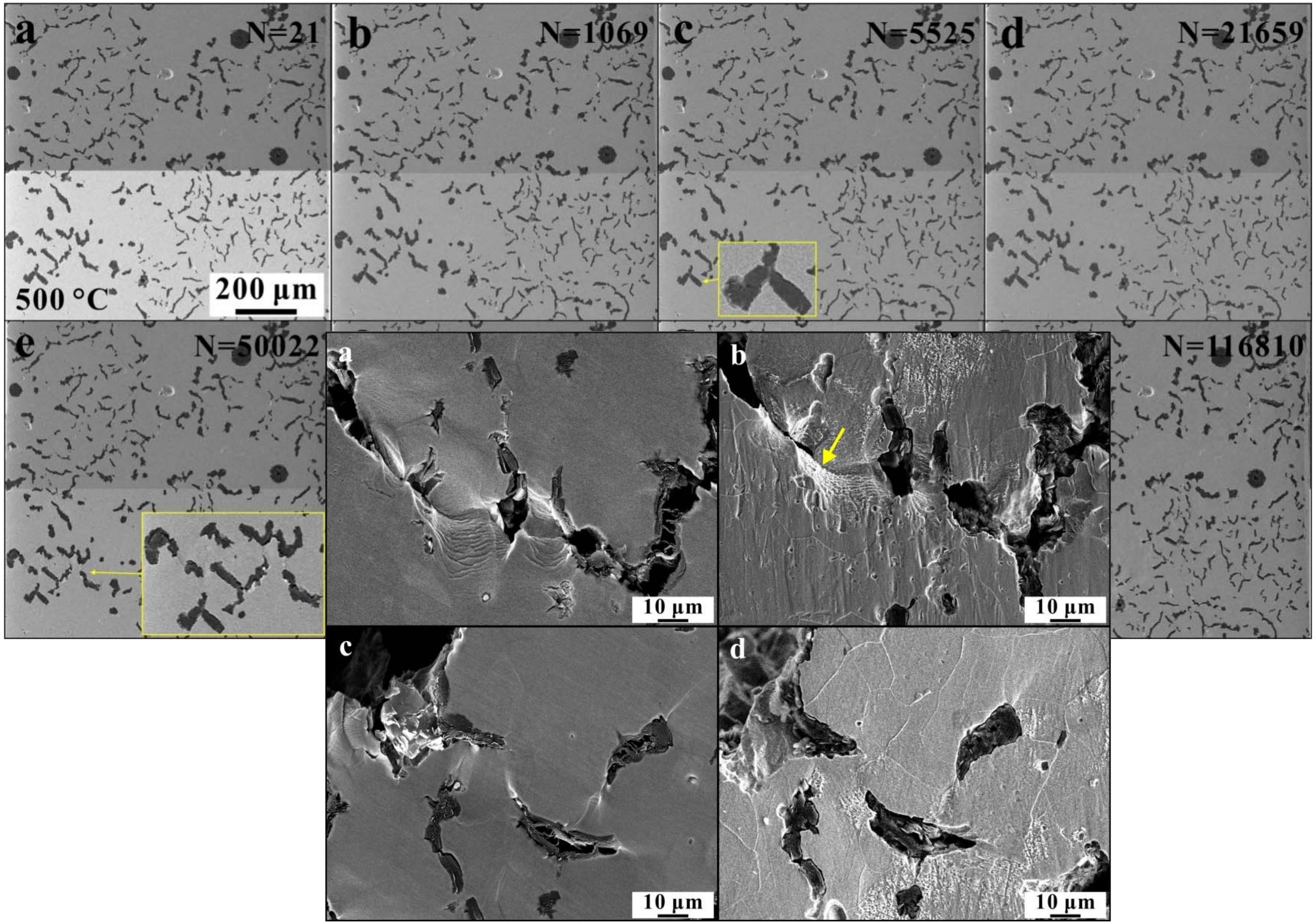
1. Mechanism analysis of CGI

S. I

25°C

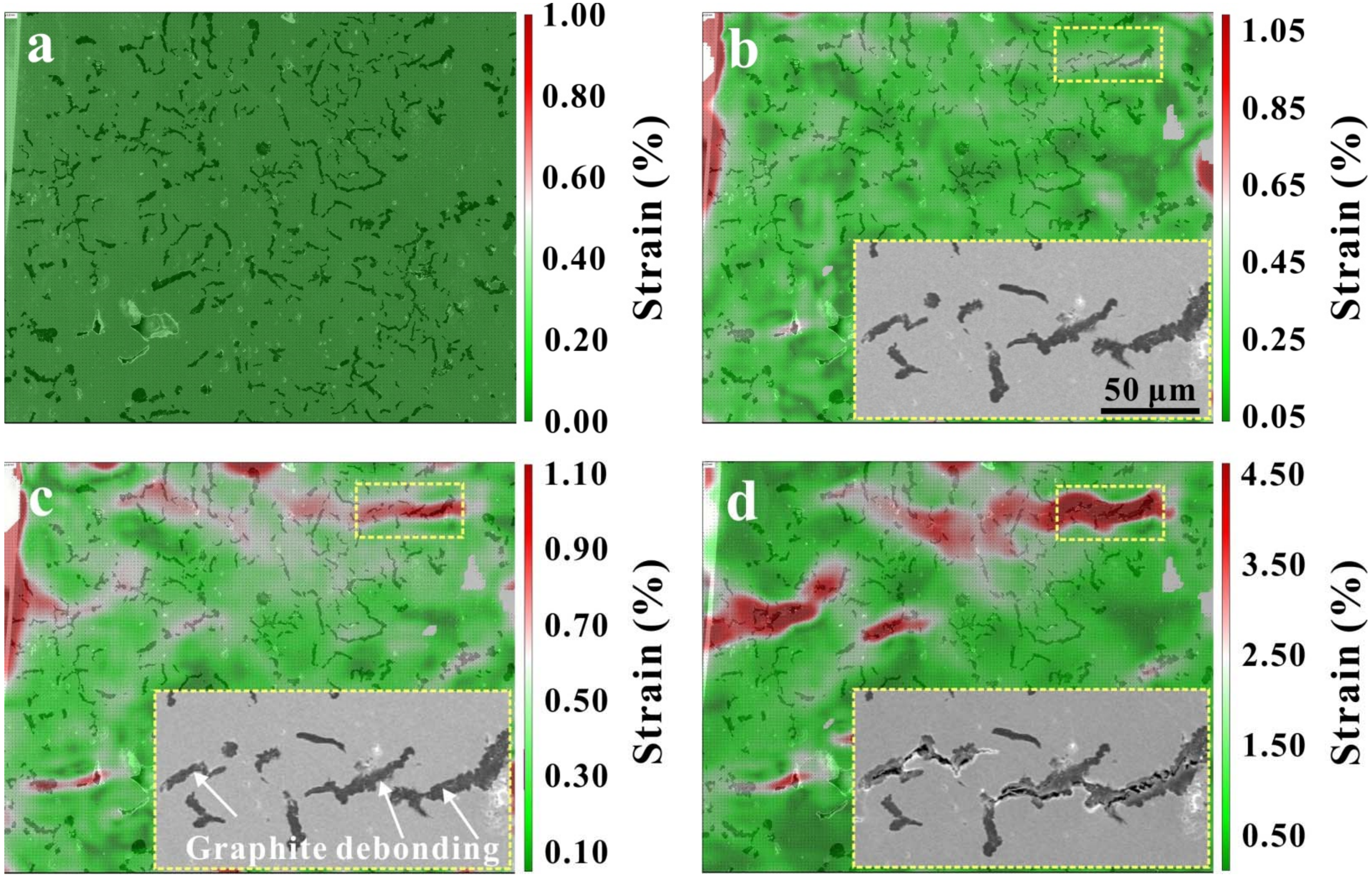


1. Mechanism analysis of CGI



500°C

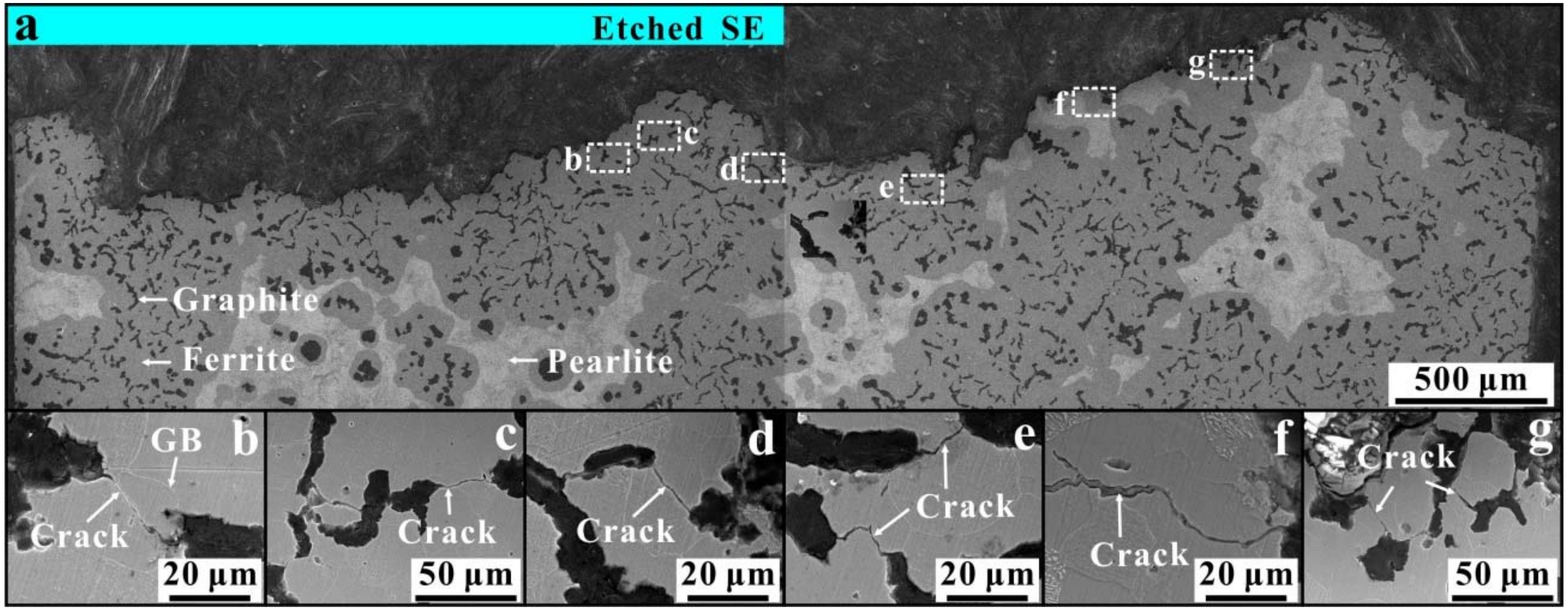
1. Mechanism analysis of CGI



25°C S. I : (a) N= 0；(b) N=156；(c) N=506 and (d) N=120009

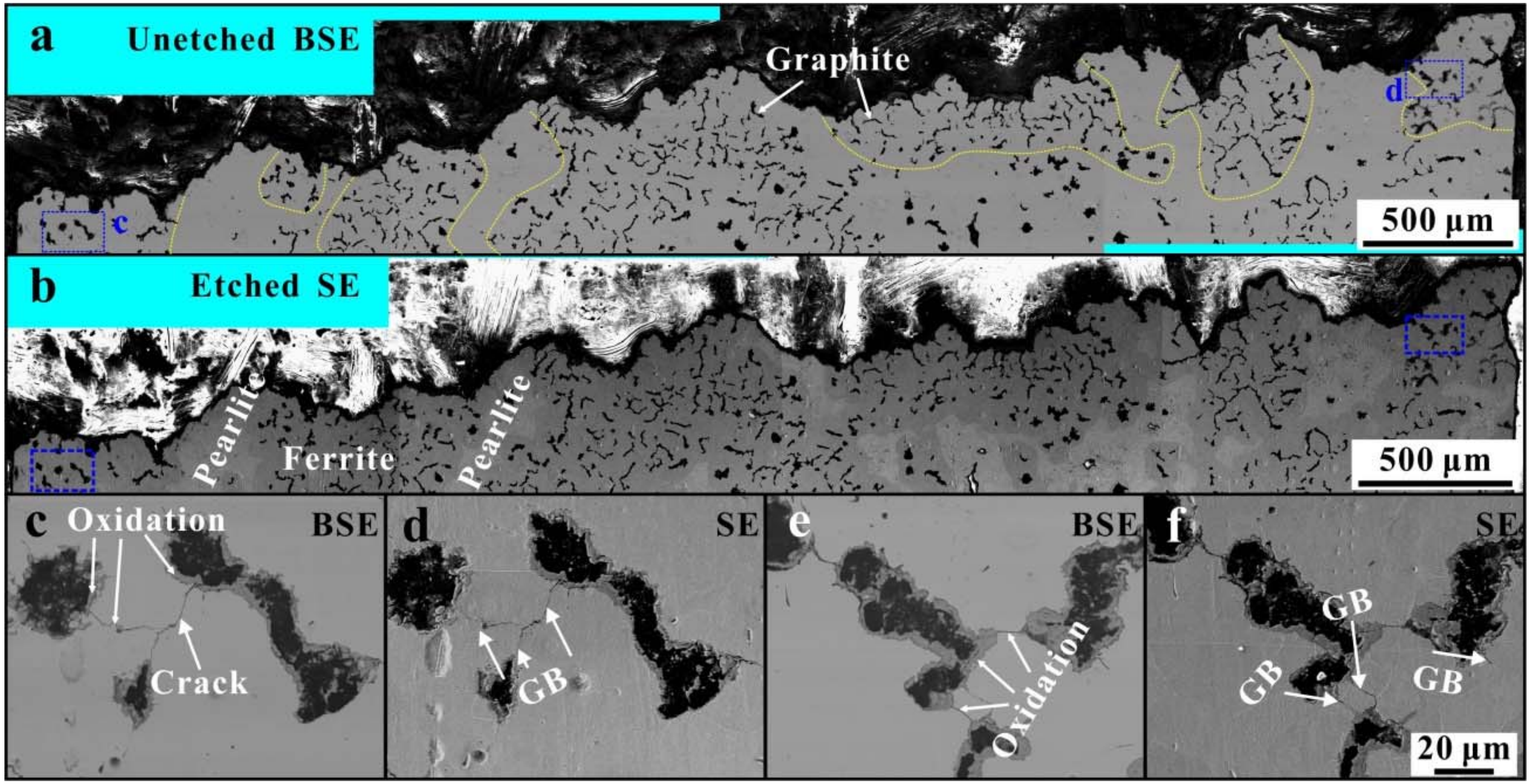
1. Mechanism analysis of CGI

25°C | S. I



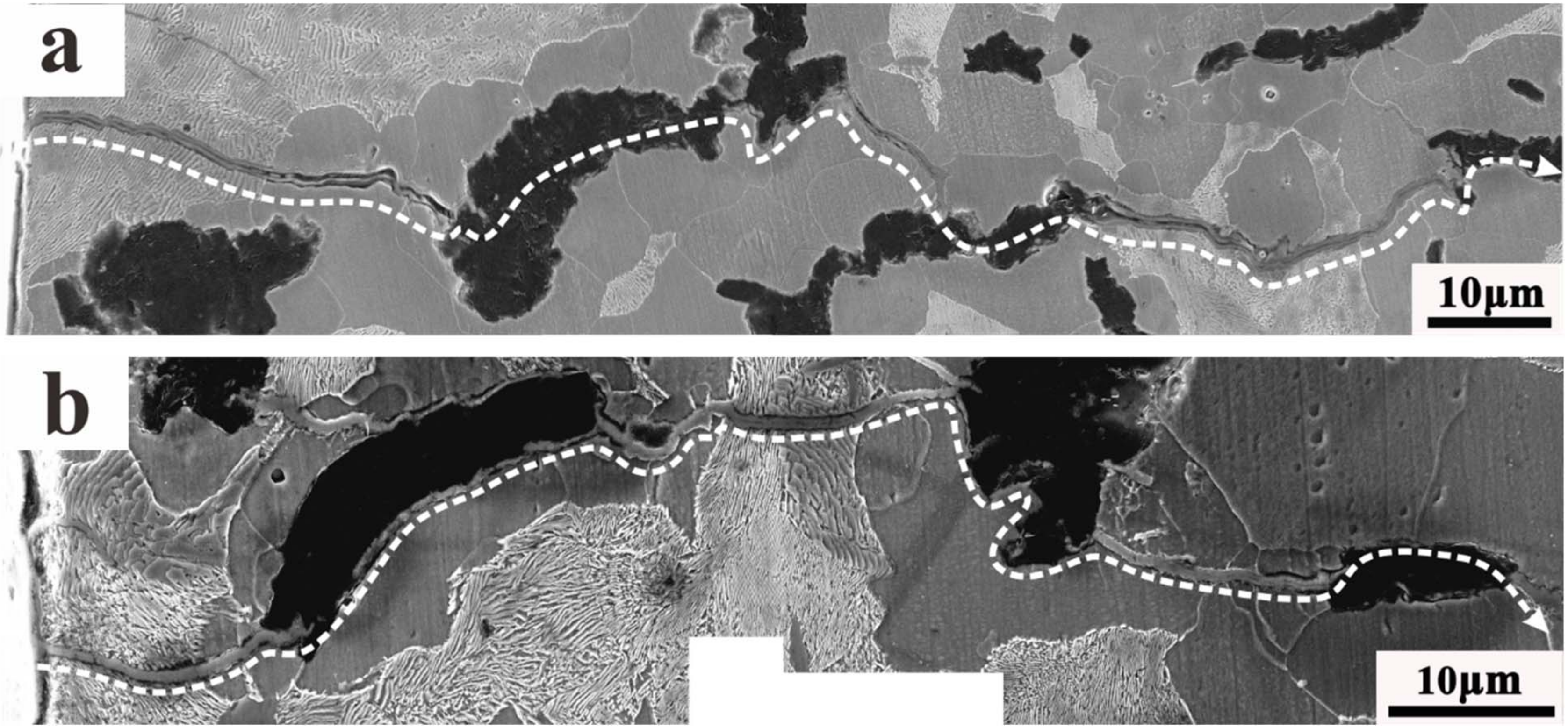
Typical profile morphology : σ_a = 160MPa, N_f = 489151

500°C | S. I



Typical profile morphology : σ_a = 170MPa, N_f = 163812

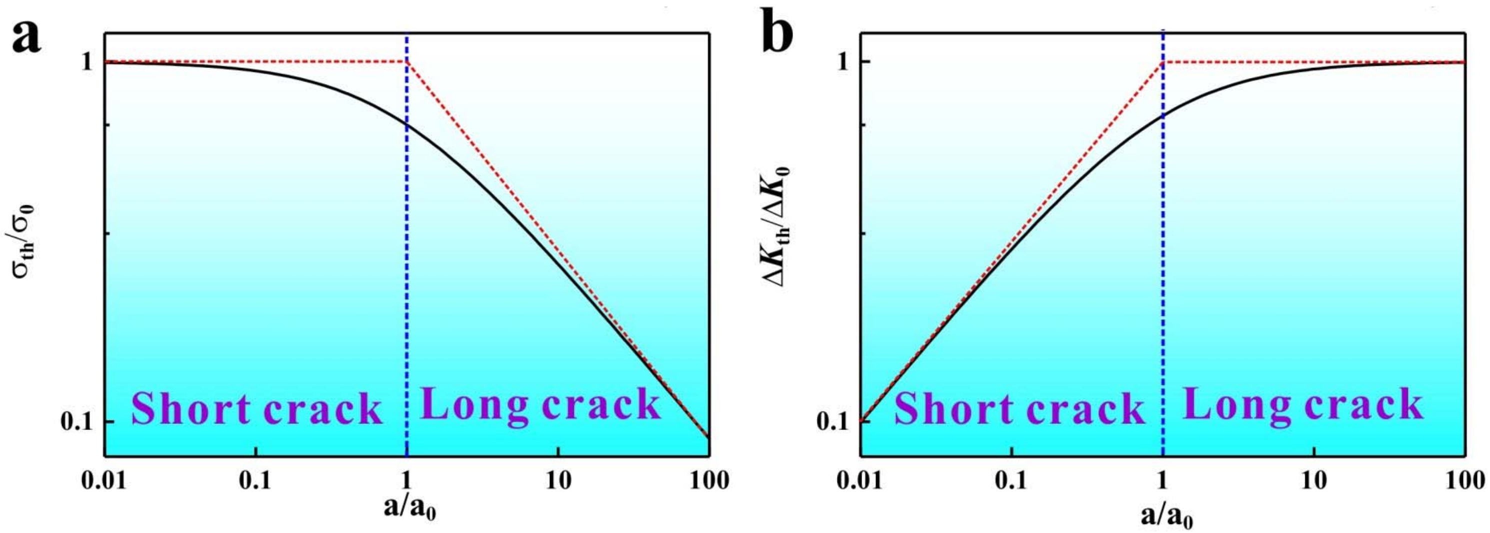
1. Mechanism analysis of CGI



