RESIDUAL STRESSES AND THEIR EFFECTS ON FATIGUE RESISTANCE

RESIDUAL STRESSES AND THEIR EFFECTS ON FATIGUE RESISTANCE

- To improve fatigue resistance we should try to avoid tensile mean stress and have compressive mean stress. This can often be achieved by using 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 and their potential to improve or ruin components subjected to millions of load cycles can hardly be overestimated.

RESIDUAL STRESSES AND THEIR EFFECTS ON FATIGUE RESISTANCE

- EXAMPLES
- PRODUCTION OF RESIDUAL STRESSES & FATIGUE RESISTANCE
- RELAXATION OF RESIDUAL STRESSES
- MEASUREMENT OF RESIDUAL STRESSES
- STRESS INTENSITY FACTORS FOR RESIDUAL STRESSES
- SUMMARY AND DOS AND DON'TS IN DESIGN

EXAMPLES

- S-N behavior of a Ni-Cr alloy steel subjected to rotating bending with three different surface conditions involving
  - smooth (solid circles),
  - notched (x's), and
  - notched shot-peened (open squares) specimens.

- With the notched shot-peened specimens, the fatigue resistance is essentially the same as the smooth specimens. Thus, the notch became perfectly harmless after it was shot-peened due to the desirable residual compressive stresses.

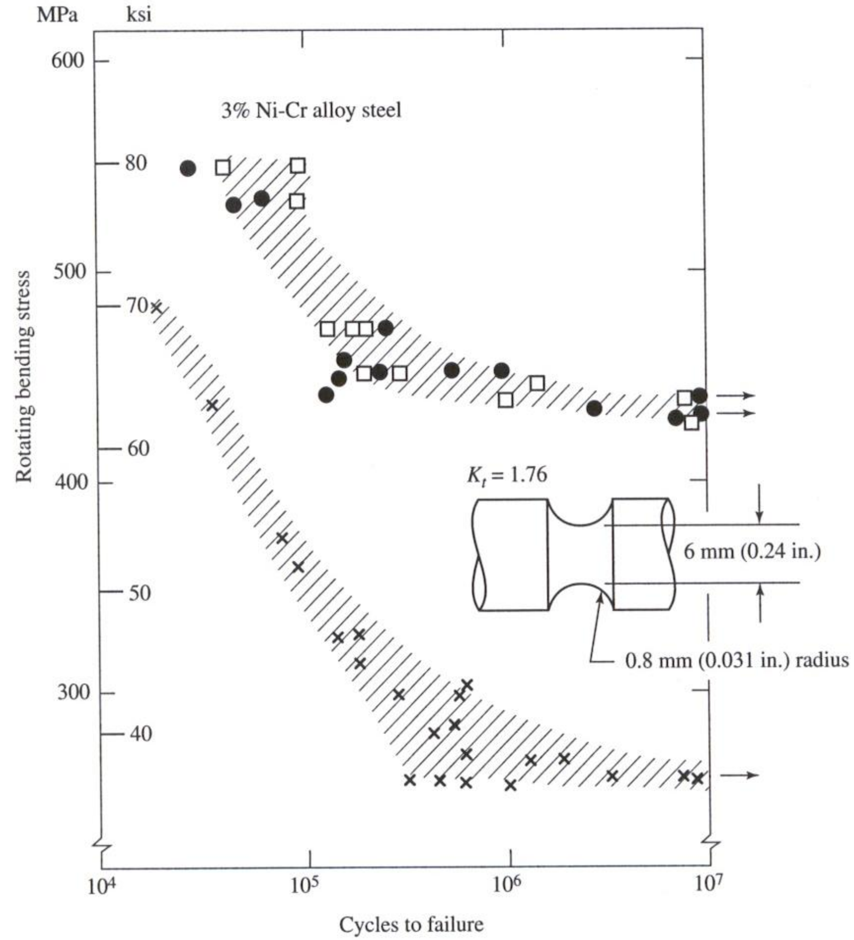


Figure 8.1 *S–N* behavior for smooth, notched unpeened, and notched peened specimens [1] (reprinted with permission of Pergamon Press). (●) smooth, polished, (x) notched, (□) notched, shot-peened.

- Effect of residual stresses produced by **prestretching** (tensile overload) on fatigue strength and fatigue notch factor of specimens of 4340 steel with two different notches and at two hardness levels.
  - The residual stresses eliminated the notch effect almost completely.
  - Note that with the residual stresses induced by stretching, the worst notched specimens became much stronger than the best notched specimens without residual stresses.

TABLE 8.1 Fatigue Strengths and Fatigue Notch Factors with and without Residual Stresses

S_u, MPa	900			1700		
(K_t)	(1)	(2.15)	(3.2)	(1)	(2.15)	(3.2)
Without stretching						
S_f, MPa	400	205	160	630	240	190
(K_f)	(1)	(1.95)	(2.5)	(1)	(2.6)	(3.3)
With stretching						
S_f, MPa	390	390	370	635	620	610
(K_f)	(1.03)	(1.03)	(1.08)	(0.99)	(1.02)	(1.03)

