

红外热像法在材料疲劳性能测试中的应用

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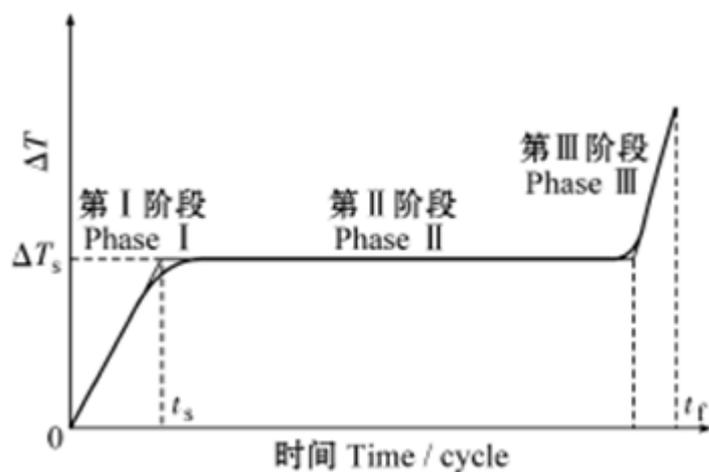
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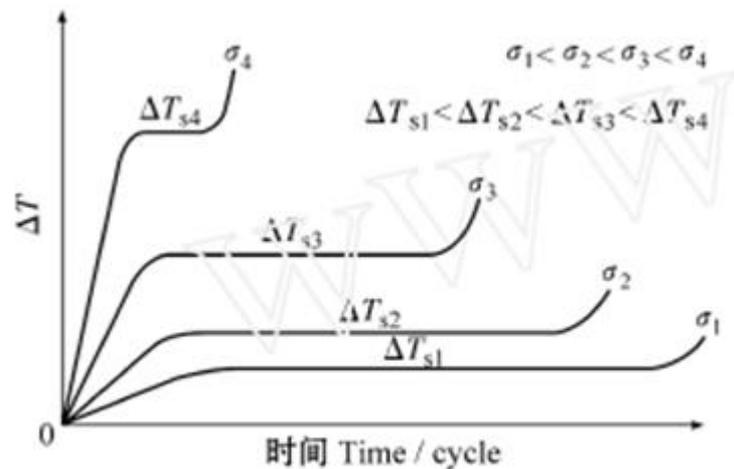
结论

一、研究背景

- 疲劳实验耗时耗力
- 疲劳过程中的温度变化反映了破坏过程中材料微观状态的变化，可以用来了解和解释疲劳的基本现象
- 疲劳极限的测试



疲劳试验过程中试样表面温升变化示意图



不同载荷作用下试样表面温升变化示意图

Risitano (单线法)

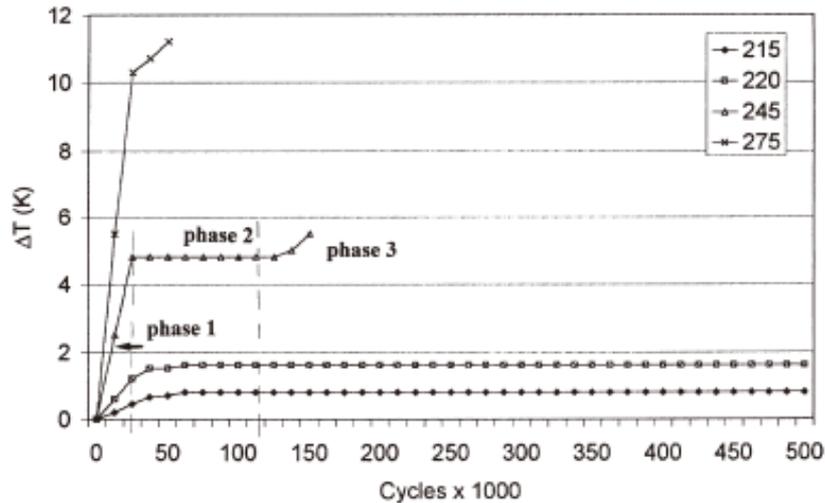


Fig. 4. Maximum thermal increments in specimens under fatigue loading at different applied stresses. The applied stresses ($\Delta\sigma=\sigma_{\max}/2$, $R=0$) are indicated in MPa on the legend. The three phases are shown for the test performed at 245 MPa.

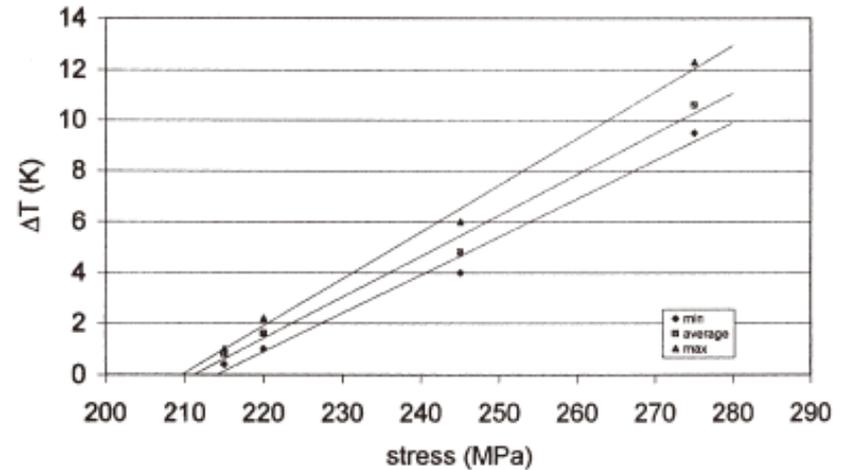


Fig. 6. Fatigue limit derived from the analysis of the stabilisation temperature (phase 2 of Fig. 4).