S.III：(a) 400 °C；(b) 500 °C

Fatigue crack initiation and propagation

2. Quantitative relation of CGI



Critical crack size

$$a_0 = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta \sigma_e}\right)^2,$$

$a = a_0$

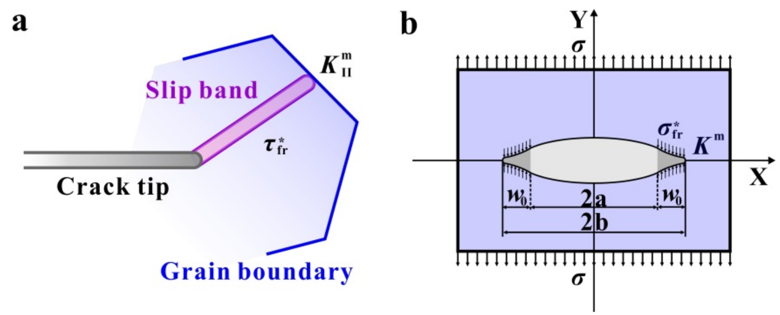
a_0 different

BSB model — Slip band blocked by grain boundary

$$\sigma_w = \frac{\sigma_e}{\sqrt{a/a_0 + 1}}$$

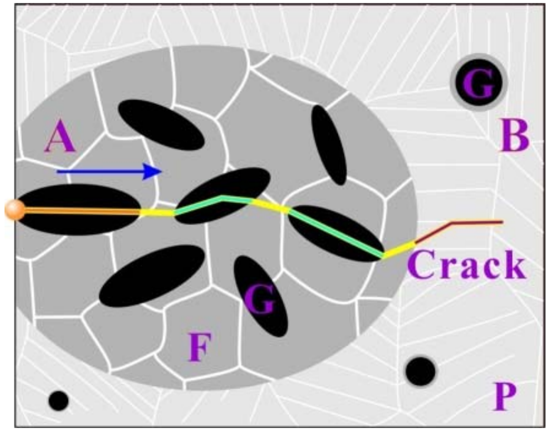
a- Semi crack length

a_0-Plastic zone size



Kitagawa H, et al. ASM, Metals Park, Ohio. 1976.El-Haddad MH, *et al. Eng. Fract. Mech.* 1979 11: 573.Tanaka K, *et al. Int. J. Fracture.* 1981 17: 519.