PRODUCTION OF RESIDUAL STRESSES & FATIGUE RESISTANCE

PRODUCTION OF RESIDUAL STRESSES & FATIGUE RESISTANCE

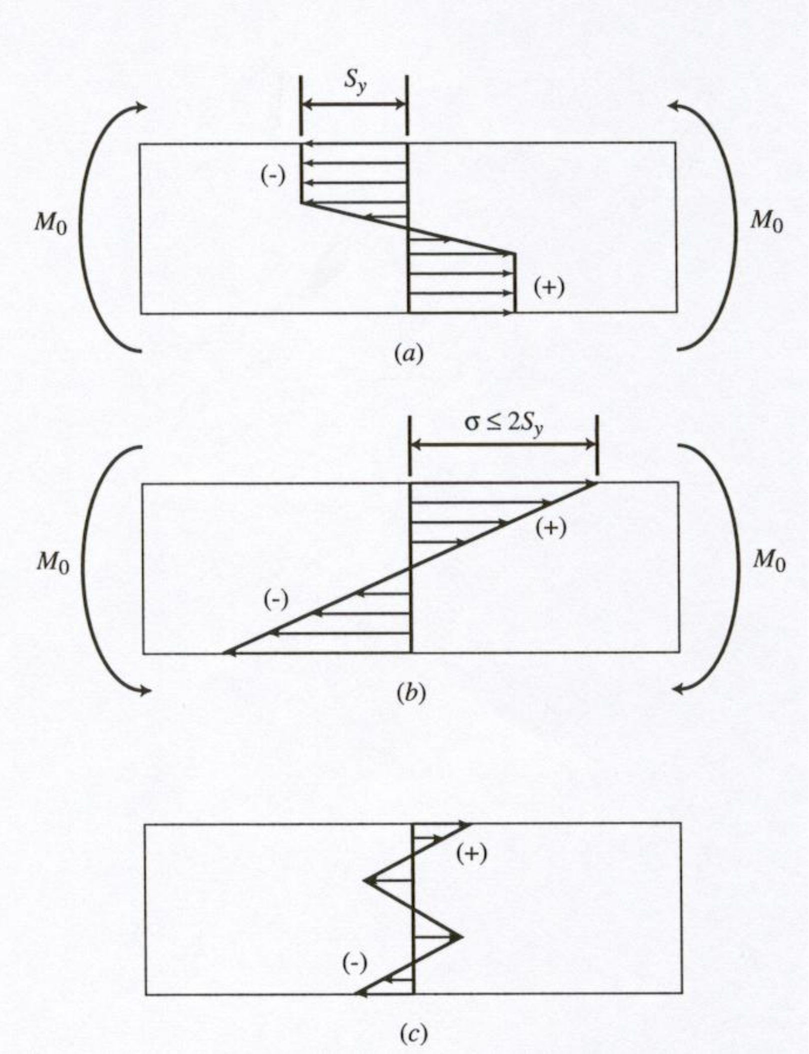
- The many **methods** of inducing residual stresses in parts can be divided into four main groups:
  - Mechanical Methods
  - Thermal Methods
  - Plating
  - Machining

MECHANICAL METHODS

- Mechanical methods of inducing residual stresses:
  - Rely on applying external loads that produce localized inelastic deformation.
  - Upon removing the external loading, elastic “springback” occurs that produces both tensile and compressive residual stresses.
  - Both tensile and compressive residual stresses must be present in order to satisfy all equations of internal force & moment equilibrium, $\Sigma F = \Sigma M = 0$.

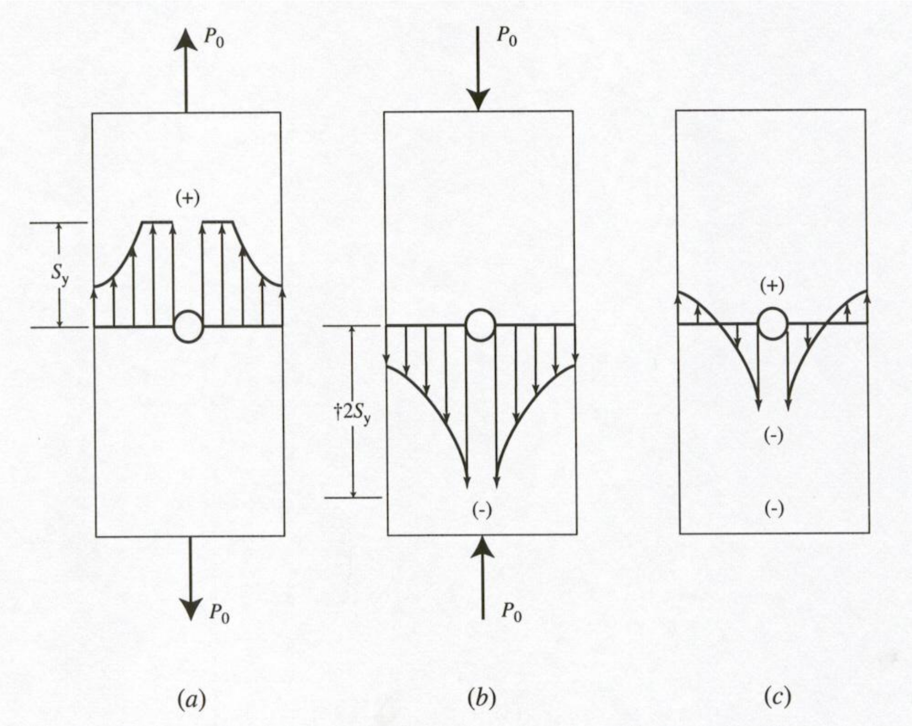
MECHANICAL METHODS

- Figure 8.2 shows this process for inelastic bending of a beam behaving in an elastic-perfectly plastic manner.
  - Quantitative calculations are possible (left as a homework problem).
  - The beam in Fig. 8.2c will have better fatigue resistance at the bottom fibers than at the top fibers.
  - Thus, straightening of parts by bending is usually detrimental due to the undesirable tensile residual stresses that form in regions overloaded in compression.
  - If the material were not elastic-perfectly plastic, the residual stress distribution in Fig. 8.2c would be non-linear.



MECHANICAL METHODS

- **Stretching** (tensile overload) of the notched specimen shown.
  - Again, the material is assumed to be elastic-perfectly plastic.
  - Nonuniform tensile stress distribution during the inelastic loading.
  - The summation of the inelastic loading stresses and the elastic unloading stresses result in the residual stress distribution shown in Fig. 8.3c.
  - Note that tensile overloads with notches result in desirable residual compressive stresses at the notch, while compressive overloads with notches result in undesirable residual tensile stresses at the notch



MECHANICAL METHODS

- The most widely used mechanical processes for producing beneficial compressive surface residual stresses for enhancing long and intermediate fatigue life are: (1) **shot-peening** and (2) **surface rolling**.

