Aalto University
School of Engineering

MEC-E8006 Fatigue of Structures

Lecture 9: Influence of residual stresses

Course contents

Week		Description
43	**Lecture 1-2**	**Fatigue phenomenon and fatigue design principles**
	Assignment 1	Fatigue Damage process, design principle and Rainflow counting – dl after week 43
44	**Lecture 3-4**	**Stress-based fatigue assessment**
	Assignment 2	Fatigue life estimation using stress-based approach – dl after week 44
45	**Lecture 5-6**	**Strain-based fatigue assessment**
	Assignment 3	Fatigue crack initiation life by strain-based approach – dl after week 46
46	**Lectures 7-8**	**Fracture mechanics -based assessment**
	Assignment 4	Fatigue crack propagation life by fracture mechanics – dl after week 46
47	**Lectures 9-10**	**Fatigue assessment of welded structures and residual stress effect**
	Assignment 5	Fatigue life estimation of welded joint – dl after week 48
48	**Lecture 11-12**	**Multiaxial fatigue and statistic of fatigue testing**
	Assignment 6	Fatigue life estimation for multiaxial loading and statistical analysis – dl after week 48
49	**Exam**	**Course exam**
	Project work	Delivery of final project (optional) – dl on week 50

Assignment are delivered in pdf format using MyCourse and the following naming ***AssignmentNumber_FirstName_Surname.pdf.***

Learning outcomes

After the lecture, you

- *understand* the reasons for residual stresses
- *understand* the effect of residual stress on fatigue strength
- *can* define the affecting mechanics

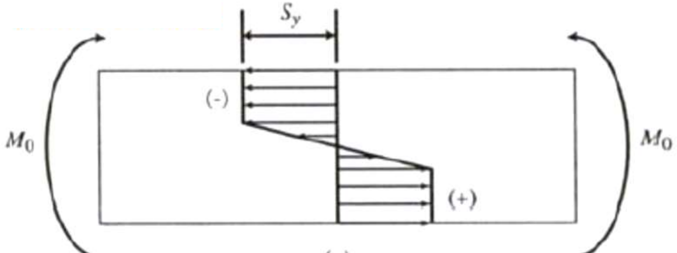
Contents

- Residual stress and their influence on fatigue strength
- Methods inducing residual stresses
- Residual stress in welded joints
- Determination of residual stress and its consideration in fatigue analysis

Definition of residual stresses

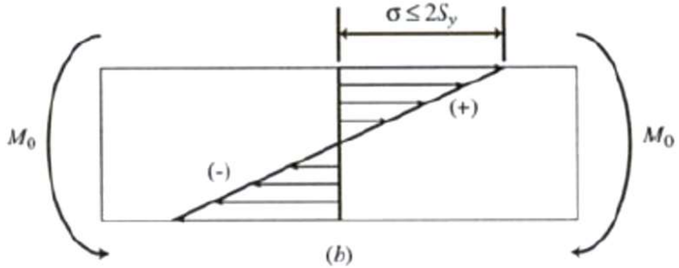
Case example: Plate inelastic bending

Stress distribution during inelastic bending; positive moment is applied so that upper and lower surface yield



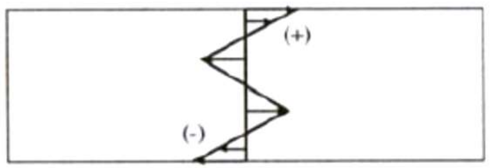
(a)

Elastic spring back stress distribution; elastic recovery during unloading



(b)

The sum of the inelastic and elastic spring back stress distribution; plate has zero external load, and self-equilibrating ***residual* stresses** (ΣM=0, Σ F=0)

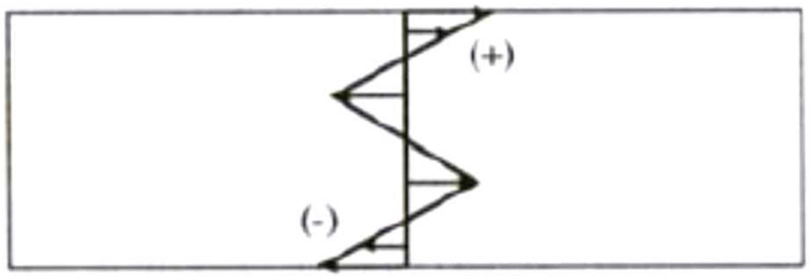


(c)

Definition of residual stresses

Residual stresses are in equilibrium within a part, without any external load

- They are called residual stresses because they remain from a previous operation
- Residual stresses exist in most manufactured parts

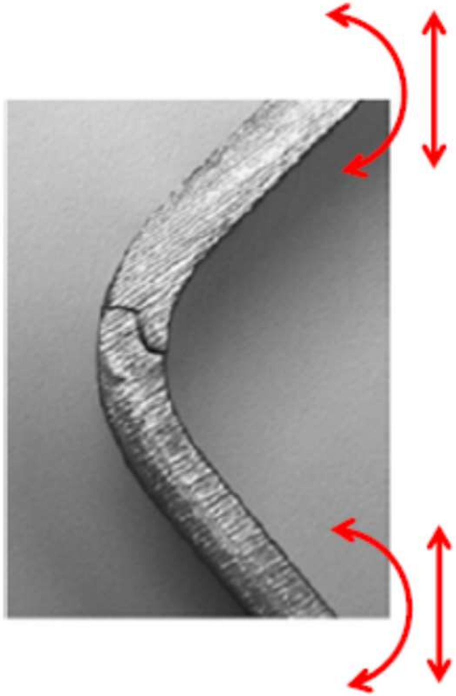


(c)

Influence of residual stresses

In fatigue, residual stresses influence on

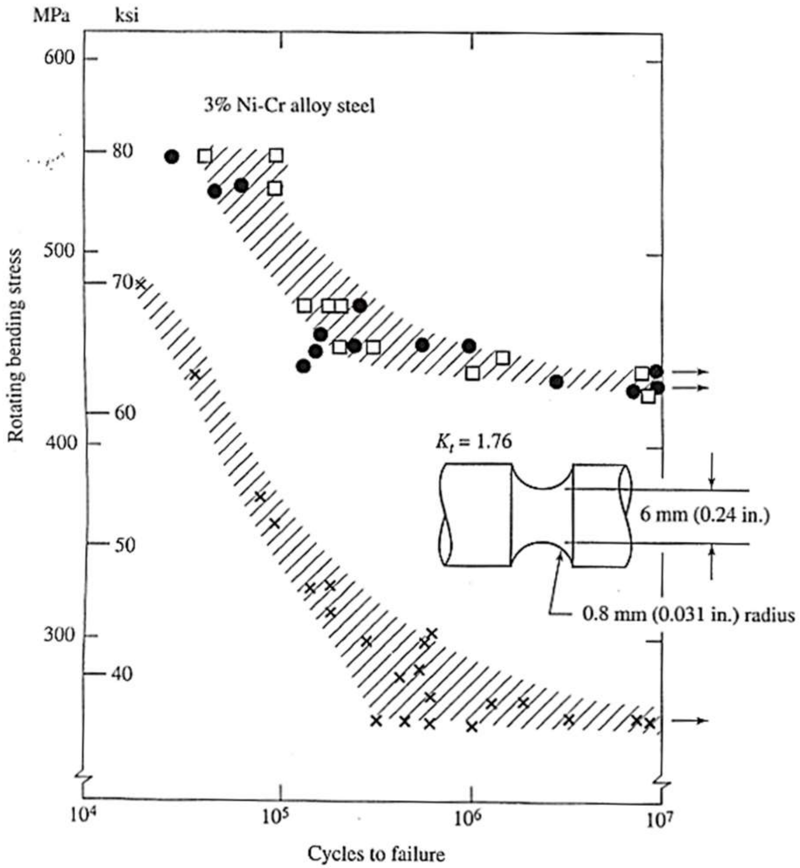
- the number of cycles needed to form a crack,
- the growth rate of cracks, and
- the direction of crack propagation



Positive or negative

Influence of residual stresses

Example: Ni-Cr alloy steel (rotating bending)



