

残余应力和齿轮弯曲疲劳极限 间的定量关系

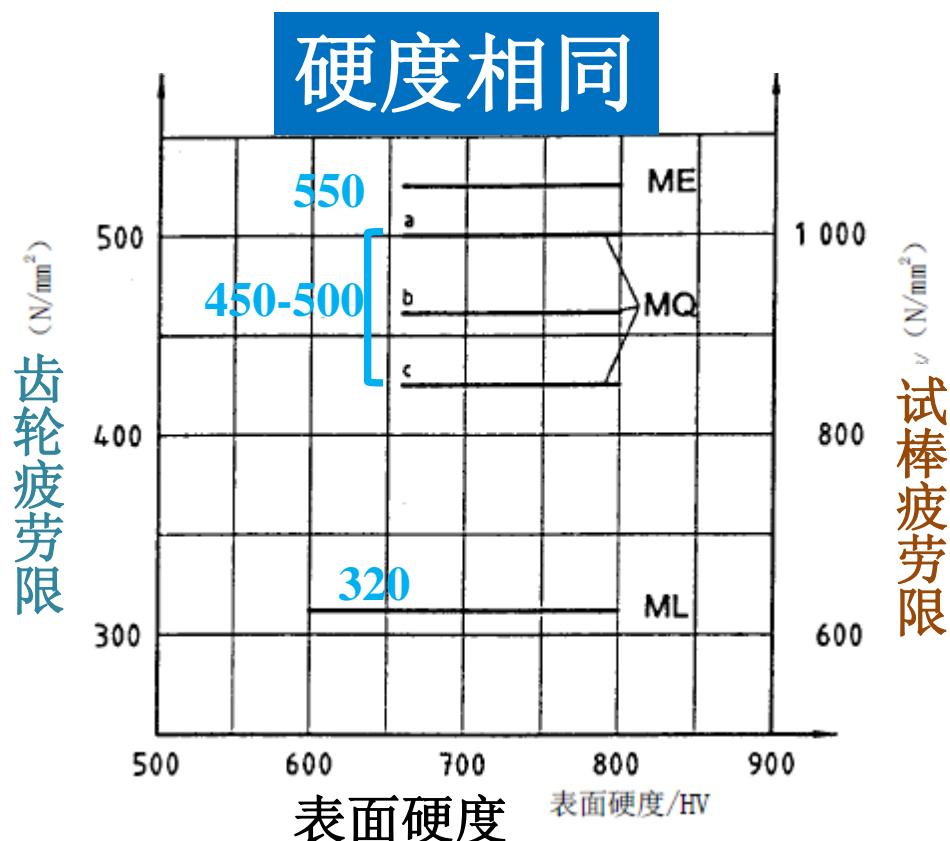
昌宇应力技术（上海）有限公司

白涛 博士

渗碳淬火齿轮

弯曲疲劳限：三级

疲劳限 MPa	ML	MQ	ME
	320	450-500	550



材料、热处理工艺差异

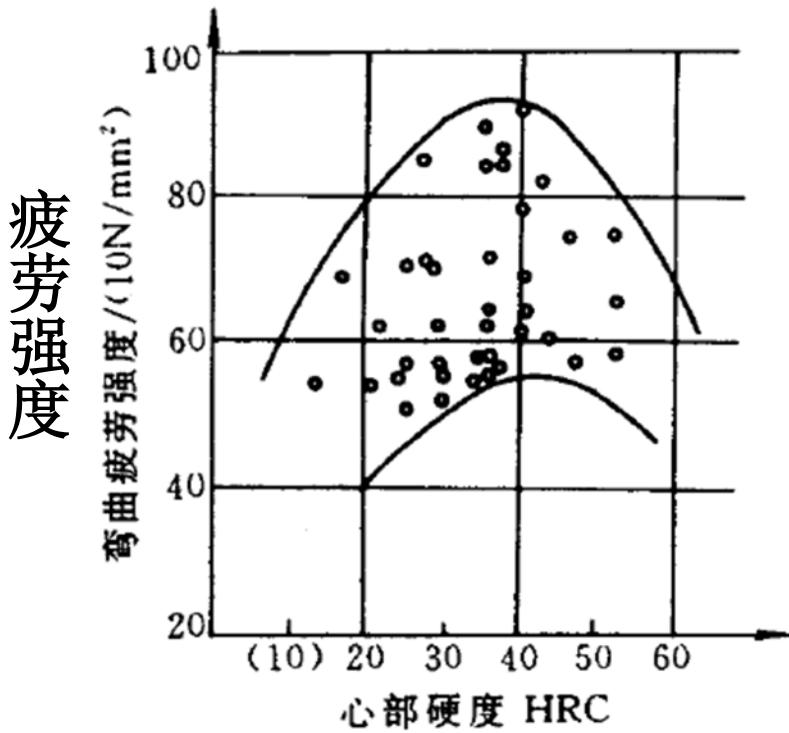
- 原材料**
- ✓ 钢坯成分, 均匀性
 - ✓ 夹杂物, 含氧量
 - ✓ 锻造比, 晶粒度