- Both methods use local plastic deformation, one by the pressure of the impact of small balls, the other by the pressure of narrow rolls.

- Surface rolling is widely used in the production of threads. It is very economical as a forming operation for bolts and screws, as well as beneficial for fatigue resistance.

MECHANICAL METHODS

- **Rolling** is also used for producing desired compressive residual stresses in fillets for components such as crankshafts, axles, gear teeth, turbine blades, and between the shank and head of bolts.

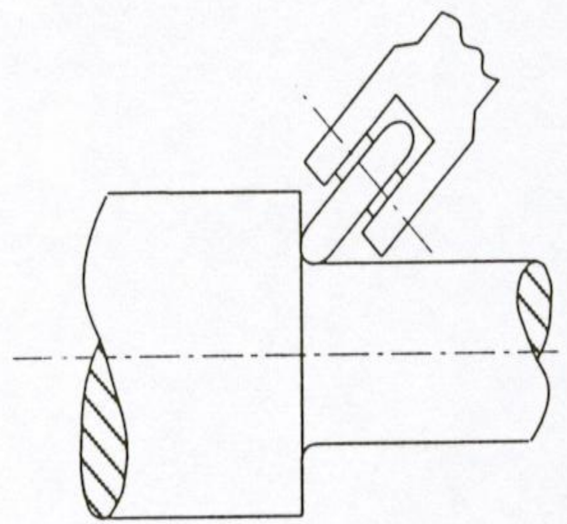


TABLE 8.2 Fatigue Strength at 10^5 Cycles, 0.2 Hz, AISI 8635 Steel [6,7]

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

MECHANICAL METHODS

- **Shot-peening** has been used successfully with steels, ductile iron and aluminum, titanium, and nickel base alloys.
- Small balls (shot) that range from 0.18 to 3.35 mm with different size specifications are thrown or shot at high velocities against the work piece.
- They produce surface dimples and would produce considerable plastic stretching of the skin of the part if this were not restrained by the elastic core.

MECHANICAL METHODS

- Compressive stresses are thus produced in the skin. The depth of the compressive layer and the dimpled surface roughness are determined by
  - the material of the work piece
  - the intensity of peening, which depends on
    - size of shot,
    - Material of shot,
    - velocity or flow rate of the shot,
    - time of exposure.
- The magnitude of the compressive residual stress depends mainly on the material of the work piece.

MECHANICAL METHODS

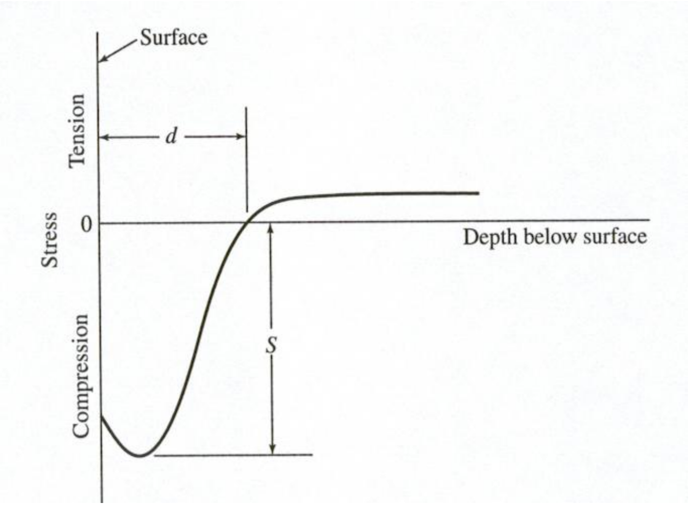
- The **intensity of shot-peen** is specified in Almen numbers.
  - Excessive intensities may produce excessive surface roughness and excessive tensile stresses in the core of the work piece.
  - Insufficient intensities may fail to provide enough protection against fatigue failures.
  - Recommended shot-peening intensities along with other shot-peening suggestions can be found in ref. 11.

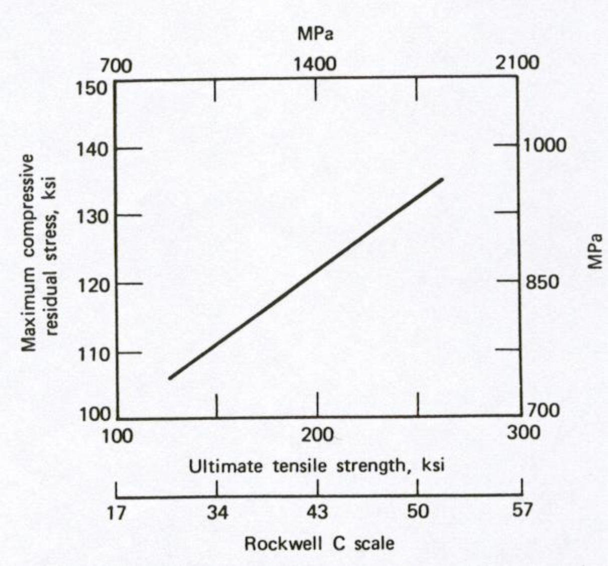
MECHANICAL METHODS

- Typical stress distribution produced by **shot-peening**.

  - The depth of the residual compressive stress, distance d, ranges from about 0.025 to 0.5 mm (0.002 to 0.02 in).

  - The relation of the stress peak to material hardness is shown in Fig. 8.6.





MECHANICAL METHODS

- **Shot-peening** is used on many parts:
  - From small blades for chain saws to large crankshafts for diesel locomotives.
  - Application to high performance gears and to springs is almost universal.
  - Figure 8.7, for carburized gears, shows a tenfold fatigue life increase.