Three different surface conditions

(●) Smooth

(x) Notched

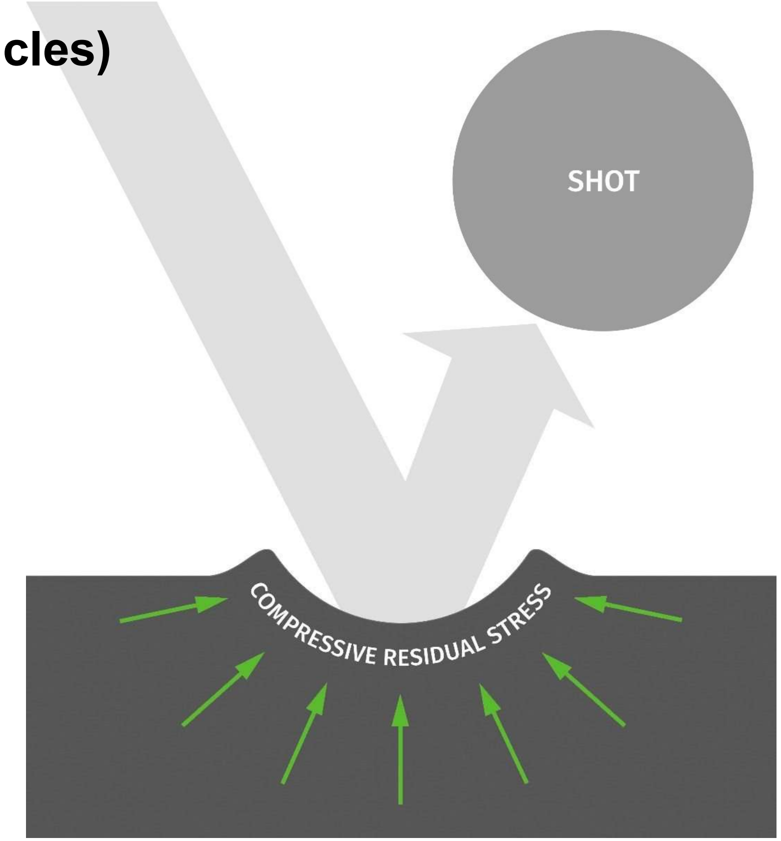
(□) Notched shot-peened

Fatigue resistance of notched shot-peened specimens is similar to that of smooth specimens

- The notch became harmless after shot-peening due to the residual compressive stresses

Influence of residual stresses

Shot-peening
Cold working process
(round metallic, glass or ceramic particles)



Methods inducing residual stresses

Methods, which induce residual stresses, can be divided into four main groups:

– Mechanical methods

– Thermal methods

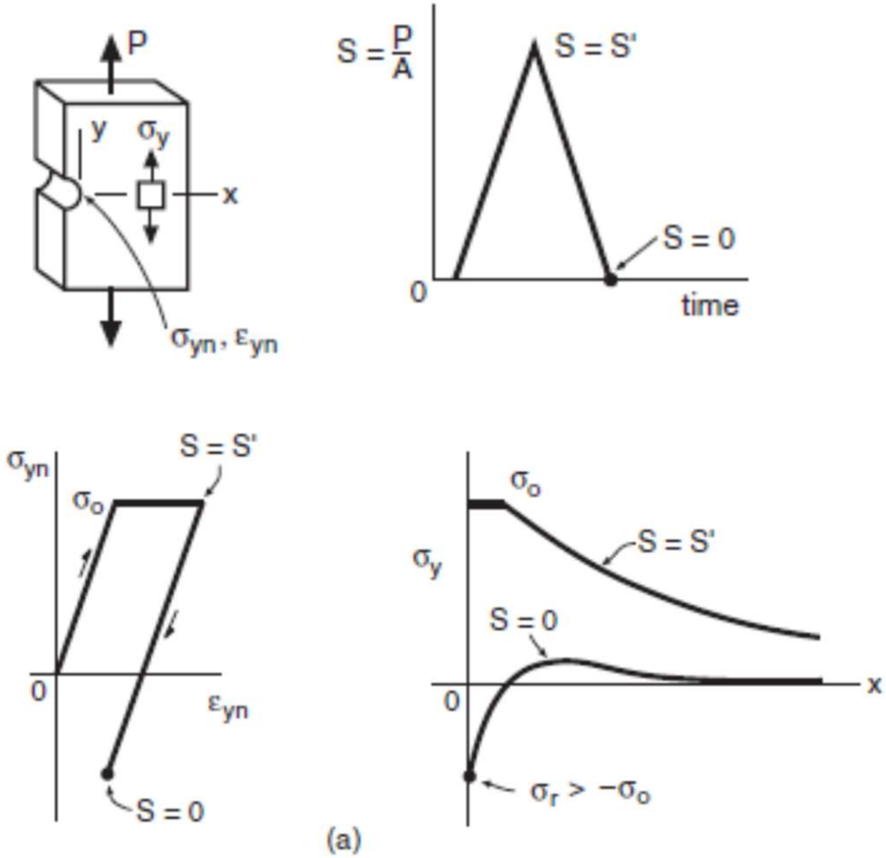
– Plating

– Machining

Methods inducing residual stresses

Mechanical methods

External load produces inelastic deformation

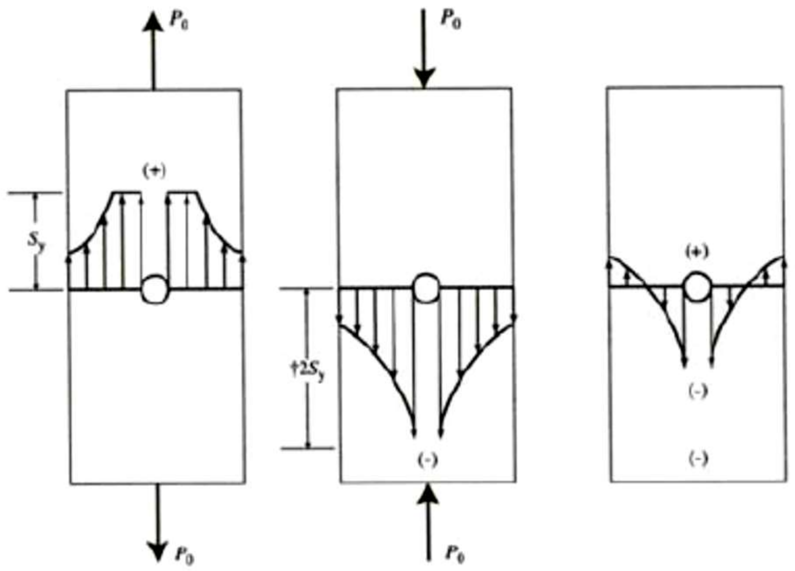


Stress–strain behavior at the notch and residual stress distributions after loading and unloading

Methods inducing residual stresses

Stretching (tensile overload) of the notched specimen

- Non-uniform tensile stress distribution during the inelastic loading (a)
- Elastic recover during unloading (b)
- Resultant residual stress after inelastic loading and elastic unloading (c)



a) b) c)

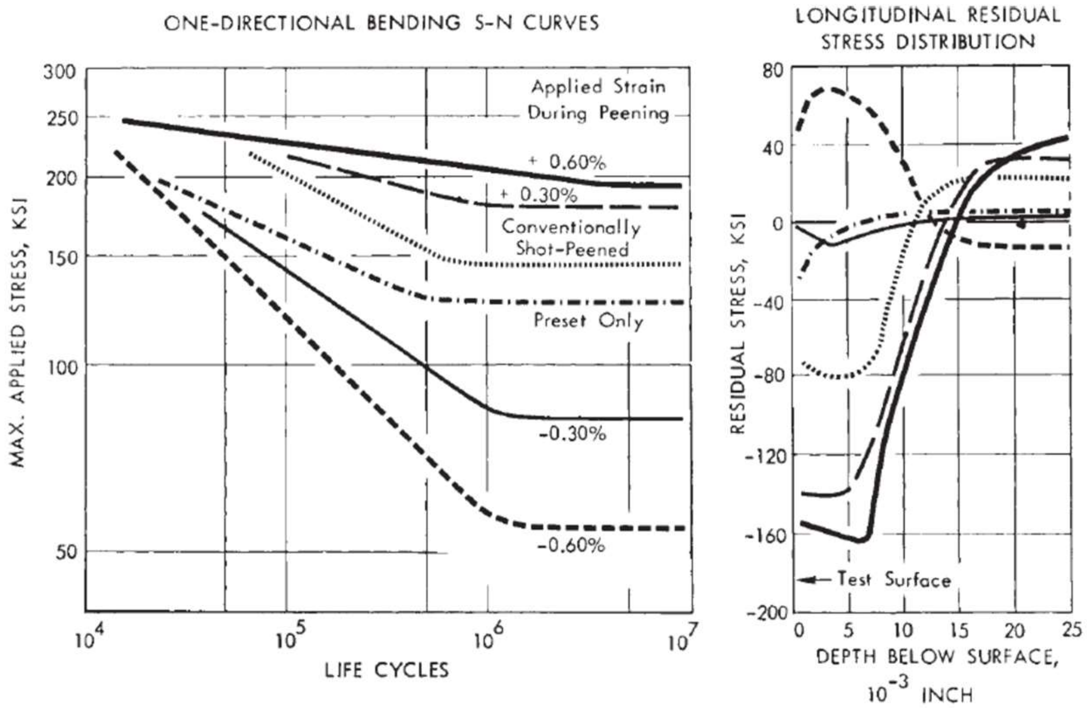
Tensile overloads with notches result in residual compressive stresses at the notch