渗碳层

- 含碳量及深度
- 黑色组织
- 析出碳化物
- 残余奥氏体
- 淬火缺陷

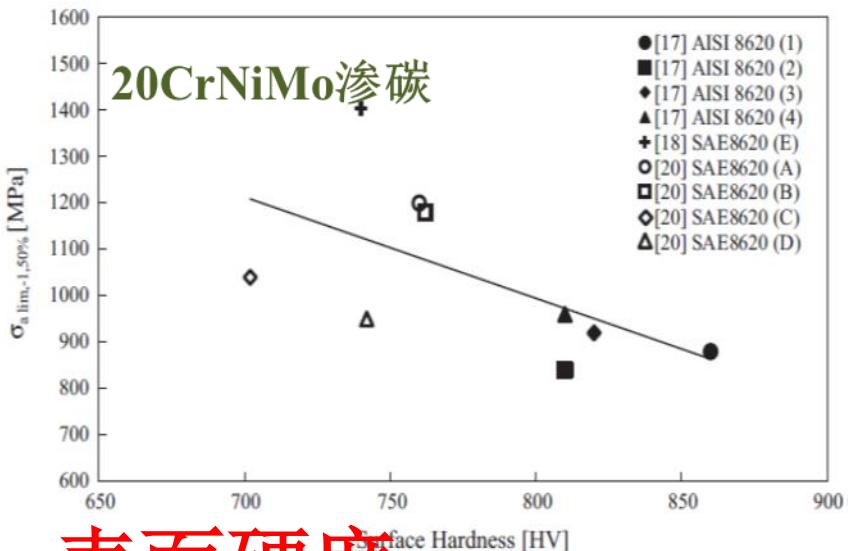
单纯提高硬度有一定限度

2015, 意



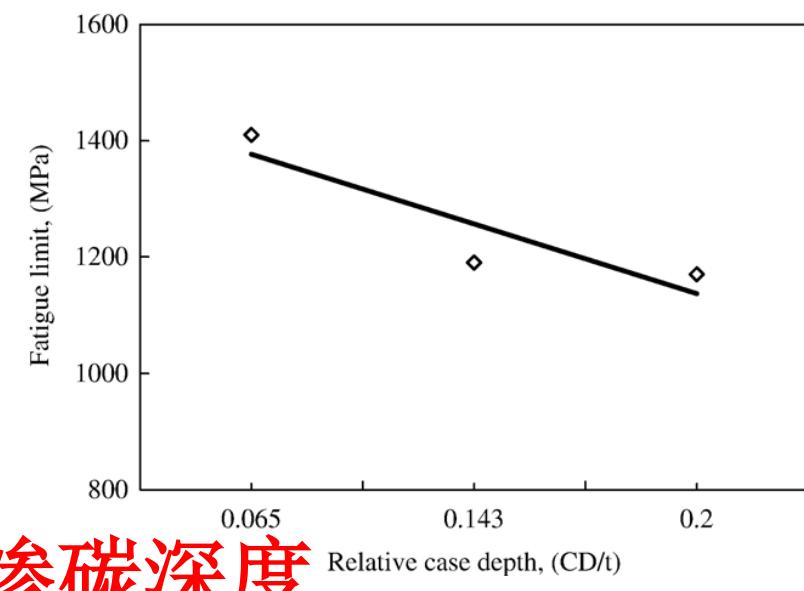
心部硬度

疲劳强度



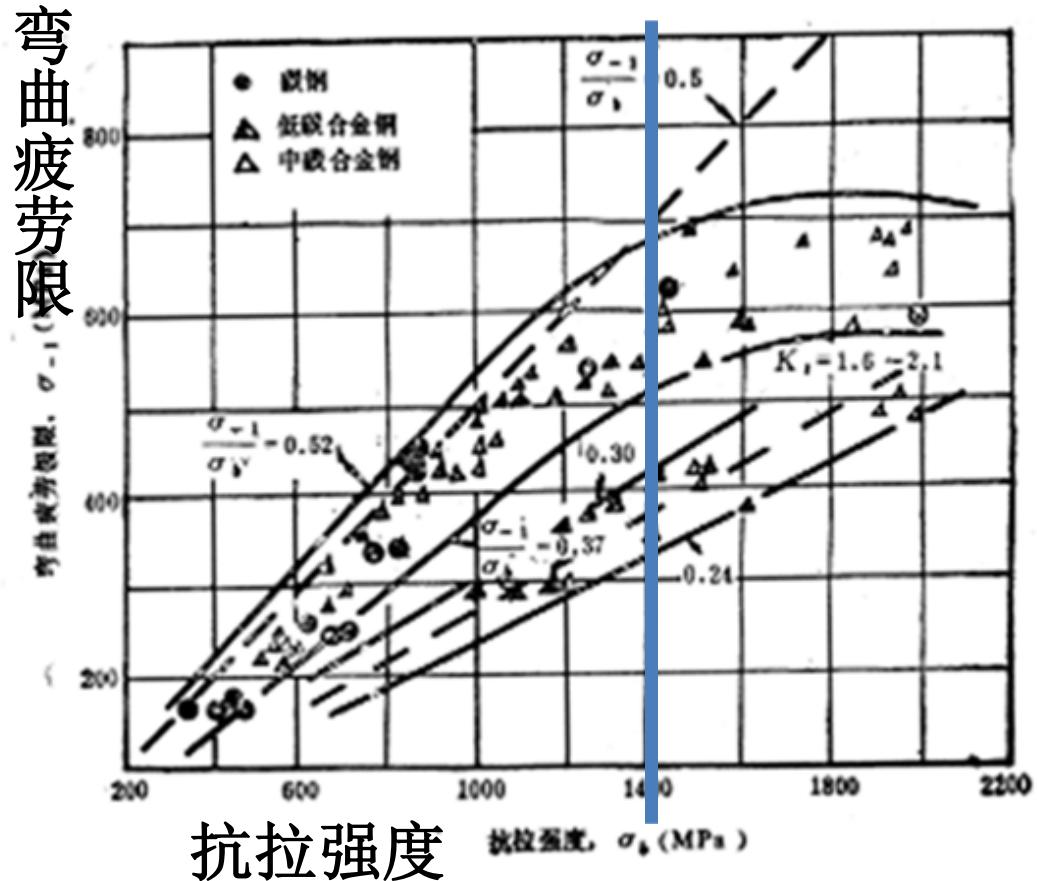
表面硬度

疲劳限



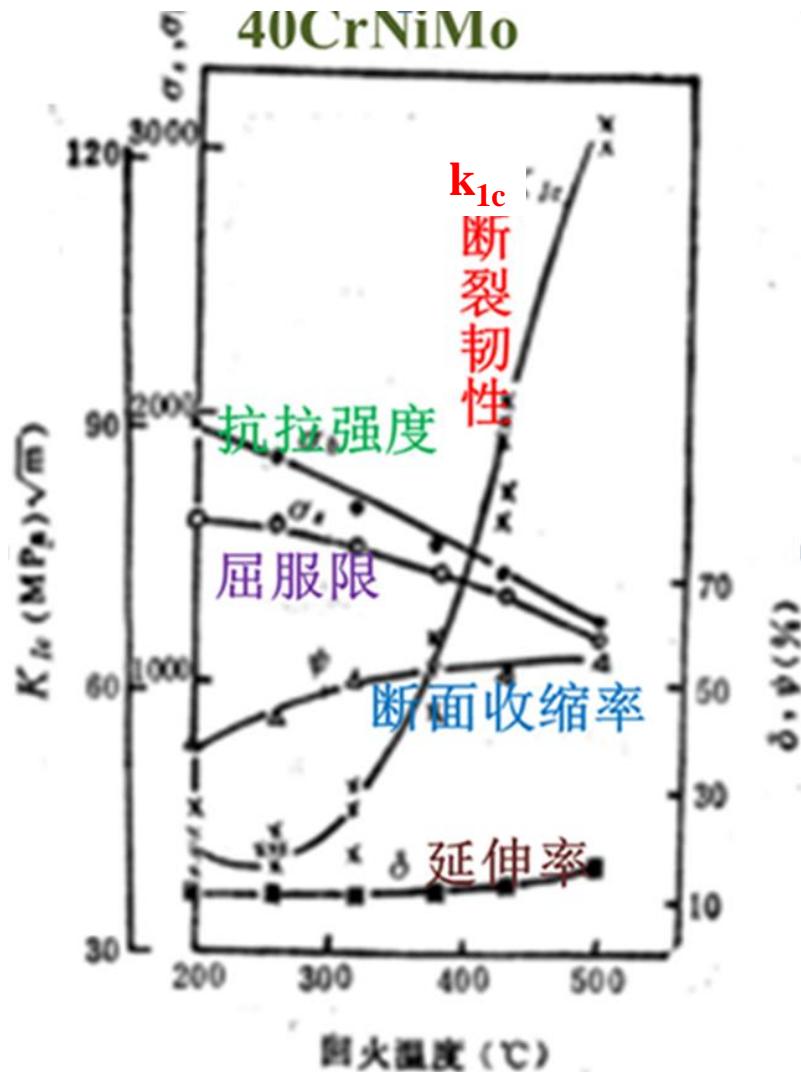
渗碳深度

$<1400 \text{ MPa}$ $\sigma_1/\sigma_b = 0.5$



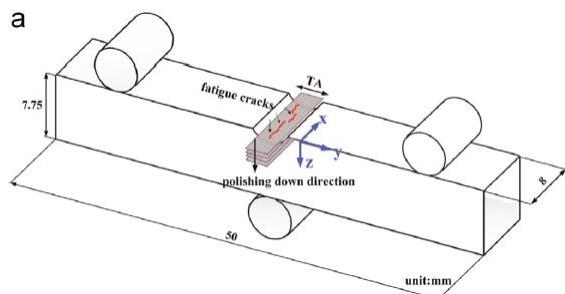
强度高塑性下降，**夹杂处**
应力集中，塑性低，易形
成**裂纹**

硬度↑ $k_{1c} \downarrow$
 k_{1c} 裂纹扩展阻力



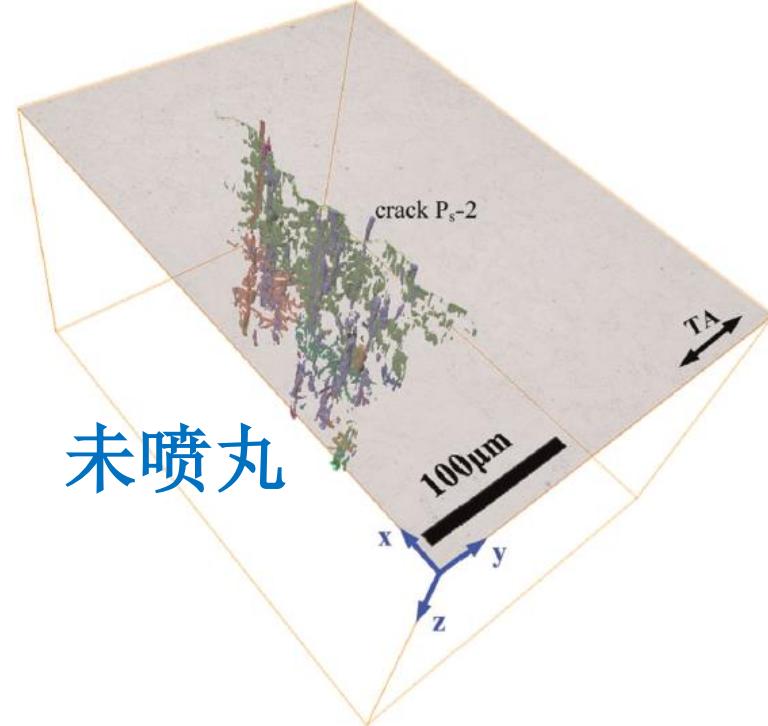
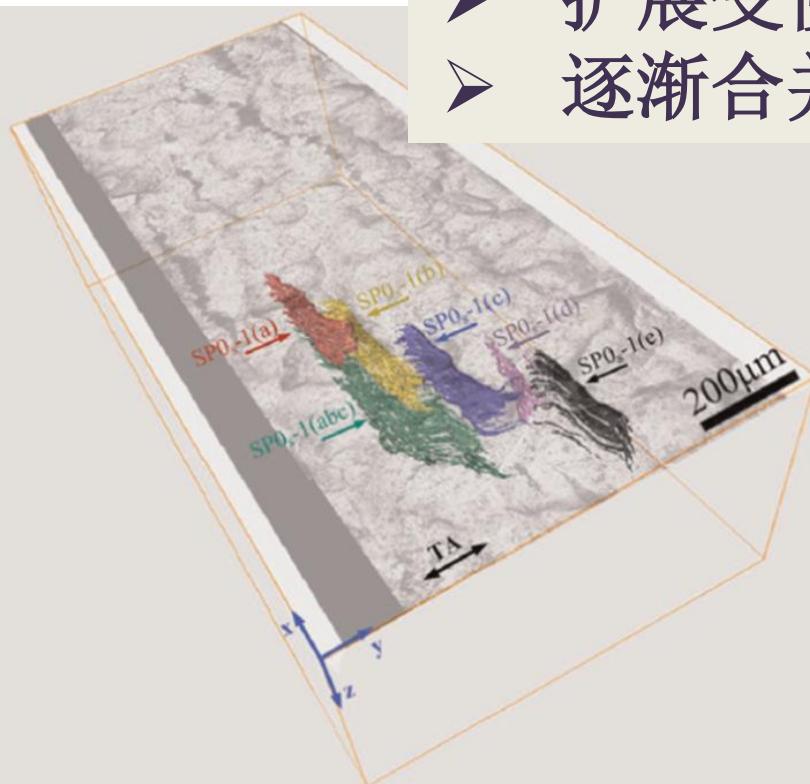
疲劳裂纹3D扩展