2. Quantitative relation of CGI



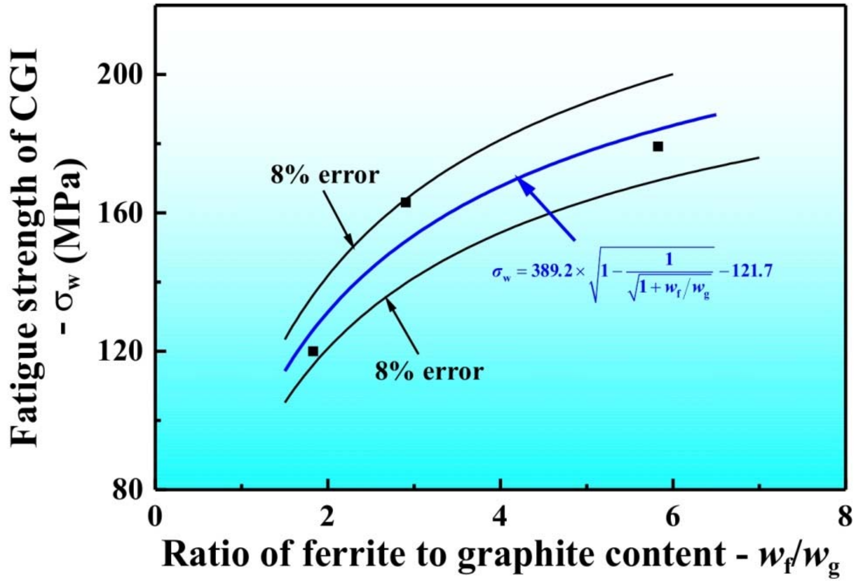
Graphite $\sqrt{Area_g}$

Ferrite $\sqrt{Area_g + Area_f} - \sqrt{Area_g}$

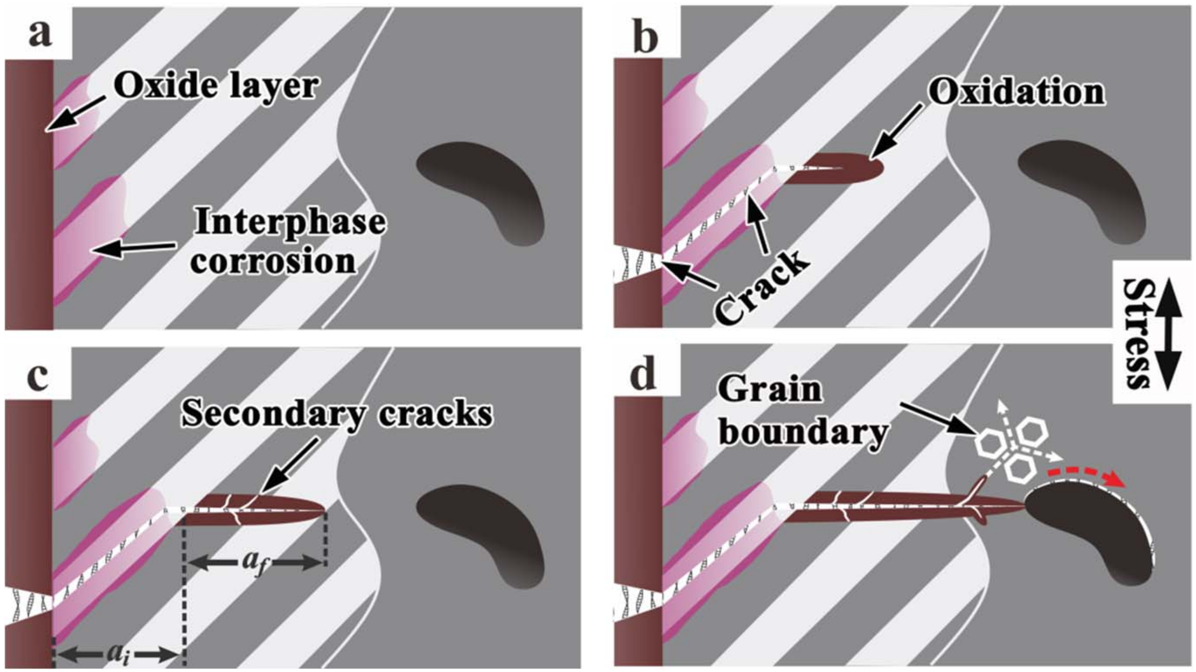
Fatigue strength of CGI

$$\sigma_w = \sigma_w^f \sqrt{1 - \frac{1}{\sqrt{1 + Area_f / Area_g}}}$$

$$\sigma_w = \sigma_w^f \sqrt{1 - \frac{1}{\sqrt{1 + w_f / w_g}}}$$

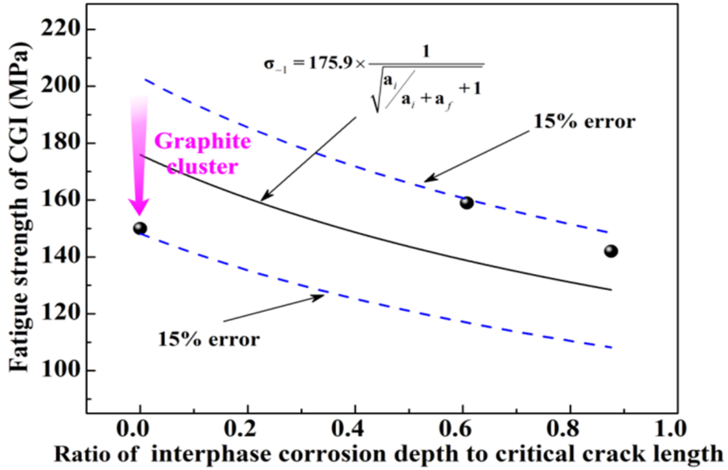


2. Quantitative relation of CGI



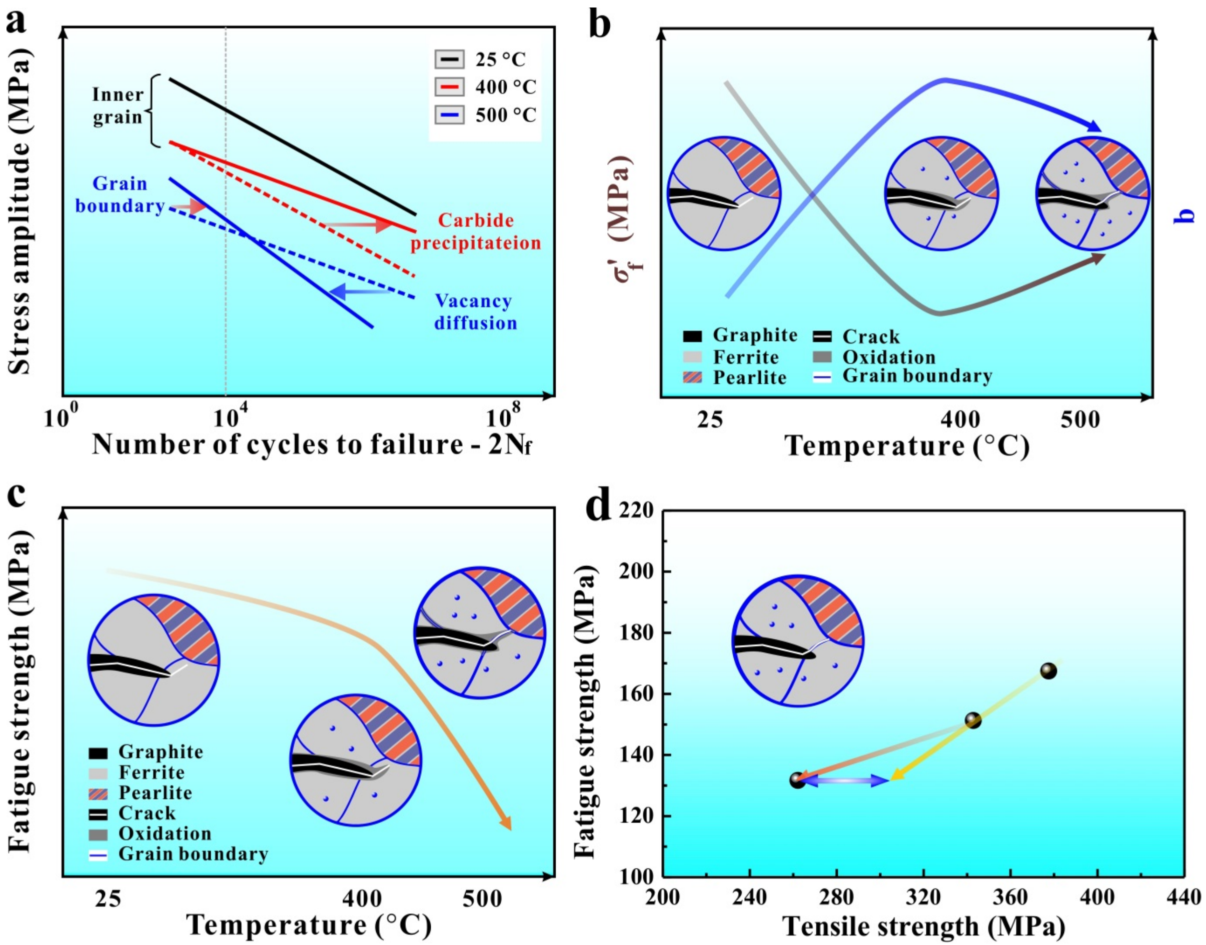
Fatigue strength of CGI

$$\sigma_w = \sigma_w^f \frac{1}{\sqrt{1+\frac{a_i}{a_i+a_f}}}$$



3. Brief summary

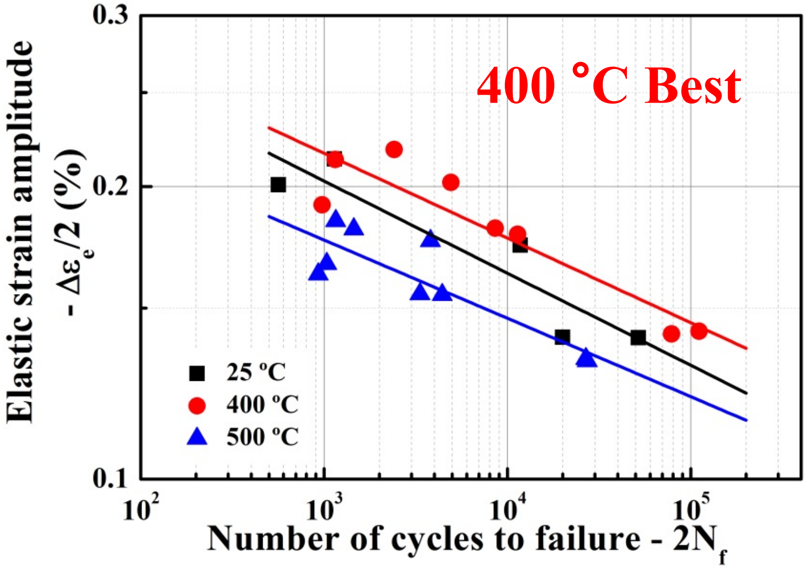
Temperature influence

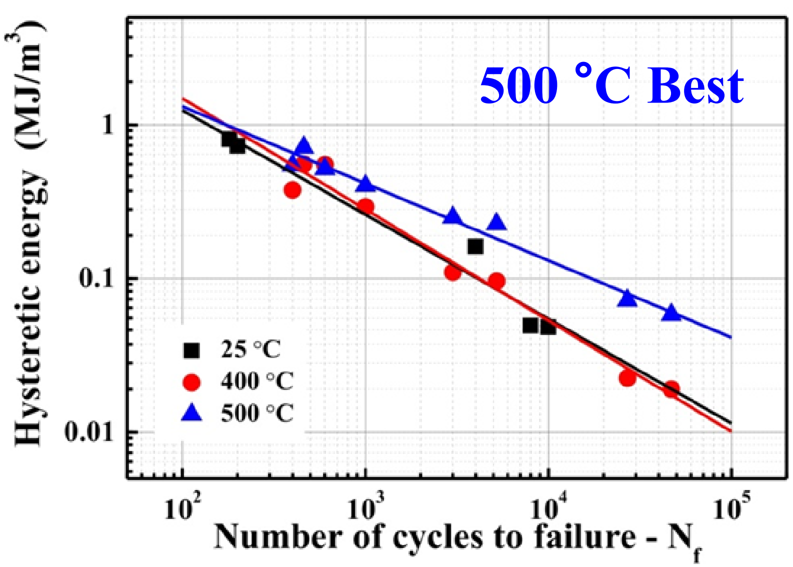


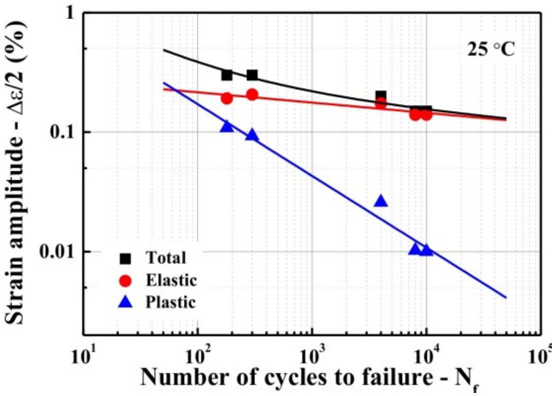
(a) S-N ; (b) Basquin relation;(c) fatigue strength; (d) relation between tensile and fatigue strengths

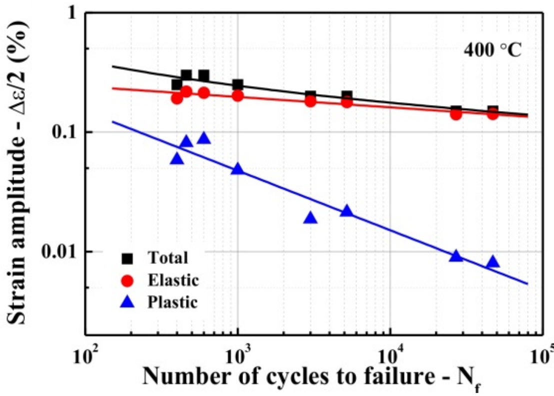
四、疲劳寿命预测模型与损伤机制
Fatigue life prediction model and damage mechanism

