残余应力评价与调控技术

Evaluation and Relieving of Residual Stress

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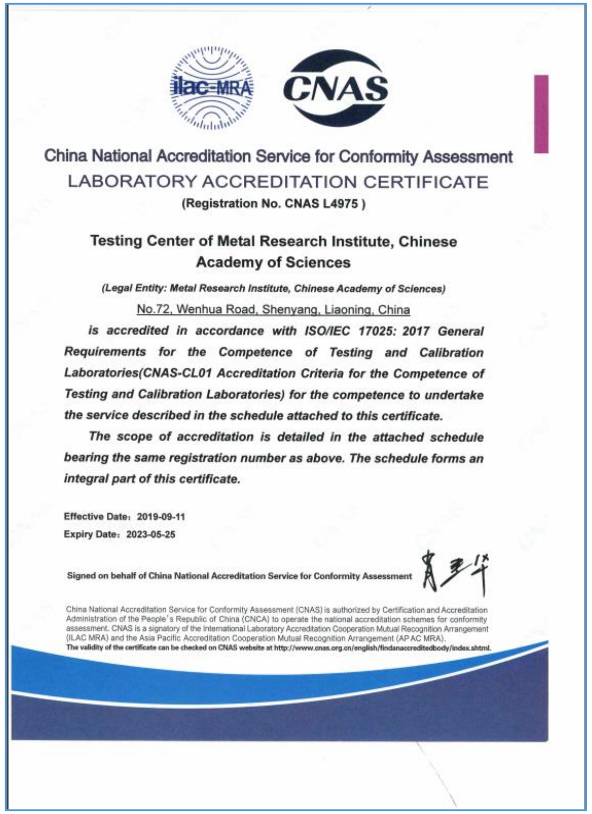
1、实验室简介 Briefing on Lab

本实验室是我国应力测试领域唯一拥有CMA 和 CNAS双认证认可单位。具有独创的应力测试技术“压痕应变法”、“DHD 深孔法”和“R-N 切割法”和多种应力消除技术。编写了五部与残余应力相关的国家标准。

The Lab is only one qualified division with CMA and CNAS accreditation and certificationin in the field of residual stress determination in China. The Lab is possessed of own stress measuring method such as “Indentation strain-gage method”, “Deep-Hole Drilling method”, “R-N Sectioning relaxation strain-gage method”, etc. On the other hand, the Lab has exclusively some stress-relief techniques. Five national standards have been prepared.


China National Accreditation Service for Conformity Assessment

LABORATORY ACCREDITATION CERTIFICATE

(Registration No. CNAS L4975)

Testing Center of Metal Research Institute, Chinese Academy of Sciences

(Legal Entity: Metal Research Institute, Chinese Academy of Sciences)

No.72, Wenhua Road, Shenyang, Liaoning, China

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金属材料　残余应力测定　压痕应变法

Metallic materials—Residual stress determination—The indentation strain-gage method

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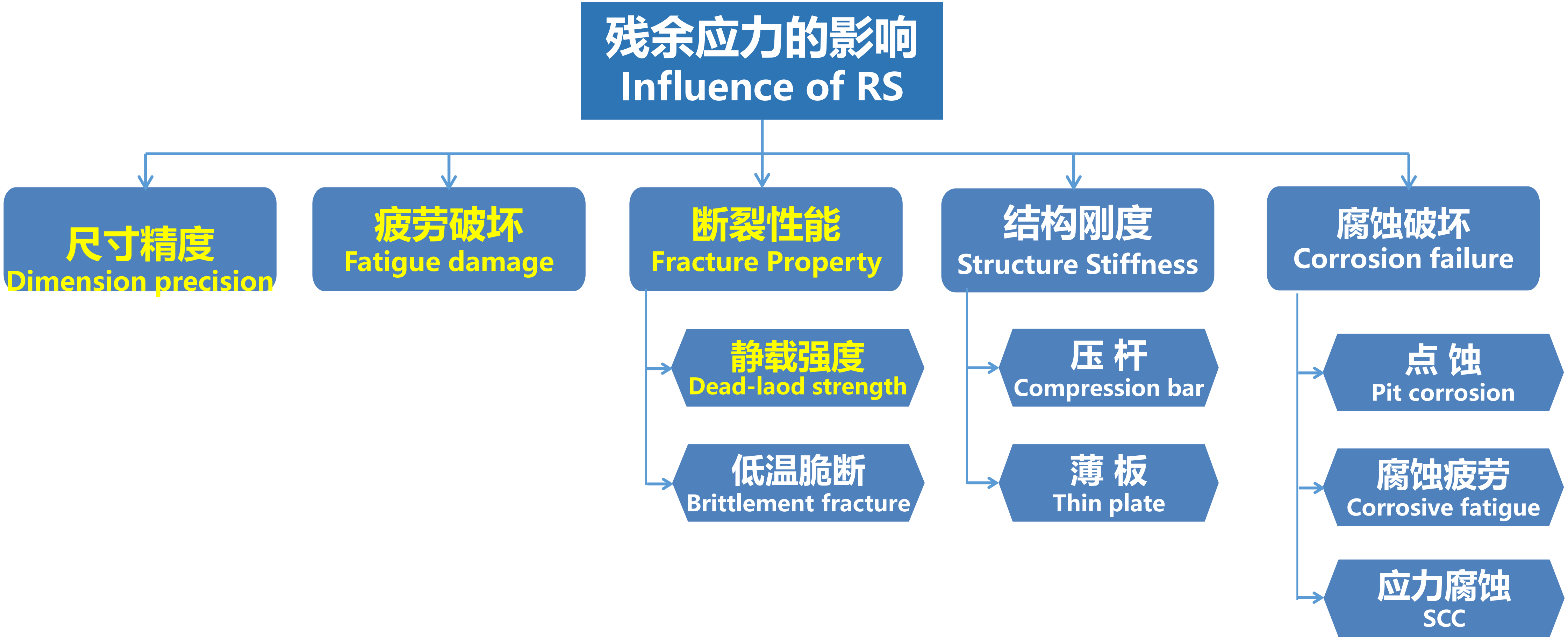
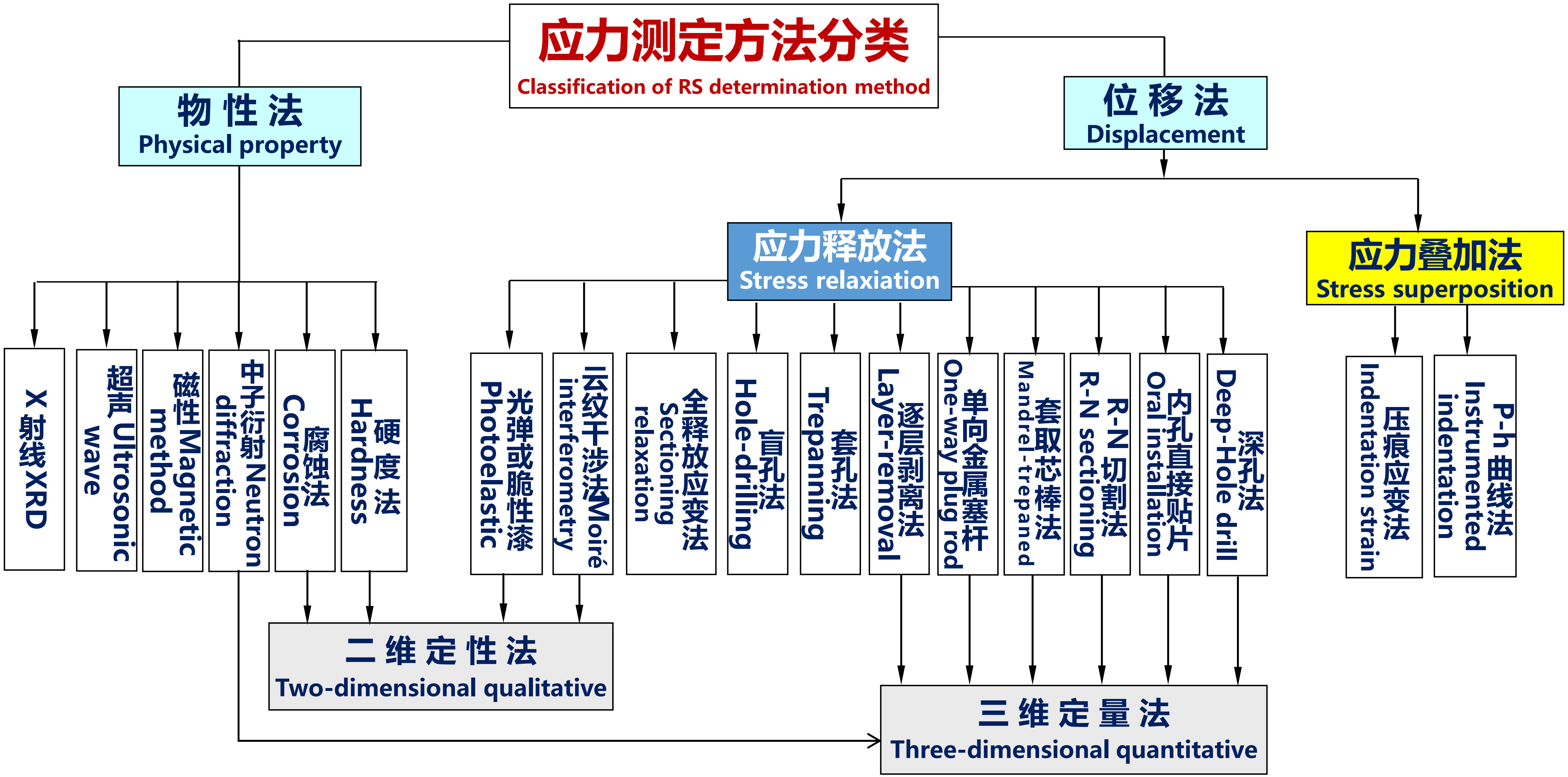
中国国家标准化管理委员会　发布

2、残余应力的作用 Influence of Residual Stress



3、残余应力测量技术 Methods for RS Determination



3、残余应力测量技术 Methods for RS Determination

—— 几种主流应力测定方法评价
Evaluation of some leading measuring methods

◆ X射线衍射法（X-ray diffraction，XRD）

多晶体金属材料晶面间距d一定，受应力作用d就要发生正比于应力的变化。

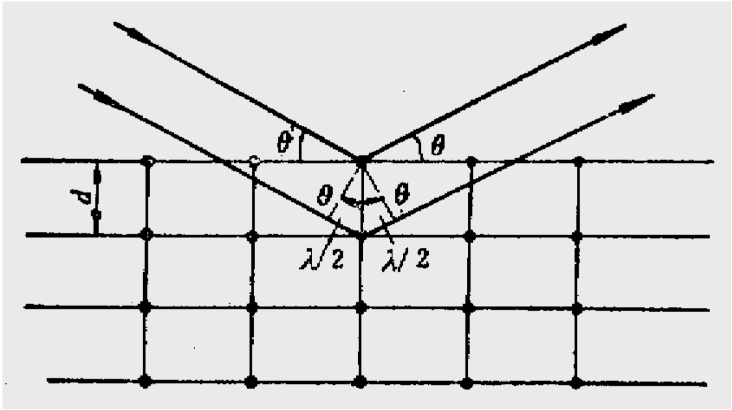
The crystal plane spacing d of polycrystalline metal materials is constant, which is changed in proportion to stress.