Compressive overloads with notches result in residual tensile stresses at the notch

Methods inducing residual stresses

Shot-peening

- Used in many parts
- The depth of the residual compressive stress ranges from about 0.025 to 0.5 mm.
- The maximum residual stress is depended on material ultimate strength



Shot peened steel leaf springs

Methods inducing residual stresses

Rolling

- Compressive residual stress of fillets for components such as crankshafts, axles, gear teeth, turbine blades

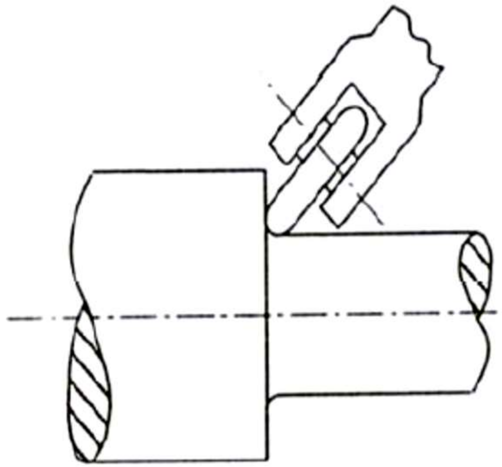


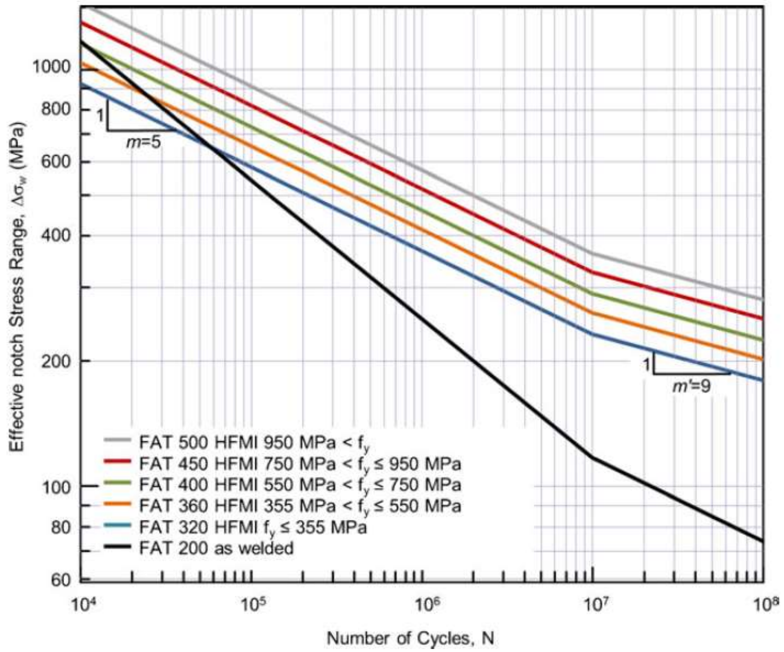
TABLE 8.2 Fatigue Strength at 10^5 Cycles, 0.2 Hz, AISI 8635 Steel [6,7]

Environment	Rolled Threads S_{Nf} − MPa (ksi)	Cut Threads S_{Nf} − MPa (ksi)	% Increase from Rolling
Air	510 (74)	303 (44)	68
3.5% NaCl	414 (60)	290 (42)	43
$H_2S + CH_3COOH$ + 5% NaCl	317 (46)	<276 (40)	>15

Methods inducing residual stresses

High frequency peening of welds

Fatigue resistance



(Marquis et al., 2013)

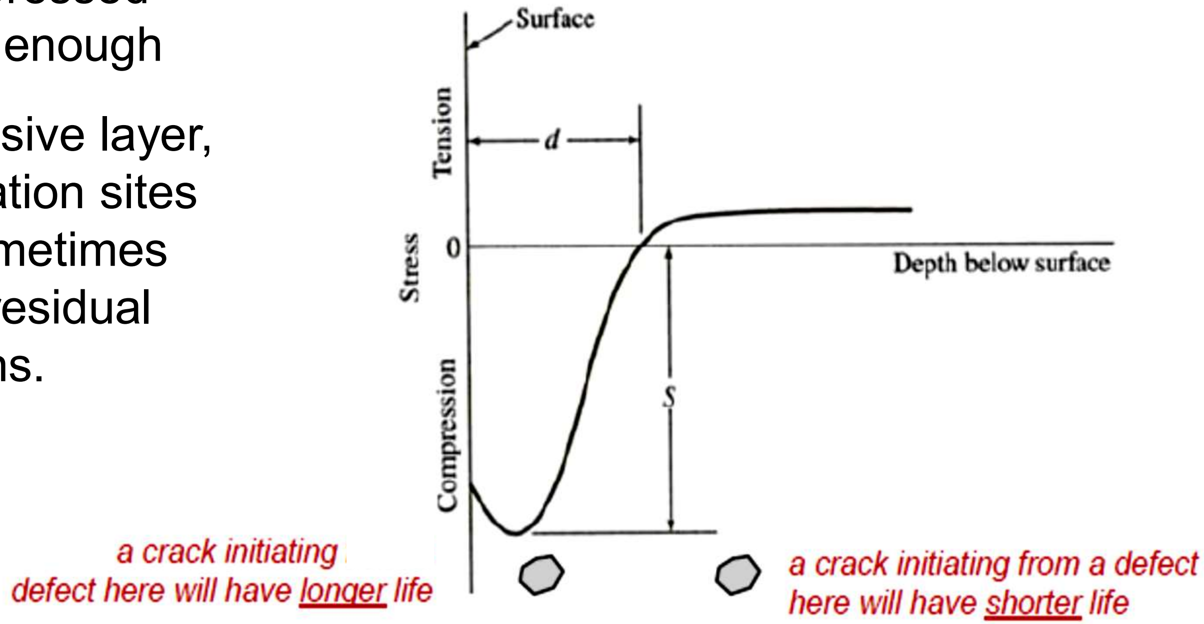
After the treatment

Before the treatment (As weld)

Methods inducing residual stresses

Mechanical methods

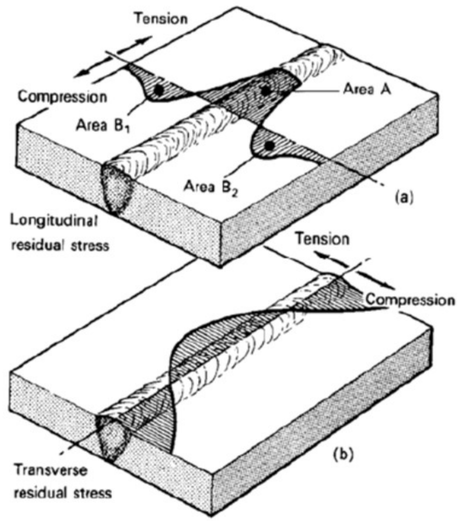
- Adequate depth of the compressively stressed layer is important; the compressed layer must be deep enough
- Due to the compressive layer, fatigue crack nucleation sites and growth may sometimes shift to subsurface residual tensile stress regions.



Methods inducing residual stresses

Thermal processes

- used in manufacturing procedures for forming parts
- includes several manufacturing processes such as casting, forging, hot-rolling, extrusion, injection molding, welding, brazing, quench and tempering, temper stress relief, flame or induction hardening, carburizing, and nitriding
- Induce a wide variety of residual stress and their effect may be beneficial or detrimental



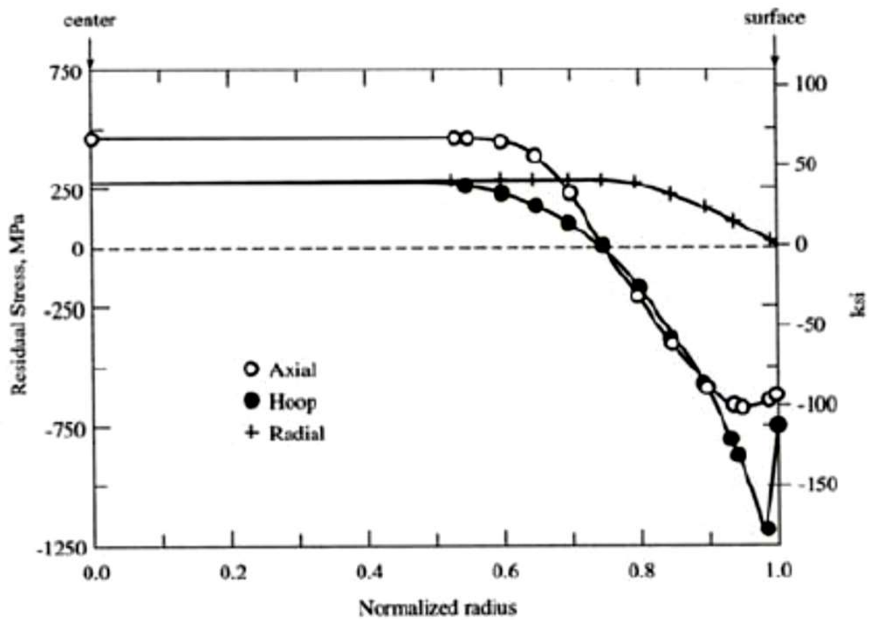
Methods inducing residual stresses

Induction hardening

- Surface hardening and compressive residual stress is accomplished by thermal treatment