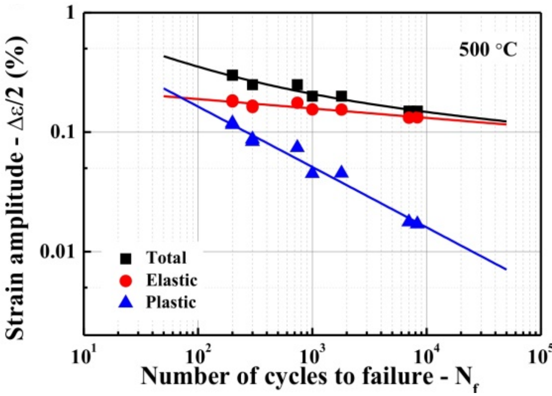
1. LCF properties and mechanism at HTs







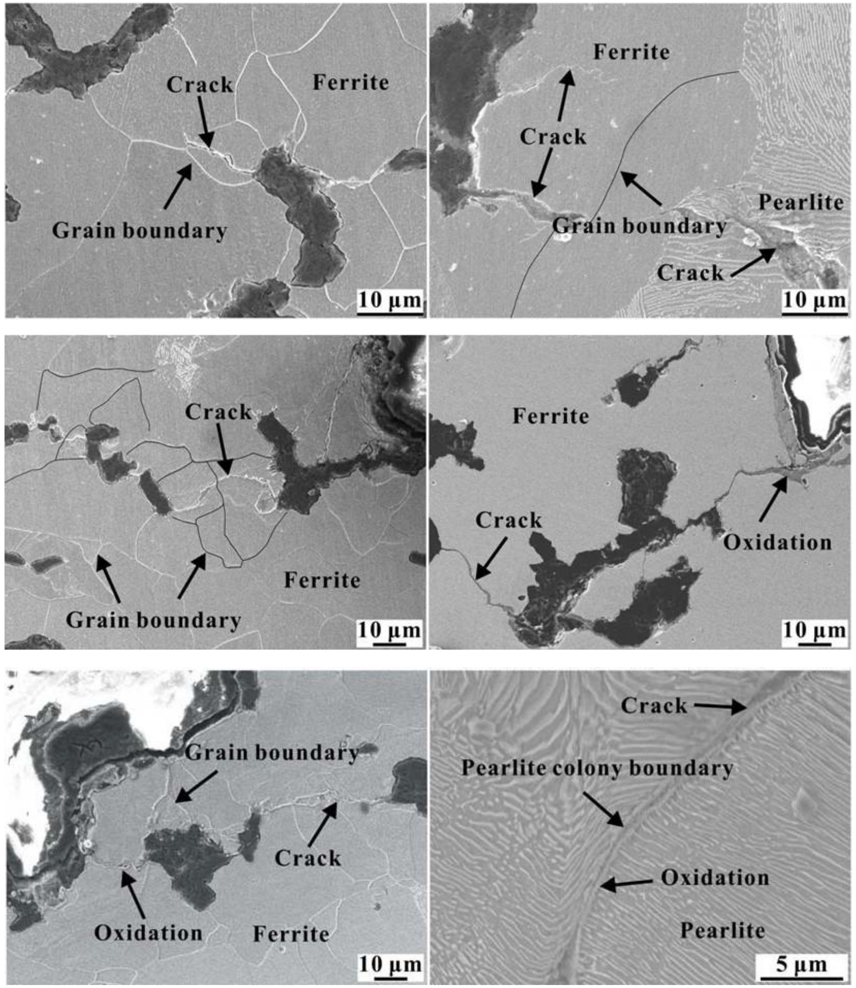


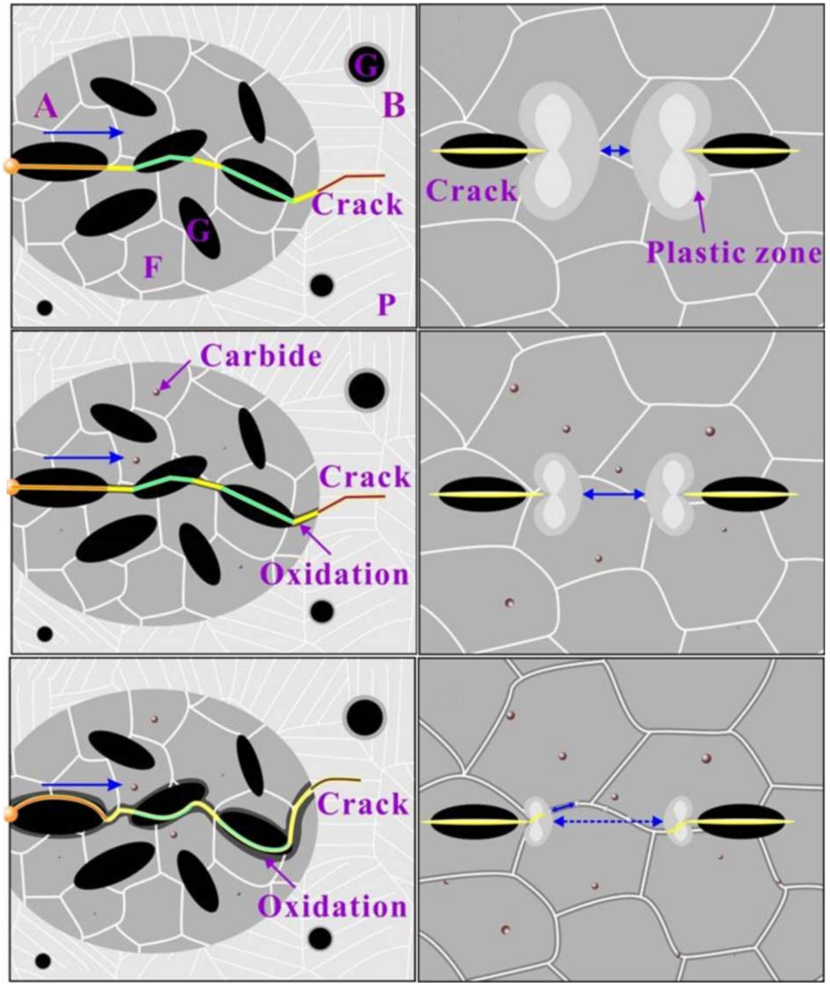


Non-monotonic change of fatigue life with temperature

Qiu Y, Pang JC*, *et al. Int. J. Fatigue* 2018; 117: 450.

1. LCF properties and mechanism at HTs



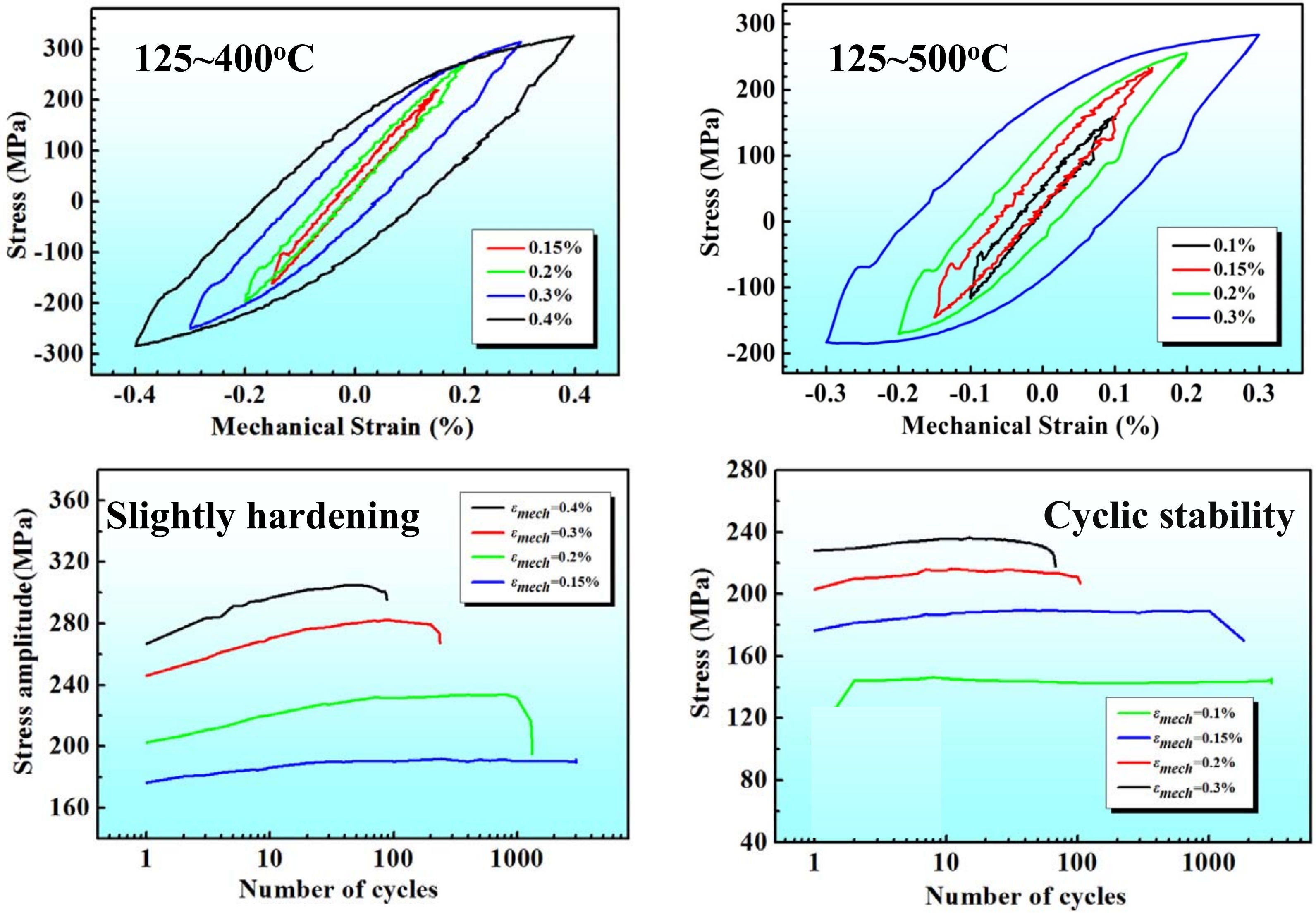


Crack propagation

Damage mechanism

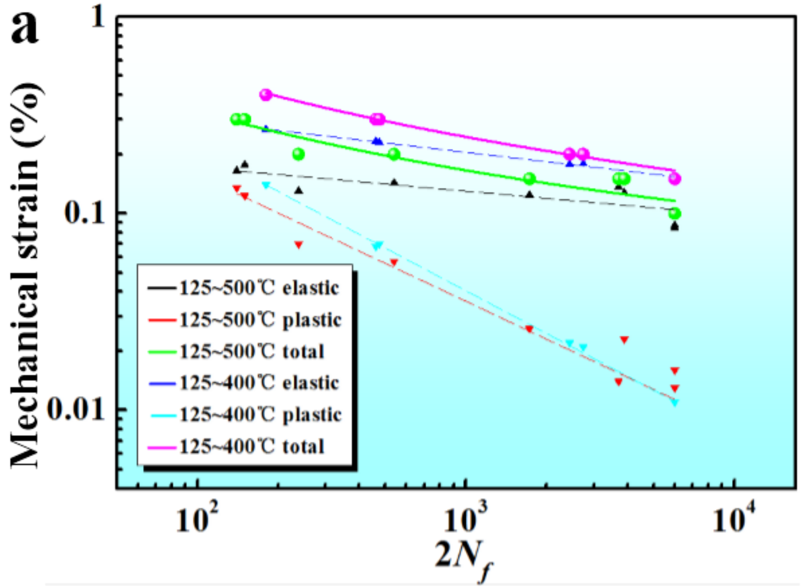
Qiu Y, Pang JC*, *et al. Int. J. Fatigue* 2018; 117: 450.

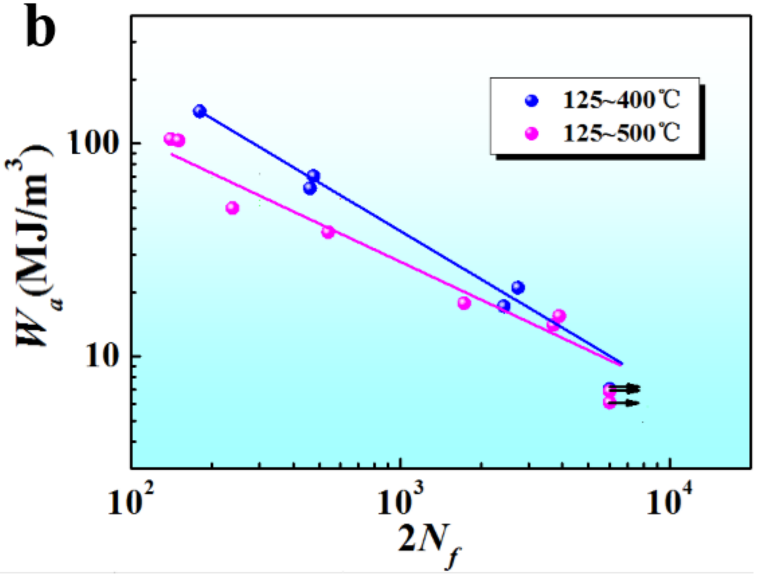
2. TMF properties and mechanism

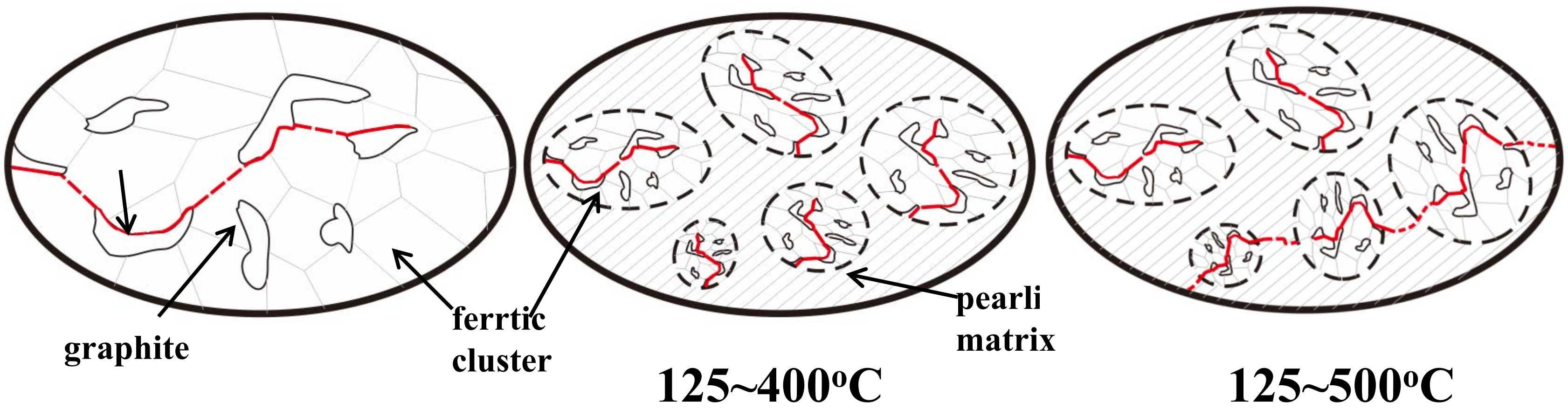


Hysteresis loop and cyclic behavior curves

2. TMF properties and mechanism





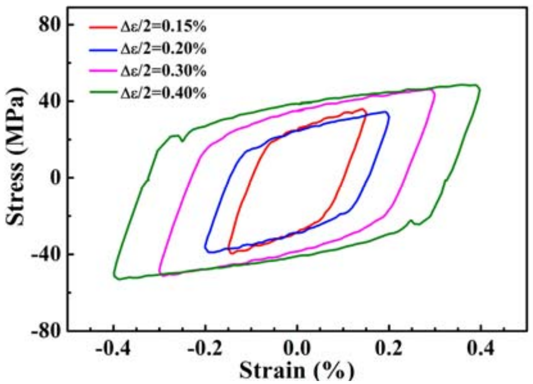


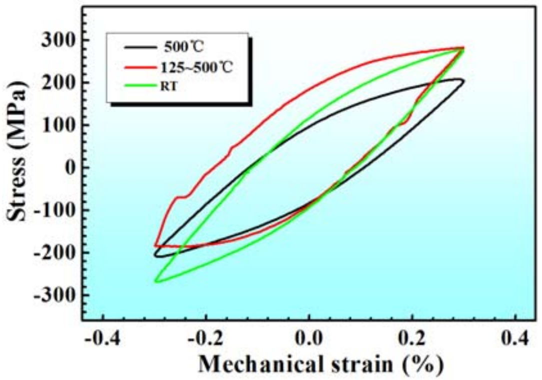
Behavior&mechanism: LCF at HTs ≈ TMF No creep & oxidation

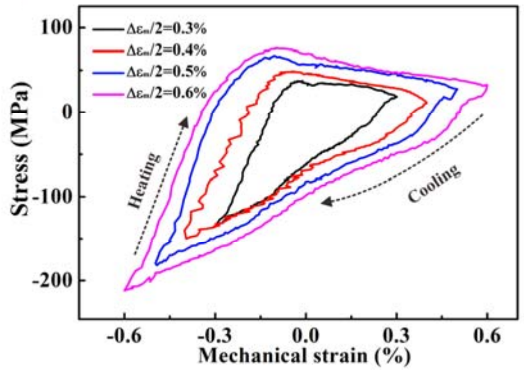
Zhang MX, Pang JC*, *et al*. *Mater. Sci. Eng. A.* 2017; 698: 63.