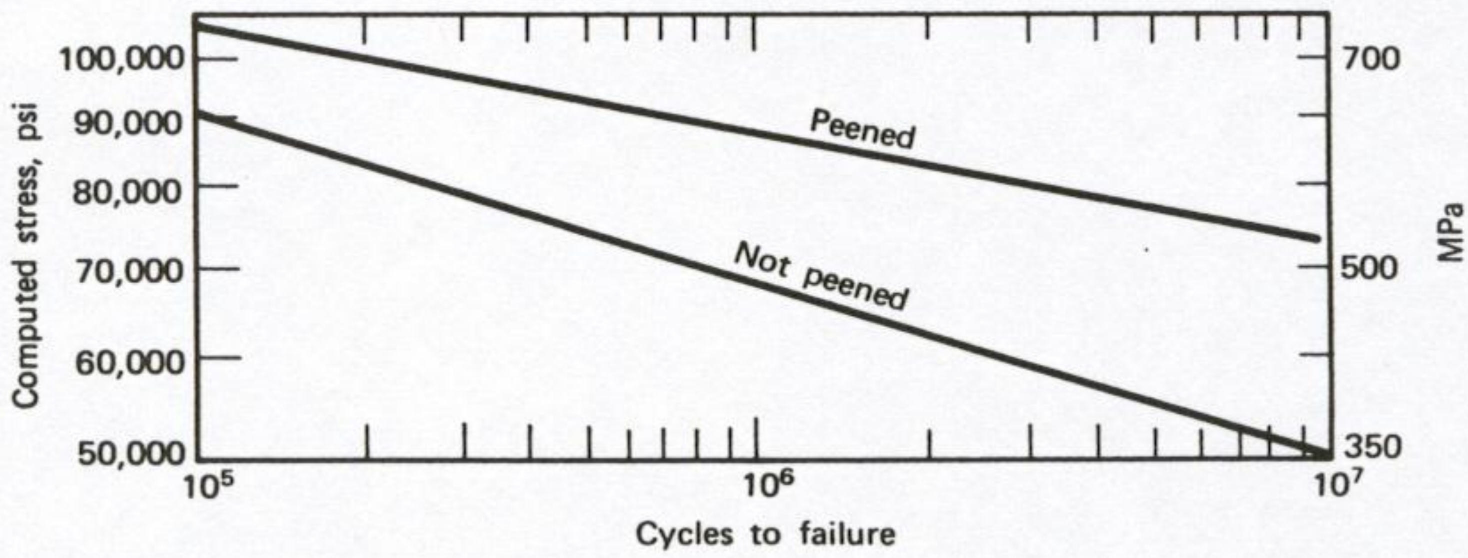
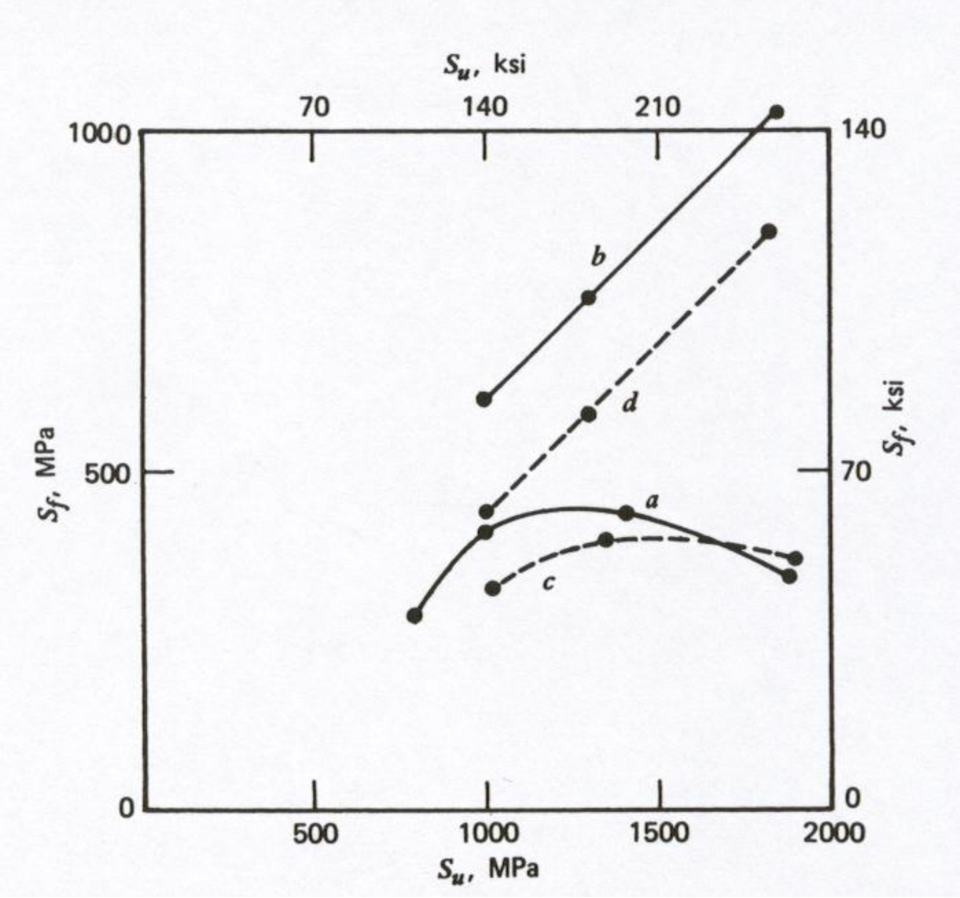


Figure 8.7 Effect of shot-peening on fatigue behavior of carburized gears [13] (reprinted with permission of McGraw-Hill Book Co.).

MECHANICAL METHODS

- Residual stresses are especially valuable when used with harder materials because the full potential of greater yield strength can be used only if the damaging effect of notches can be overcome.

- Fig. 8.8 shows that shot-peening increased the fatigue limit by a factor of 1.25 to 1.5 for $S_u \approx$ 1000 MPa (145 ksi), and 2 to 2.5 for $S_u \approx$ 1800 MPa (260 ksi).
  - a) shaft not peened
  - b) shaft peened
  - c) scratched plate not peened
  - d) scratched plate peened



MECHANICAL METHODS

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

- Other mechanical processes that achieve improvement of fatigue strength by compressive residual stresses include
  - coining around holes,
  - expansion of holes,
  - hammer-peening of welds.