分层切片

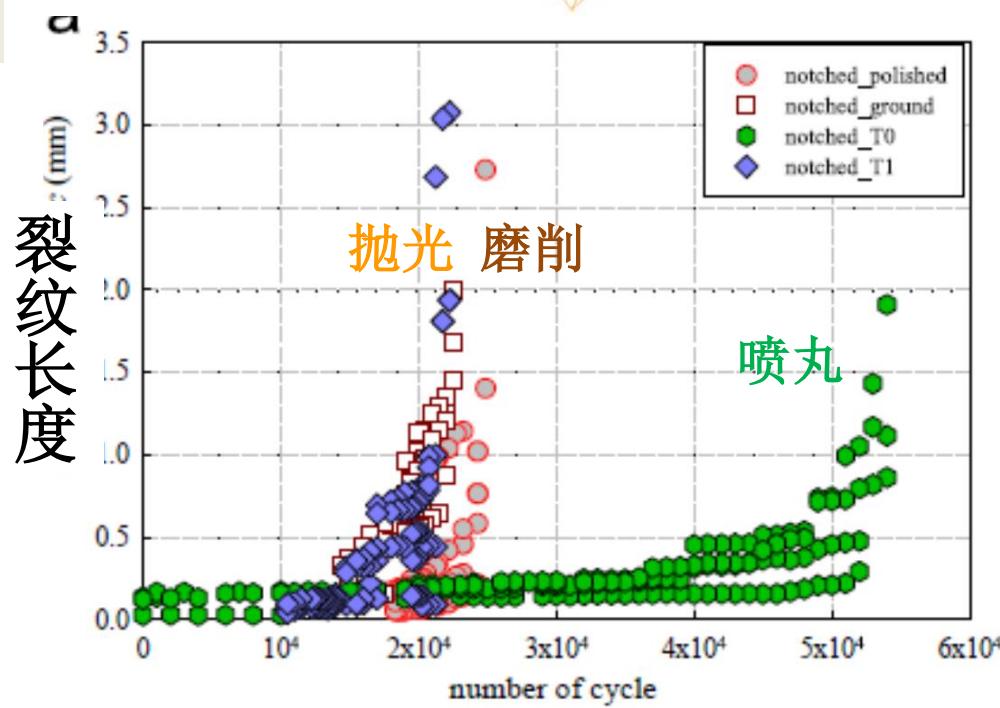


喷丸后

- 扩展变慢
- 逐渐合并



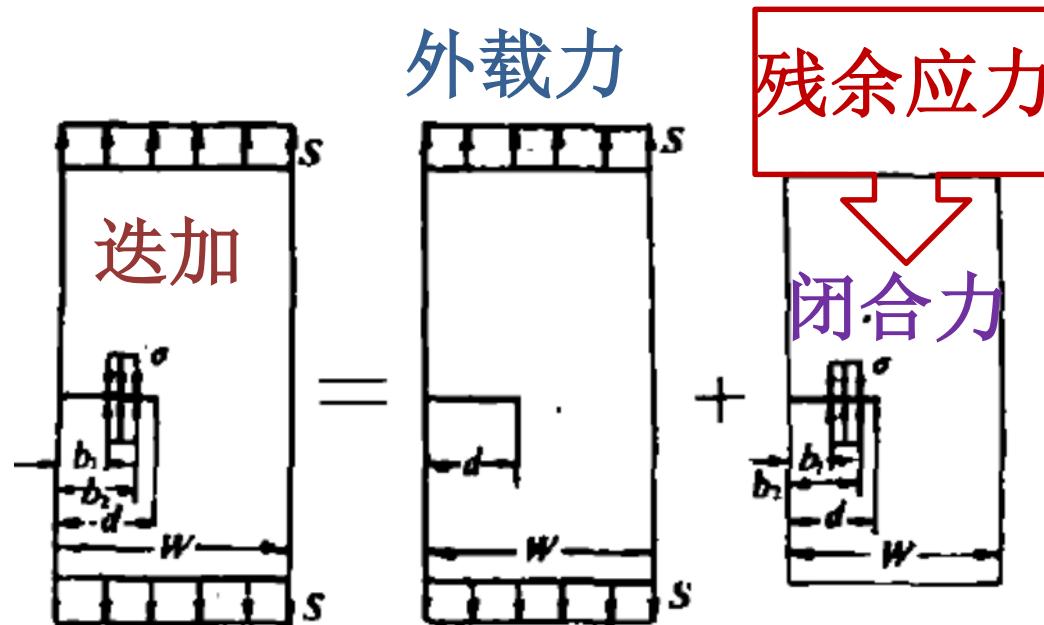
未喷丸



抛光 磨削

喷丸

残余应力作用在裂纹面



一般共识 不同处理

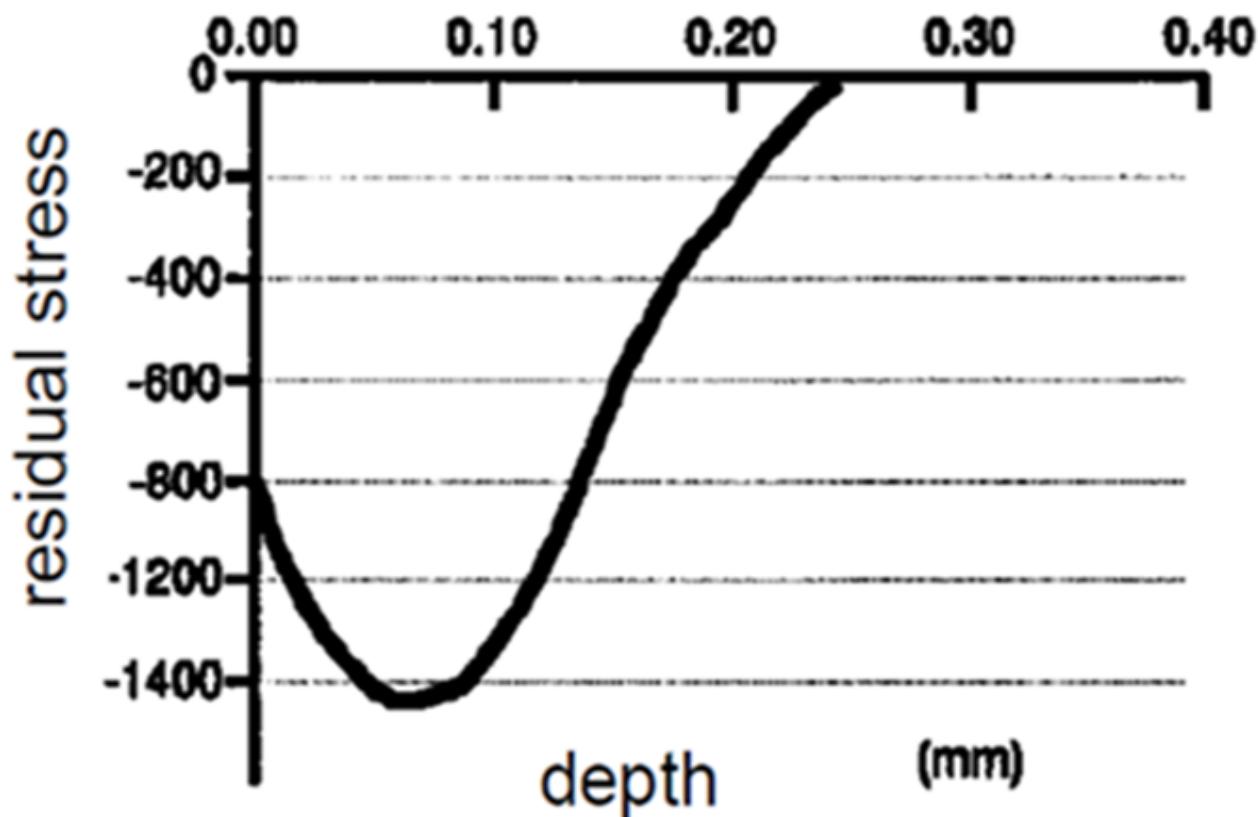
作为力学参量，定量进入设计

纳入残余应力

弯曲疲劳

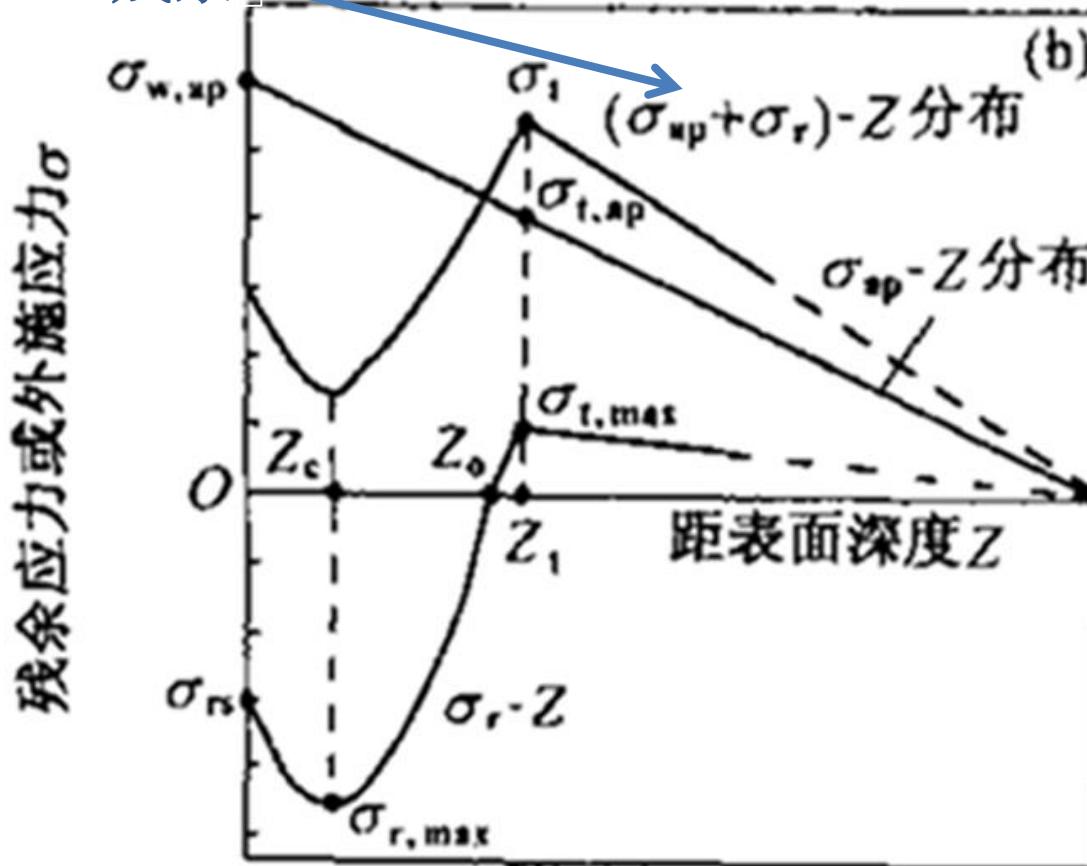
设计

喷丸后残余应力沿深度分布的典型曲线：



部分工作的处理方法