Example: SAE 1045 40 mm diameter steel shaft

- Residual stress distributions from surface hardening
- Induction hardened shafts with surface or subsurface failure have significantly greater fatigue resistance than non-hardened shafts



Methods inducing residual stresses

Plating by electrolytic means can involve

- Soft plating materials such as zinc, tin, lead, or copper, or harder plating materials such as chromium and nickel

Plating of parts is done

- To increase corrosion resistance and for esthetic appearance
- To increase wear resistance plating (chromium)

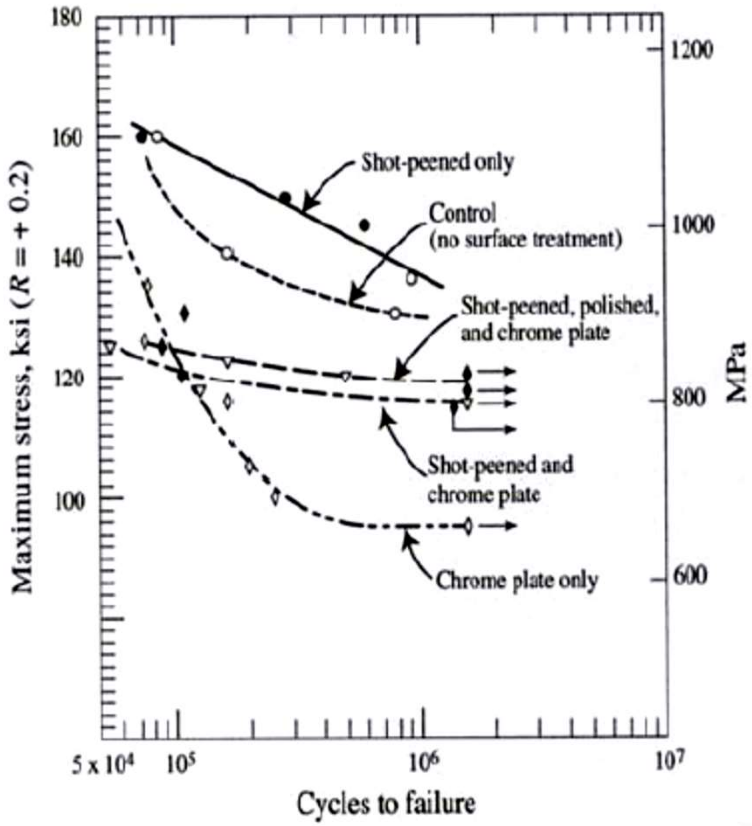
Electroplating with chromium or nickel will

- create significant residual tensile stresses in the plating material along with microcracking
- contribute to significant reduction in fatigue resistance of chromium or nickel plated parts
- the reductions are greatest in higher strength steels at longer and intermediate lives, and depend upon the plating thickness

Methods inducing residual stresses

Example: Chrome plating of 4130 steel

- Detrimental fatigue aspects due to chromium plating.
- Methods that produce desirable compressive surface stresses such as shot-peening, nitriding, or surface rolling can be used to nullify much of the detrimental fatigue aspects of chromium or nickel plating.
- This has been done successfully, both before and after the electroplating.



Methods inducing residual stresses

Machining operations such as turning, milling, grinding, polishing, and honing can significantly affect fatigue resistance.

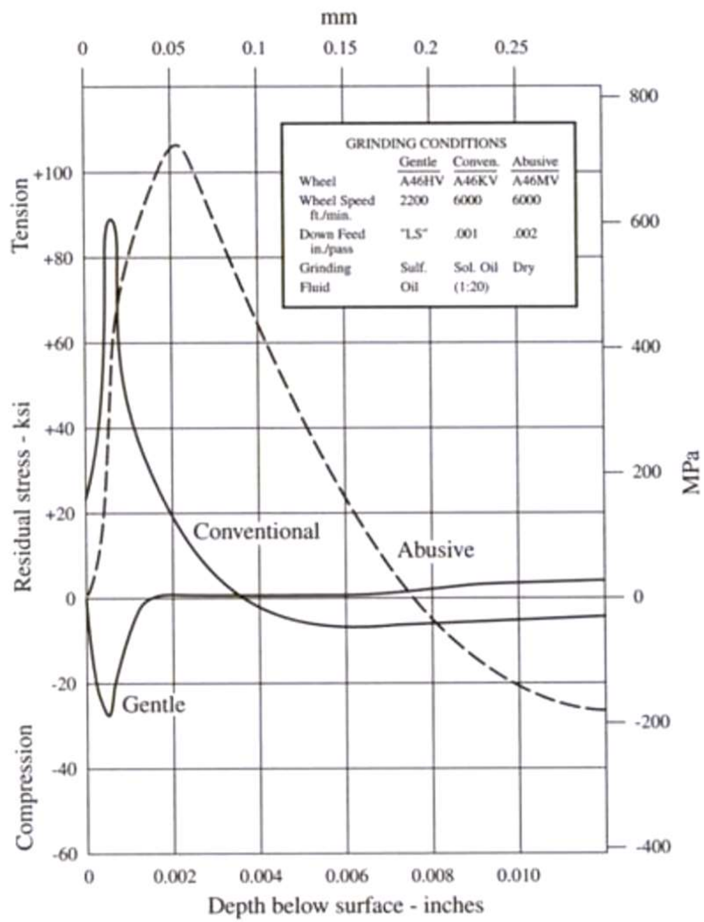
These methods all involve surface operations where fatigue cracks usually nucleate and grow.

- They can involve four major factors that affect fatigue resistance, -- surface finish -- cold working -- possible phase transformations -- residual stresses.
- All four of these factors contribute to fatigue resistance, however residual stresses may be the most dominant factor.
- The greatest effects of machining on fatigue resistance is at longer and intermediate lives.

Methods inducing residual stresses

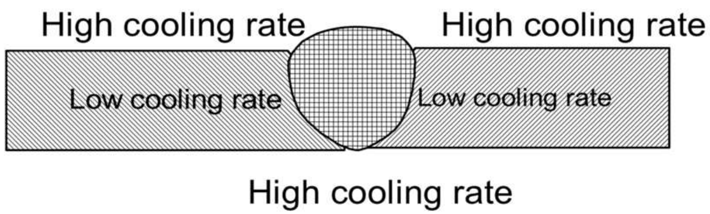
Machining

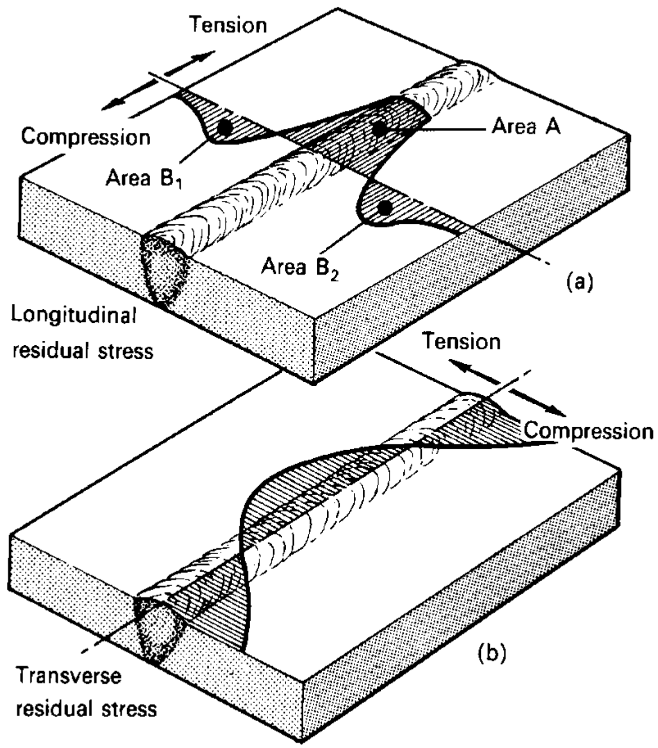
- Residual stress depth, sign and magnitude as well as surface finish are depended on
    - cutting velocity
    - tool pressure
    - feed
    - tool geometry
    - cooling
- Grinding causes also high variety in residual stresses and fatigue strength