Risitano (单线法)

Comparison between the traditional (Stair-case, SC) and the thermographic (TH) method for several materials and components^a

Component	Material	R	SC	TH	Err.%	Ref.
Specimen	C70 Steel	0	216	212	-1.8	[9]
Specimen	C30 Steel	0	414	400	-3.5	[17]
Specimen	2024 Al alloy	0	239	215	-10.0	[17]
Specimen	Fibreglass	0.1	13.2	14.3	+8.3	[33]
Specimen	Fibreglass	0.1	15.8	15	-5.1	[33]
Specimen	Fibreglass	0.1	15.2	15.3	+0.6	[33]
Specimen	Fibreglass	0.1	14.1	14.1	-	[33]
Butt welded joint	FeP04 Steel	0.1	227	229	+0.9	[31]
Butt welded joint	FeP04 Steel	0.1	242	230	+5.0	[31]
Butt welded joint	FeP04 Steel	0.1	182	185	+1.6	[31]
Butt welded joint	FeP04 Steel	0.1	240	234	+2.5	[31]
Butt welded joint	FeP04 Steel	0.1	235	197	-16.2	[31]
Butt welded joint	FeP04 Steel	0.1	215	210	-2.3	[31]
Specimen with blind hole	C30 Steel	-1	164	162	-1.2	[21]
Connecting rod	SGCI	0	20.0	18.5	-7.5	[10]
Connecting rod	MCI	0	19.9	20.0	+0.5	[10]
Connecting rod	MCI	0	25.2	24.2	-4.0	[10]
Connecting rod	SGCI	-1	27	28.8	+6.7	[10]
Connecting rod	MCI	-1	25.5	23.2	-9.0	[10]
Connecting rod	MCI	-1	27.2	28.0	+2.9	[10]
Connecting rod	SGCI	-1.84	30.0	30.5	+1.7	[10]
Connecting rod	MCI	-1.84	26.3	25.7	-2.3	[10]
Connecting rod	MCI	-1.84	34.0	30.5	+10.3	[10]

Luong (双线法)

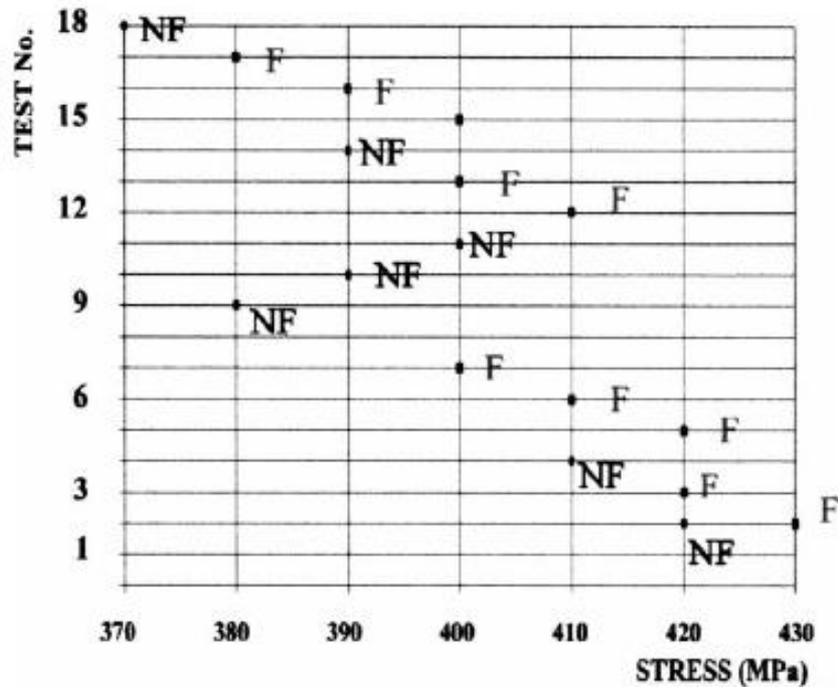


Fig. 1. Standard staircase determination of fatigue limit of XC55 steel.

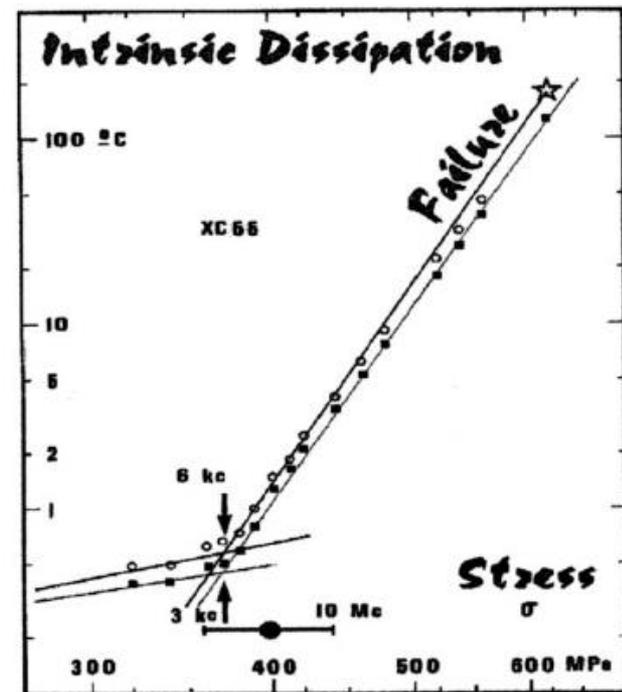


Fig. 3. Graphical determination of fatigue limit of XC55 steel.

$$\rho C \left(\frac{d\theta}{dt} + \frac{\theta}{\tau_{eq}} \right) = s_{the} + d_1$$

问题与挑战：

适用范围： 低强度材料，塑性较好 vs 高强度材料，塑性较差
无明显疲劳极限的材料如何利用？

发展应用： 微塑性变形阻力？

二、实验材料和仪器

材料成份 (GCr15)

元素	C	Cr	Mn	Si	P、S	Fe
含量%	1.02	1.45	0.35	0.28	<0.025	其余

热处理状态:

650°C保温2.5h, 真空炉冷;
845°C、CO₂气氛下保温1h, 油淬;
150°C、600 °C回火2h

材料的力学性能

回火温度 (°C)	维氏硬度 Hv (kgf/mm ²)	拉伸实验 (MPa)	
		σ_y	σ_b
150	820	NA	2372
600	327	909	1044

原始奥氏体晶粒尺寸: 13.8 μ m

马氏体针宽度: 378 nm

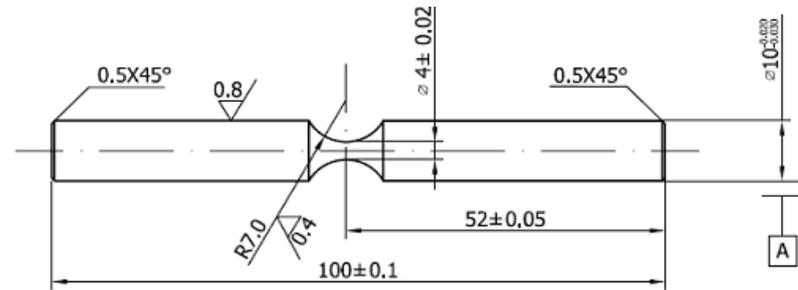
常规频率疲劳试样: 87件

超声频率疲劳试样: 102件

疲劳试验机及试样

旋转弯曲(RB): ($R = -1$)