THERMAL METHODS

- **Thermal processes** used in manufacturing procedures for forming parts
  - include 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.

- **Surface hardening** of steel is a chief example.
  - If it is properly done it leaves components with a surface skin (case) that is hard and in compression.
  - Surface hardening can be accomplished by induction hardening, carburizing, nitriding, severe quenching of carbon steel, or similar methods.

THERMAL METHODS

- Residual stress distributions from surface hardening in an SAE 1045 40 mm diameter steel induction hardened shaft with a case hardness of about Rc 55 and a core hardness of about Rc 10.
  - The transition from compression to tension for the axial and hoop residual stresses occur in the same region as the microstructure and hardness transitions.
  - High applied stresses may relax the surface residual compressive stresses and shift the fatigue failure to the surface.
  - Induction hardened shafts with surface or subsurface failure have significantly greater fatigue resistance than non-hardened shafts.

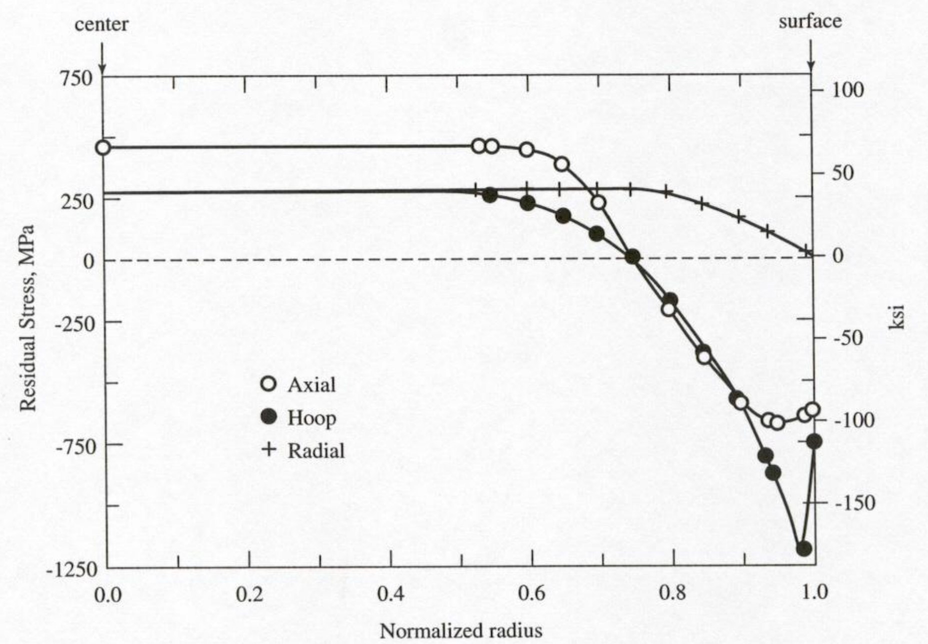


Figure 8.9 Typical residual stress distributions of SAE 1045 induction hardened 40 mm (1.57 in.) diameter steel shaft specimens as measured by x-ray diffraction [14] (copyright ASTM; reprinted with permission).

THERMAL METHODS

- **Carburizing** and **nitriding** are similar to induction hardening, except the surface compressive residual stresses and case depth are not as deep.

- Thermal treatments can also produce detrimental effects.

- The heat applied in welding can produce tensile stresses up to the yield strength of the material. They reduce fatigue strength and exacerbate the effects of notches and cracks.

PLATING

- 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.
  - in addition, chromium plating is used to increase wear resistance and to build up the size of worn and undersized parts.
- 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.

PLATING

- With lower strength steels, or under low cycle fatigue, significant plasticity can occur from external loading that relaxes the residual stresses.

- During electroplating hydrogen can be introduced into the base metal that can cause a susceptibility to hydrogen embrittlement. This is best circumvented by thermal stress relieving the chromium plated parts, usually above about 400^{o}C (750^{o}F), which drives out the undesirable hydrogen and also relaxes some of the residual stresses.

PLATING

- Figure 8.11 shows the influence of chrome plating on fatigue resistance of 4130 steel heat treated to 1100 MPa (160 ksi).
  - 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.

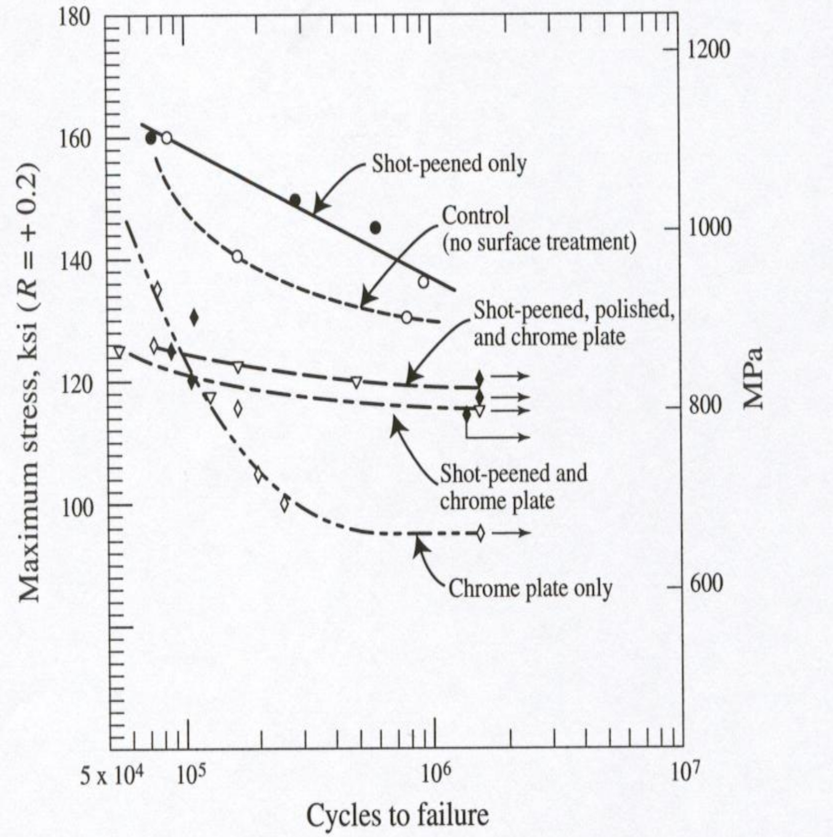


Figure 8.11 Influence of chromium plating and chromium plating with shot-peening on the axial loaded fatigue behavior of 4130 steel [19] (reprinted with permission from the Society of Automotive Engineers).