Residual stresses in welded joint

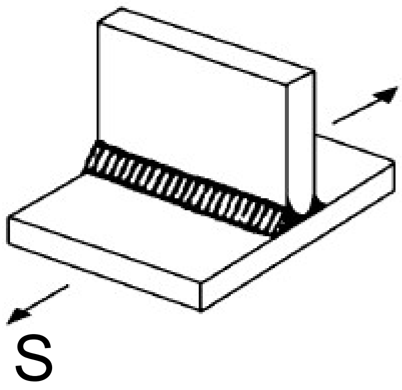
- Due to heating and cooling process
- High variation in the welded joint in both longitudinal and transversal direction

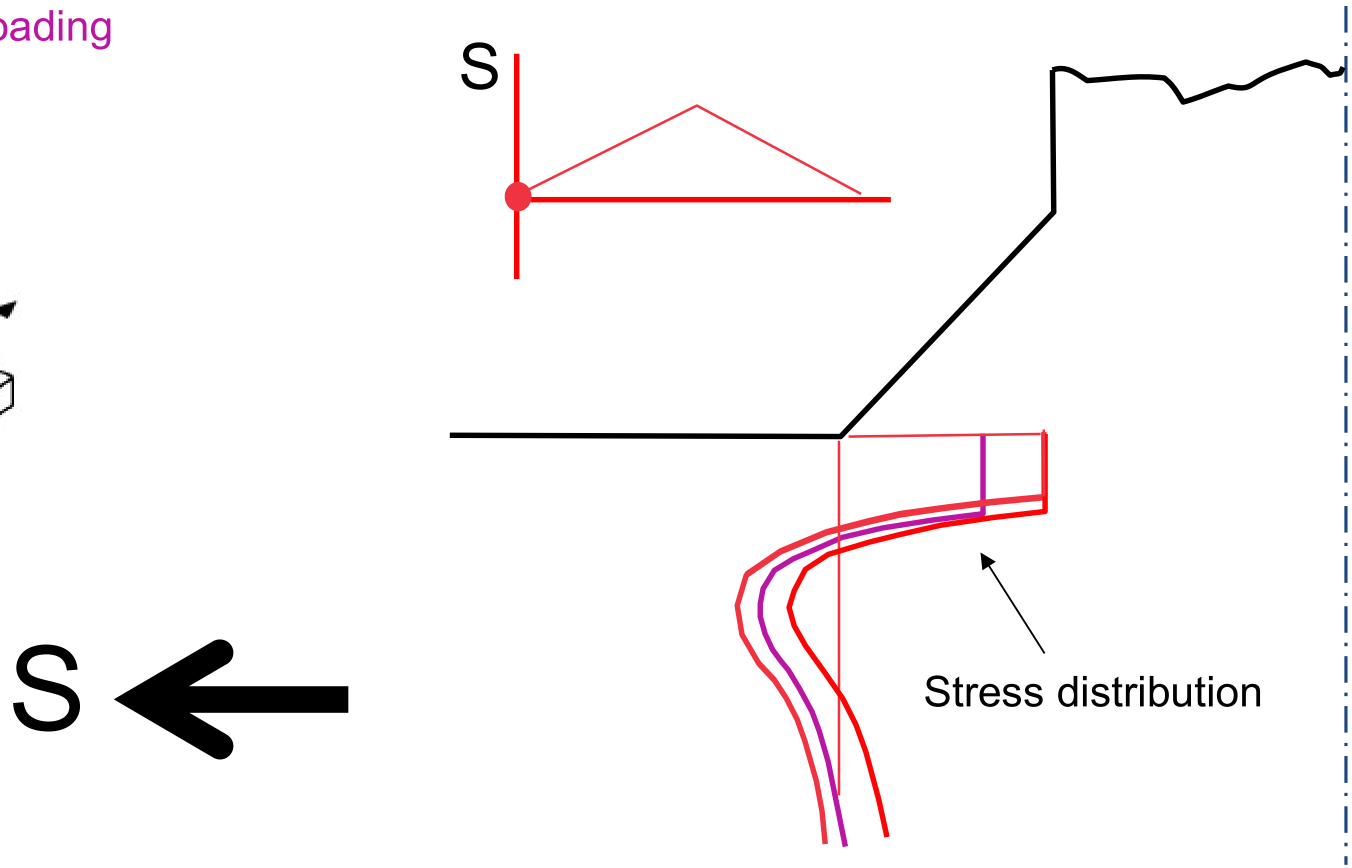




Residual stresses in welded joint

Development of notch stress σ
during reversal loading





Residual stresses in welded joint

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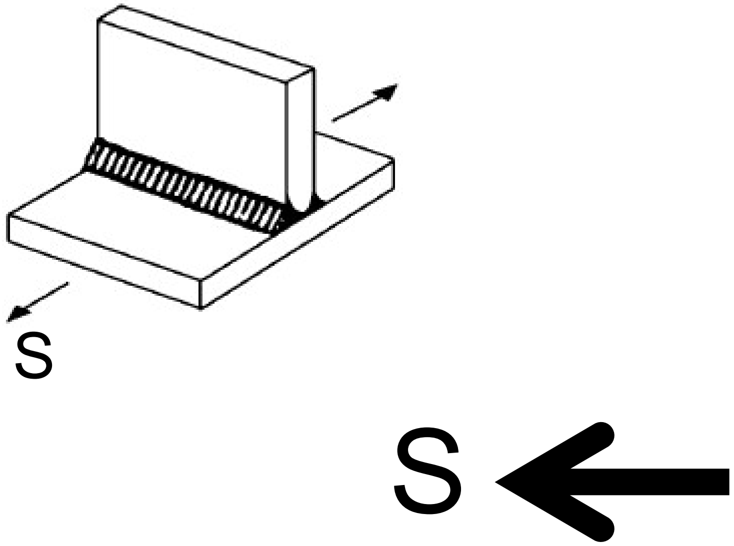