一束波长为λ的单色平行光—X射线以入射角θ入射到某特定晶面（hkl）时，如能满足Bragg公式：

$$2d\sin\theta=n\lambda$$

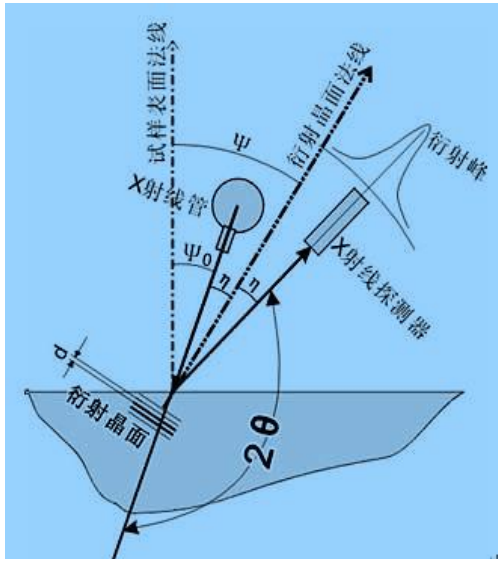
X射线在反射角方向因干涉而加强（获得衍射峰），根据这一原理即可求得d值。以不同角度入射到物体表面可测出不同方向d值，连续增大为拉应力，连续减小为压应力。

X-rays satisfying Bragg's law are strengthened by interference in the direction of the reflection angle (diffraction peaks obtained). According to this principle, the d value can be obtained.



Diffraction produced from a monochromatic light reflecting off the adjacent crystal plane

3、残余应力测量技术 Methods for RS Determination



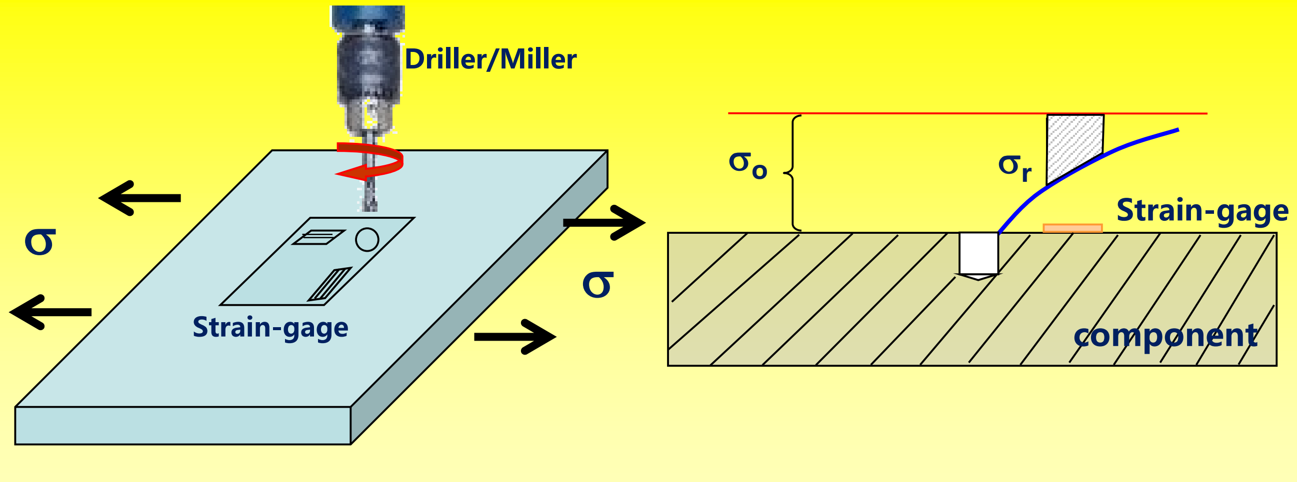
X射线衍射法具有非破坏性，较多用于测定极表层内材料的残余应力，它对被测构件表面要求较高，20μm深度内不容许引入附加应力。此方法受表面显微组织影响较大（晶粒大小、织构等），测试设备昂贵，使用灵活性较差。

XRD method is nondestructive, it is mainly applied to determine the RS in the surface layer permitting no additonal stress during surface preparetion within 20μm depth. It is affected seriously by microstructures including grain sizes and textures. On the other hand, the equipment is expensive, operation is not flexible.

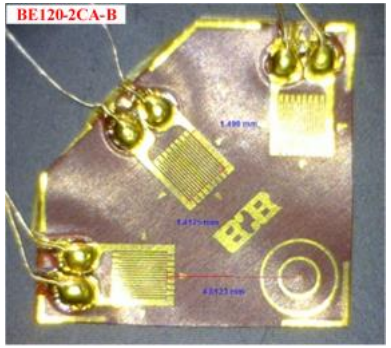
◆ 钻孔应变法（盲孔法，Hole-Drilling Strain-Gage Method）

构件表面钻Φ1.5~2.5mm盲孔（钻深不小于孔径），采用应变片测量释放应变。破坏性较小，测量精度较高，不受材料组织结构影响，是目前工程结构中比较流行的方法。美国ASTM于1973年列入相关标准（E837），我国标准为GB/T 31310。

ϕ1.5~2.5mm blind holes is drilled on the surface of the component (the depth is more than the hole diameter), and the strain gauge is used to measure the relaxed strains. The destructiveness is small, the measurement accuracy is high, and it is not affected by the microstructures. It is a popular method in the current engineering structure. ASTM listed it in the standard E837 in 1973, and the Chinese national standard is GB/T 31310.



Schematic diagram of the principle of measuring residual stress by hole-drilling method



Three-way rectangular rosette

3、残余应力测量技术 Methods for RS Determination

原始残余应力场（σ_{max}，σ_{min}）中，贴有45°三向直角应变花，钻孔后的释放应变ε_i（i=1，2，3）与残余应力的关系：In the original residual stress field (σ_{max}, σ_{min}), 45° three-direction right-angle strain-gages is attached, and the relationship between the relaxed strain ε_i and the residual stress after drilling:

$$\varepsilon_1 = A(\sigma_{max}+\sigma_{min}) + B(\sigma_{max}-\sigma_{min})\cos(-2\beta)$$

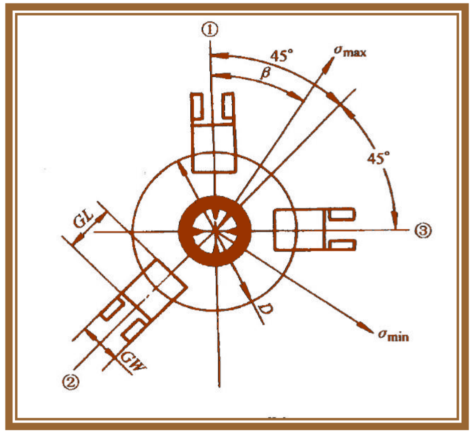
$$\varepsilon_2 = A(\sigma_{max}+\sigma_{min}) + B(\sigma_{max}-\sigma_{min})\cos(90^\circ-2\beta)$$

$$\varepsilon_3 = A(\sigma_{max}+\sigma_{min}) + B(\sigma_{max}-\sigma_{min})\cos(180-2\beta)$$

A、B称为释放系数或标定系数，是测量系统的常数。由上式可得：A and B are called calibration coefficients, which are constants of the measurement system.

$$\sigma_{max}, \sigma_{min} = \frac{\varepsilon_1+\varepsilon_3}{4A} \pm \frac{\sqrt{(\varepsilon_3-\varepsilon_1)^2+(\varepsilon_3+\varepsilon_1-2\varepsilon_2)^2}}{4B}$$

$$\beta = \frac{1}{2}\arctan\frac{2\varepsilon_2-\varepsilon_3-\varepsilon_1}{\varepsilon_1-\varepsilon_3}$$



3、残余应力测量技术 Methods for RS Determination

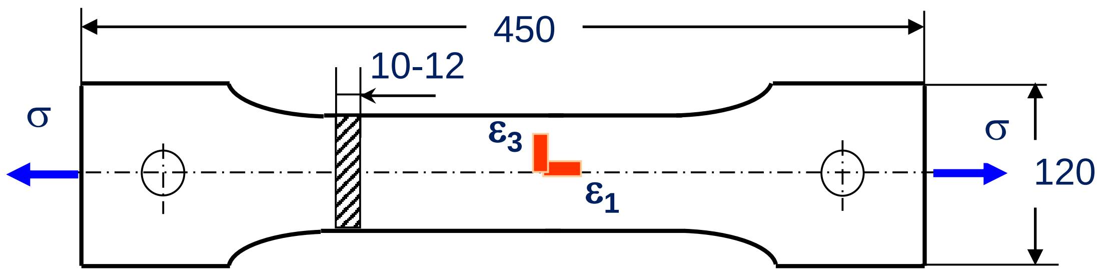
■ **系数A、B可由计算或实验方法标定得到**

The coefficients A&B may be achieved by the calculation or experimental coliberation.