加载频率: 52.5 Hz



$$P = \frac{\pi D^3}{32\alpha L} \times \sigma$$

$\alpha=1.05$ 为应力集中系数

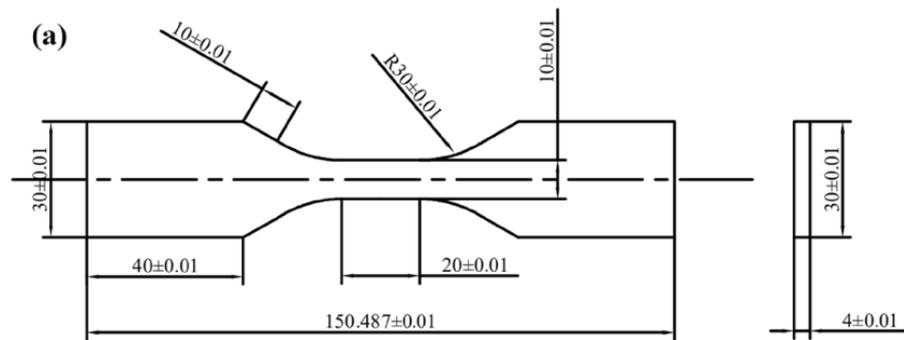
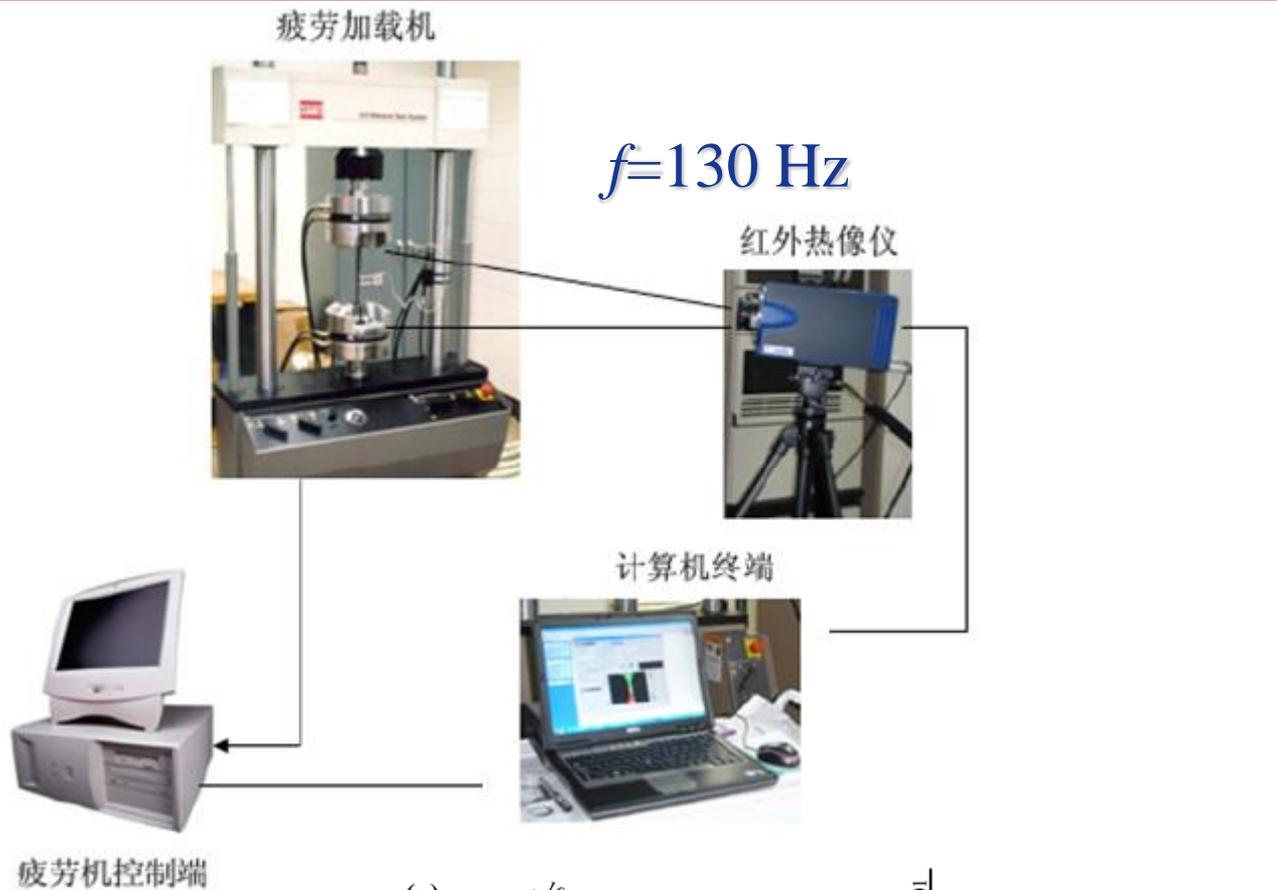
D (mm) 为试样最小截面的直径

L (mm) 为加载端到最小截面处的距离

σ (MPa) 为试样表面承受的最大应力

P (N) 为施加的载荷总重量

红外测温装置及试样



三、实验结果及分析

- 疲劳热像法理论基础
- 实验结果介绍
- 基于位错滑移的损伤机理分析
- 材料微塑性变形激活模型

疲劳热像法理论基础

HCF/VHCF加载过程中的热平衡方程

$$\rho C \dot{T} - \nabla \cdot (k \nabla T) = \left(\Sigma - \rho \frac{\partial \psi}{\partial E} \right) : \dot{E} - \rho \frac{\partial \psi}{\partial \zeta} \cdot \dot{\zeta} + \rho T \frac{\partial^2 \psi}{\partial T \partial E} : \dot{E} + \rho T \frac{\partial^2 \psi}{\partial T \partial \zeta} : \dot{\zeta} + q_e \quad (1)$$