$\sigma_{\text{外载}} + \sigma_{\text{残余}}$



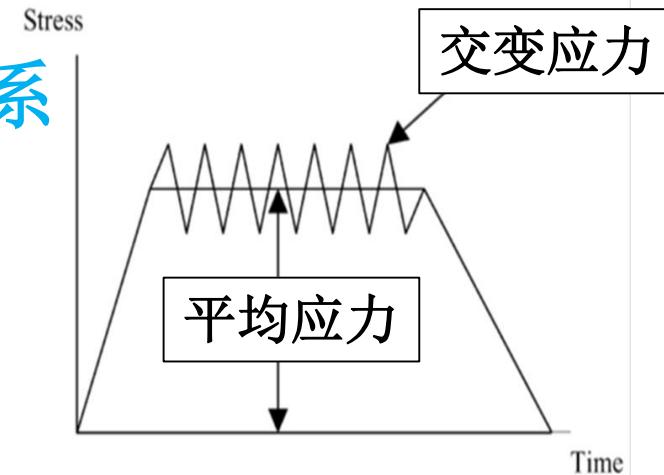
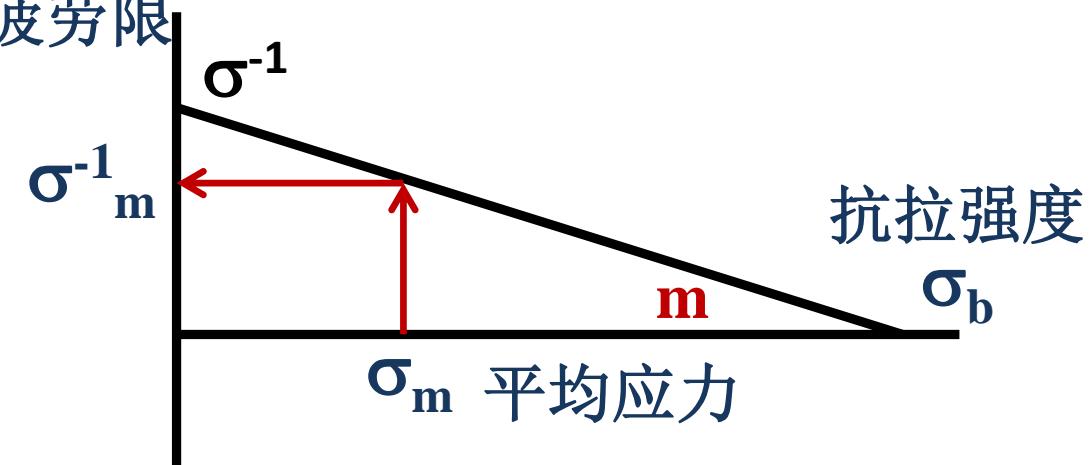
残余应力+外载应力

静 + 动 ?

平均应力≠交变应力

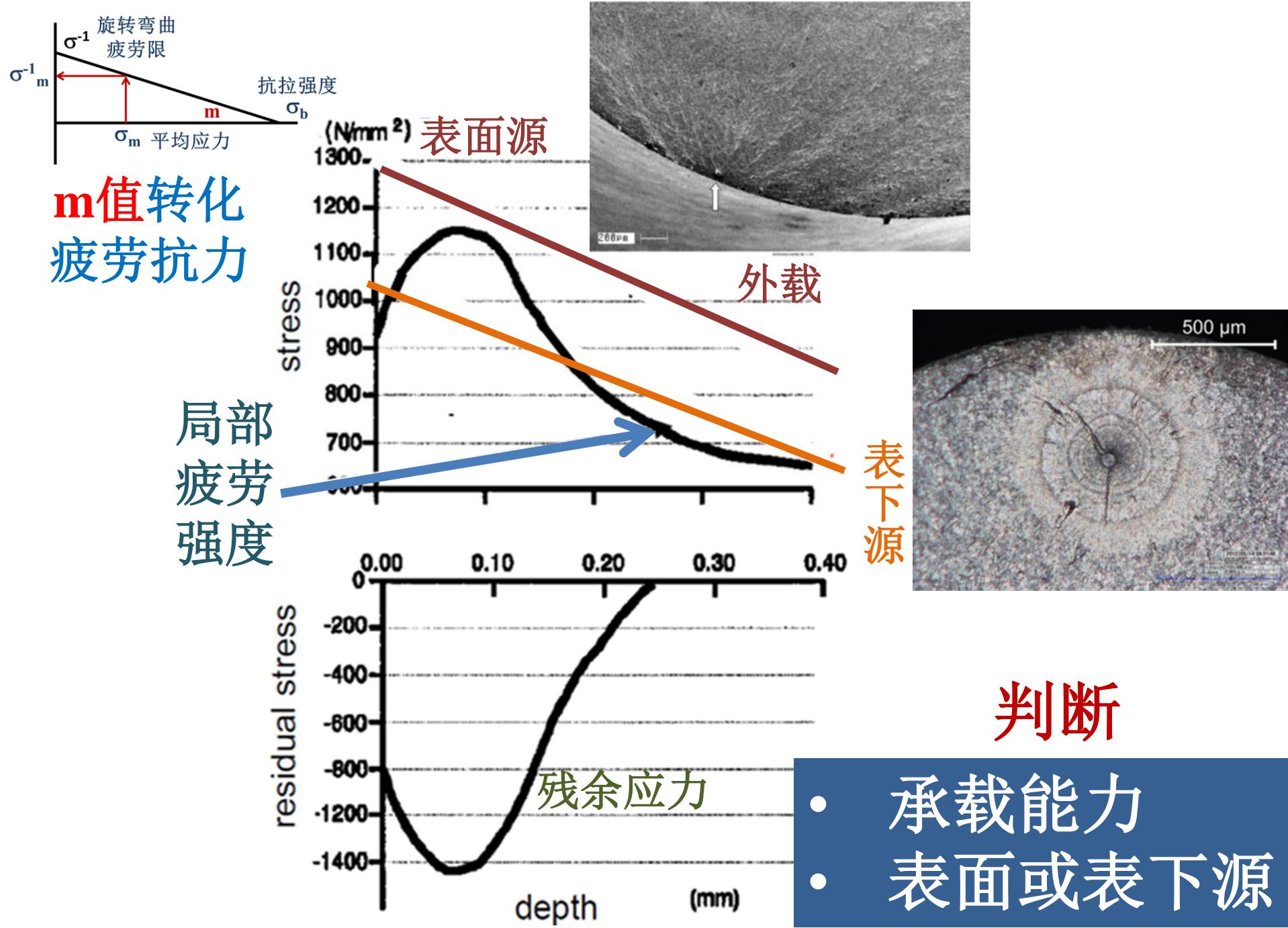
静、动载对材料破坏作用不同

弯曲
疲劳限 静动强度间关系: Goodman关系

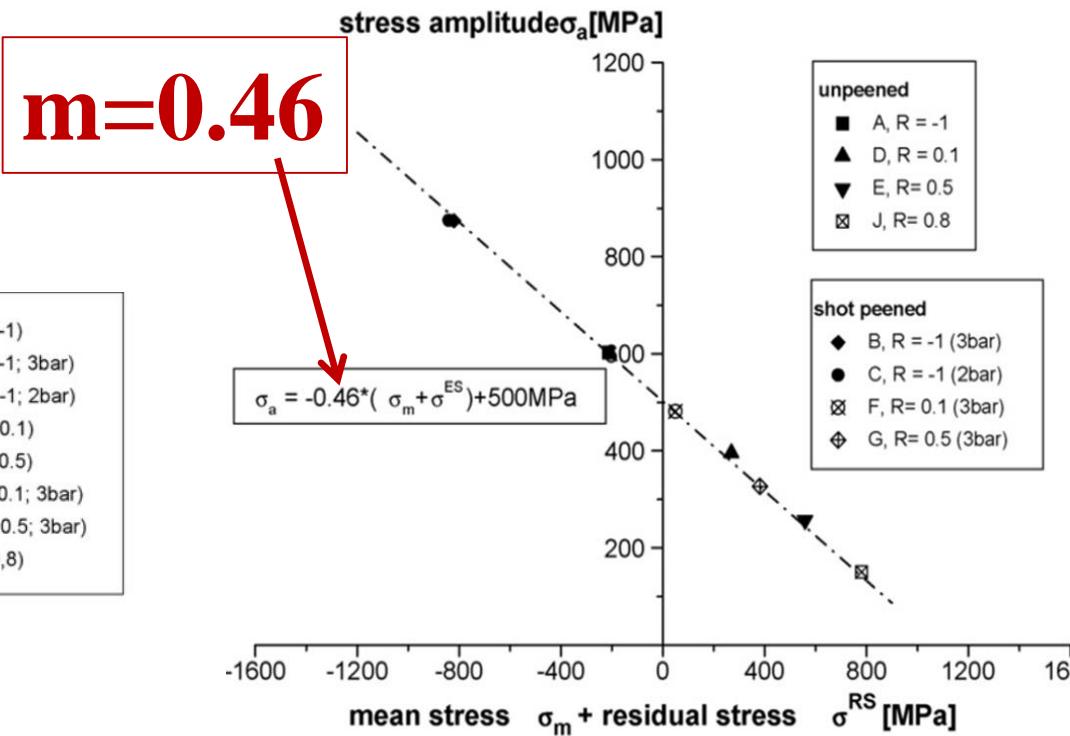
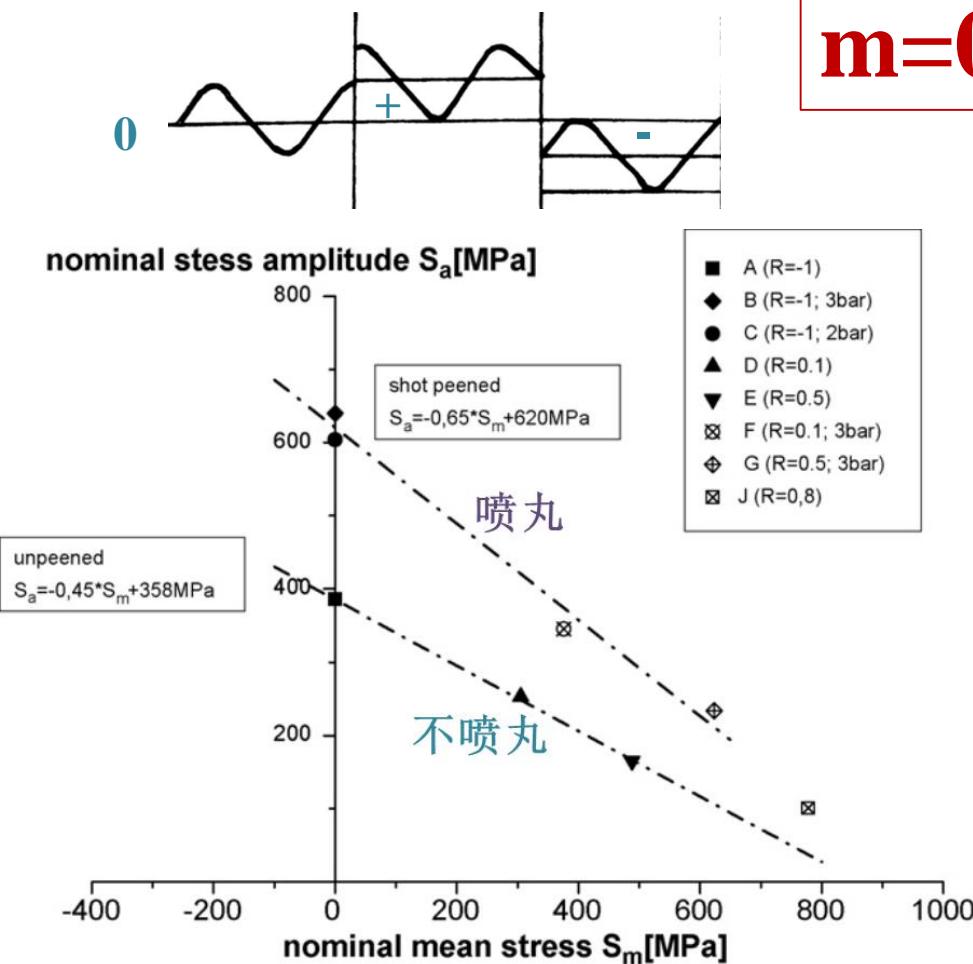