■ **高应力场或低速钻孔下推荐采用实验标定**

It is better to achieve the coefficients A&B by experimental coliberation than calculation under high-level stress field or adopting low speed drilling.

$$A = \frac{\Delta\varepsilon_1 + \Delta\varepsilon_3}{2\sigma} \qquad B = \frac{\Delta\varepsilon_1 - \Delta\varepsilon_3}{2\sigma}$$



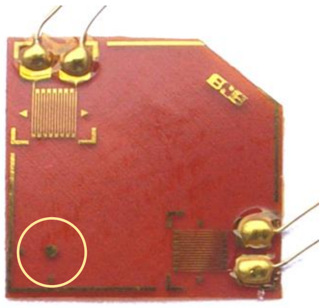
3、残余应力测量技术 Methods for RS Determination

可直接使用双向应变花测定X、Y方向的残余应力，此时需将应变栅1和应变栅3沿X方向和垂直X方向粘贴，按如下公式计算：

The biaxial rectangular rosette may be applied directly to the determination of RS along the defined direction X and Y, as following formula:

$$\sigma_x = \frac{\varepsilon_1(A+B) - \varepsilon_3(A-B)}{4AB}$$

$$\sigma_y = \frac{\varepsilon_3(A+B) - \varepsilon_1(A-B)}{4AB}$$



3、残余应力测量技术 Methods for RS Determination

- 盲孔法测定残余应力的2个误差来源：孔边应力集中造成的塑性变形；刃具切削产生的加工应变。

There are two error sources for the drilling hole method to determine residual stress: plastic deformation caused by stress concentration at the edge of the hole; machining strains caused by cutting of the tool.

- 残余应力超过60%σ_y时，开始出现误差。残余应力达到σ_y时，由孔边塑变引起的误差达到10%左右。

When the residual stress exceeds 60%σy, error begins to appear. When the residual stress reaches σy, the error caused by the plastic deformation of the hole edge reaches about 10%.

- 加工应变引起的误差与制孔方法有关：40万转/分的超高速磨头，加工应变可以忽略。低转速麻花钻头或铣刀的加工应变较大，同时与残余应力水平有关。残余应力越大，加工应变也越大，且与释放应变同号。

The error caused by the machining strain is related to the hole-making method: The machining strain may be ignored for the ultra-high-speed grinding head of 400,000 rpm. The machining strain from a low-speed twist drill or milling cutter is relatively large, which is also related to the level of residual stress. The greater the residual stress, the greater the machining strain.

3、残余应力测量技术 Methods for RS Determination

◆ 全释放应变法 (Sectioning relaxation strain-gage method)

破坏性方法，通过截面切割使残余应力得以全部释放而测出二维或三维应力。测量原理简单，精度较高，常作为其它方法的对比验证。A kind of destructive method, the residual stress can be fully relaxed by sectioning and 2D or 3D stress measured. The principle is simple and the accuracy is high, and it is often used as a comparative verification of other methods.

1）切条法（Slitting method for two-dimensional stress determination)

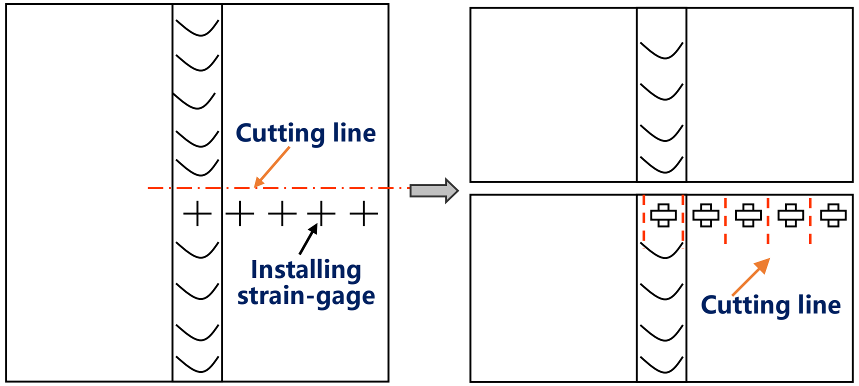
$$\sigma_x = -\frac{E}{1-\mu^2}(\Delta\varepsilon_x + \mu\Delta\varepsilon_y)$$

$$\sigma_y = -\frac{E}{1-\mu^2}(\Delta\varepsilon_y + \mu\Delta\varepsilon_x)$$

$$\sigma_{\max}, \sigma_{\min} = -\frac{E}{2}\left[\frac{\Delta\varepsilon_1 + \Delta\varepsilon_3}{1-\mu} \pm \frac{\sqrt{(\Delta\varepsilon_3 - \Delta\varepsilon_1)^2 + (\Delta\varepsilon_3 + \Delta\varepsilon_1 - 2\Delta\varepsilon_2)^2}}{1+\mu}\right]$$

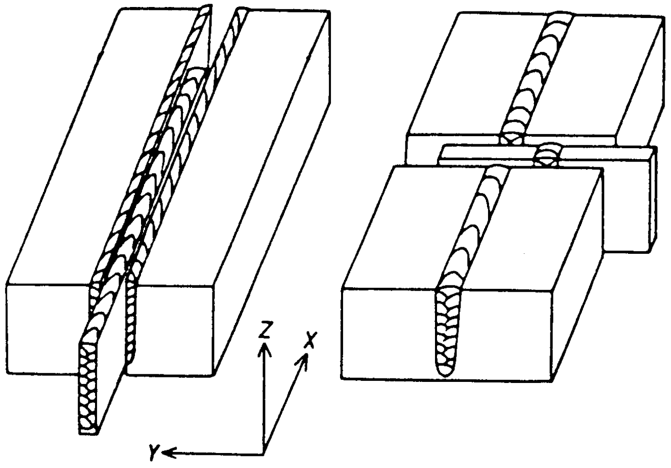
$$\beta = \frac{1}{2}\arctan\frac{\Delta\varepsilon_3 + \Delta\varepsilon_1 - 2\Delta\varepsilon_2}{\Delta\varepsilon_3 - \Delta\varepsilon_1}$$

需要注意：切割时应力释放是整个截面上的平均结果，如果切块内应力梯度较大，还需厚度减薄。The stress relaxed is the average result on the entire section. If the stress gradient in the block is large, the thickness must be reduced.



2）R-N切割法（R-N method for three-dimensional stress determination)

为测定三向应力，原方法需要准备两块同样试板：一块沿焊缝轴向切取纵向薄片，一块沿垂直焊缝方向切取横向薄片。切割纵向（或横向）薄片前，先在上下表面粘贴应变片，因在X轴（或Y轴）方向应变变化近似线性，有：

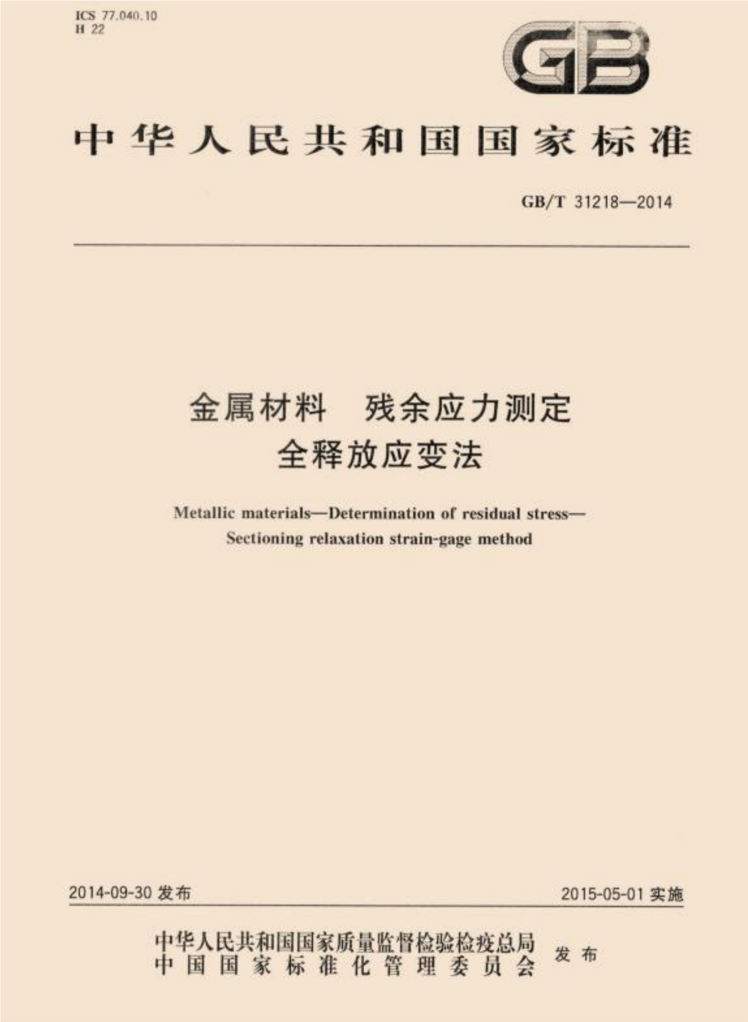


In order to measure the three-dimensional stress, the original method needs to prepare two identical test plates: one to cut the longitudinal slice along the weld axis, and the other to cut the transverse slice along the vertical weld direction. Before cutting the longitudinal (or transverse) slat, install the strain gauges on the upper and lower surfaces first, the strain change in the X-axis (or Y-axis) direction is approximately linear：

$$\Delta\sigma_x = E\{\Delta\varepsilon_{xB} + (\Delta\varepsilon_{xT} - \Delta\varepsilon_{xB})Z/h\} + \mu(\sigma_y + \sigma_z)$$

再在板条的中间截面上粘贴应变片，即在纵向薄片上水平贴测纵向应力的单向应变片，在横向薄片贴测横向应力和厚度方向应力的单向应变片，然后分割大小。Then install the strain gauge on the middle section of the slat：the strain gauge for measuring the longitudinal stress horizontally on the longitudinal slat, and the strain gauge for measuring the transverse stress and the stress in the thickness direction on the transverse sheet, and then dividing it.