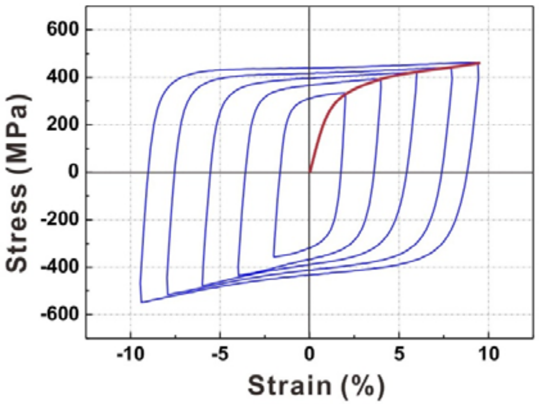
3. Simply quantitative relation: Hysteresis energy

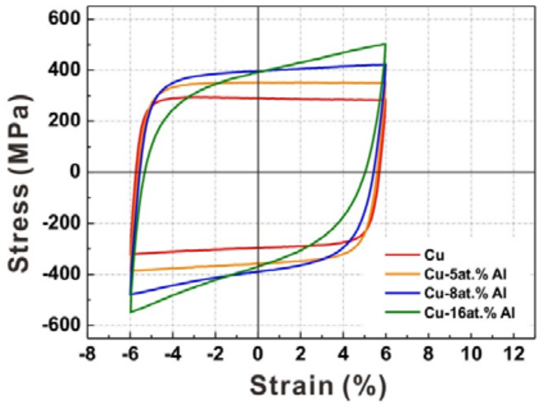
LCF at HTs | **Bridge: Energy** | **TMF**

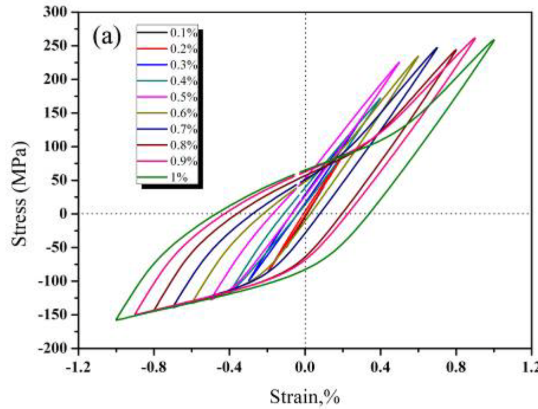








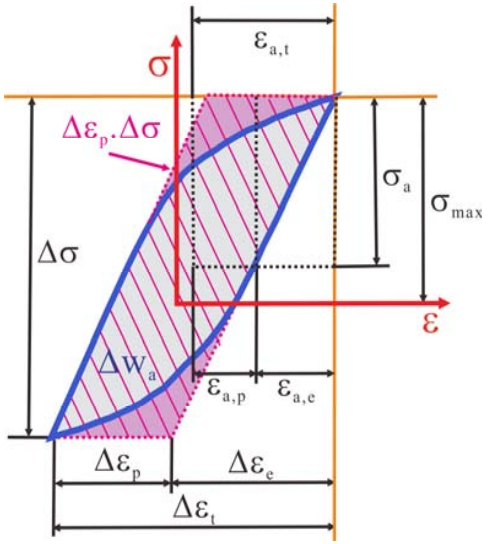


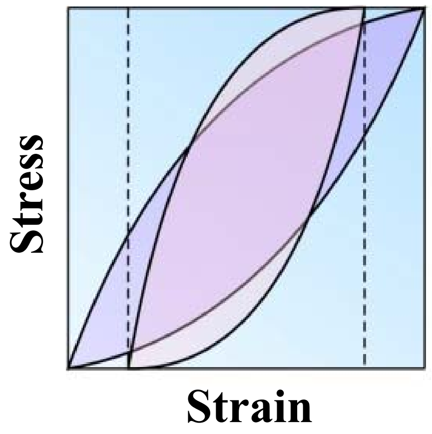


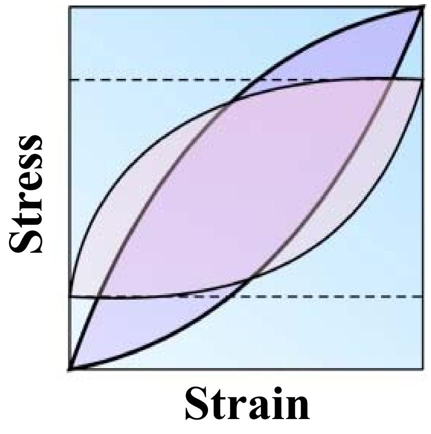
LCF at RT

Different mechanism, similar form, reflected by hysteresis energy

3. Simply quantitative relation: Hysteresis energy







Prediction model at RT： Hysteresis energy reflect damage

Energy model

$$D_i = \left(\frac{W_i}{W_0}\right)^{\beta}$$

$$\text{Damage} = \left(\frac{\text{Energy}}{\text{Toughness}}\right)^{\beta}$$

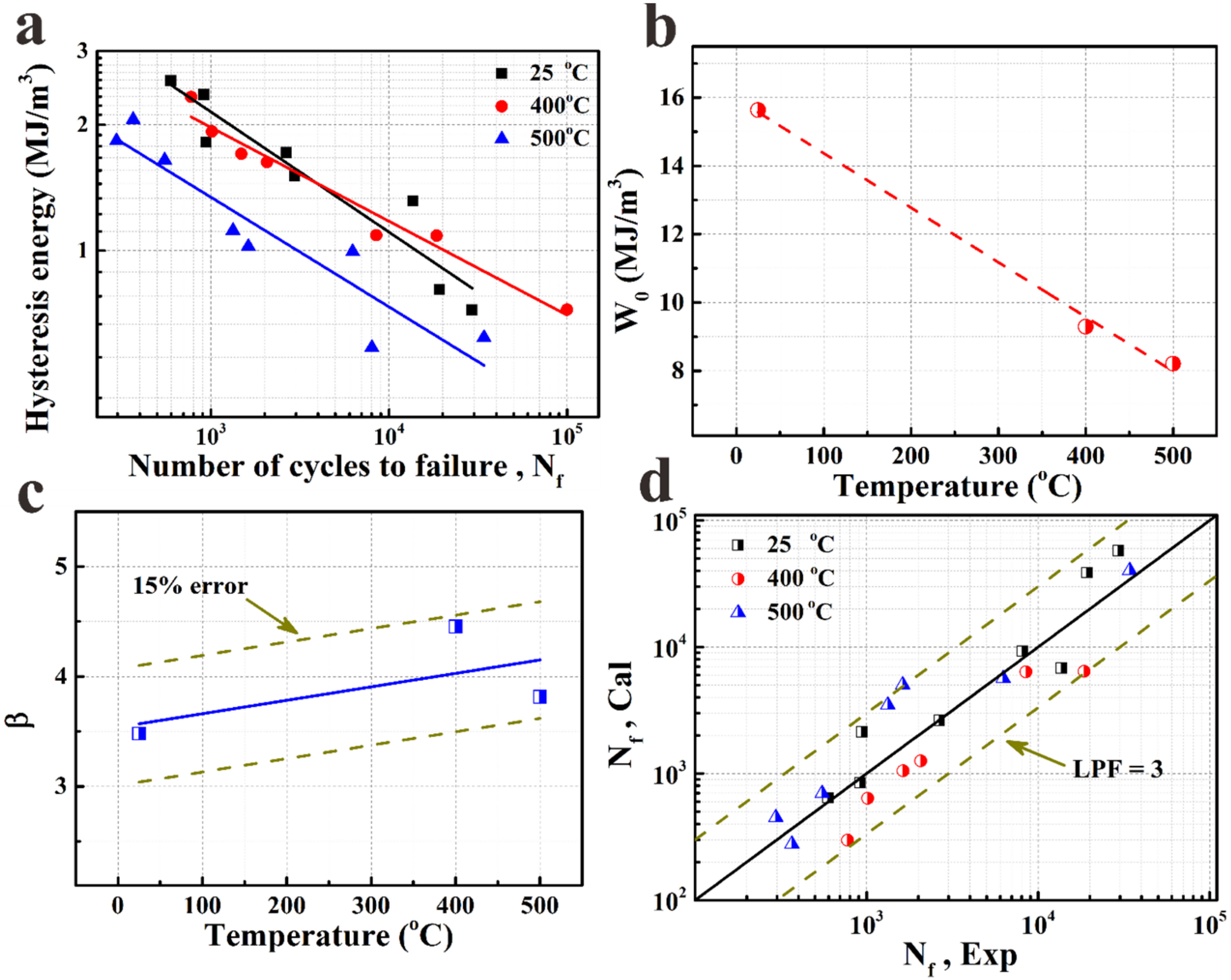
External

Internal

Energy model can obtain life prediction and optimization at RT

Liu R *et al. Acta Mater.*, 2015; 83: 341; Shao CW, *et al. Acta Mater.*, 2016: 103: 781.

3. Simply quantitative relation: Hysteresis energy



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

$$W_0=aT+b$$

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

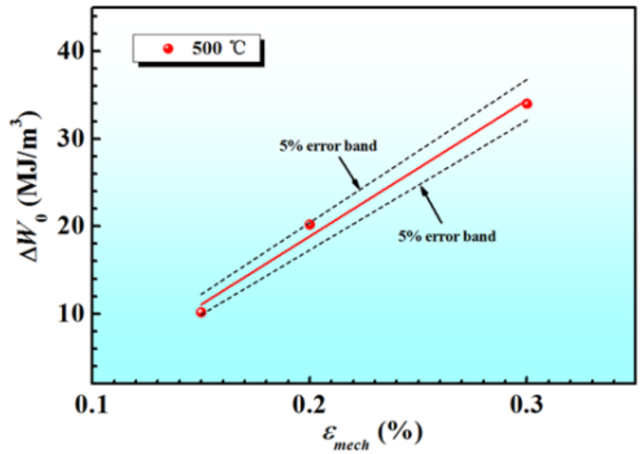
$$N_f=\left[\frac{(aT+b)}{W_s}\right]^{1/(mT+n)}$$

Introduce the temperature parameter, obtain LCF model at HTs

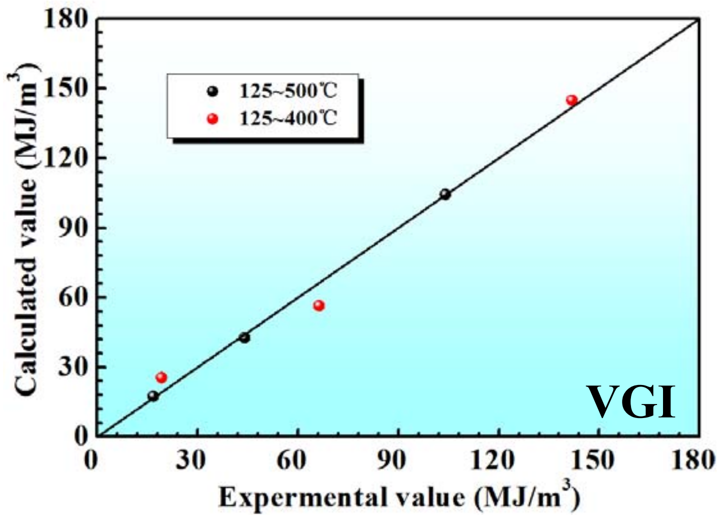
3. Simply quantitative relation: Hysteresis energy for TMF