其中 ψ 为亥姆霍兹自由能， q_e 为外热源，

$$d_1 = \left(\Sigma - \rho \frac{\partial \psi}{\partial E} \right) : \dot{E} - \rho \frac{\partial \psi}{\partial \zeta} \cdot \dot{\zeta} \quad \longrightarrow \quad \text{内耗}$$

$$S_{\text{the}} = \rho T \frac{\partial^2 \psi}{\partial T \partial E} : \dot{E}$$

$$S_{\text{ic}} = \rho T \frac{\partial^2 \psi}{\partial T \partial \zeta} : \dot{\zeta}$$

热弹性效应引起的温升

$$\Delta T_e = -\frac{\alpha}{\rho C} \cdot T \cdot \Delta \Sigma \quad \longrightarrow \quad \text{一般不超过 } 0.1^\circ\text{C}$$

q_e 表示由温升导致的能量耗散

$$q_e = -\rho C \frac{\theta}{\tau}$$

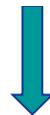
疲劳热像法理论基础



$$\rho C \left(\frac{\partial \theta}{\partial t} + \frac{\theta}{\tau} \right) - k \nabla^2 \theta = d_1$$

在温度稳定段：

$$\rho C \frac{\theta}{\tau} - k \frac{\partial^2 \theta}{\partial x^2} = d_1$$



(2)

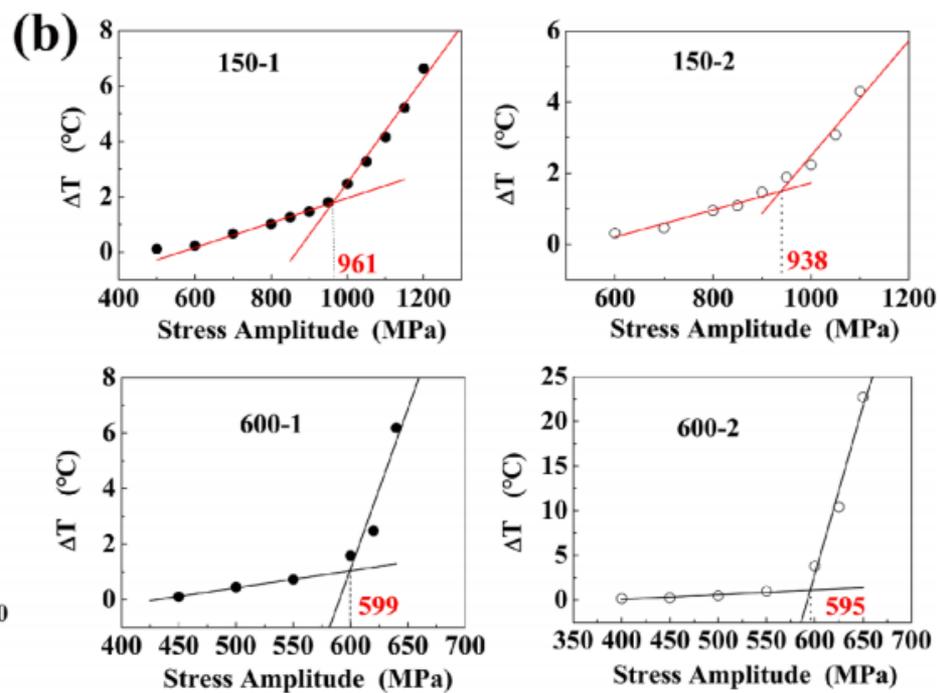
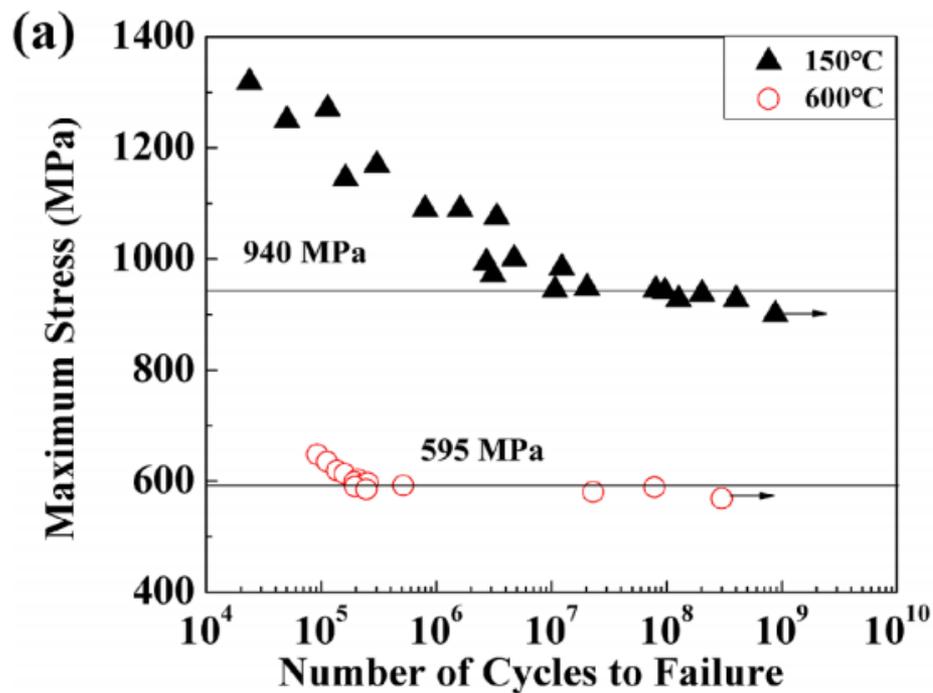
$$\theta(x) = A1 \cdot e^{rx} + A2 \cdot e^{-rx} + A3 \quad : r = \sqrt{\frac{\rho C}{k\tau}} \quad A3 = \frac{\tau d_1}{\rho C}$$