3、残余应力测量技术 Methods for RS Determination



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GB/T 31218—2014

金属材料　残余应力测定
全释放应变法

Metallic materials—Determination of residual stress—
Sectioning relaxation strain-gage method

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中华人民共和国国家质量监督检验检疫总局
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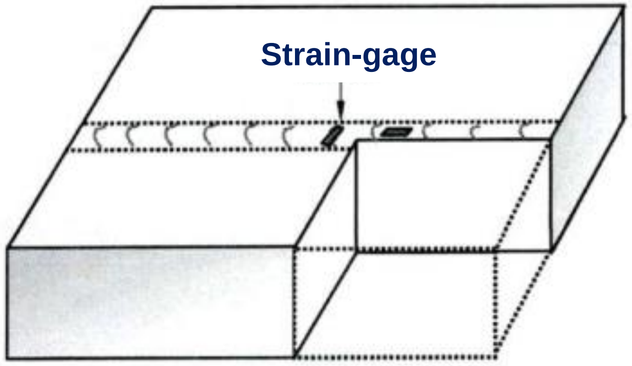
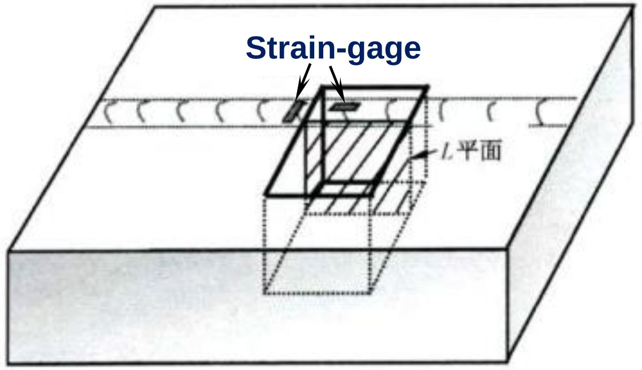


Use a single test plate to detect three-dimensional stress

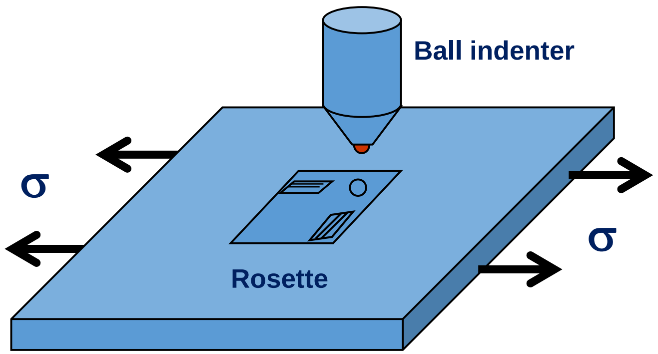


A improving method using a single test plate to detect three-dimensional stress

◆ 压痕应变法（Indentation strain-gage method）

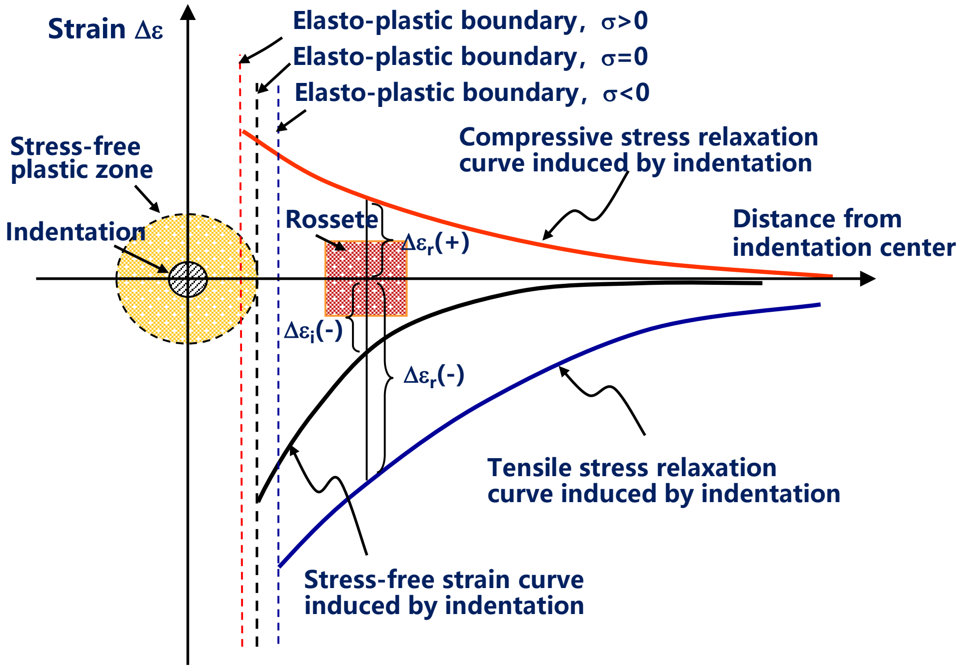
90年代金属所独立研究压痕应变法的特点和工程实用性，开发了相应设备，编制了国家标准。

用冲击加载制造压痕，应变花记录压痕外弹性区应变增量变化。表明：球形压痕产生的应变增量与应力场中的弹性应变成正比（三次方）。



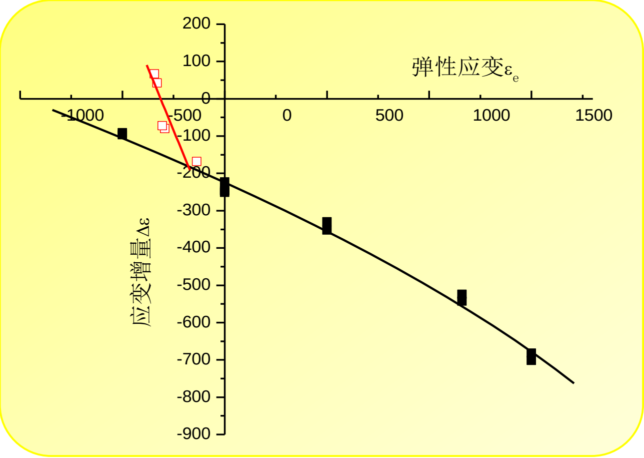
In the 1990′s, the IMR independently studied the feature and engineering practicability of the indentation strain method, developed related equipment, and compiled national standard.

The indentation made by impact loading and strain change recorded by strain rosette installed in the elastic zone outside the indentation, it shows that the strain produced by the ball indentation is proportional to the elastic strain in stress field.



3、残余应力测量技术 Methods for RS Determination

确定不同材料的应力计算函数时，可采用如右图所示的方式在一系列应力条件下，固定能量打击压痕后获得对应材料的应变增量Δε-弹性应变ε_e的关系曲线，按三次方拟合方程。



应力测试时，利用标定获得的三次方应力计算函数，求得残余应变（ε_x、ε_y），按胡克定律计算沿应变片方向的原始残余应力:

$$\sigma_x = \frac{E}{1-\nu^2}(\varepsilon_x + \nu\varepsilon_y)$$

$$\sigma_y = \frac{E}{1-\nu^2}(\varepsilon_y + \nu\varepsilon_x)$$

When determining the stress calculation function of different materials, the method shown on the right figure can be used to obtain the strain increment Δε—elastic strain ε_e relationship curve of the material under a series of stress conditions with a fixed energy. The equation should be fitted as cubic relation.

In the stress measurement, use the cubic stress calculation function obtained by calibration to obtain the residual strain (ε_x and ε_y), and calculate the original residual stress along the direction of the strain gauge according to Hooke′s law.

3、残余应力测量技术 Methods for RS Determination

Type KJS–3

Type KJS–3P

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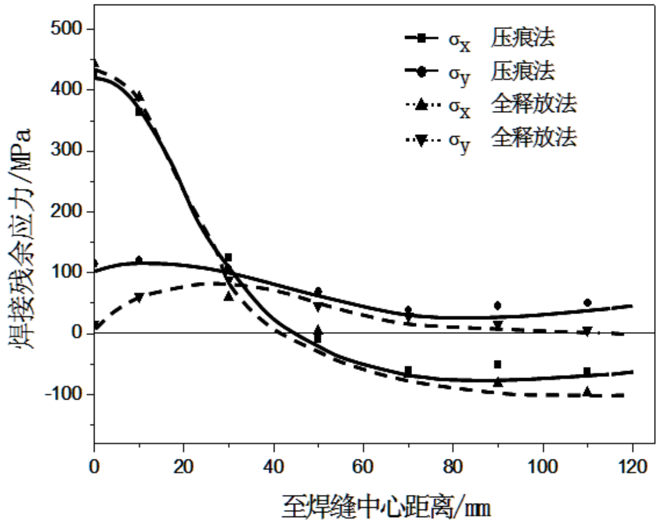
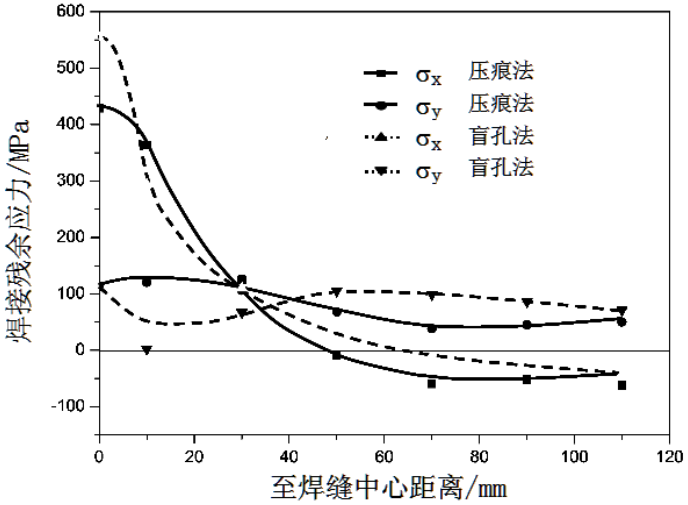