$$\text{动} \rightarrow \sigma_m^{-1} = \sigma^{-1} - m \sigma_m \quad \text{静}$$

残余应力对疲劳的作用: m 值



渗碳钢 不同平均应力疲劳

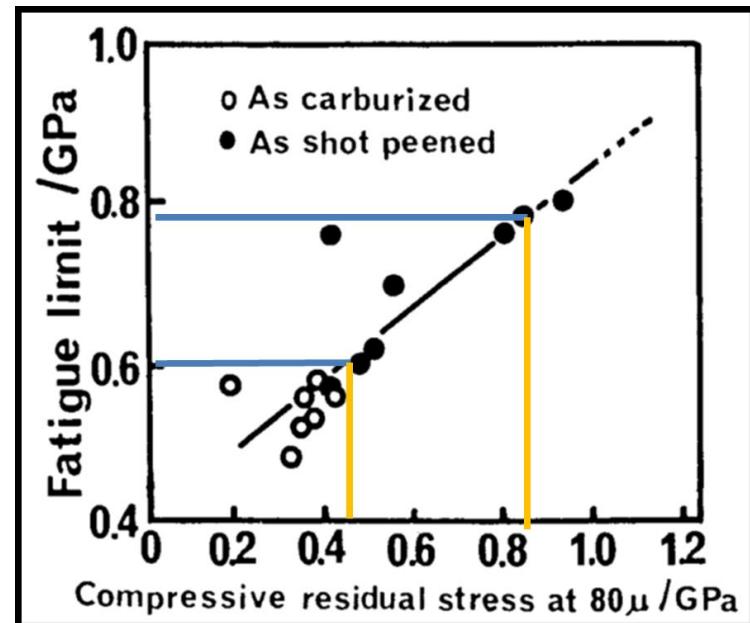
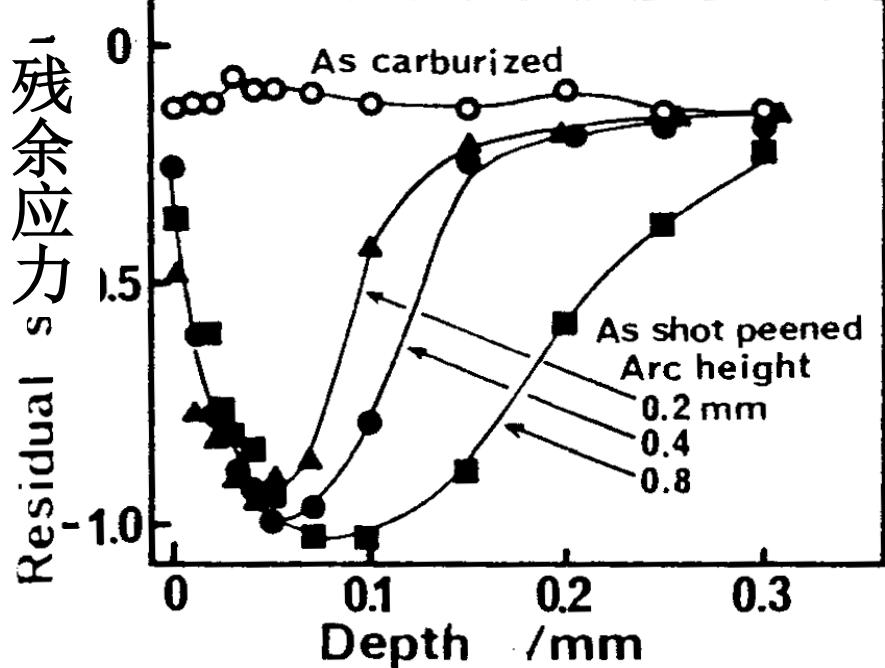


平均应力+残余应力

平均应力

20CrMnMo渗碳 旋转弯曲疲劳

a) Residual stress

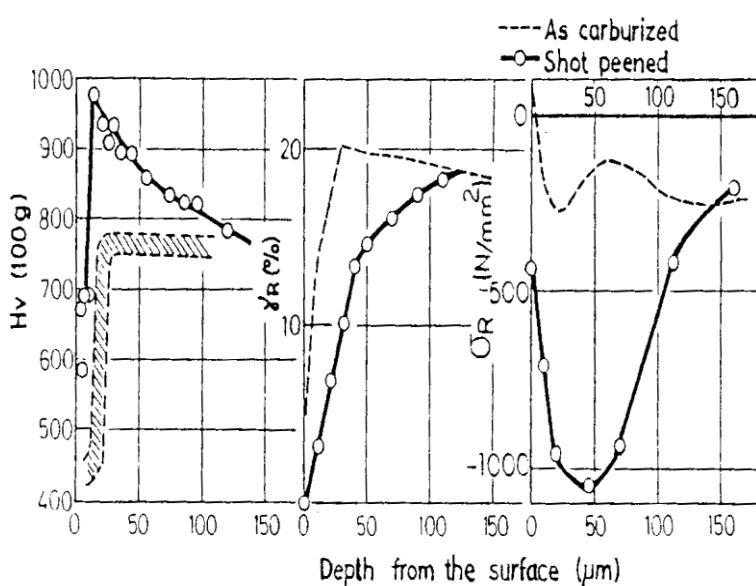


m=0.45

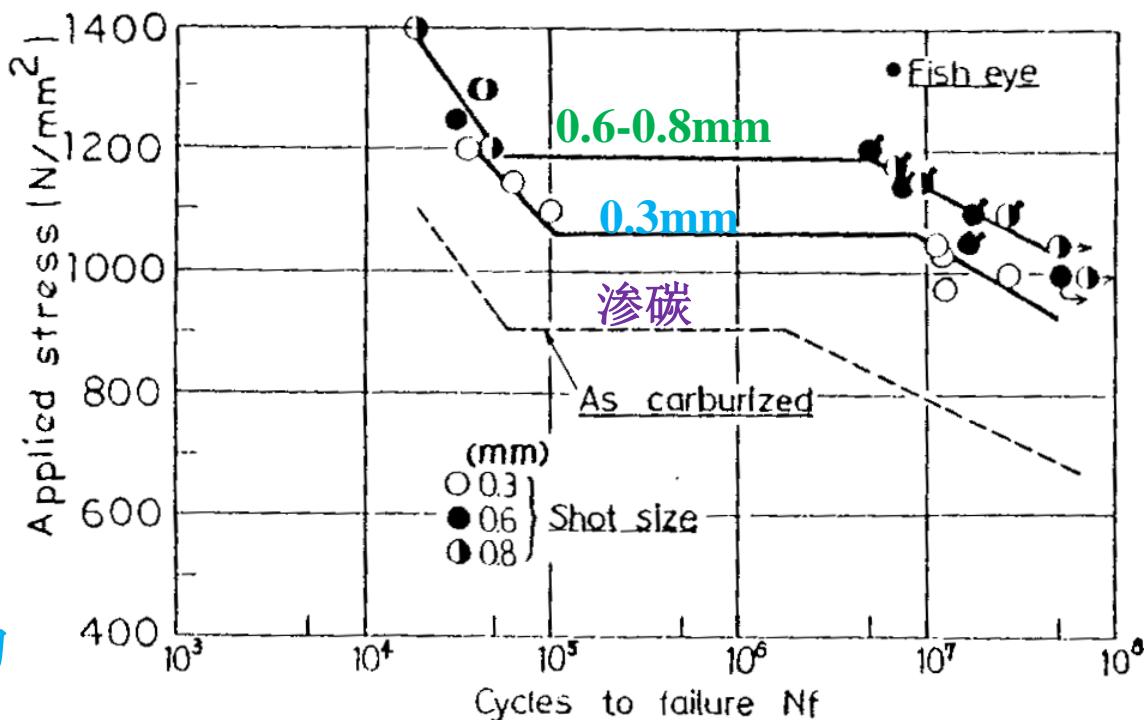
- 3种喷丸强度0.2A-0.8A
- 硬度，残奥影响相似
- 残余应力不同起**主要作用**