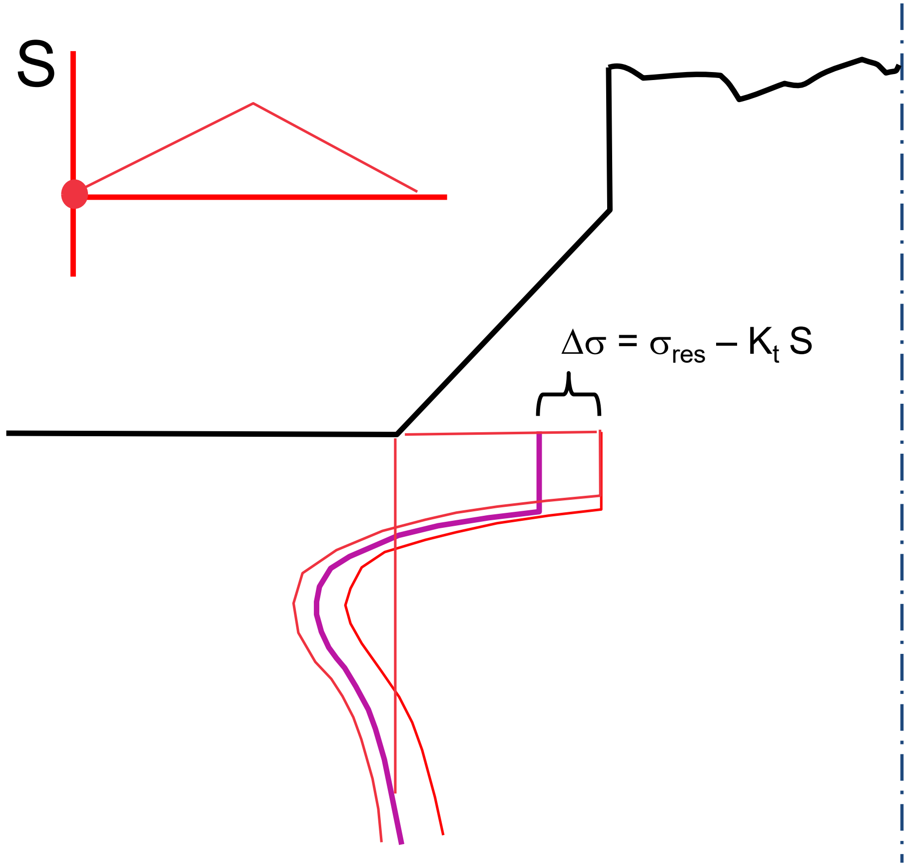

Residual stresses in welded joint

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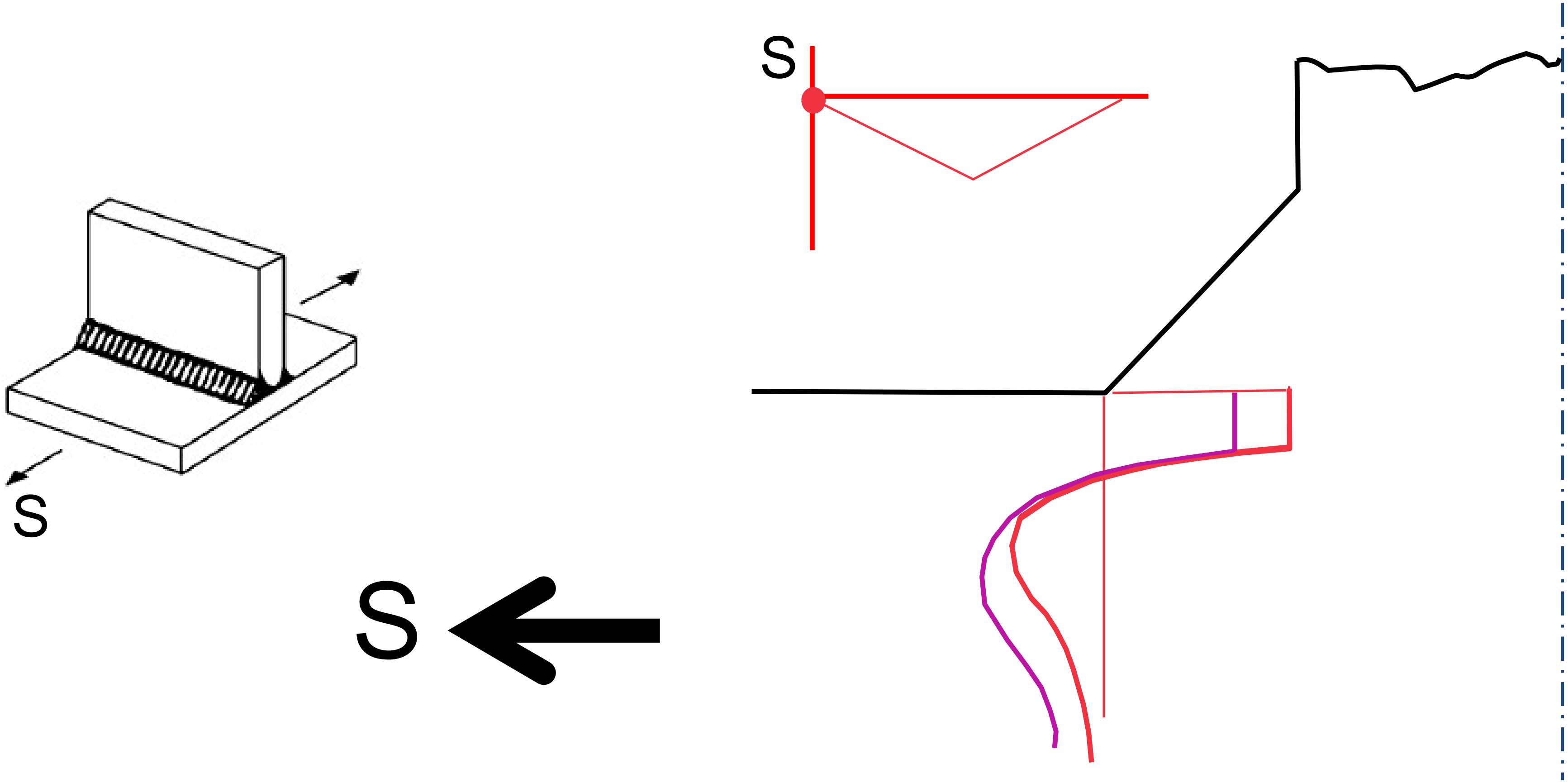

Residual stresses in welded joint

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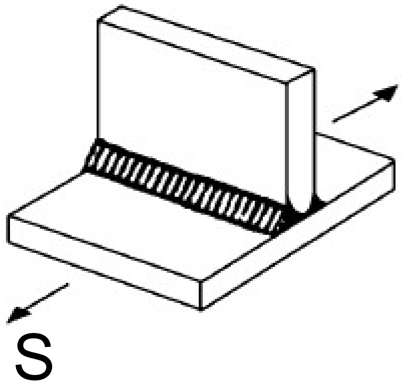