Biaxial tensile testing machine

Comparing biaxial tensile results with indentation strain-gage method

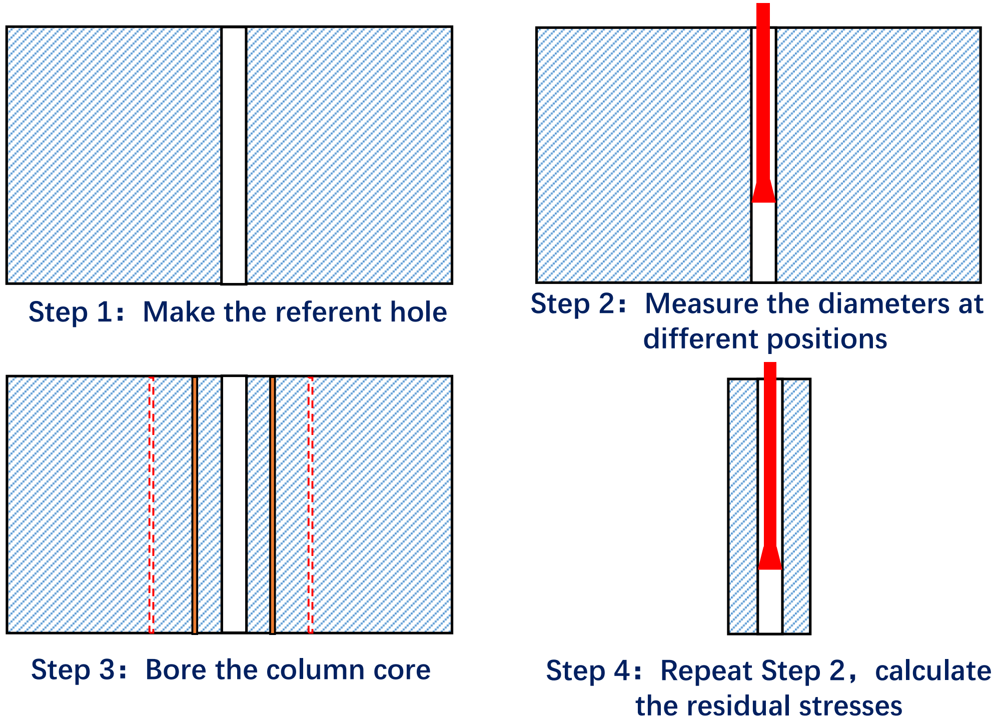
Test Point	Biaxial tensile result			Indentation strain-gage mehtod	
	Load ratio Fx/Fy, kN	Dislpay strain εx/εy	Related stress ratio σx/σy, MPa	Measued strain Δεx/Δεy	Measured stress ratio σx/σy, MPa
1	39.2/39.2	382/413	113/119	-242/-253	103/109
2	44.8/44.8	657/547	185/167	-303/-307	164/166
3	50.0/46.0	828/767	234/228	-307/-368	208/218
4	44.8/22.4	799/259	199/110	-337/-231	171/111
5	50.0/30.0	743/459	199/152	-350/-271	190/148

3、残余应力测量技术 Methods for RS Determination

◆ DHD深孔法（Deep-Hole Drilling Method）

开发了低成本、高精度深孔法——一种局部损伤的应变释放方法，通过测量套孔前后测孔直径变化，计算应变释放量，利用柔度矩阵计算相应的残余应力。

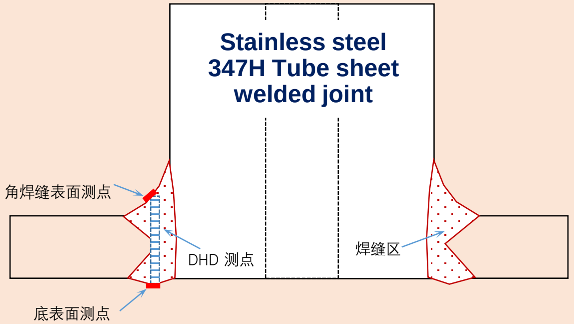
Developed a low-cost, high-precision Deep-Hole Drilling method — a strain relief method for local damage. By measuring the diameter change of the hole before and after the trepanning, the value of strain relief is calculated, and the corresponding residual stress is calculated by the flexibility matrix.

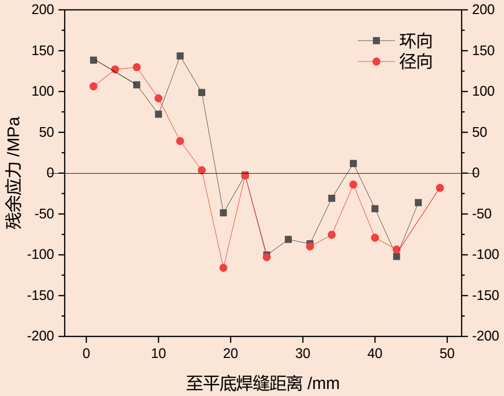


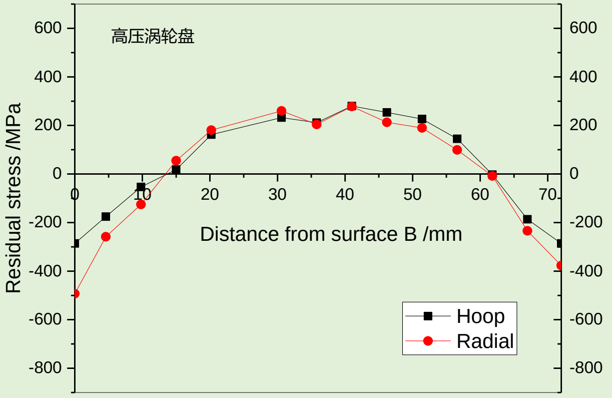
$$\begin{bmatrix} \varepsilon(\theta_0, z_i) \\ \varepsilon(\theta_{45}, z_i) \\ \varepsilon(\theta_{90}, z_i) \end{bmatrix} = -\frac{1}{E} \begin{bmatrix} 3 & -1 & 0 \\ 1 & 1 & 4 \\ -1 & 3 & 0 \end{bmatrix} \begin{bmatrix} \sigma_x(z_i) \\ \sigma_y(z_i) \\ \sigma_{xy}(z_i) \end{bmatrix}$$

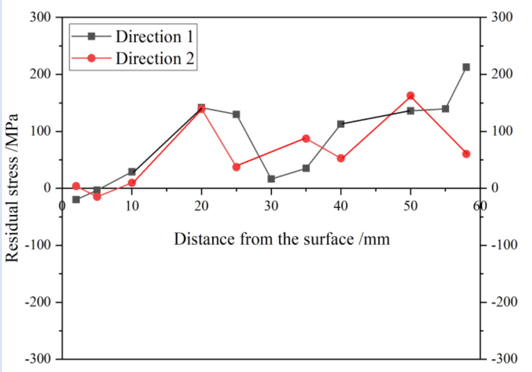
$$\varepsilon(\theta_k, z_i) = \frac{c(\theta_k, z_i) - c_0(\theta_k, z_i)}{c_0(\theta_k, z_i)}$$

3、残余应力测量技术 Methods for RS Determination









4、残余应力数值模拟 Simulation of RS

残余应力的数值模拟是一项重要技术，可以针对不同加工工艺进行全场、瞬态和残留应力状态进行分析，是实验方法的重要补充。影响模拟精度的因素很多，例如材料的物理性能随温度的准确变化，对于焊接接头来说尤为重要。

课题组采用独有的仪器化压入技术，可以获得焊接接头不同区域，包括焊核、热影响区和母材的实际力学性能，进而可以完成残余应力场的精确模拟。

The simulation of residual stress is an important way, which may analyze the whole field, transient state and residual state of stress for different processing, being is an important supplement to the experimental method. There are many factors affecting the accuracy of the simulation. For example, the exact change of material physical properties with temperature is important for welded joint.

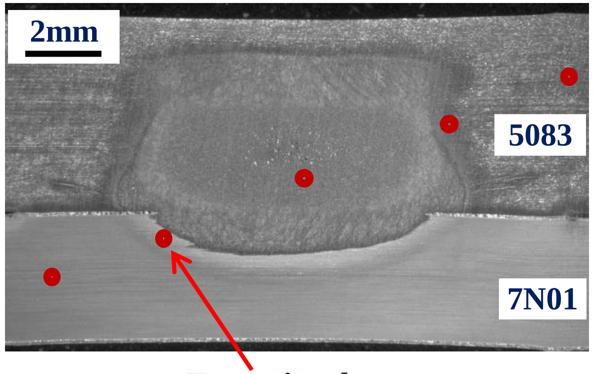
The Lab applied a unique instrumented indentation technology to obtain the actual mechanical properties of different areas of the welded joint, including the nugget, heat-affected zone （HAZ） and base metal, and then realized the accurate simulation of the residual stress field.

4、残余应力数值模拟 Simulation of RS

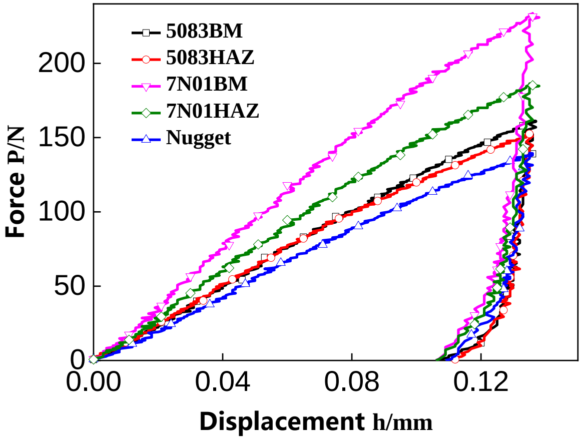
—— 异种不等厚铝合金点焊接头残余应力精确模拟介绍

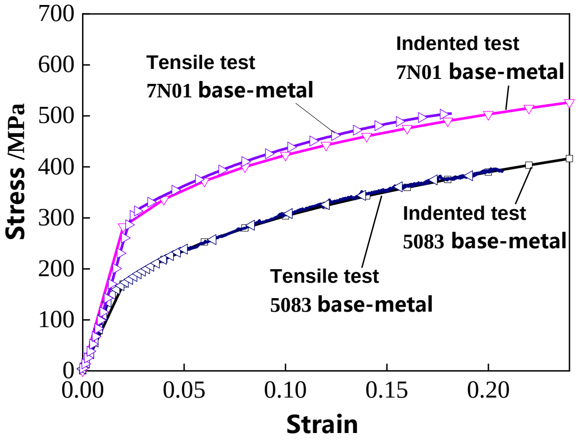
Accurate simulation of residual stress in spot welded joints of dissimilar aluminum alloys with unequal thickness