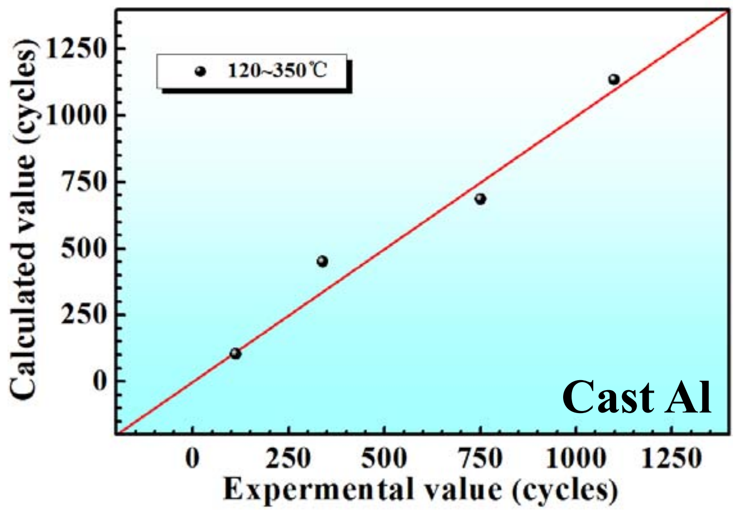
TMF energy → **LCF at constant T**

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



Application: replace TMF by LCF at constant temperature



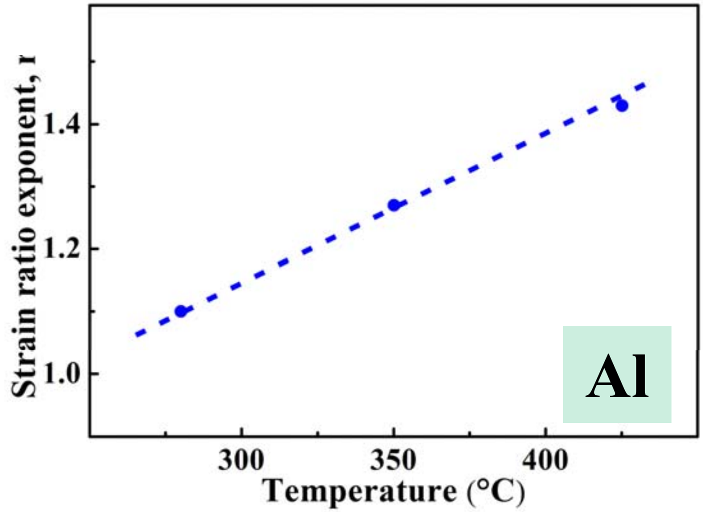


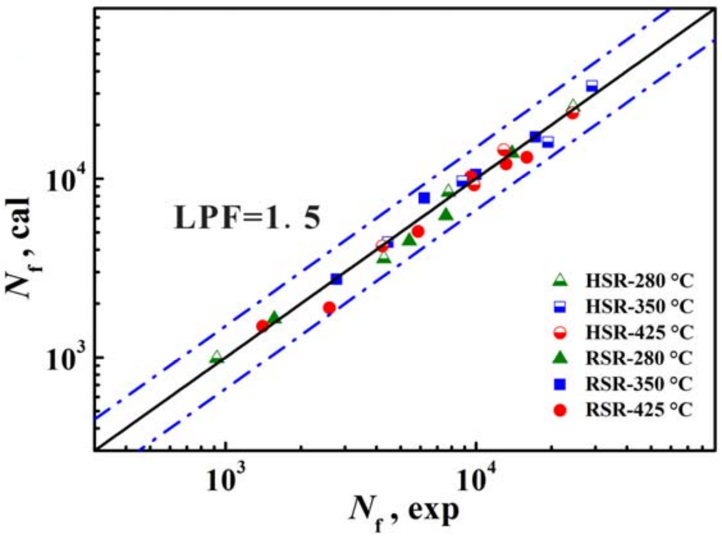
Simplify test, reduce cost, increase efficiency

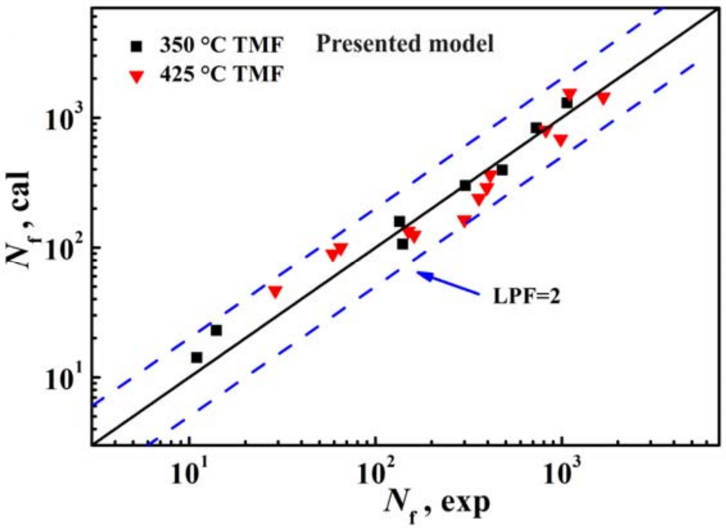
4. Simply quantitative relation: Hysteresis energy for Al-Si

$$N_f = \dot{\varepsilon}^{1-r} \cdot \left(\frac{W_0}{W_s} \right)^{1/\beta}$$

$$W_s^{TMF} = W_0 \left(\nu_{LCF} / \nu_{TMF} \right)^{-\beta(1-k)} \cdot N_f^{-\frac{1}{\beta}}$$



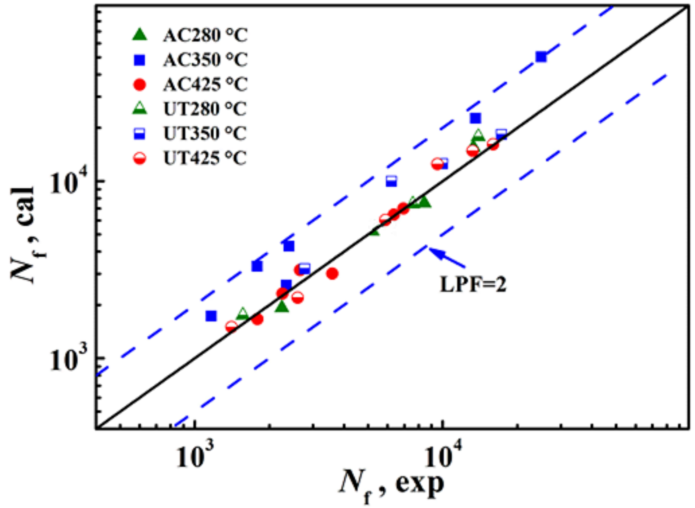


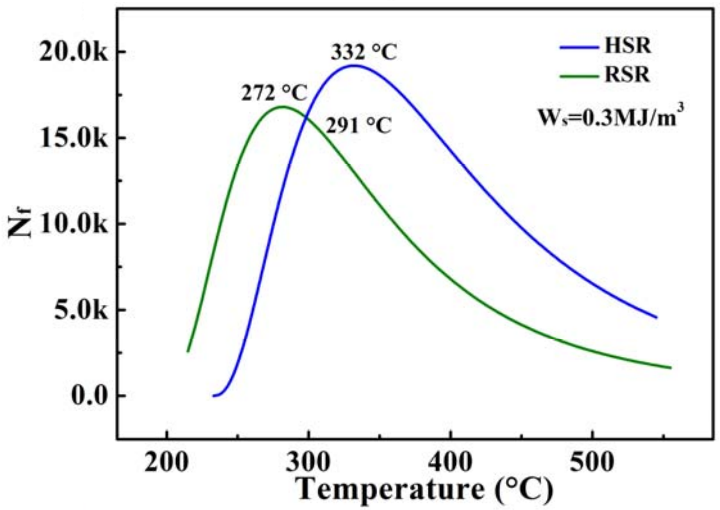


Strain ratio r: Introduction of r can reflect coupling damage mechanism of creep and fatigue

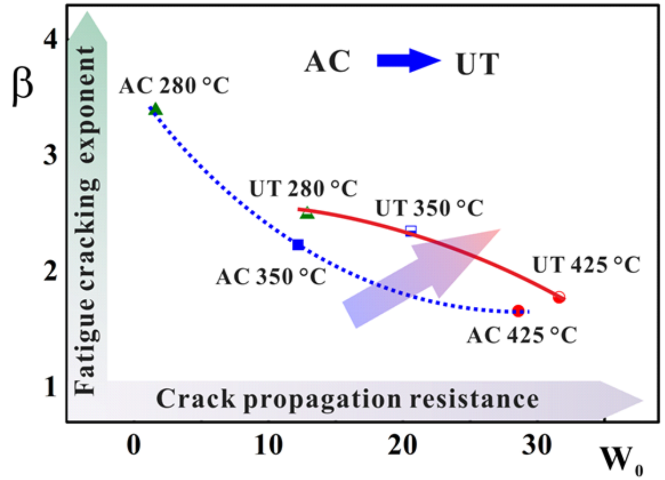
4. Simply quantitative relation: Hysteresis energy for Al-Si

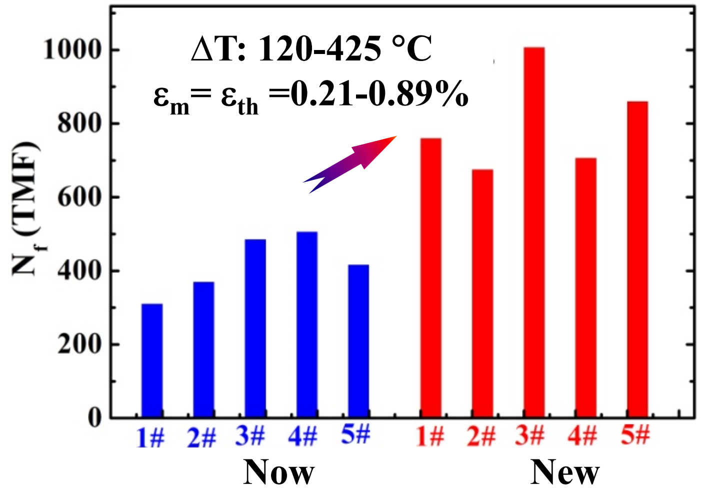
Life prediction





Property optimization





New model predict well, optimize property

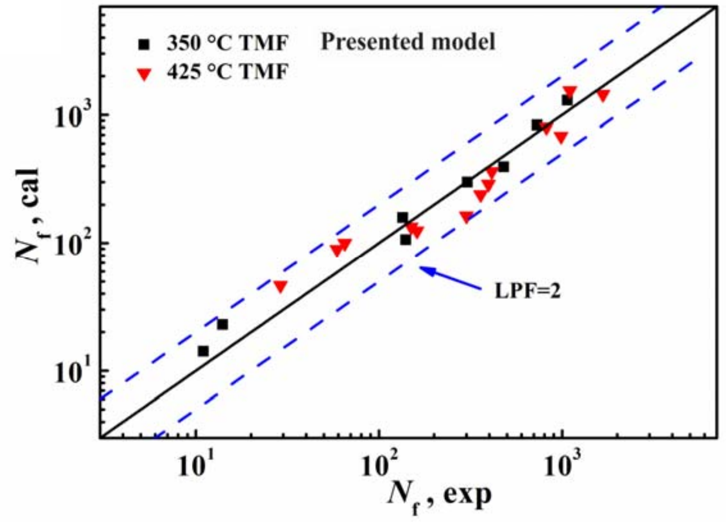
5.Brief summary

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

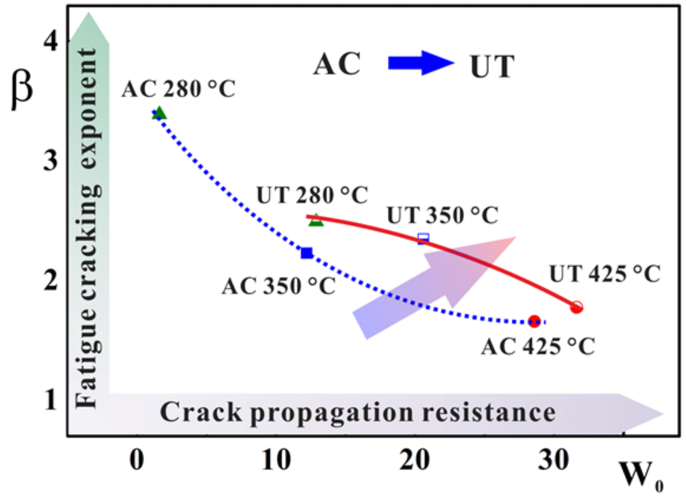
$$W_{a,TMF}=A+K\varepsilon_{mech}+W_{a,LCF}$$

$$W_s^{TMF}=W_0\left(\nu_{LCF}/\nu_{TMF}\right)^{-\beta(1-k)}\cdot N_f^{-\frac{1}{\beta}}$$