$$d_1 = \frac{\rho C}{\tau} A3 = k r^2 A3$$

实验结果介绍

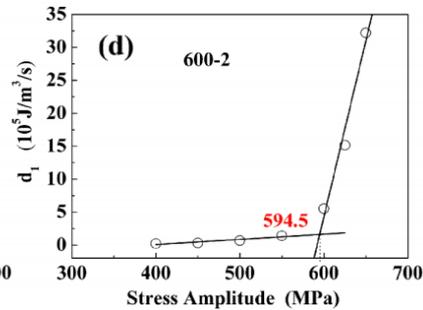
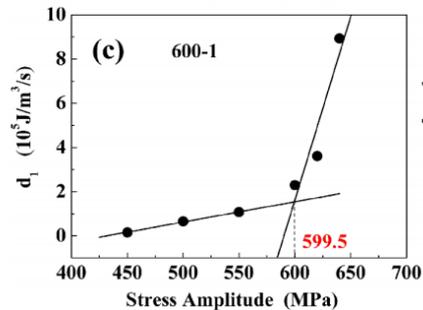
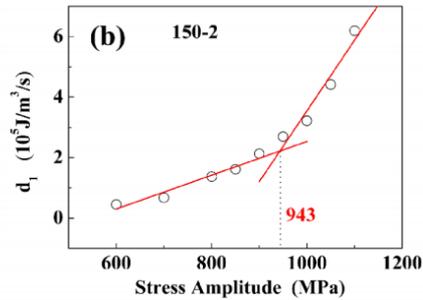
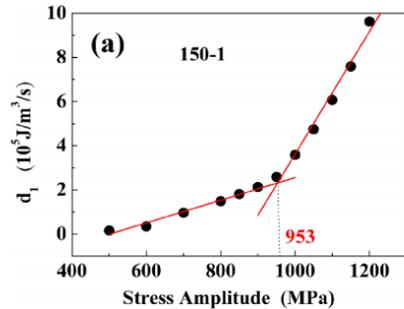
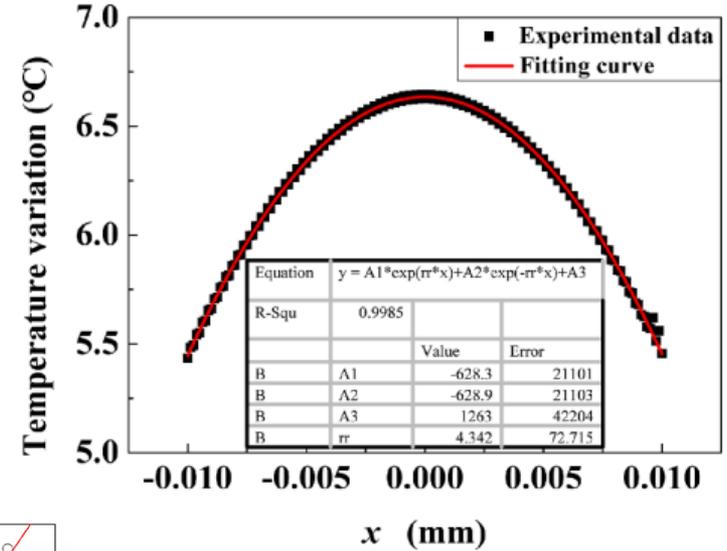
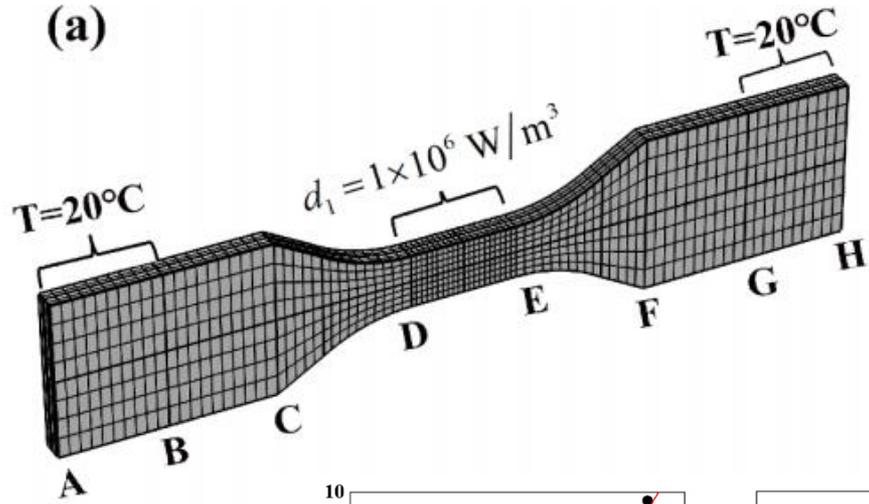
S-N曲线及试样温升