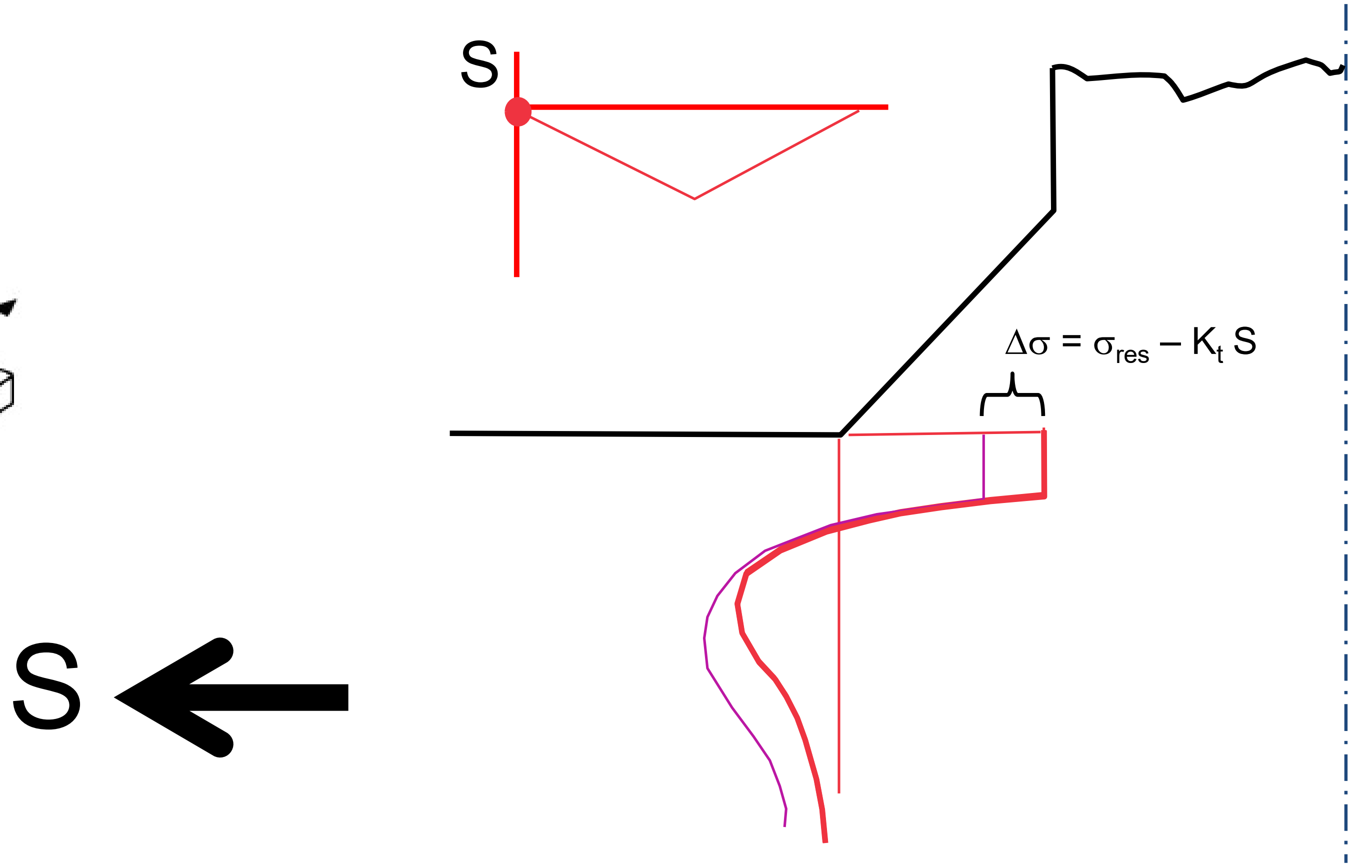

Residual stresses in welded joint

Development of notch stress σ
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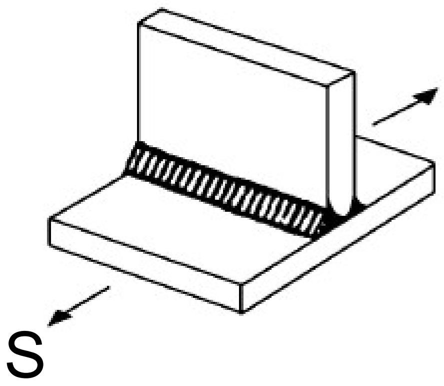
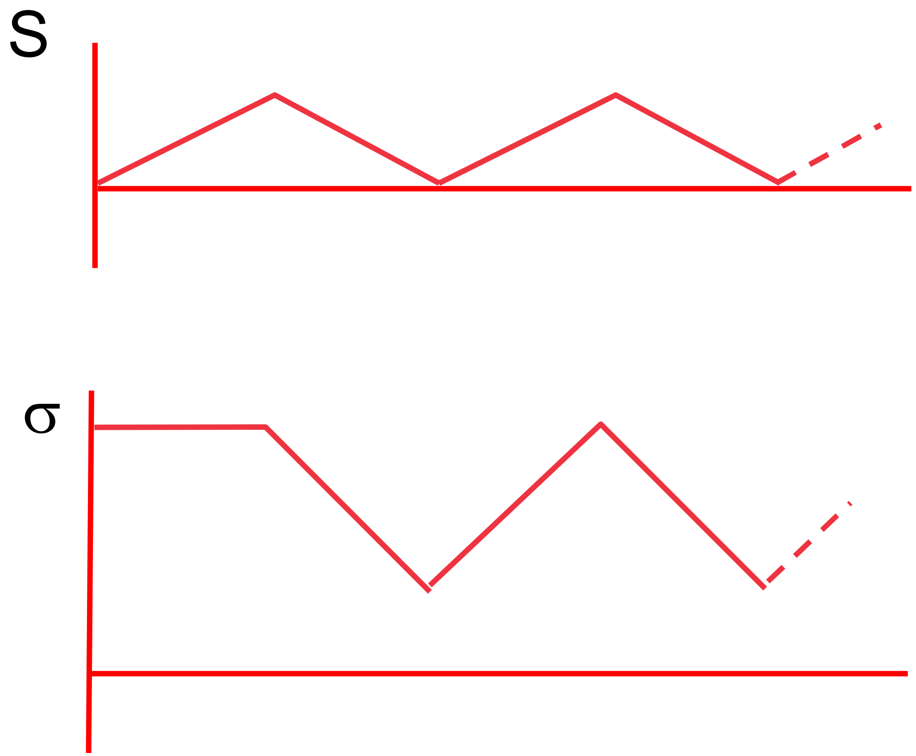
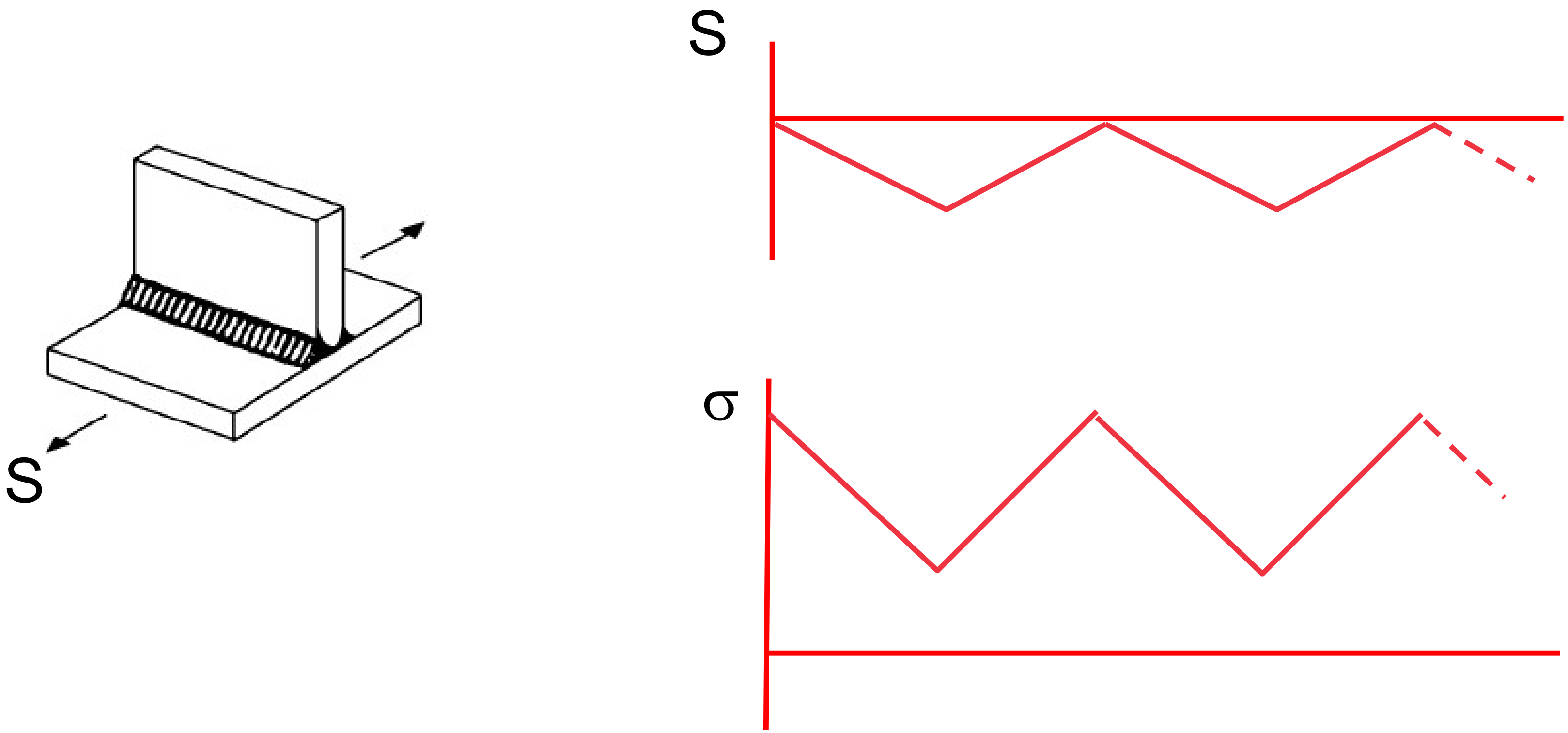


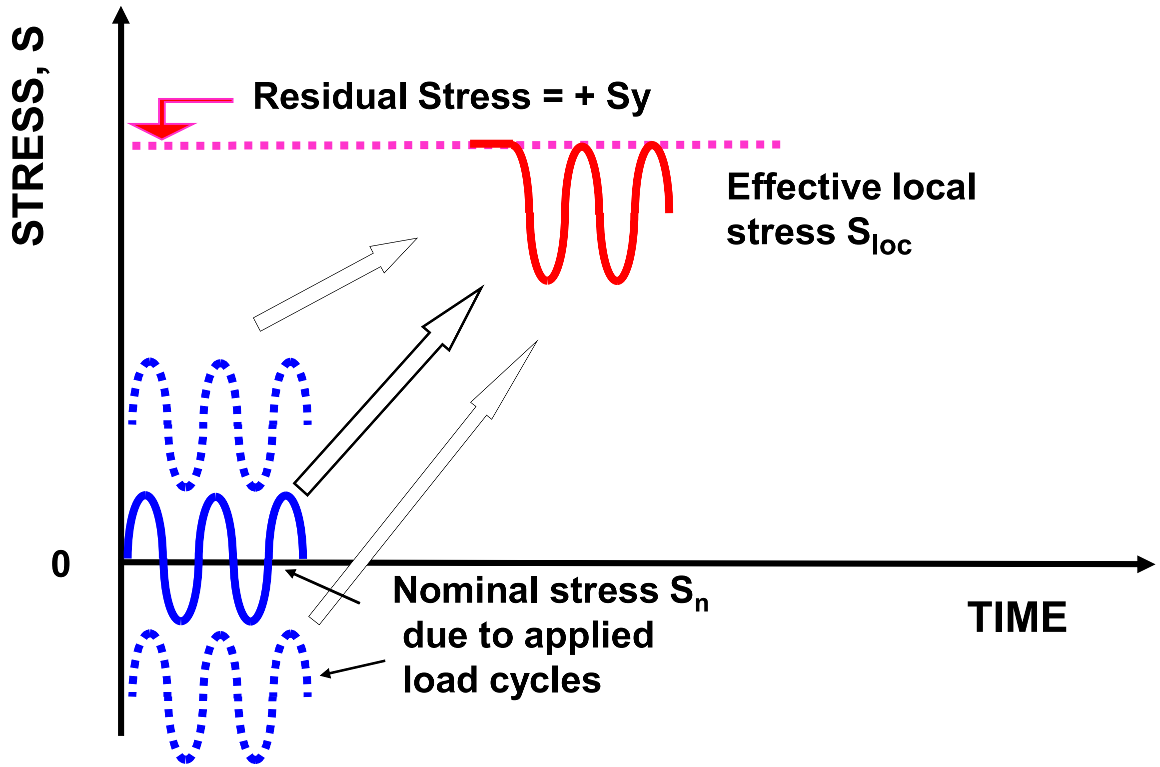


Residual stresses in welded joint

Development of notch stress σ
during reversal loading



Residual stresses in welded joint



Residual stresses determination

Residual stresses may be determined:

- Analytically (i.e. the local strain approach)
- Computationally with finite element analysis
- Experimentally (the most common methods)

Determination of surface residual stresses can be non-destructive, while subsurface residual stress determination methods are mostly destructive.