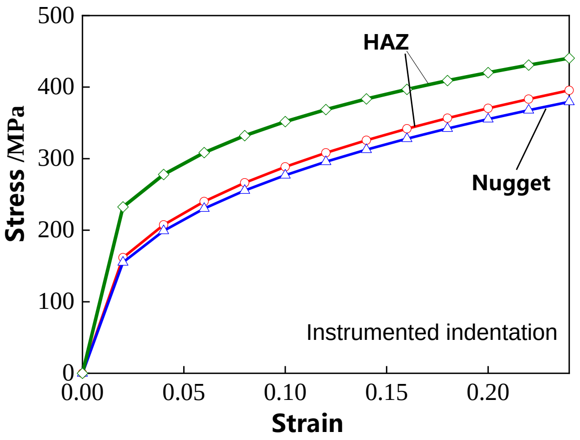
Type IBIS-3 mechanical property tester based on instrumented indentation technique



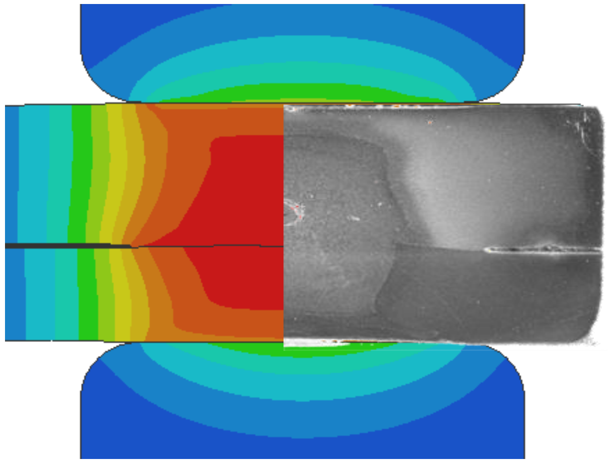
Test points by instrumented indentation



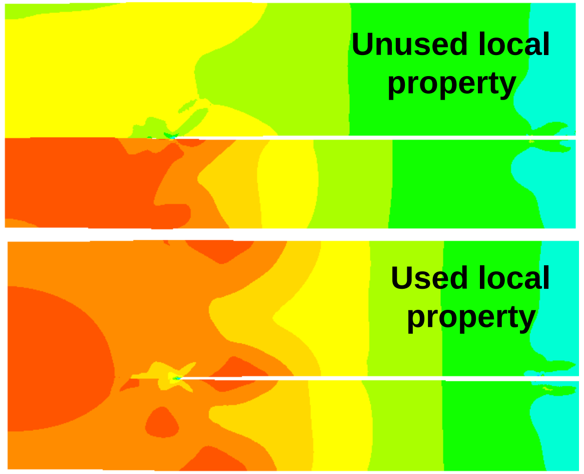




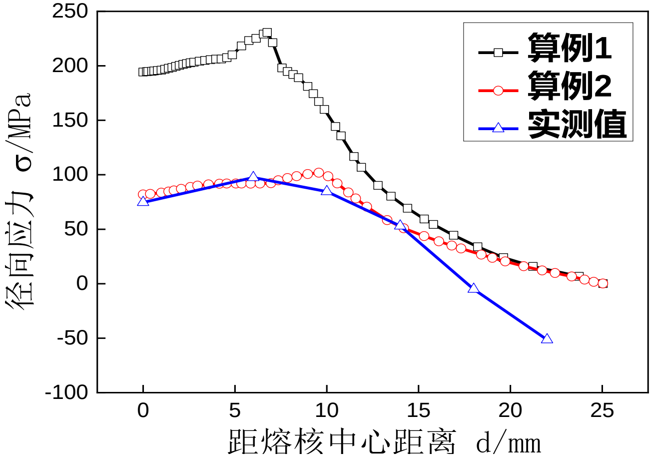
4、残余应力数值模拟 Simulation of RS

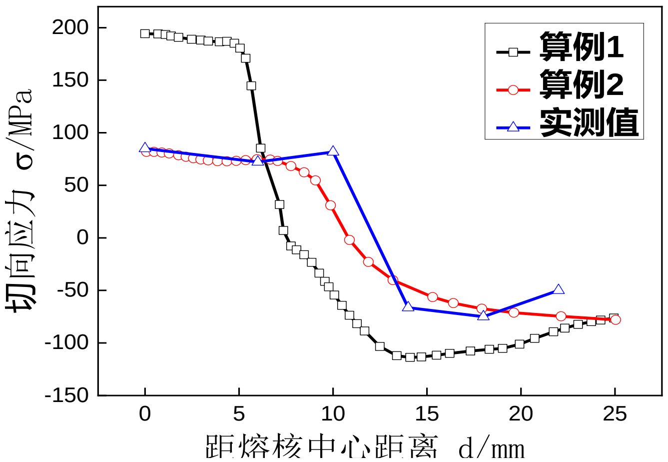


Spot welding model



Nephogram of radial stress



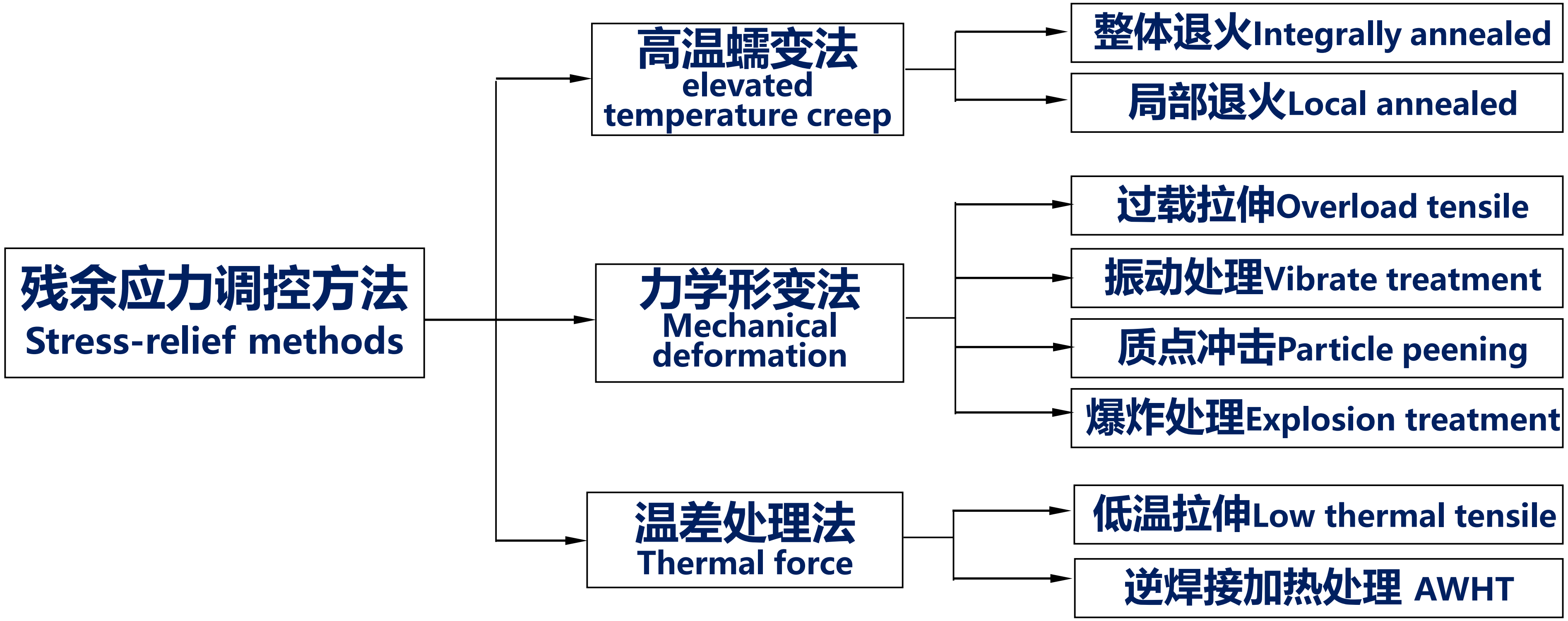


Residual stress distribution：case 1：Unused local property；case 2：Used local property；measuring method：sectioning relaxation

5、残余应力调控技术 Stress-relief techniques

从经济性和可行性考虑，一般只对特殊场合下的重要产品提出应力调控需求，如在腐蚀或疲劳环境下，或工作在低温下且材料厚度达到一定数值。

From economic and feasibility, stress-relief requirement is generally only proposed for important products under special occasions, such as in corrosive or fatigue environment, or working at low temperature with a heavy section.