常规频率疲劳最高周次达 10^9 (220天/件)，红外热像法实验测试仅需不到1天时间

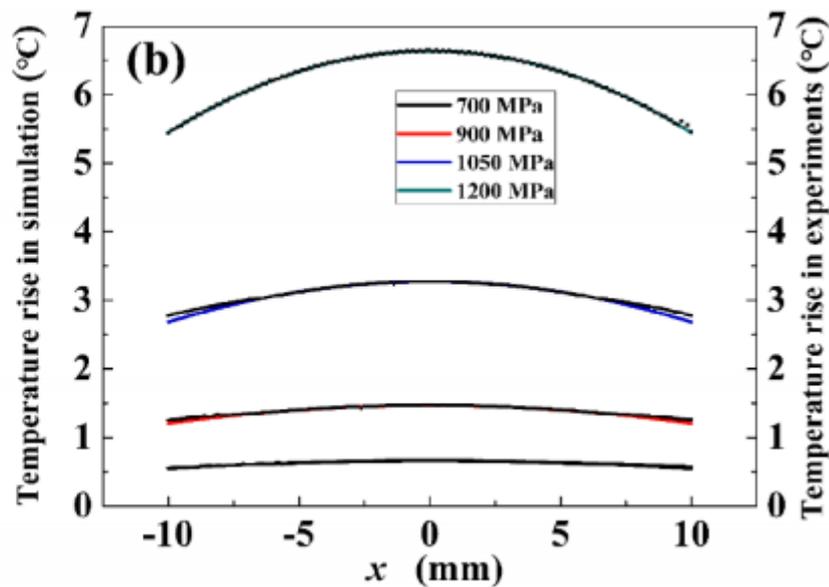
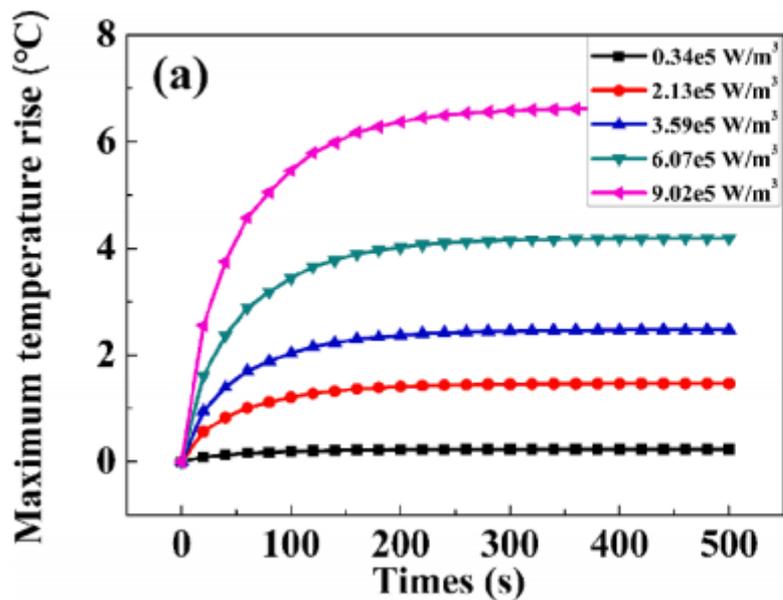
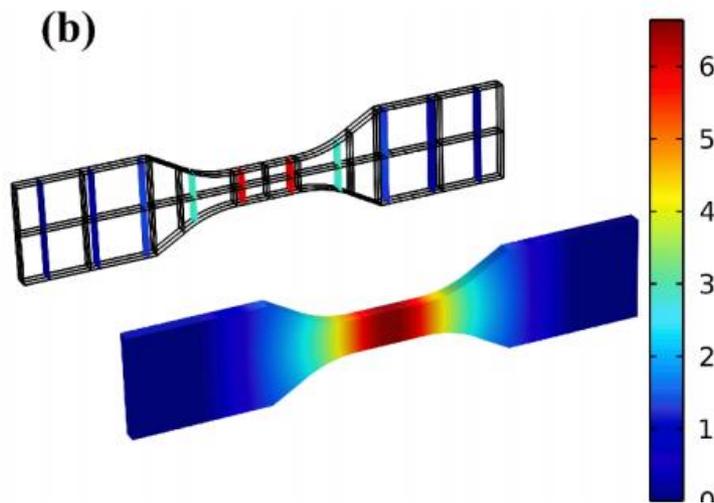
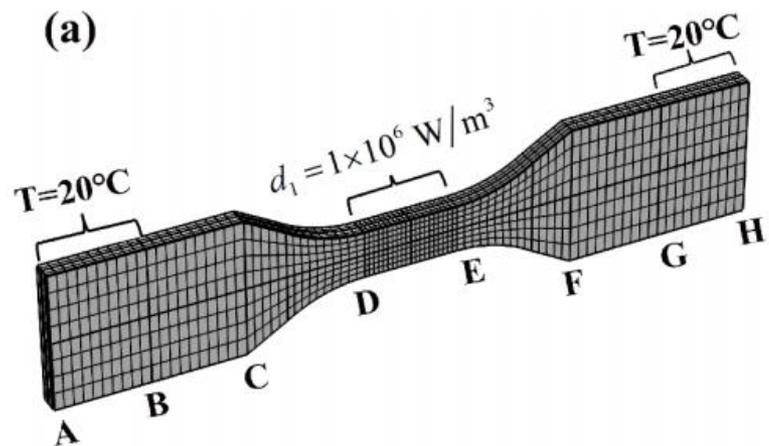
实验结果介绍