Residual stresses determination

The Society for Experimental Mechanics *Handbook of Measurement of Residual Stresses* describes the major experimental methods for determining residual stresses.

- hole-drilling and ring core
- layer removal
- sectioning
- X-ray diffraction
- neutron diffraction
- ultrasonic
- magnetic methods

ASTM has standard test methods for the hole-drilling method and for X-ray diffraction measurements.

Residual stresses determination

The **hole-drilling** method involves:

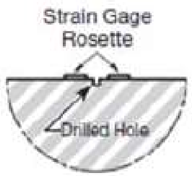
- drilling a small hole typically 1.5 to 3 mm deep through a three element radial strain gage rosette attached to the part.
- the strain gage relaxation around the hole from the drilling is then measured and converted to biaxial residual stresses in the hole vicinity.

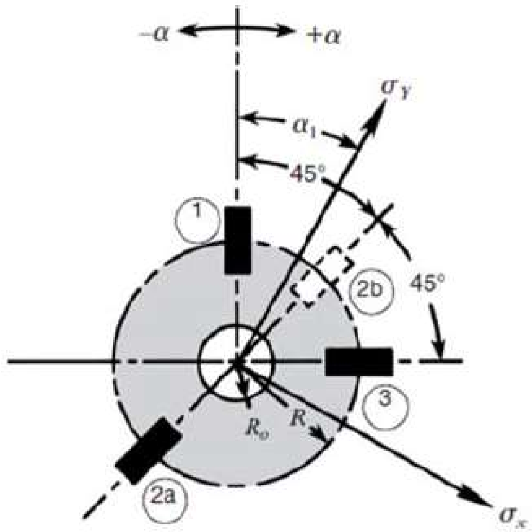
Sectioning methods are used to measure subsurface residual stresses by:

- Removing a beam, ring, or prism specimen from a residual stressed part of concern..
- The surface is subjected to repetitive surface layer removal by electrochemical polishing, etching, or machining.
- The curvature changes or deflections of the specimen for each layer removal is measured and these measurements are then related to residual stress magnitudes.

Residual stresses determination

Hole drilling method





$$\sigma_{max} = \frac{\varepsilon_1 + \varepsilon_3}{4A} - \frac{1}{4B}\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}$$

$$\sigma_{min} = \frac{\varepsilon_1 + \varepsilon_3}{4A} + \frac{1}{4B}\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}$$

$$\tan 2\alpha = \frac{\varepsilon_1 - 2\varepsilon_2 + \varepsilon_3}{\varepsilon_1 - \varepsilon_3}$$

Residual stresses determination

X-ray diffraction can be used non-destructively to measure surface residual stresses and destructively for subsurface values.

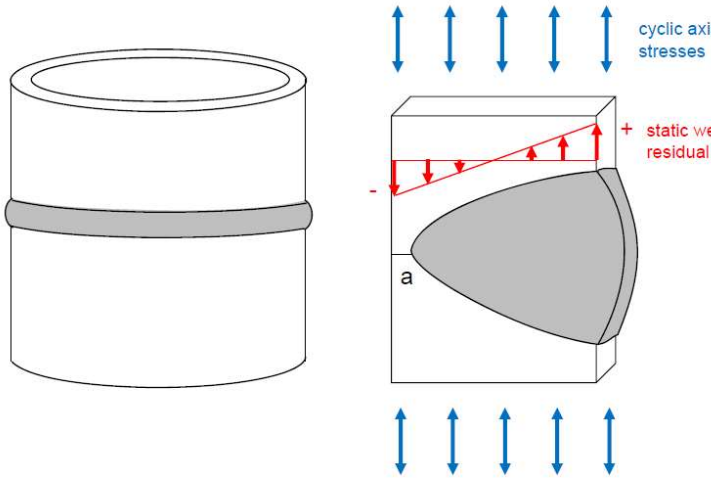
- Residual stresses cause crystal lattice distortion and a measurement of interplaner spacing of the crystal lattice indicates the residual stress magnitude.
- By electrochemical polishing away thin layers of metal, subsurface residual stresses can be measured.

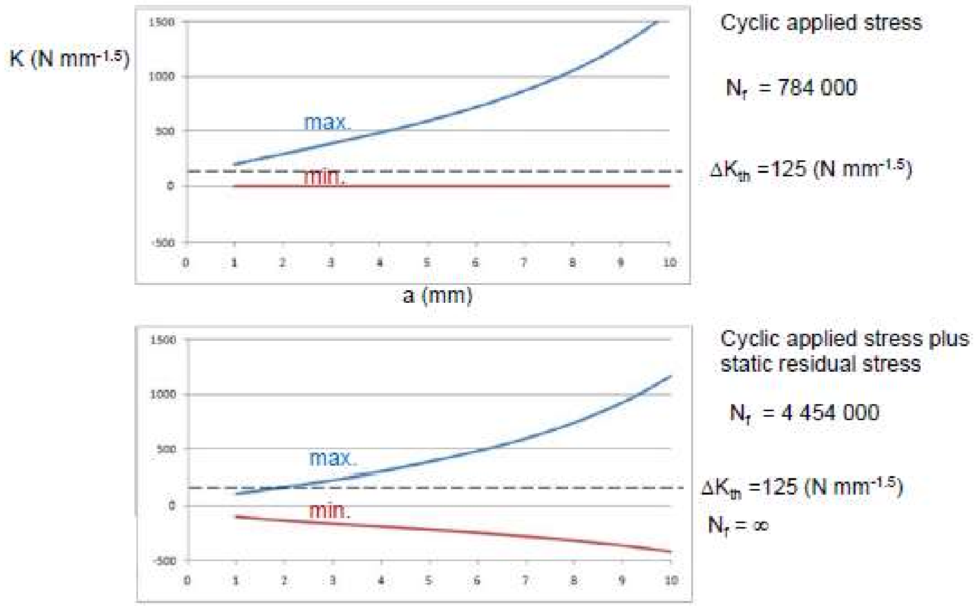
Both portable and non-portable X-ray diffraction equipment are available for many diverse situations making the X-ray diffraction method very popular.

Typical precision of X-ray diffraction residual stress measurements can be as low as $\pm$ 7 MPa or up to $\pm$ 35 MPa .

Residual stresses in fatigue analysis

Example: One-side welded pipe connection





Application of LEFM to study the influence of residual stress on fatigue life

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Residual stresses in fatigue analysis

- Similitude exists between mean stress and residual stress and S-N, ε-N, and da/dN-ΔK methods can be used for both mean and residual stresses.
- The residual stresses persist as long as the sum of residual stress and applied stress does not exceed the pertinent yield strength, S_y or S_y', of the materials.
- Thus residual stresses are more beneficial (and potentially more harmful) when applied to hard metals with high yield strengths.
- In softer metals such as mild steel the residual stresses can be more easily decreased by yielding.
- Therefore mild steel is not usually shot-peened and it can be welded with fewer precautions than harder materials.

Residual stresses in fatigue analysis

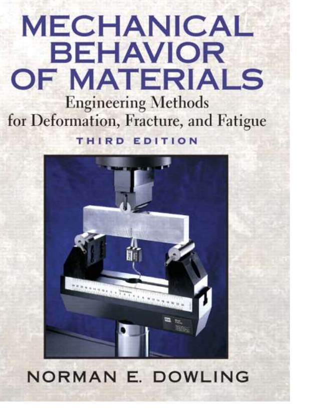
- Loading in one direction only, as in springs and most gears, will not destroy beneficial residual stresses.
- Automobile leaf springs are usually shot-peened on the tension side. In springs, as in other parts that are loaded predominantly in one direction, an overload applied early in the life introduces desirable residual compressive stresses at the proper surface.
- Springs, hoists, and pressure vessels are strengthened by proof loading with a load higher than the highest expected service load.
- Thermal stress relief can also relax residual stresses. At proper stress relief temperatures, residual stresses will relax with time in a decreasing exponential manner. Different materials will have different best stress relief temperatures and time at temperature.

Readings – Course material

Course book

Mechanical Behavior of Materials Engineering Methods for Deformation, Fracture, and Fatigue, Norman E. Dowling

- Section 9.6.4, 10.9.2, 13.3-13.6



Additional papers and reports given in MyCourses webpages

- Sticchi, M., Schnubel, D., Kashaev, N., and Huber, N. Review of Residual Stress Modification Techniques for Extending the Fatigue Life of Metallic Aircraft Components. Appl. Mech. Rev. 2015, 67:010801.
- James, M.N. Residual stress influences on structural reliability, Engineering Failure Analysis, 2011, 18:1909-1920.