20CrMnMo渗碳 旋转弯曲疲劳

0.3, 0.6, 0.8mm钢丸，速度46 m/s



硬度 残奥 残余应力



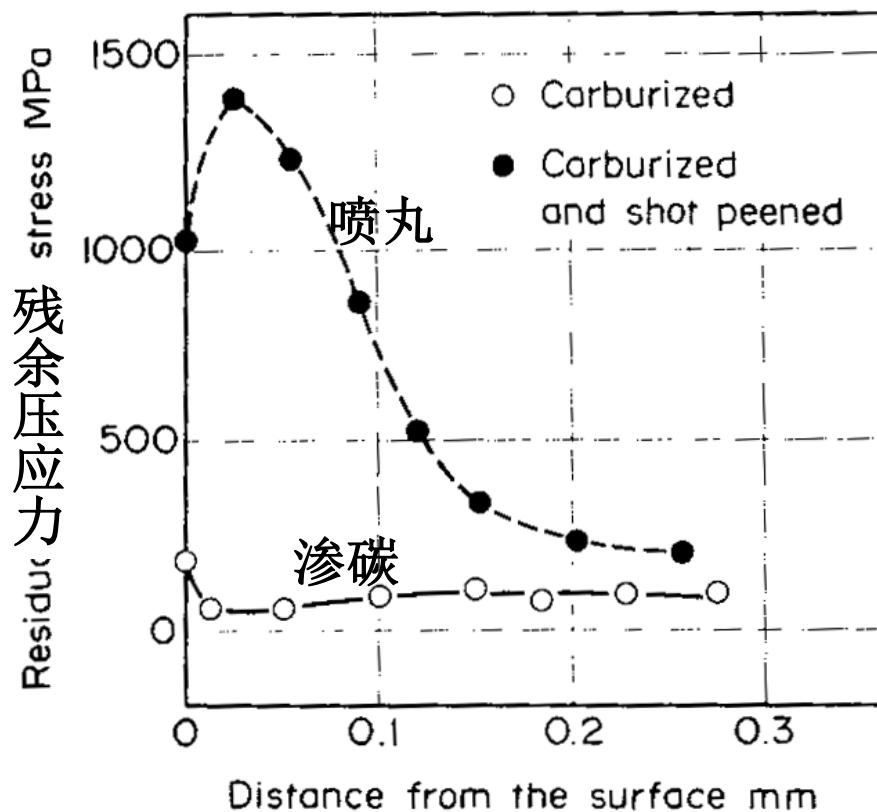
0.6-0.8mm喷丸效果

m=0.35

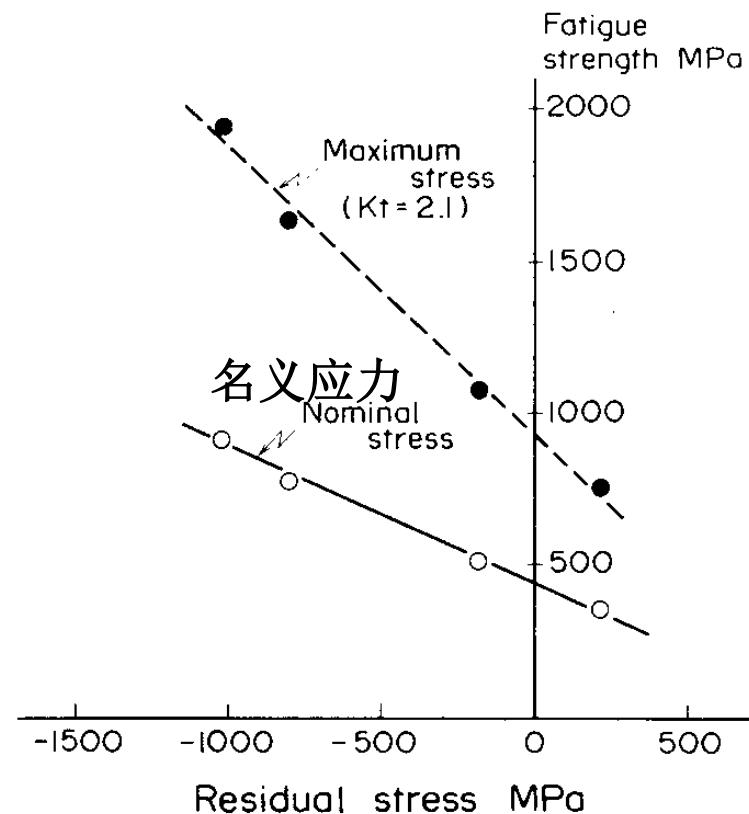
20CrMnMo渗碳

缺口旋转弯曲疲劳

缺口应力集中系数 $k_t = 2.1$
0.6mm钢丸，HRC55



极大值：1400MPa



名义应力计算

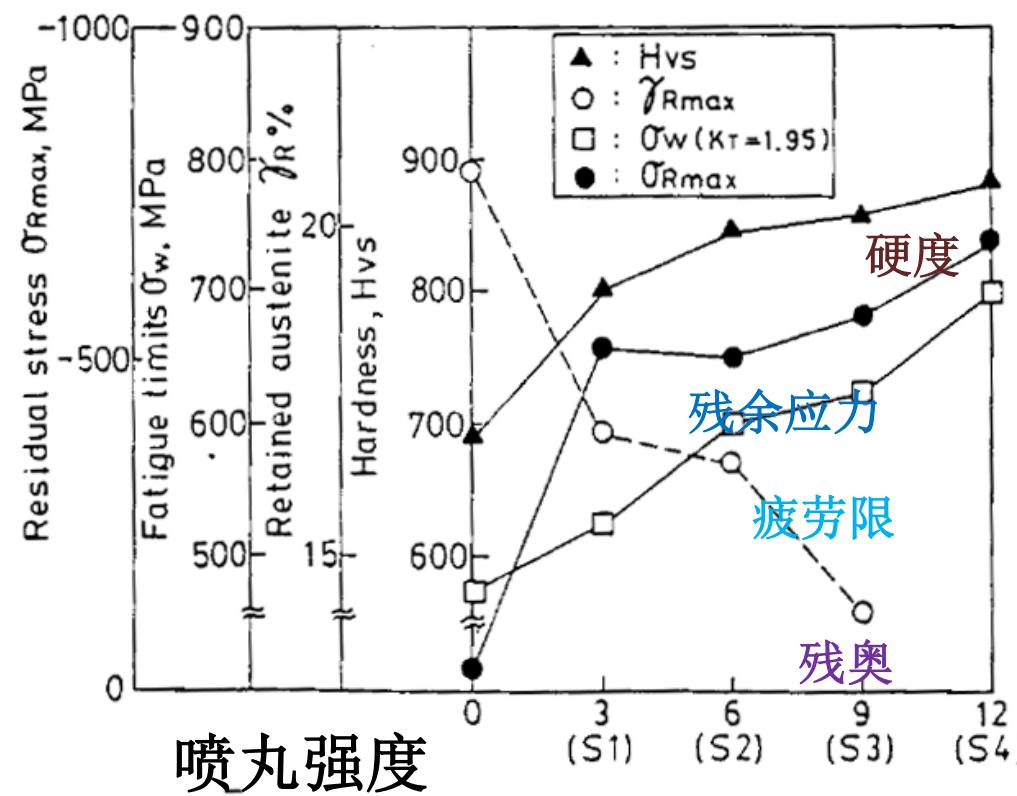
$$m=0.39$$

缺口 $k_t=1.95$ 旋转弯曲疲劳

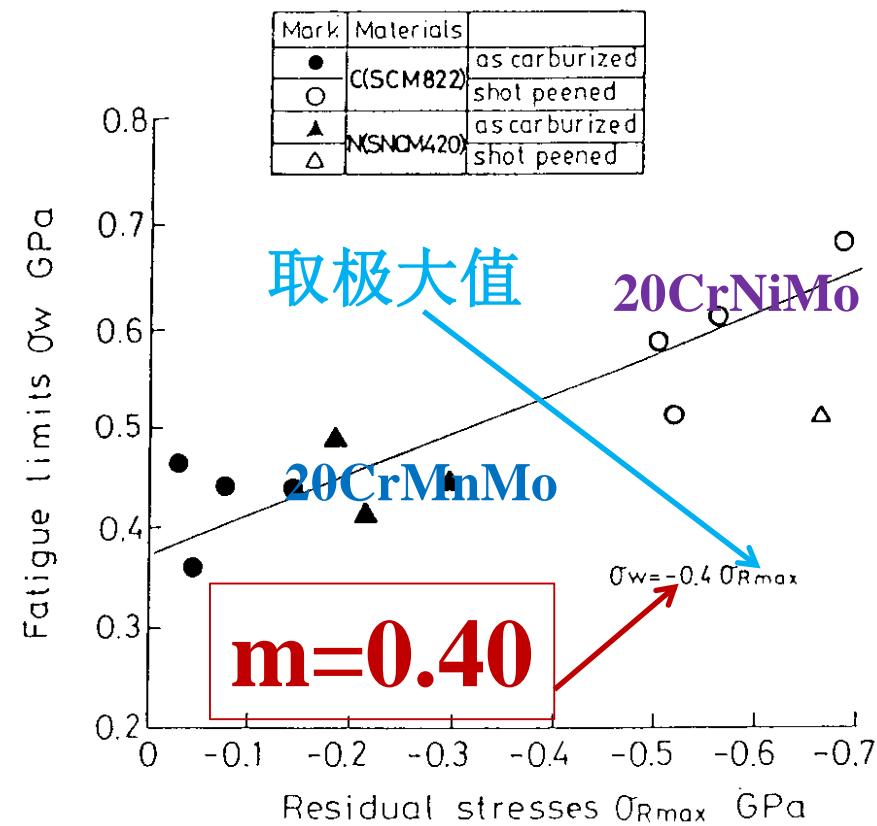
20CrMnMo

20CrNiMo

- 4种喷丸强度0.31A-0.43A
- 同时测定残奥，硬度



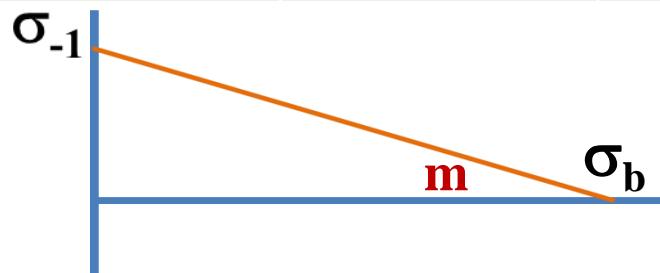
不同钢的疲劳限和
残余应力可成线性



教科书数据

无关残余应力

	铁素体	珠光体	奥氏体	马氏体	索氏体
σ_{-1}/σ_b	0.57-0.63	0.38-0.41	0.35-0.45	0.23-0.47	0.56-0.60
中值	0.60	0.40	0.40	0.35	0.58