试样温升温度分布



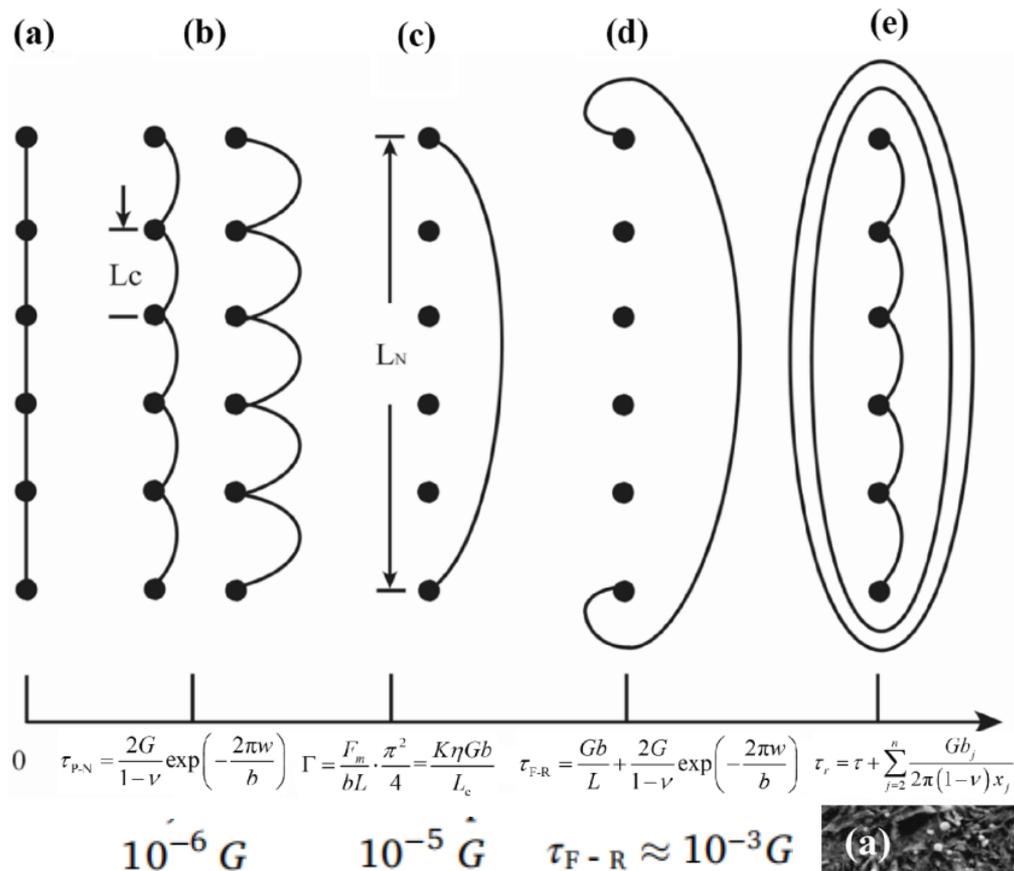
实验结果介绍

试样温升仿真

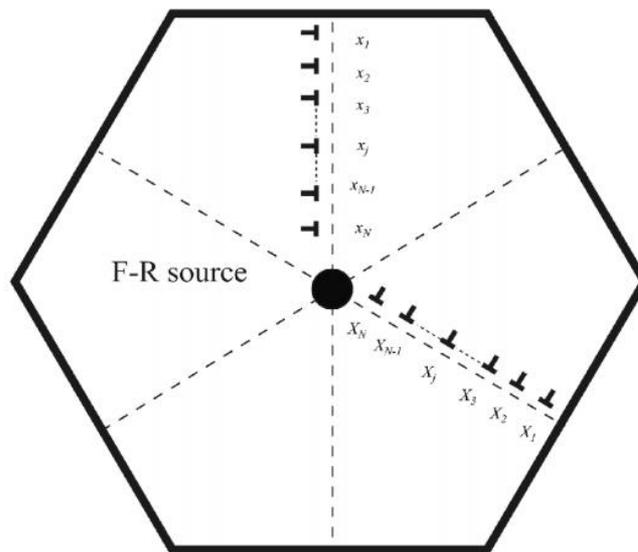


基于位错滑移的损伤机理分析

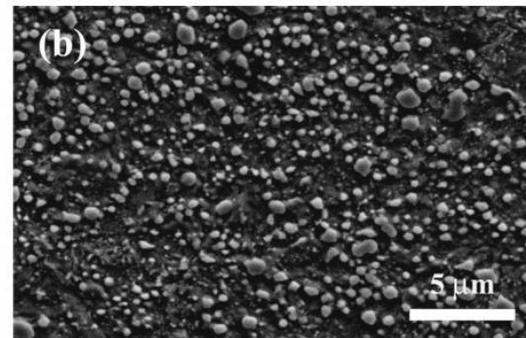
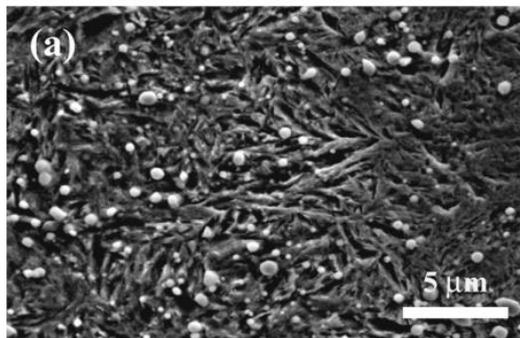
位错滑移模型



位错晶界堆积模型

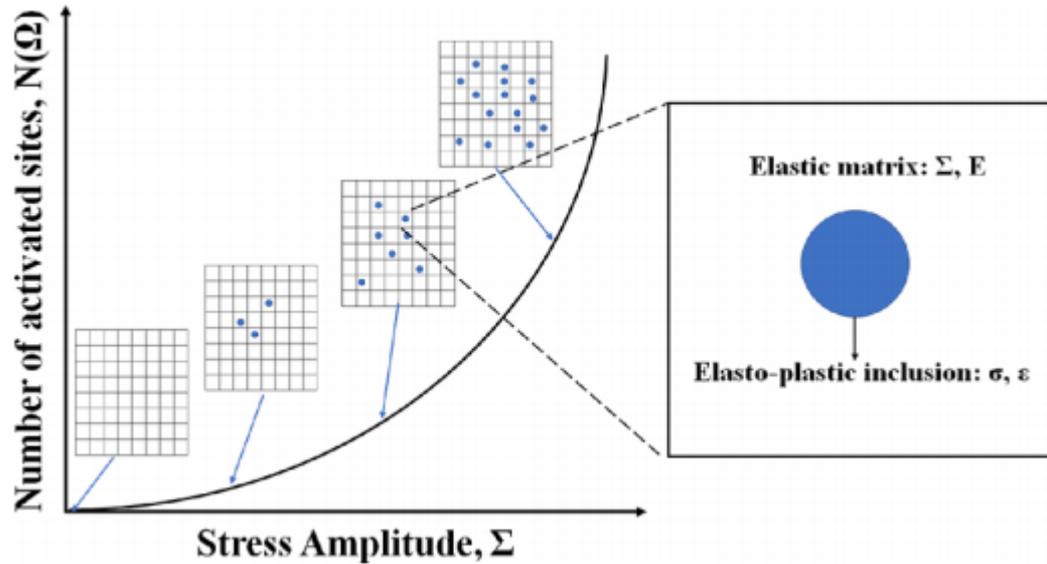


$$\tau_r = \tau + \sum_{j=2}^n \frac{Gb_j}{2\pi(1-\nu)x_j}$$



材料微塑性变形激活模型

塑性区激活理论



泊松分布

$$P_k(\Omega) = \frac{[-N(\Omega)]^k}{k!} \exp[-N(\Omega)]$$

$$N(\Omega) = \lambda V_{\Omega}$$

$$\lambda(\Sigma_a) = \frac{1}{V_0} \left(\frac{\Sigma_a}{S_0} \right)^m = \frac{1}{(S_0 V_0^{1/m})^m} \Sigma_a^m$$