◆ 热处理（Heat Treatment，HT/PWHT）

（焊后）热处理为传统方法（消除应力效果整体80%，局部30%）。除部分有特殊要求的部件采用调质处理，奥氏体不锈钢采用固溶处理外，大部分材料的热处理是指退火处理。PWHT后可能发生：

（1）残余应力松弛Stress relaxation；
（2）组织结构和力学性能发生相应变化Changes in microstructures and properties；
（3）减少扩散氢含量（焊接接头）Reduction in diffusion H (welded joint)；
（4）消除应变时效脆化Elimilate strain-age brittlement；
（5）产生变形Deformation produced；
（6）高温应变脆化 High-temperature strain brittlement；
（7）合金元素偏析脆化Brittlement produed by alloy element segregation；
（8）热应力裂纹Cracking indued by thermal stress；
（9）再热裂纹Reheat cracking。

5、残余应力调控技术 Stress-relief techniques

不同材料焊后热处理消除应力特点
PWHT feature for different materials

铸铁Cast iron
低碳钢Mild steel
C-Mn钢C-Mn steel

- T=550~650°C
- δc≥38mm(B.F.)
- Possibly decrease in strength

调质高强钢
High-strength Q&T steel

- T<Temper Tem.
- δc≥32mm(B.F.)
- Decrease in strength, brittlement

奥氏体不锈钢
Austenite stainless steel

- T ≥850~900°C
- SCC is main problem
- Usually no application

异种钢(复合板)
Dissimilar steel (clad plate)

- SCC is main problem
- No obvious effect

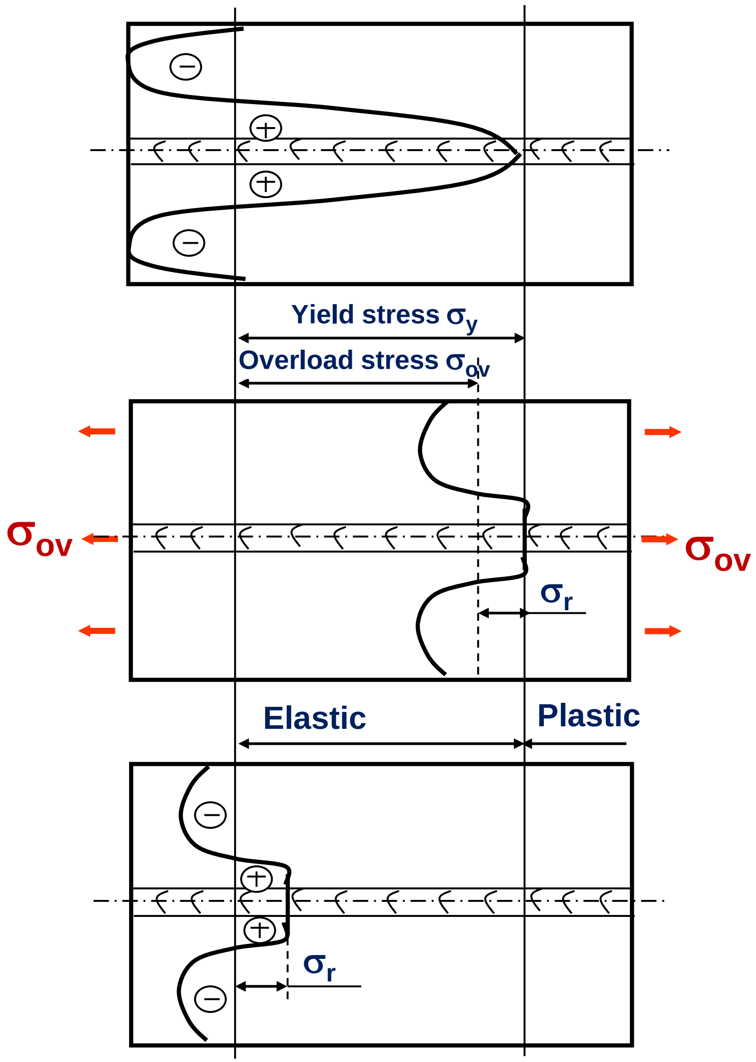
5、残余应力调控技术 Stress-relief techniques

◆ 过载拉伸处理（Overload Tensile Treatment）

有机械拉伸、机械碾压、水压过载等工艺。过载消除应力效果取决于过载应力水平σ_{ov}，过载后剩余的应力σ_r为：

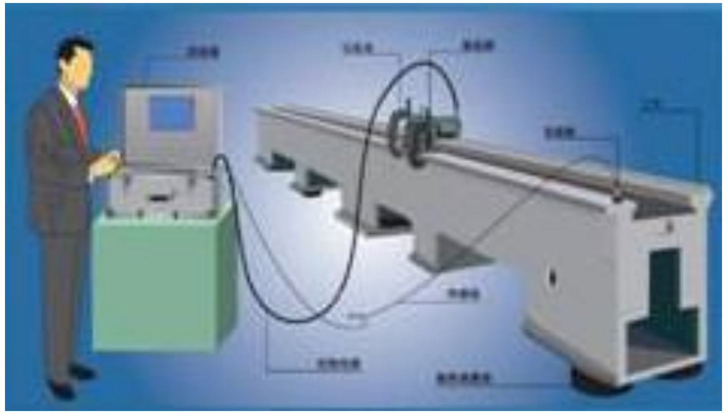
$$\sigma_r=\sigma_y-\sigma_{ov}$$

Overload tensile treatment includes such as mechanical stretching, mechanical rolling, and hydraulic overload. The effect of overload stress-relief depends on the overload stress level σ_{ov}, the residual stress σ_r after the overload is $\sigma_y-\sigma_{ov}$.



Schematic diagram of stress relief by overload tensile treatment

◆ 振动消除残余应力处理（Vibrate Stress-Relief Treatment，VSR）



激振器使结构产生一个或多个共振或亚共振并持续一定时间实现应力降低的方法。共振后结构共振频率下降，振幅提高。振动引起的动应力和残余应力叠加超过材料屈服点时产生应力松弛。

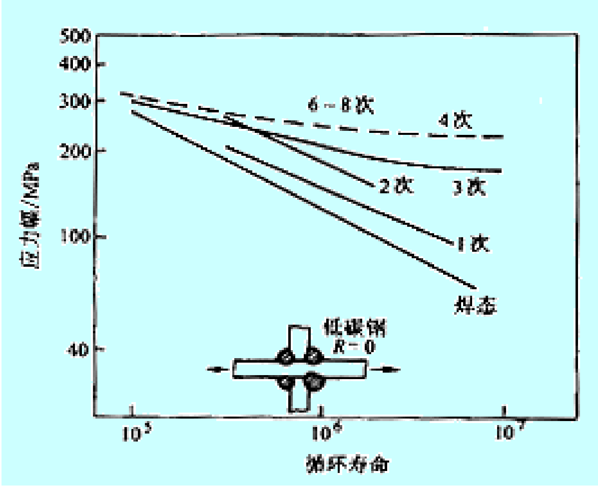
VSR处理的成本约为热处理的10%，能源消耗为热处理的1%。由于消应效果的局限性，主要用途还是稳定构件尺寸。

The vibration exciter makes a structure produce one or more resonances or sub-resonances for a certain period of time to achieve stress reduction. After resonance, the resonance frequency of the structure decreases and the amplitude increases. When the superposition of dynamic stress and residual stress caused by vibration exceeds the yield point of the material, the stress relaxation occurs.
The cost of VSR treatment is about 10% of heat treatment, and energy consumption is 1% of heat treatment. Due to the limitation of the effect, its main application is to stabilize the size of the component.

◆ 质点冲击处理（Particle Peening Treatment）

用锤头或高速粒子（喷丸）冲击工件表面，或用超声冲击工具打击工件表面，可在表面形成塑性变形层，引入压缩残余应力。锤击能有效提高结构抗疲劳能力，但可控程度低，可能引入微裂纹、产生应变脆化等。喷丸对提高抗疲劳能力非常有效，并有较好的质量可控性，在解决疲劳问题中得到更多应用。超声冲击操作方便、灵活，处理范围可控，压应力层较薄。

The surface of a workpiece is impacted with a hammer or high-speed particles (shot peening), or hit the surface with an ultrasonic impact tool, which can form a plastic deformation layer on the surface and introduce compressive residual stress. Hammering can effectively improve the fatigue resistance of the structure, but the controllability is low, and it may introduce micro-cracks and strain embrittlement. Shot peening is very effective in improving fatigue resistance, and has better quality controllability, and it has been used more in solving fatigue problems. The ultrasonic impact is convenient and flexible, and the compressive stress layer is thin.



The effect of shot peening times on fatigue life

Application of Ultrasonic peening on the vessel

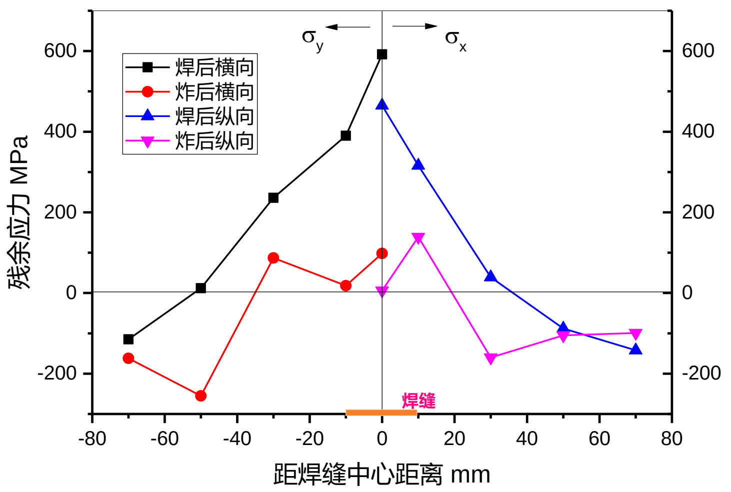
◆ 爆炸消除应力处理 （Local Explosion Treatment）

通过固定在焊缝附近炸药的掠过爆轰造成的冲击波和残余应力的交互作用，使金属内部较大深度产生微观塑性形变，达到消除应力目的。爆炸处理具有显著的消除焊接残余应力效果，方法简便灵活。已在数百件大中型结构上获得使用。国家标准为GB/T 26078。

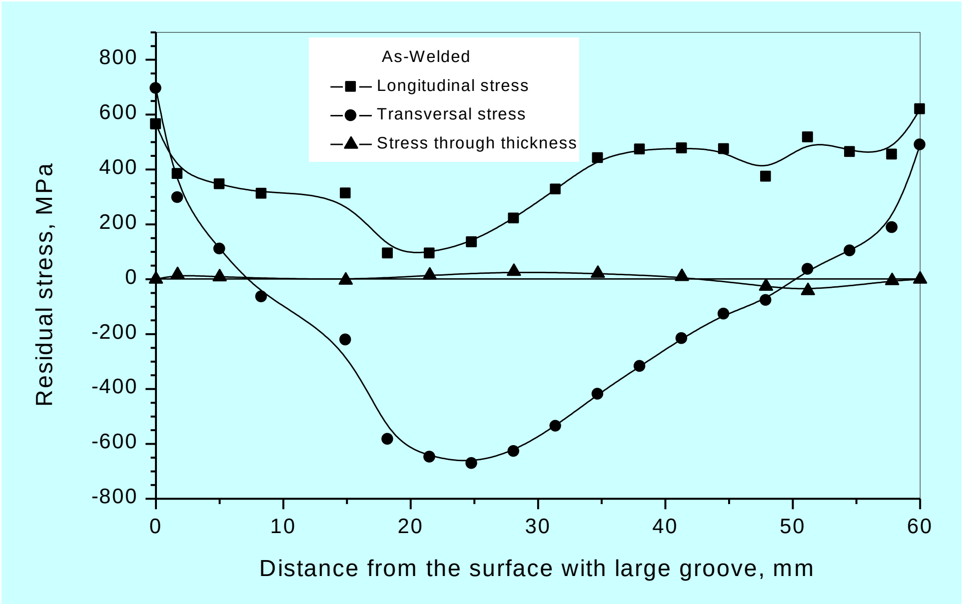
Explosive layout photo of welding test plate