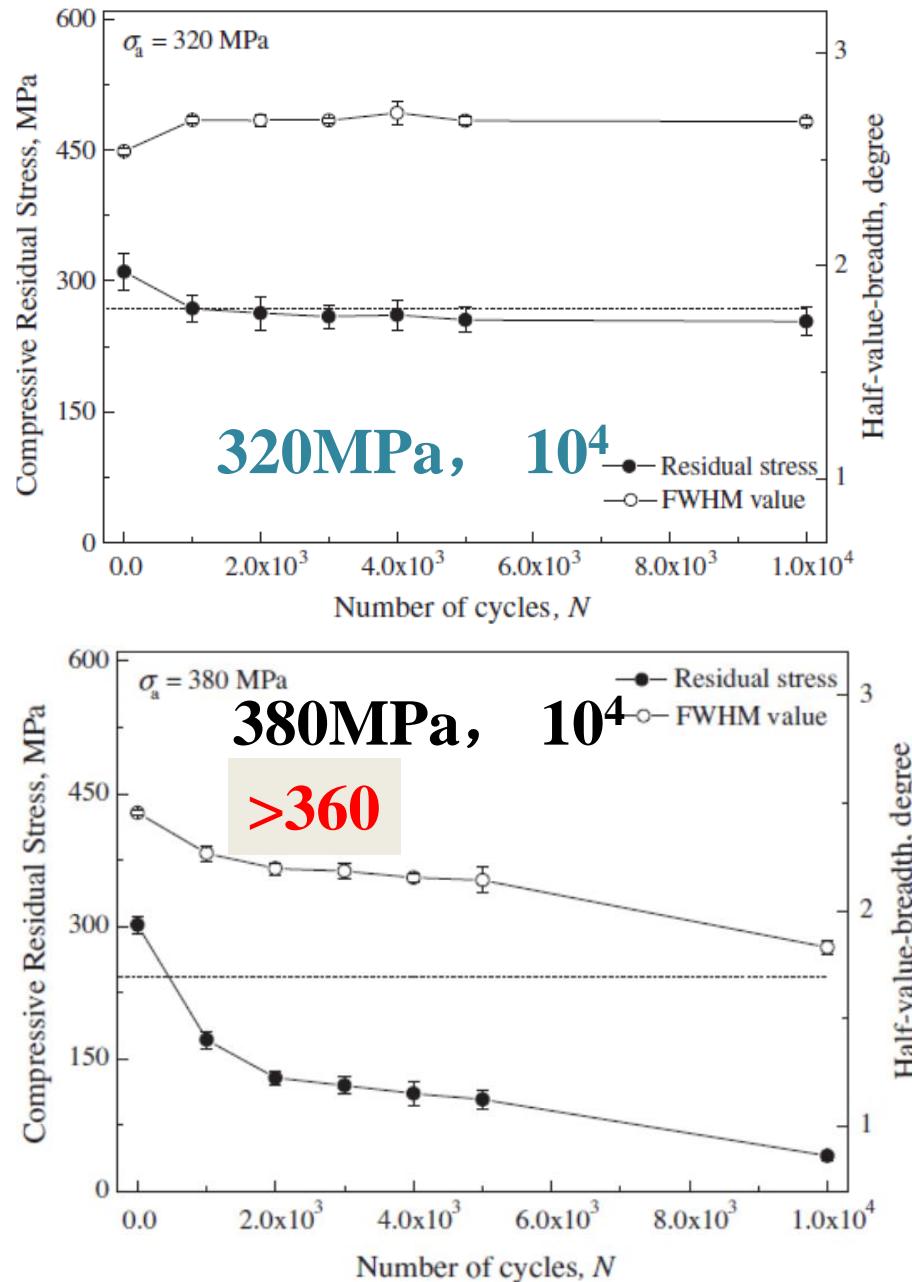
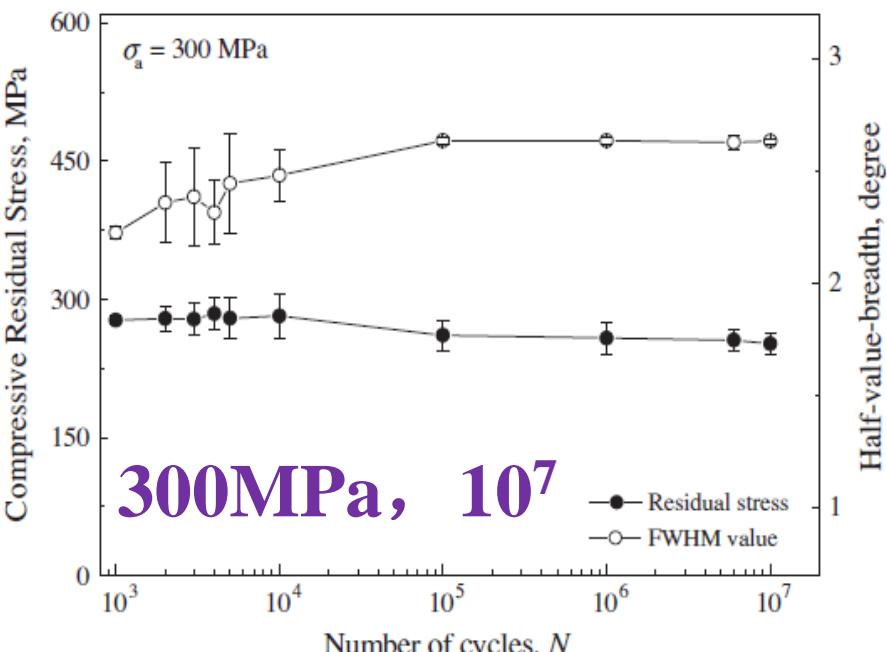
含残余应力

作者	德	神户	住友	小松	日钢
m值	0.46	0.39	0.40	0.35	0.45

不同源数据相符

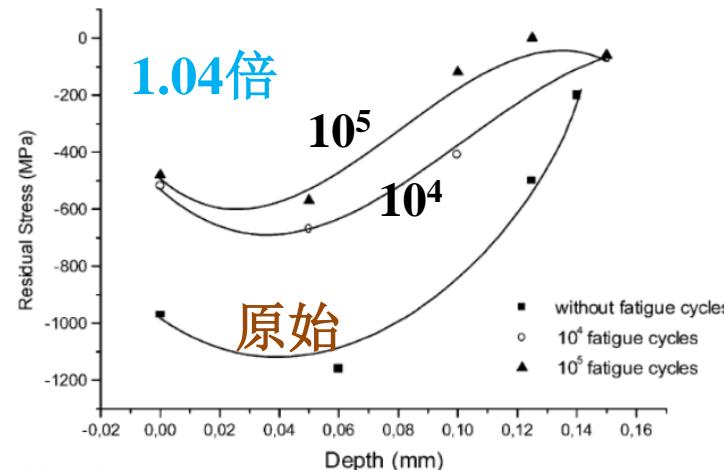
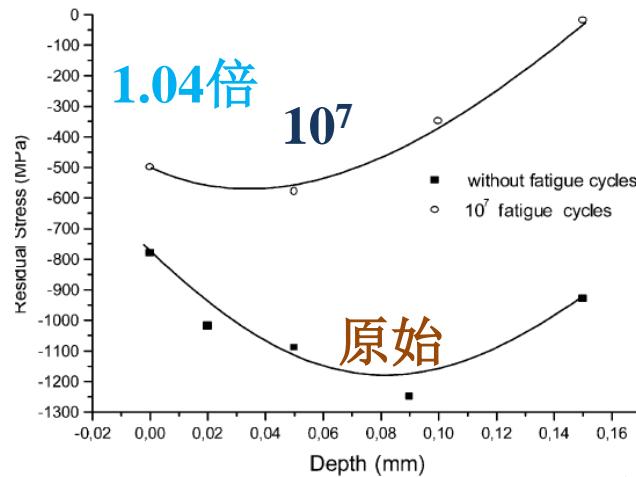
运行中残余应力衰减