Prediction model at HTs + suitable correction = TMF life prediction



High accuracy, Less test

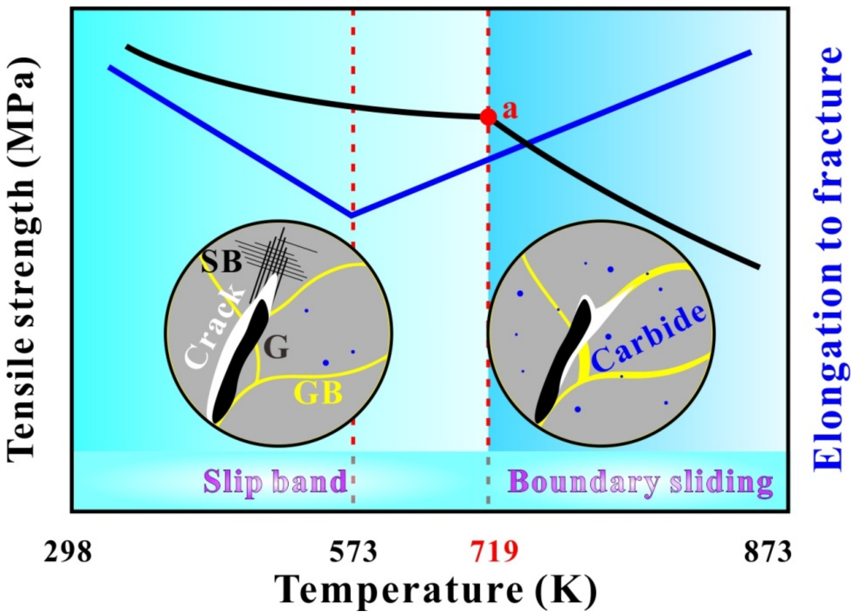


Life optimization

五、主要结论
Main conclusion

Conclusion: Strength prediction at HTs

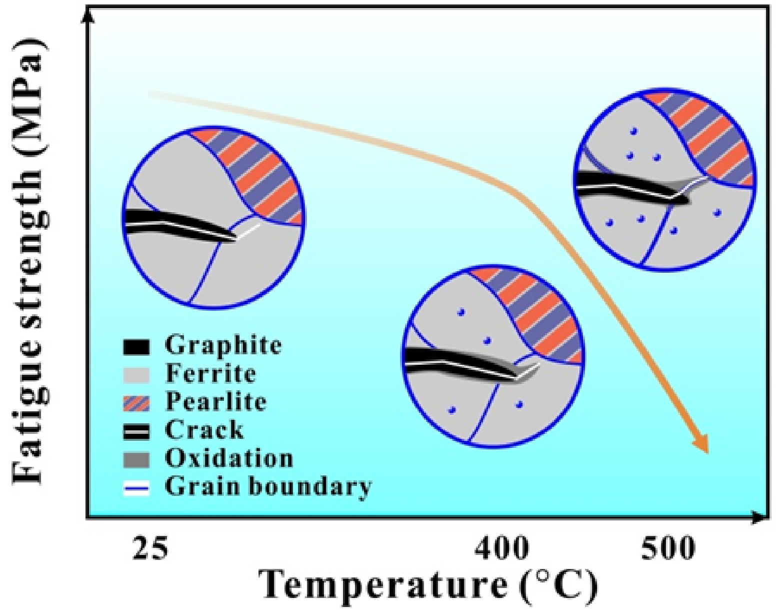
Tensile strength



$$\sigma_b = \sigma_0 \exp(-BT) \cdot \exp(AT \ln T),\ T \le 450°C$$

$$\sigma_b = \sigma_0 \exp(Q/RT),\ T > 450°C$$

Fatigue strength



$$\sigma_w = \sigma_w^f \sqrt{1 - \frac{1}{\sqrt{1 + w_f / w_g}}}$$

Based microscopic mechanism

Conclusion: Life prediction at HTs

TMF life prediction

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

$$W_s^{TMF} = W_0\left(\nu_{LCF}/\nu_{TMF}\right)^{-\beta(1-k)} \cdot N_f^{-\frac{1}{\beta}}$$

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

LCF life prediction at HTs

$$N_f = \dot{\varepsilon}^{1-r} \cdot \left(\frac{W_0}{W_s}\right)^{1/\beta}$$

Temperature correction

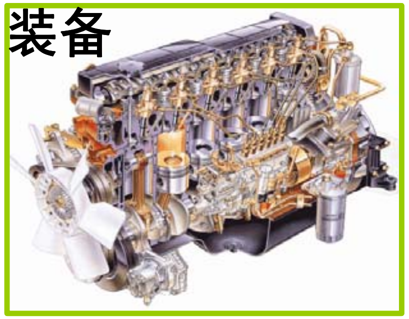
Strain ratio correction

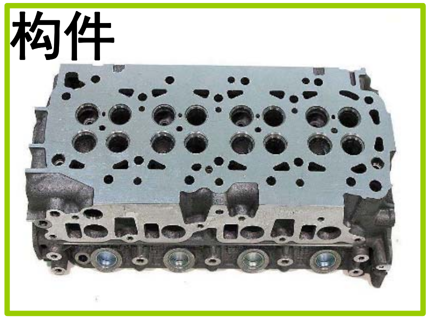
LCF life prediction at RT

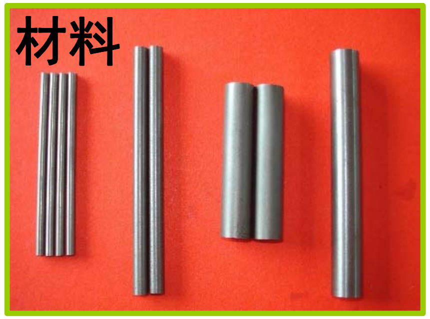
$$N_f = (W_0 / W_s)^{1/\beta}$$

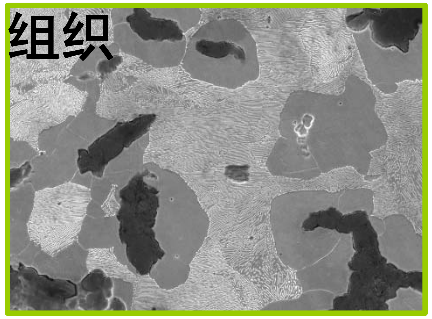
Predict well | **Simplify model** | **Optimize well**

Challenge & Prospect









关键共性问题理性简便解决方案

以小测大　化繁为简

材料 ⟷ 构件

检测　预测　监测

材料数据	温 载 谱	方法模型	软件系统
指标标准	获取方法	教材文献	商用软件
选材取样	处理方法	标准规范	自编软件
文献推测	标定验证	专利软件	自编插件
数据共享	全面准确	简单准确	经济普适

Suggested Readings

Tensile, fatigue properties, damage mechanism, temperature

1. Qiu Y, Pang JC*, *et al* , *Mater. Sci. Eng. A* 2016; 664: 75.
2. Qiu Y, Pang JC*, *et al* , *Mater. Sci. Eng. A* 2016; 667: 290.
3. Zhang MX, Pang JC*, *et al* , *Mater. Sci. Eng. A* 2017; 698: 63.
4. Zhang YY, Pang JC*, *et al, Mater. Sci. Eng. A* 2018;713:260.
5. Qiu Y, Pang JC*, *et al* , *Int. J. Fatigue* 2018; 112: 84.
6. Jing GX, ….Pang JC*, *et al, Eng. Fail. Anal.* 2018 ; 90: 36.
7. Qiu Y, Pang JC*, *et al* , *Mater. Sci. Eng. A* 2018; 724: 324.
8. Zou CL, Pang JC*, *et al, Mater. Sci. Eng. A* 2018; 724: 606.
9. Qiu Y, Pang JC*, *et al* , *Int. J. Fatigue* 2018; 117:450.
10. Zou CL, Pang JC*, *et al, Mater. Sci. Eng. A* 2019; 763: 138101.
11. Liu QY, ….Pang JC*, *et al, Mater. Sci. Eng. A* 2019; 764: 138248.
12. Zhang MX, Pang JC*, *et al* , Mater. Sci. Eng. A 2020;771:138671.
13. Zou CL, Pang JC*, *et al, Int. J. Fatigue* 2020; 135: 105576.
14. Zhang YY, Pang JC*, *et al* , *J. Mater. Res. Technol.* 2020; 9: 7002.

Suggested Readings

Tensile, fatigue properties, damage mechanism, temperature

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.

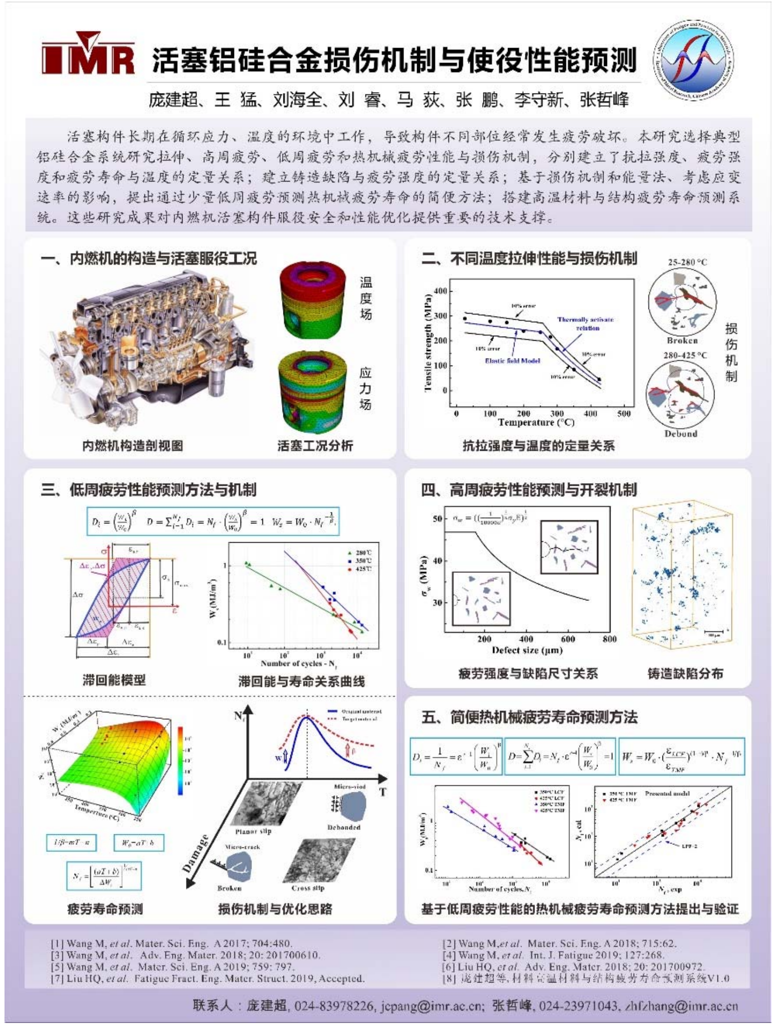
8. Wang M, Pang JC*, *et al, J. Mater. Res. Technol.* 2019; 8:4556.

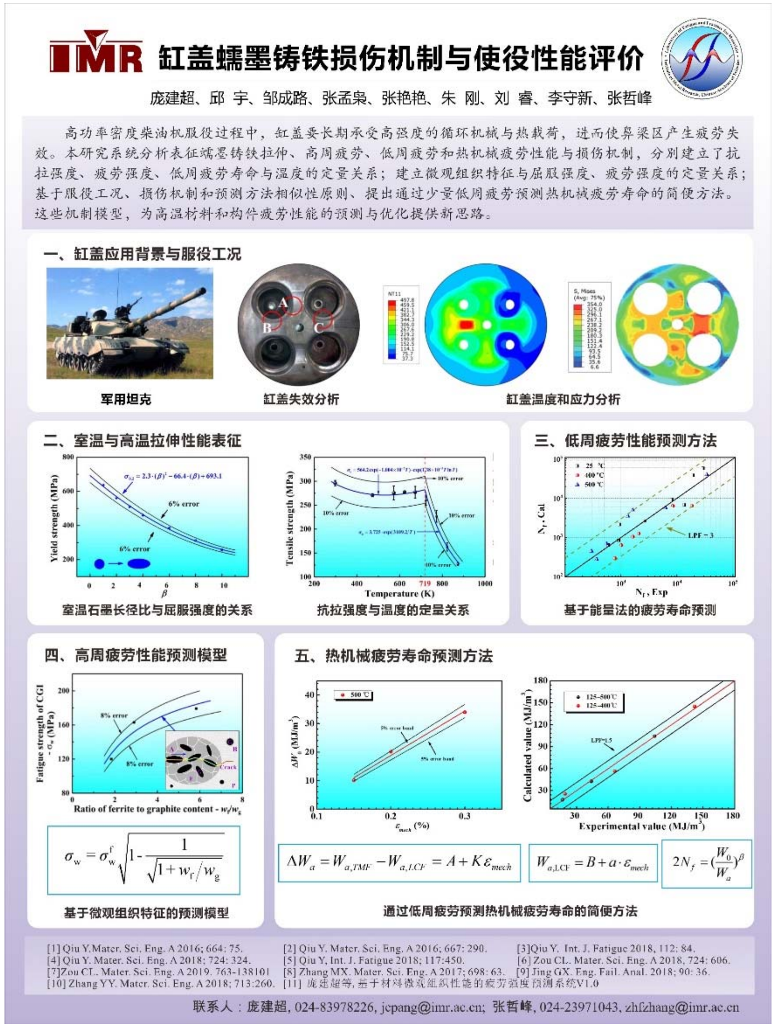
9. Liu HQ, Pang JC*, *et al, Mater. Charact.* 2020; 159:110032.