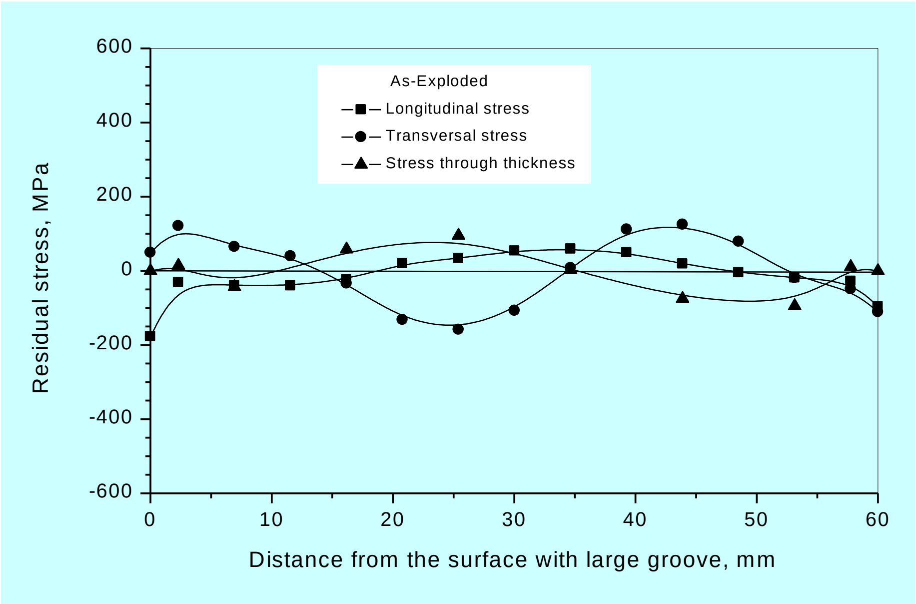
Through the interaction of the shock wave and residual stress caused by the detonation by the explosive installed on the welded joint, a large depth of microscopic plastic deformation is generated inside the metal, then the purpose of stress-relief is achieved. Explosive treatment has a significant effect of eliminating welding residual stress, and the method is simple and flexible. It has been used in hundreds of large and medium-sized welded structures. The national standard is GB/T 26078.

5、残余应力调控技术 Stress-relief techniques



Three-dimentional RS distribution before and after explsion treatment in 60mm thick HSLA weldment





5、残余应力调控技术 Stress-relief techniques

催化裂化装置反应塔爆炸处理
Explosive treatment of reactors for the catalyse-cracking facility

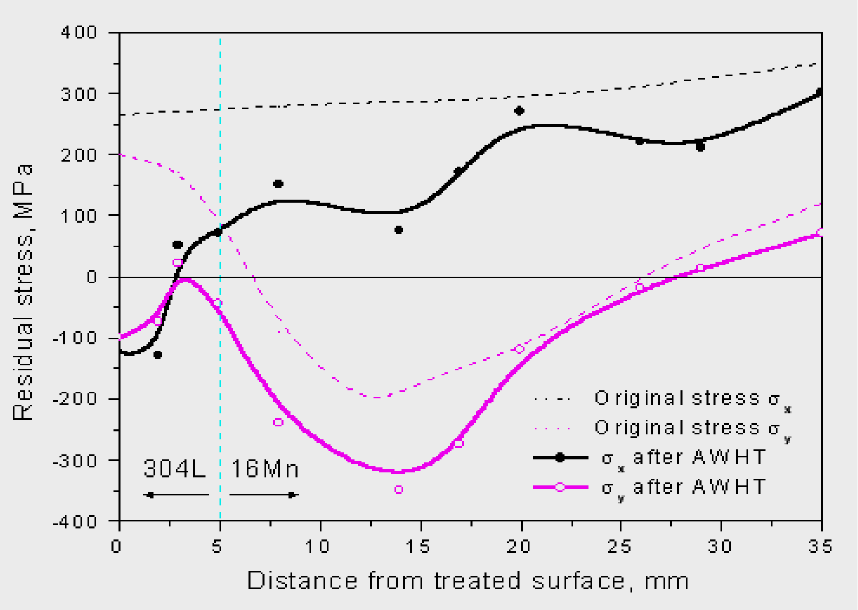
三峡工程压力钢管(**ϕ12.4m**×**60mm)**爆炸处理
Penstocks of the Three-Gorges Project

5、残余应力调控技术 Stress-relief techniques

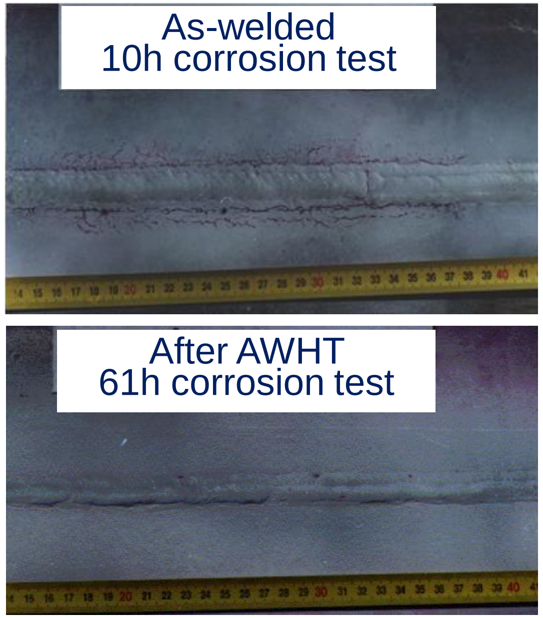
◆ 逆焊接加热处理(Anti-Welding Heating Treatment，AWHT)

与焊接加热相反，采用冷却介质使处理区获得比相临区低的负温差，造成该区冷却收缩产生伸长塑性形变，达到消除应力目的，甚至形成双向压应力。彻底解决不锈钢复板容器的SCC问题。

Contrary to welding heating, the cooling medium is used to produce a negative temperature difference in the treatment area than the adjacent area, which causes the cooling and shrinkage of this area to produce elongation plastic deformation, achieving the purpose of eliminating stress and even forming two-way compressive stress. SCC problem of stainless steel composite plate containers can be solved thoroughly.



The distribution of RS before and After AWHT

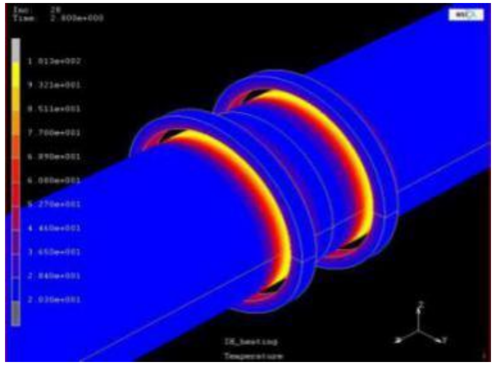


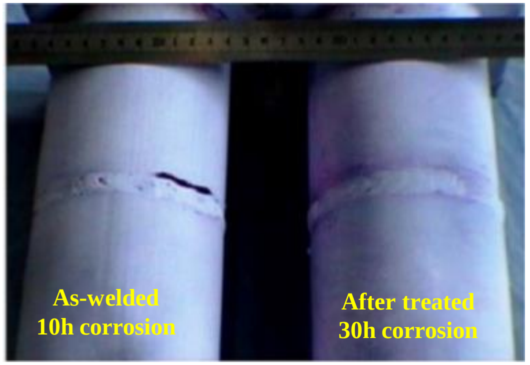
Corrosion test results before and After AWHT

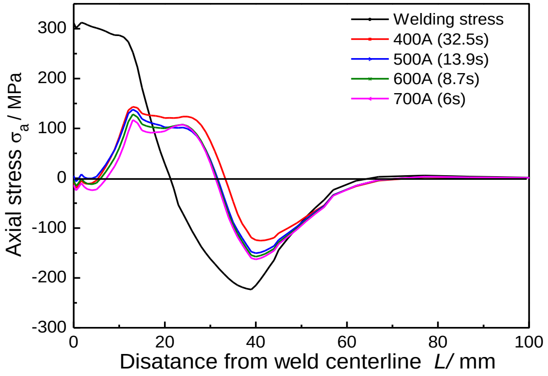
◆ 小径管温差处理 (Thermal-difference Treatment for tubes)

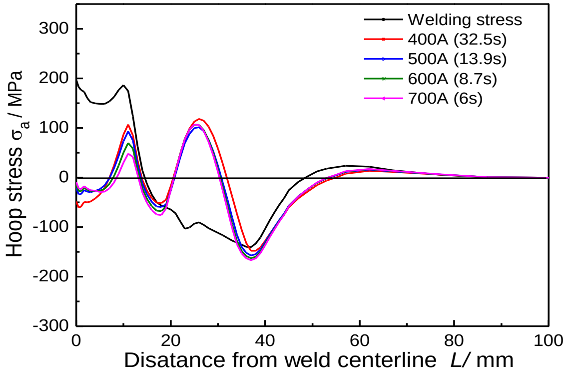
利用小径管环向焊缝残余应力形成特点，采用压应力区感应加热膨胀工艺拉伸收缩焊缝，达到降低焊缝应力的目的，彻底解决小径管腐蚀泄漏的难题。

Utilizing the characteristics of the formation of residual stress in the circumferential weld of small diameter pipes, the compression stress zone induction heating expansion process is used to stretch the weld to achieve the purpose of reducing weld stress. It completely solves the problem of corrosion leakage of tubes.









Thank you
for your attention!