PLATING

- The softer electrolytically deposited materials, such as zinc, tin, lead, or copper, often have only a small influence on fatigue resistance in air environments, but may contribute to improved fatigue resistance in corrosive environments.

- Galvanizing (hot-dip zinc coating), however, has a significant degradation in air fatigue resistance, particularly with higher strength steels, attributed to greater susceptibility to plating cracking.

MACHINING

- Machining operations such as turning, milling, planing, broaching, and abrasion operations such as 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.

MACHINING

- During machining, residual stress depth, sign, and magnitude, as well as surface finish, are dependent upon
  - cutting velocity,
  - tool pressure,
  - feed,
  - tool geometry/wear, and
  - cooling.

MACHINING

- For the many different **machining operations** and metals available,
  - surface residual stresses are usually tensile with subsurface residual compressive stresses.
  - however, the opposite also occurs in some machining/metal combinations.
  - The surface depth of tensile residual stresses is often small, about 0.02-0.2 mm (about 0.0001-0.001 in) and hence polishing can remove some of, most of, or all of the residual stresses.

- **Polishing** and **honing** are performed with lower speed, pressure and hence incorporate fewer residual stresses and a smaller effect on fatigue resistance from residual stresses. However, surface finish effects are still significant.

MACHINING

- **Grinding** also produces a wide variation in residual stresses and fatigue resistance.
  - Conventional, or abusive grinding, using high speed, high feed, water as lubricant, or no lubricant introduce significant shallow, but high magnitude, residual surface tensile stresses.
  - Gentle grinding with low speed, low feed, and oil as a lubricant can provide shallow low magnitude residual compressive surface stresses.
  - Residual stress distributions for gentle, conventional, and abusive grinding are shown ***for 4340 Q&T steel with Rc = 50***.

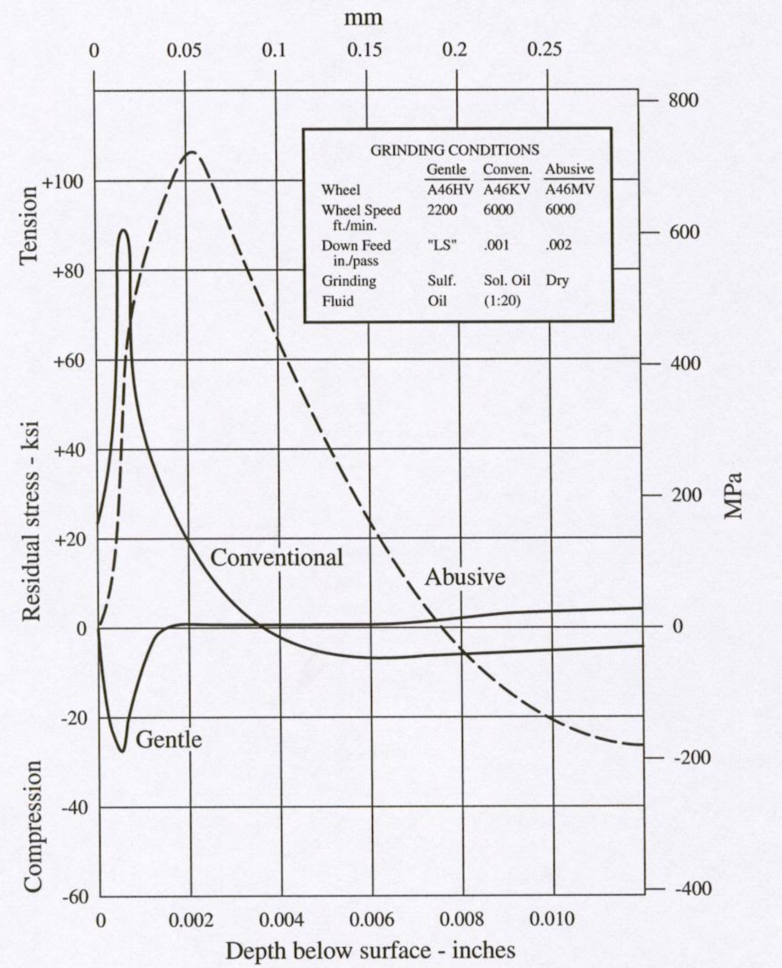


Figure 8.12 Residual stresses in Q&T 4340 steel from abusive, conventional or gentle grinding [19] (reprinted with permission from the Society of Automotive Engineers).

RELAXATION OF RESIDUAL STRESSES

- 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.

- However there is a difference.
  - The mean stresses persist as long as the mean load remains.
  - 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.

RELAXATION OF RESIDUAL STRESSES

- Residual stress determination and relaxation from simple to complex applied load histories are best obtained using the local notch strain analysis as described in Section 7.3.

- 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.

RELAXATION OF RESIDUAL STRESSES

- 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.

MEASUREMENT OF RESIDUAL STRESS

- 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 are mostly non-destructive, while subsurface residual stress determination are mostly destructive.

MEASUREMENT OF RESIDUAL STRESS

- 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.

MEASUREMENT OF RESIDUAL STRESS

- 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.

MEASUREMENT OF RESIDUAL STRESS

- **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 ± 7 MPa (±1 ksi) or up to ± 35 MPa (±5 ksi).