10. Wang M, Pang JC*, *et al, J. Mater. Res. Technol.* 2019; 8:4556.

11. Wang M, Pang JC*, *et al, Mater. Sci. Eng. A.* 2020; 783: 139279.

Representative achievement





Cast iron(CGI\SGI\FGI) cast Al(Hypoeutectic/Eutectic) Steel Cu alloy

Testing & Devolvement & Research

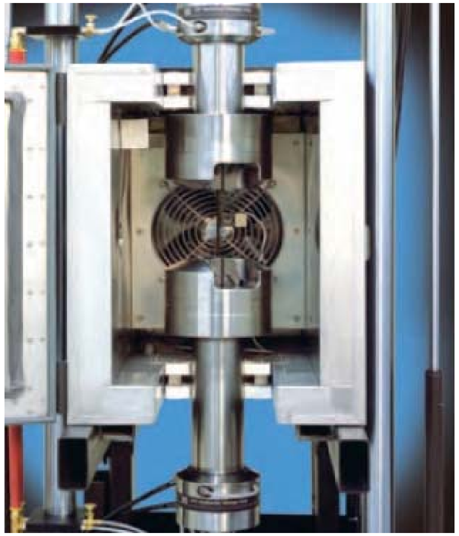
主要研究能力

热机疲劳

高温微缩

蠕　变

热 疲 劳



环境疲劳

高温超高

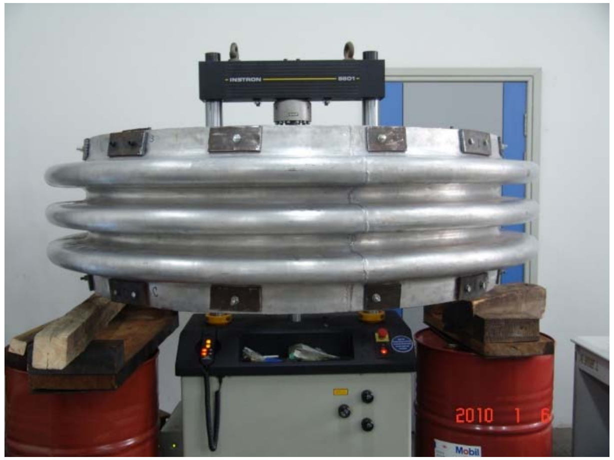
高温硬度

高温原位

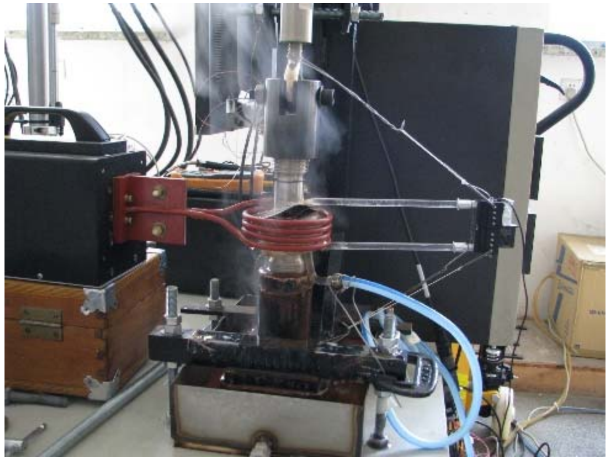
纳米压痕

力学测试平台：40余台疲劳机

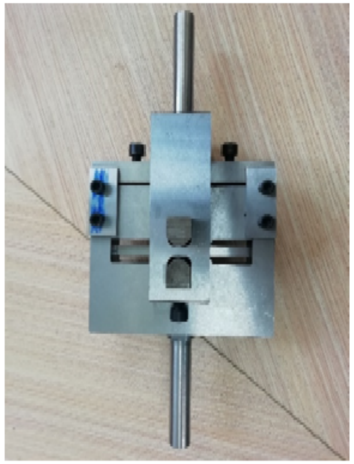
主要研究能力



波 纹 管



恒载热疲劳

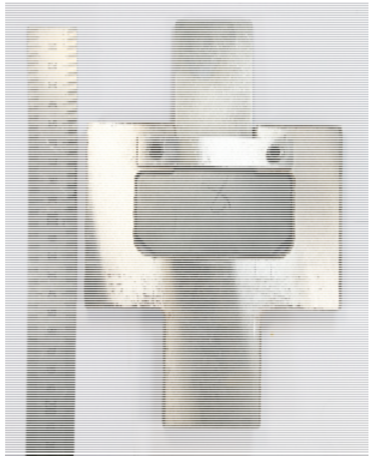


四点弯曲

叶片热机疲劳

连杆疲劳

齿轮疲劳



磁轭疲劳

结合服役工况　定制测试方案

主要研究能力

Basquin, 1910

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

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

Osttergren

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

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

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

Sehitoglu, 1989

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

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

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

$$\frac{1}{N_f^{creep}} = \Phi^{creep}\int_0^{t_c} A\exp\left(-\frac{\Delta H}{RT(\text{t})}\right)\cdot\left(\frac{\alpha_1\bar{\sigma}+\alpha_2\sigma_H}{K(T)}\right)^m dt$$

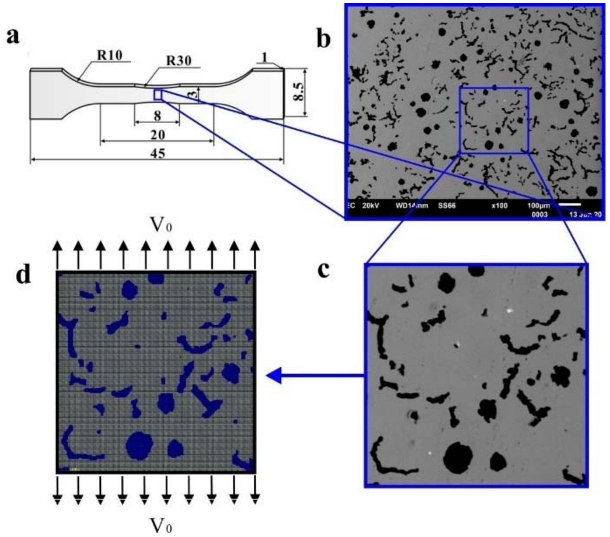
$$\Phi^{creep} = \frac{1}{t_c}\int_0^{t_c}\exp\left[\frac{1}{2}\cdot\left(\frac{(\dot{\varepsilon}_{th}/\dot{\varepsilon}_{mech})-1}{\xi^{creep}}\right)^2\right]dt$$

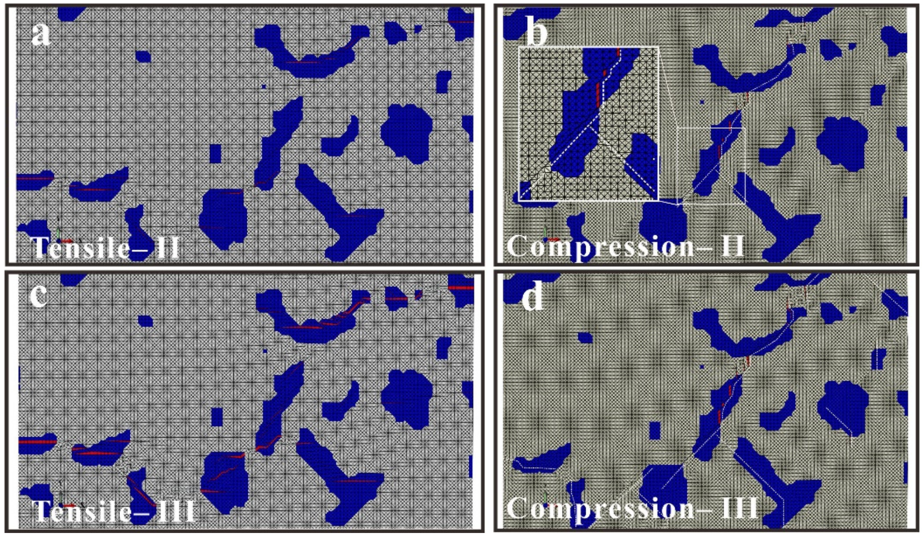
Msc.Fatigue | FEMFAT | ANSYS | ABAQUS

国际国家标准FKM IIW ASME NASA GB DIN BS EN

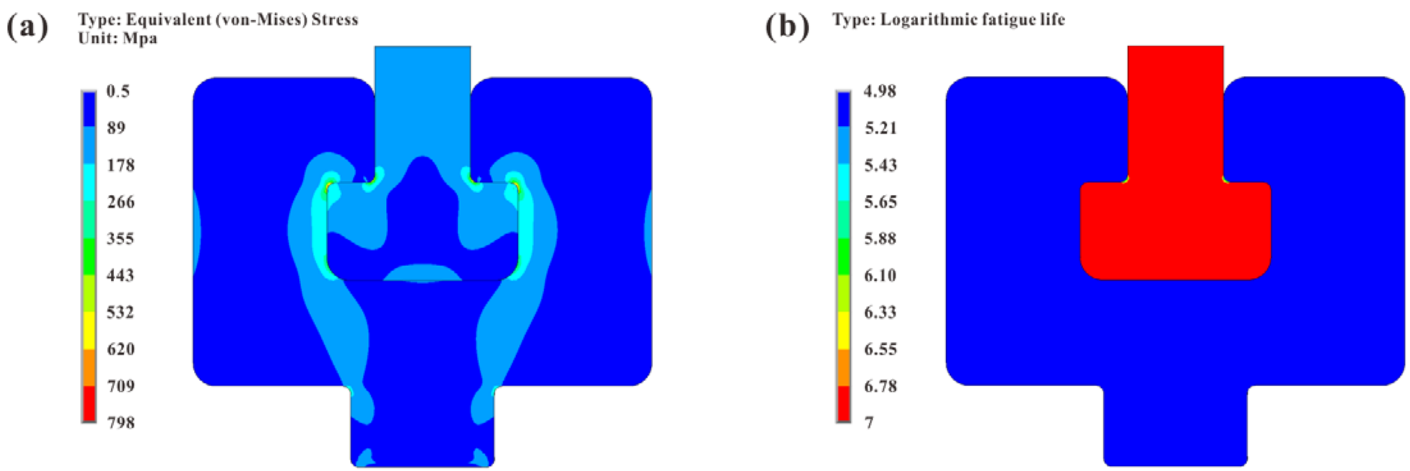
主要研究能力

基于组织力学性能



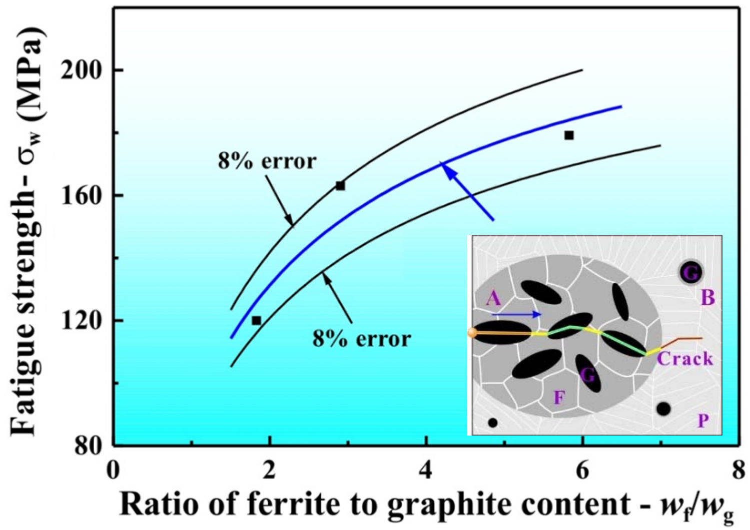


模拟构件分析

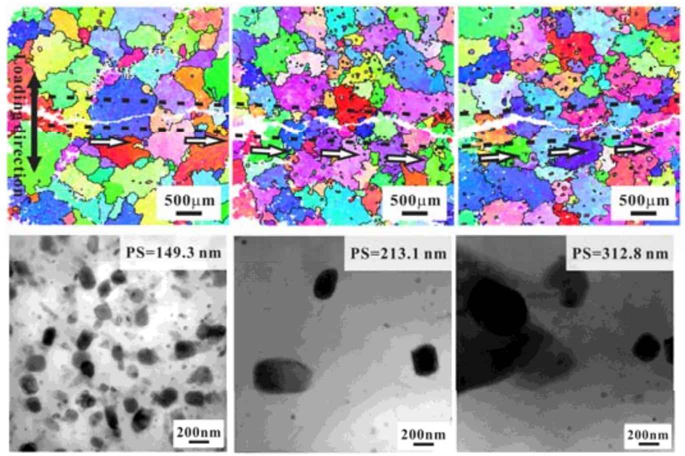


主要研究能力

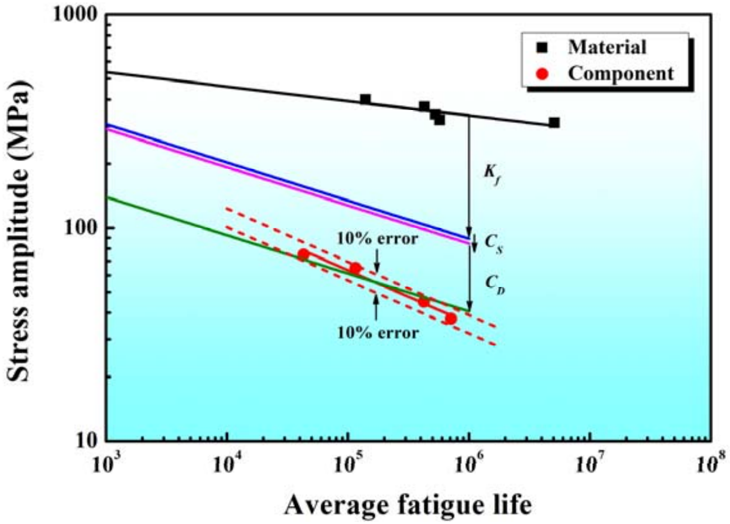
材料预测



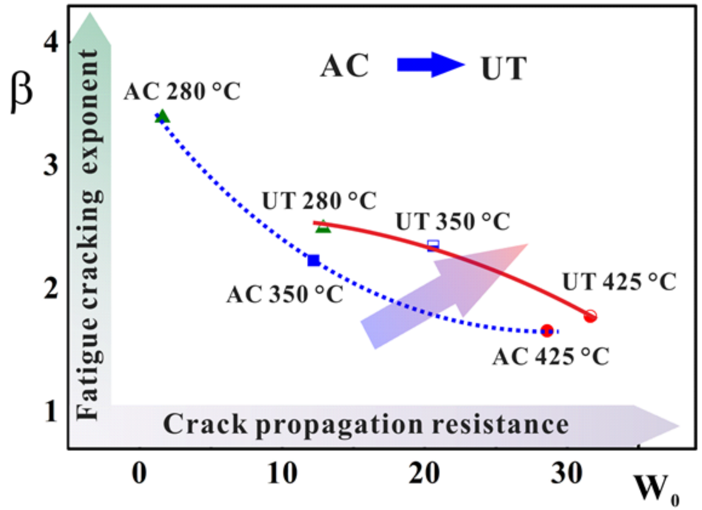
损伤机制



规构件预测



性能优化



基于服役工况测试、分析、研究和优化方案

主要研究能力

根据构件服役情况定制软件（插件）

Thank for your attention

感谢关注！敬请提问！欢迎莅临沈阳指导！

疲劳分会公众号　　庞建超个人微信

疲劳断裂学术交流V群即将建立！！！