$V_0 S_0^m$ 提供了一个可以用来衡量
微塑性激活阻力大小的参量

材料微塑性变形激活模型

由最弱连接理论，失效概率可表达为：

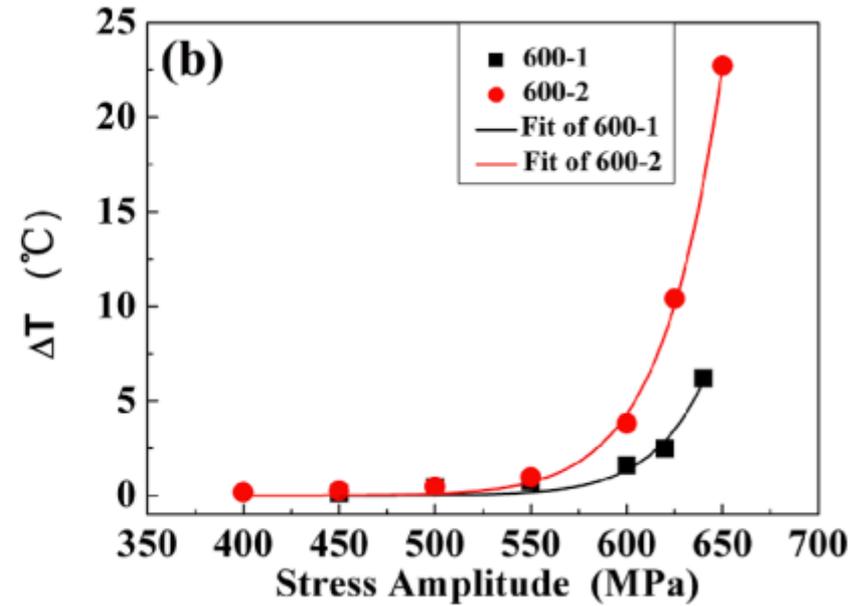
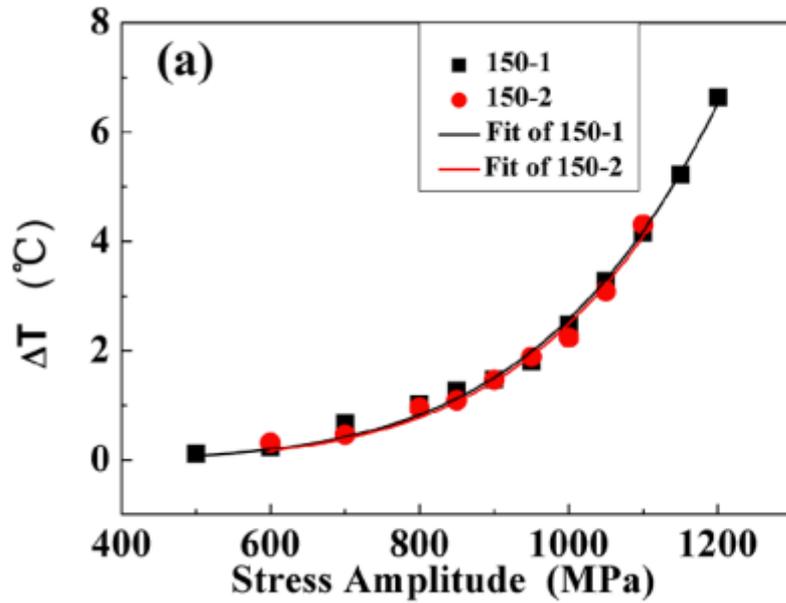
$$P_F = P_{k \geq 1}(V) = 1 - \exp[-\lambda V] = 1 - \exp\left(-\frac{V}{V_0} \left(\frac{\Sigma_a}{S_0}\right)^m\right)$$

则疲劳极限可表达为：

$$\bar{\Sigma}_\infty = S_0 \left(\frac{V_0}{V}\right)^{\frac{1}{m}} \Gamma\left(1 + \frac{1}{m}\right)$$

疲劳过程中试样温升：

$$\bar{\theta} = \eta V_0 \frac{m}{(m+1)(m+2)} \frac{\Sigma_0^{m+2}}{\left(V_0^{1/m} S_0\right)^m}$$



Calculation results by microplasticity activation model.

Specimen	m	$\bar{\Sigma}_{\infty}$ (MPa)	$S_0 V_0^{1/m}$
150-1	5.102 (4.766, 5.437)*	961	1448
150-2	5.225 (4.472, 5.979)*	938	1401
600-1	22.44 (10.00, 34.87)*	599	660.8
600-2	20.79 (18.88, 22.71)*	595	661.5

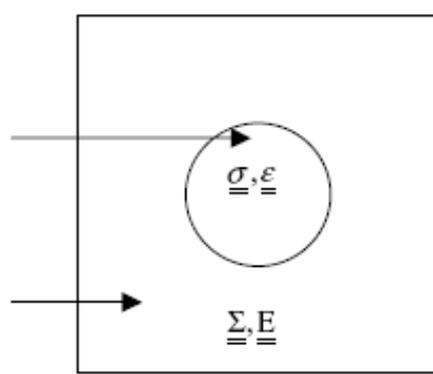
* The values in brackets present the range of 95% confidence interval.

四、结论

- ❖ 红外热像法测试材料疲劳极限适用于疲劳加载过程中温升较为明显的材料。
- ❖ 微塑性激活阻力较大的材料在疲劳实验中显示出较高的疲劳强度。

THANKS

Elasto-plastic inclusion



Elastic matrix

Fig. 2 RVE of the two-scale model

$$\underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}^e + \underline{\underline{\varepsilon}}^p \quad \underline{\underline{\sigma}} = \underline{\underline{\Sigma}} - 2\mu(1 - \beta)\underline{\underline{\varepsilon}}^p$$

$$\underline{\underline{\dot{X}}} = \frac{2}{3}C\underline{\underline{\dot{\varepsilon}}}^p$$

$$\underline{\underline{\dot{\varepsilon}}}^p = \dot{\lambda} \frac{\partial f}{\partial \underline{\underline{S}}} \quad f = J_2(\underline{\underline{S}} - \underline{\underline{X}}) - \sigma_y \leq 0$$

$$D_{\text{site}}(\Sigma_0^{\text{eq}}, \sigma_y) = \int_{\text{cycle}} V_0(\underline{\underline{\sigma}} - \underline{\underline{X}}) : \underline{\underline{\dot{\varepsilon}}}^p dt = \frac{4V_0\sigma_y}{h} \langle \Sigma_0^{\text{eq}} - \sigma_y \rangle$$

$$\Delta = \int_0^{\Sigma_0^{\text{eq}}} D(\Sigma_0^{\text{eq}}, \Sigma) \frac{d\lambda(\Sigma_a)}{d\Sigma} d\Sigma \leftarrow \text{单循环全部耗散能}$$

$$\dot{\theta} + \frac{\theta}{\tau_{\text{eq}}} = \frac{\Delta f_r}{\rho c}$$

$$\bar{\theta} = \frac{4f_r\tau_{\text{eq}}}{h\rho c} \int_0^{\Sigma_0^{\text{eq}}} \Sigma(\Sigma_0^{\text{eq}} - \Sigma) \frac{d}{d\Sigma} \left(\frac{\Sigma_a}{S_0} \right)^m d\Sigma$$

$$\bar{\theta} = \eta V_0 \frac{m}{(m+1)(m+2)} \frac{(\Sigma_0^{\text{eq}})^{m+2}}{(V_0^{1/m} S_0)^m}$$