STRESS INTENSITY FACTORS FOR RESIDUAL STRESSES

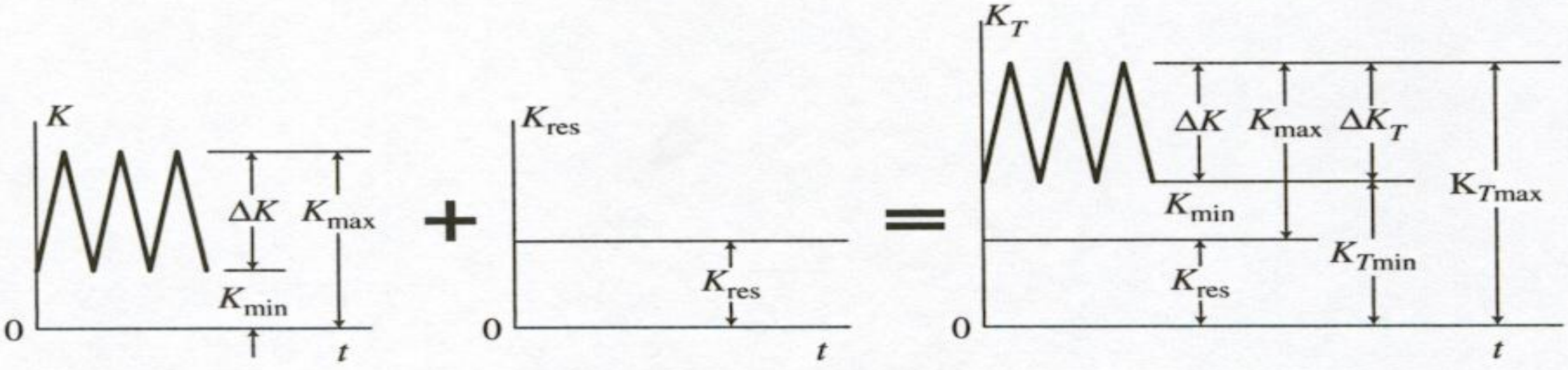
- Residual stress effects on fatigue crack growth have been handled quantitatively with crack closure models or superposition of applied stress intensity factors with residual stress intensity factors.

- **Superposition** of applied and residual stress intensity factors is appropriate due to the linear elastic models involved and hence

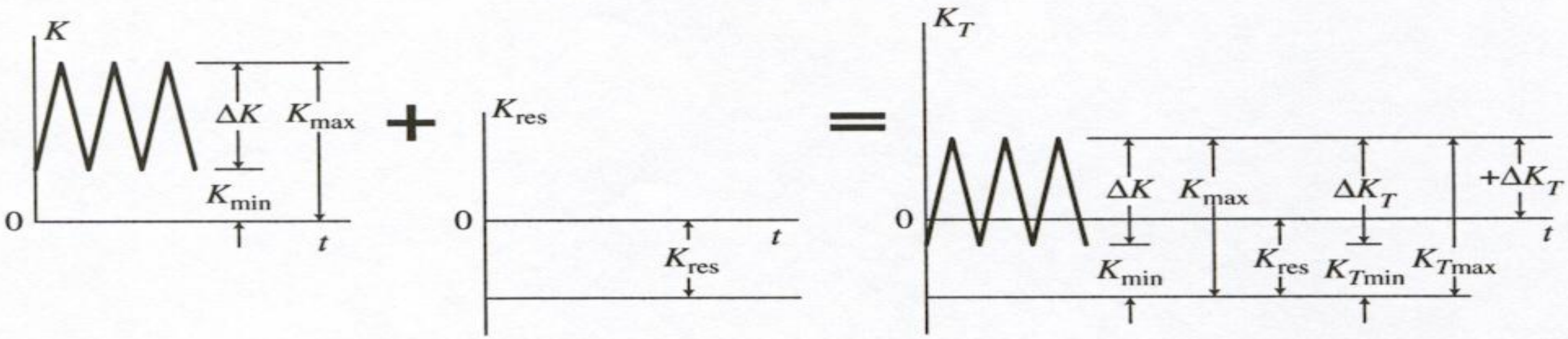
$$K_T = K_{applied} + K_{residual}$$

  where K_T is the total stress intensity factor under mode I conditions.

- To determine K_{res}, the residual stress magnitude and profile without cracks must be known or assumed. K_{res} can then be obtained by inserting a crack face at the desired location and then loading the inserted crack face with the residual stresses that exists normal to the plane of crack growth.



(*a*) Tensile K_{res}



(*b*) Compressive K_{res}

Figure 8.13 Initial stress intensity factors for applied loading, residual stresses, and superposition. (*a*) Tensile K_{res}. (*b*) Compressive K_{res}.