- 45Mn旋转弯曲疲劳
- 屈服强度**360MPa**
- 喷丸强度**0.36A**

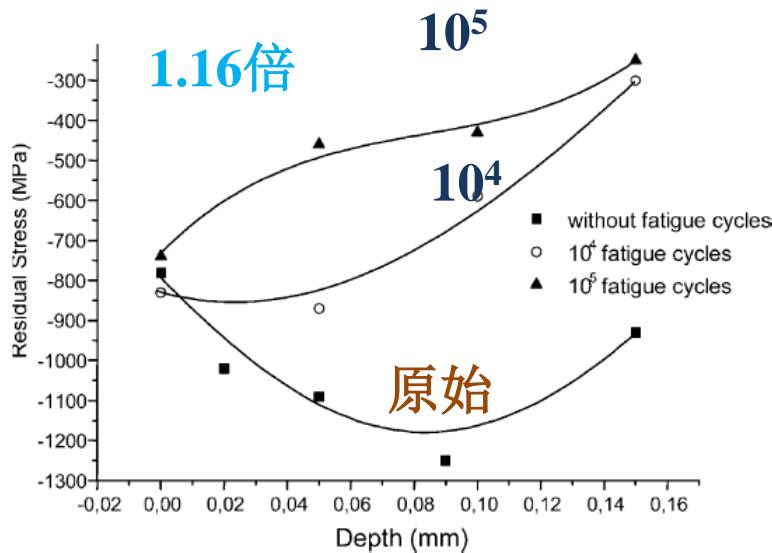


超过疲劳限的衰减

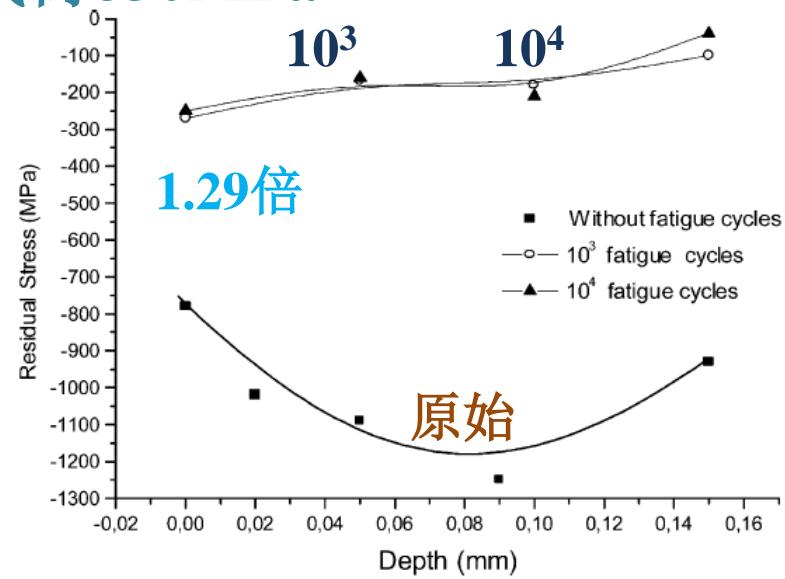
低温回火钢HRC53疲劳限800MPa



0.141A喷丸载荷830MPa



0.141A喷丸,载荷931MPa



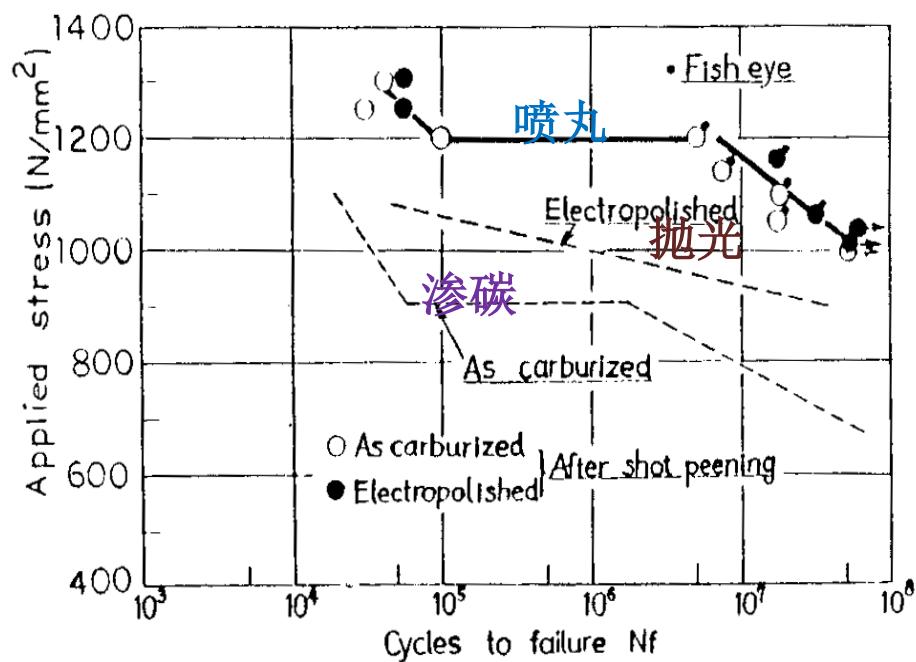
0.141A喷丸,载荷1035MPa

抑制黑色组织

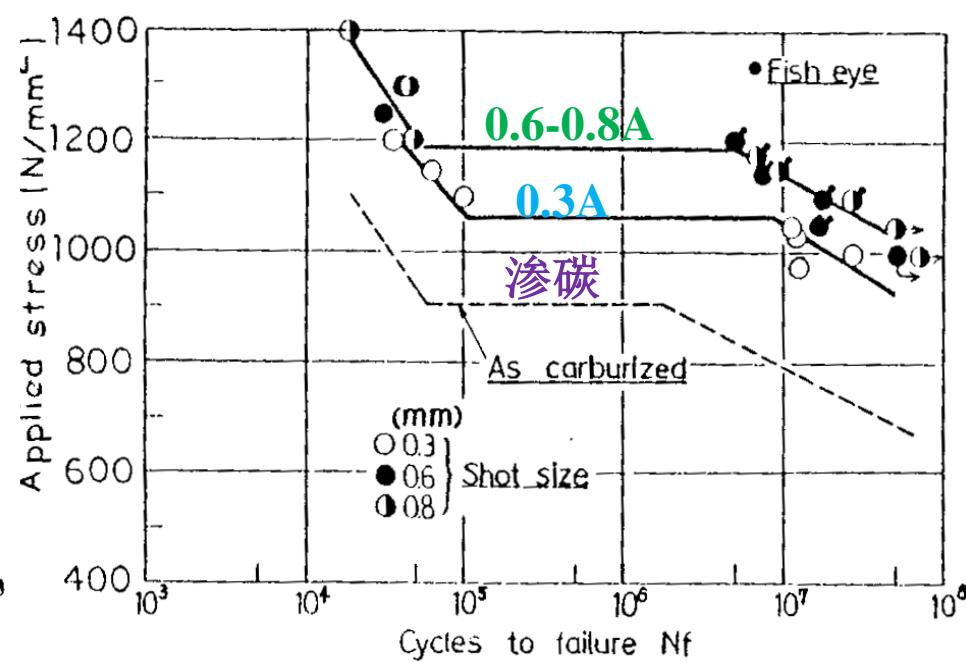
20CrMnMo黑色组织 30μ

电抛光, 0.3mm喷丸
可以减少非马影响

0.6mm, 0.8mm喷丸
完全消除非马影响



抛后再喷丸, 0.3A即可

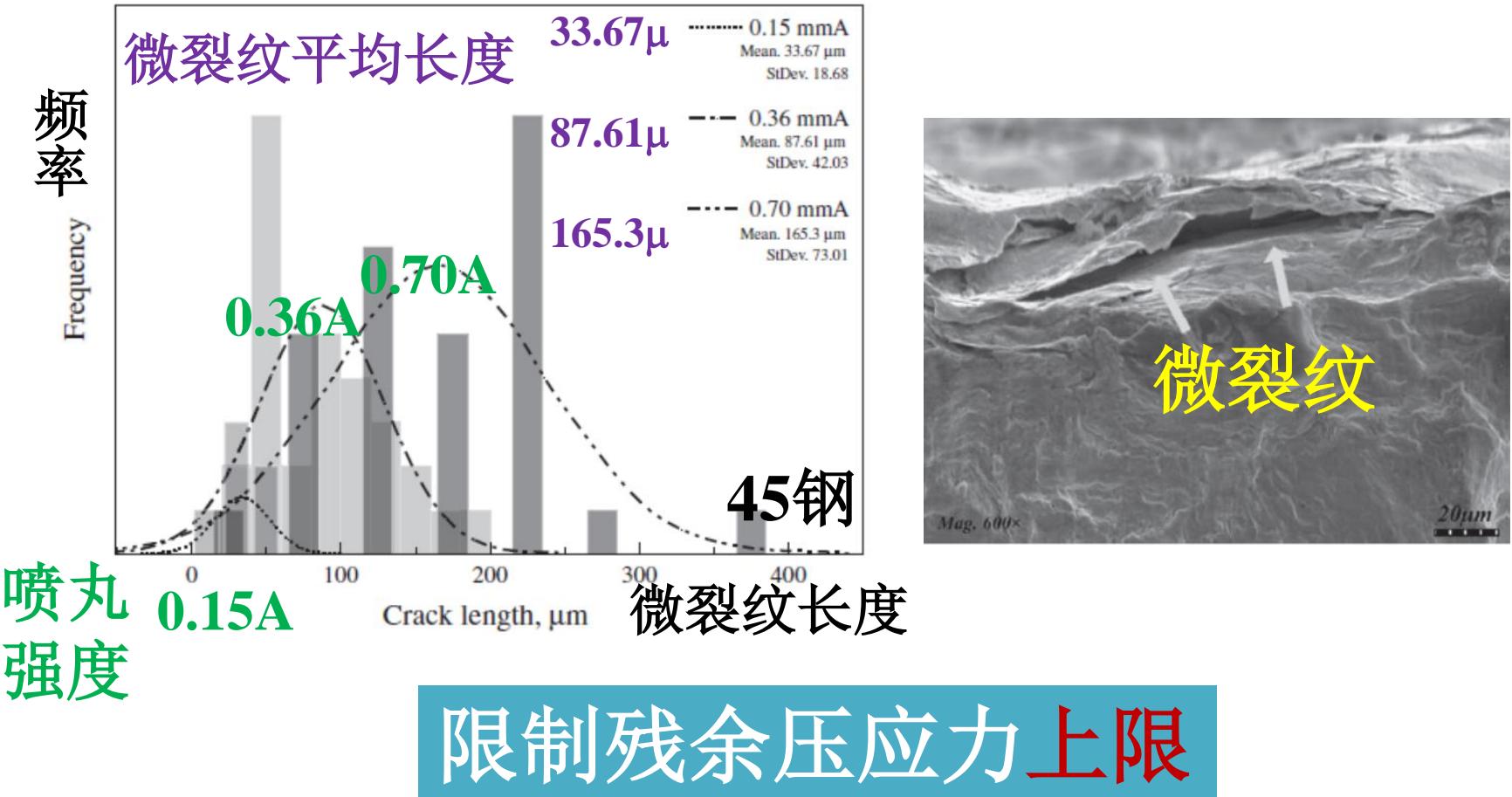


0.6A-0.8A喷丸, 无需抛光

黑色组织可视作表面缺陷

强化伴随损伤

- 喷丸强度高，残余压应力高，损伤大
- 低强度喷丸也难避免微裂纹



归 纳

□ 渗碳取300MPa \rightarrow 喷丸提高到1000MPa

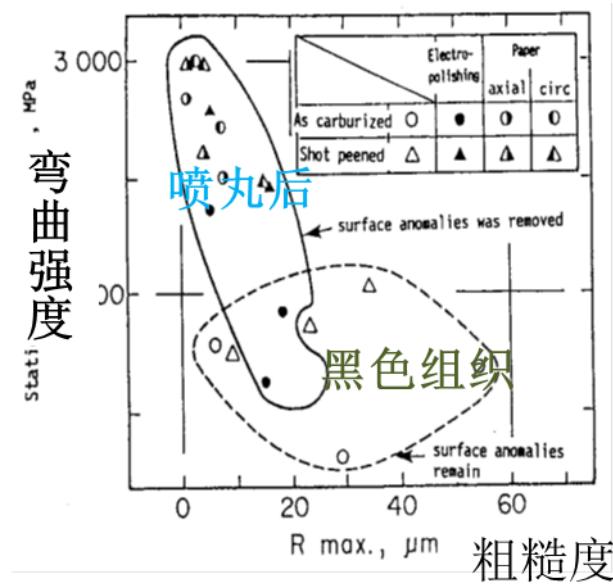
如 $m=0.4$, 疲劳限 $\uparrow 280\text{ MPa}$

疲劳限 MPa	ML	MQ	ME
	320	450-500	550

差距230MPa

- | 原材料 | 渗碳层 |
|-------------|----------|
| • 钢坯成分, 均匀性 | • 表面硬度 |
| • 夹杂物, 含氧量 | • 含碳量及深度 |
| • 锻造比, 晶粒度 | • 黑色组织 |
| | • 析出碳化物 |
| | • 残留奥氏体 |
| | • 淬火缺陷 |

□ 消除、抑制黑色组织影响



□ 主导因素是残余应力，非组织结构

喷丸控制：残余应力和损伤，粗糙度间优化



Thank You!

昌宇应力技术（上海）有限公司
商业化的残余应力和喷丸强化技术研发和应用平台

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