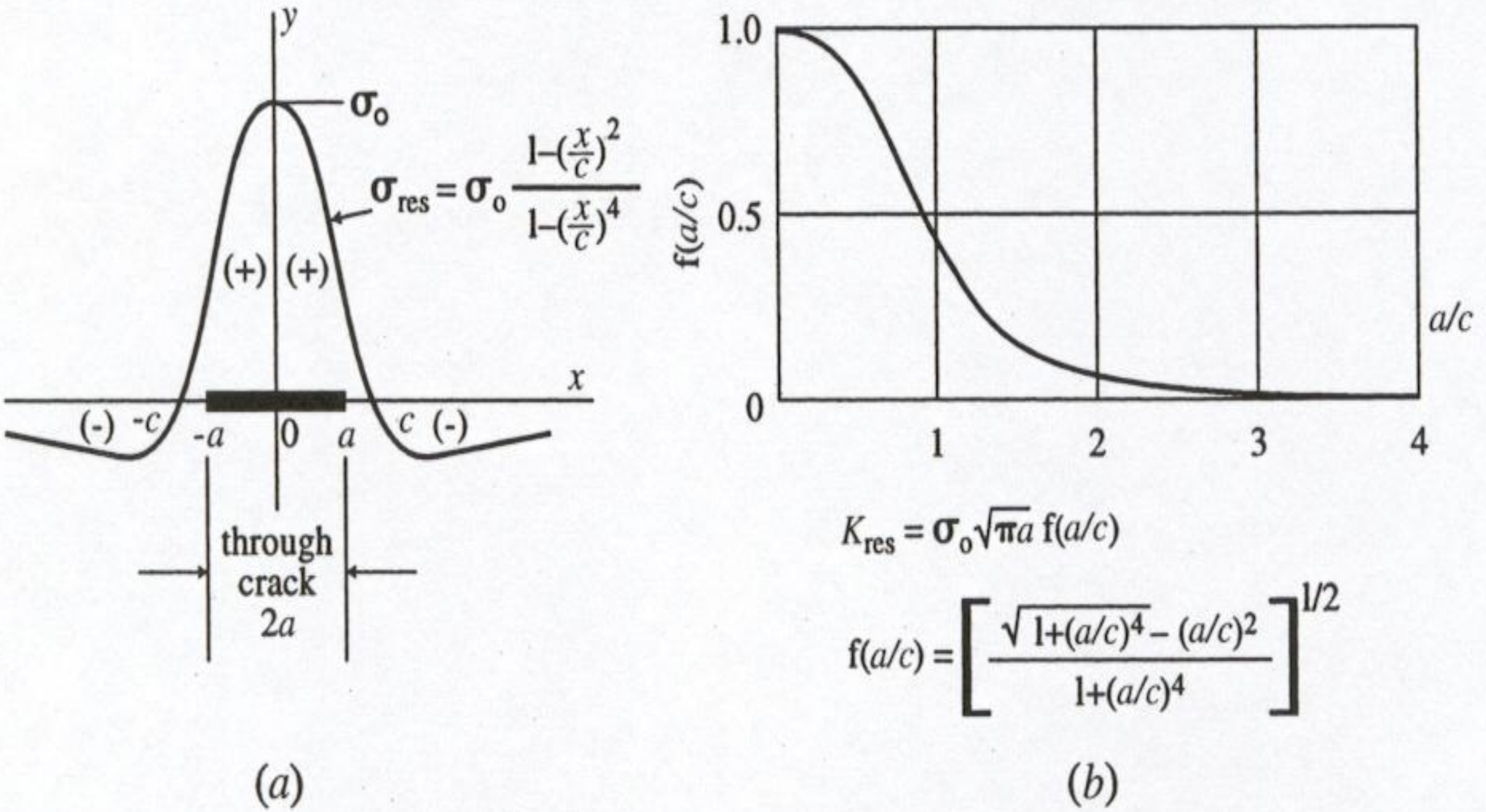


Figure 8.14 Residual stress distribution and residual stress intensity factor, K_{res}, for a longitudinal welded infinite plate containing a central through crack [27,28]. (*a*) Residual stress distribution, σ_{res}, across the plate width. (*b*) Residual stress intensity factor, K_{res} (reprinted with permission of P. C. Paris).

SUMMARY & DOS AND DON'TS IN DESIGN

- Do consider the beneficial and harmful effects of residual stresses for all long-life (high cycle) and intermediate-life fatigue applications and that the greatest influence and importance of residual stresses is at notches.

- Compressive residual stresses efficiently retard the formation and growth of cracks subjected to cyclic loading and thus enhance fatigue resistance. The opposite occurs for residual tensile stresses.

- Don't expect much help from residual stresses in very low cycle (less than 10^3 cycles) applications due to residual stress relaxation.

SUMMARY & DOS AND DON'TS IN DESIGN

- Don't forget the importance of sufficient residual compressive stress magnitude and depth.

- Residual stresses are analogous to mean stresses and therefore can be incorporated into S-N, ε-N, and da/dN-ΔK fatigue life methodologies.

- Since residual stresses are in self-equilibrium, both tensile and compressive values must exist if residual stresses are present. These can be uniaxial, biaxial, or triaxial.

SUMMARY & DOS AND DON'TS IN DESIGN

- During non-uniform inelastic loading, surface regions that yield in tension result in desirable surface residual compressive stresses when the load is removed. Surface regions that yield in compression during non-uniform inelastic loading result in undesirable surface residual tensile stresses when the load is removed.

- Residual stresses can be formed from many manufacturing methods involving mechanical, thermal, plating, and machining operations. These methods can be beneficial, detrimental or have little influence on fatigue resistance.

SUMMARY & DOS AND DON'TS IN DESIGN

- Do remember that grinding and welding can produce very harmful tensile residual stresses and that tensile overloading, peening, and surface hardening can produce very beneficial surface compressive residual stresses.

- Don't overlook the fact that straightening will introduce tensile and compressive residual surface stresses on opposite sides, and that for other than one-way bending, the method will be detrimental to fatigue resistance.

- Shot-peening and surface cold rolling are the two most common mechanical methods for introducing compressive residual surface stresses.

SUMMARY & DOS AND DON'TS IN DESIGN

- Induction hardening, carburizing, and nitriding are popular thermal methods for introducing surface residual compressive stresses for enhanced fatigue resistance.

- Hard plating such as chromium or nickel introduce surface tensile residual stresses and hence are detrimental to fatigue resistance. Soft plating such as cadmium and zinc produce small residual stresses and hence has only a small influence on fatigue resistance. Galvanizing is an exception and is detrimental. However, under corrosive environmental fatigue conditions these plating methods can enhance fatigue resistance.

SUMMARY & DOS AND DON'TS IN DESIGN

- Machining operations most often introduce surface residual tensile stresses and hence decrease fatigue resistance.

- Many of the operations that introduce undesirable residual surface tensile stresses, e.g., chrome plating or machining can have the detrimental aspects reduced or eliminated by additional beneficial treatments such as shot-peening, cold rolling, or carburizing.

- Residual stresses have greater influence in long and intermediate fatigue life than in low cycle fatigue. This is particularly true for higher strength metals.

SUMMARY & DOS AND DON'TS IN DESIGN

- Relaxation of residual stresses can result from plastic deformation and also from thermal stress relief.

- The magnitude and distribution of residual stresses are most commonly obtained using experimental methods such as X-ray diffraction, hole-drilling, or sectioning.