9

Techniques of Surface Stressing to Avoid Fatigue

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9.1 Introduction

The power of surface stressing to save or destroy fatigue life is explained by two facts: *fatigue is a surface effect* and *fatigue is a tension effect.* Like all broad statements, these two are subject to some minor qualifications which will be discussed later. The reader is cautioned not to let the qualifications overshadow these two basic facts which explain more than 99 per cent of all fatigue failures and their prevention by compressive stresses in critical surfaces.

9.2 The Surface Nature of Fatigue

A demonstration of the surface nature of fatigue is shown in Fig. 17.15, which depicts the results of fatigue tests on plates. Some of the plates were pierced by a small hole which acted as a stress raiser. The life of the pierced plates was, of course, much less than the life of the plain plates. But when the surface of the holes was removed from time to time before the damage occurring on this surface had penetrated in depth, the life of the pierced plates was extended to almost the full life of plain plates. The stress concentration itself remained, but the damage (small fatigue cracks) was removed by removing small amounts of surface material.

This demonstration may perhaps appear artificial. Very practical and direct demonstrations are found whenever fatigue failures are examined: the nucleus or origin, as evidenced by the "eye" or center of the oyster-shell zones, is at the surface. The very few exceptional cases occur when the tension stress below the surface is far greater than a permissible surface stress and when, at the same time, the surface stress is kept below the permissible limit by the presence of compressive residual stresses. How this can be achieved will be discussed in this chapter.

9.3 Fatigue Failures as Tension Failures

The effect of tension on fatigue life can be shown and expressed in several ways. Figure 2.14 shows data comparing S-N curves for samples with stress raisers loaded by pulling and loaded by pushing. Those loaded in *pushing* withstood 40,000 psi for millions of cycles without damage. The life at this stress level in *pulling* was only 10,000 cycles, and at half this stress in pulling, the life was still only 100,000 cycles. (No tensile endurance limit was established.) The pulled specimens came apart when they failed. At stresses above 40,000 psi, the pushed specimens developed cracks near the stress raiser but continued to stay in one piece. In other words, pushing was almost harmless, while pulling quickly destroyed the piece.

Most practical stress situations are more complex than the simple push and pull we have considered so far. Endurance under complex combinations of stresses is analyzed in Fig. 7.11. There it is shown how the alternating-stress endurance limit can be increased up to 50 per cent by superimposing a compressive stress and how the permissible range is decreased by a tensile stress. In practice, this means that fatigue failures may be avoided if tensile stresses are decreased, which is borne out by the results of tests on the effect of surface compression. Some of these data will be discussed under the headings of the various techniques.

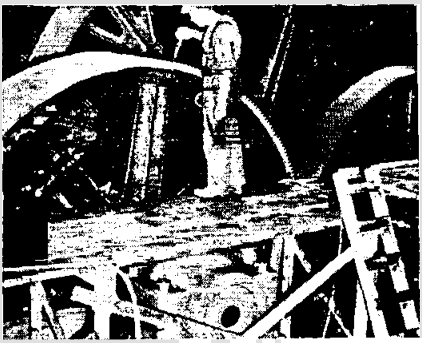


Fig. 9.1 The air-hammer peening of large gears. Failure averted by hammer peening in place; mine-hoist gears 12 ft diameter by 30 in. wide. (*Courtesy of J. O. Almen.*)

9.4 An Example

Since fatigue is both a surface effect and a tension effect, all techniques of surface stressing to reduce fatigue aim at producing *an armor of compressed material* (i.e., material which "wants to expand") on critical surfaces. Figure 9.1 shows a rather spectacular example of the application of such a technique in a manner which may seem primitive but which was highly successful.

The large gear visible in the figure is used to hoist nickel ore out of a mine. Teeth began to crack early in World War II, when nickel was essential and replacement gears were unobtainable. To prevent the imminent complete breakdown, J. O. Almen advised the operators to cut out or relieve the cracked parts of the teeth and to hammer peen the root fillets during the brief periods of rest of the hoist, beginning with the cracked teeth and continuing until all roots had been peened. As a result of this prophylactic massage, the gear continued to operate all through the war. Peening had produced the compressed armor in the critical areas, and fatigue was prevented.

9.5 Classification of Techniques

Peening is only one of many techniques of compressive stressing of surfaces. To arrange these techniques in some order we can classify them as follows:

A. Cold local yielding
  1. Overloading
  2. Straightening and cold forming
  3. Peening
    a. Hammer peening
    b. Shot peening
    c. Tumbling
  4. Surface rolling
  5. Burnishing

B. Hot local yielding
  1. Heat softening under stress
  2. Thermal contraction
    a. Quenching
    b. Flame cutting (damaging tensile stress)
    c. Welding
    d. Grinding (damaging tensile stress)

C. Transformation
  1. Quench hardening
  2. Carburizing
  3. Nitriding
  4. Plating

Often several of these techniques are used in combination, e.g., carburizing and shot peening.

SURFACE STRESSING BY COLD LOCAL YIELDING

9.6 Overstressing

Automobile suspension springs and many other springs are commonly overstressed before they are put in service. The operation is known as presetting, scragging, or bulldozing (Fig. 9.2). When the bulldozing load

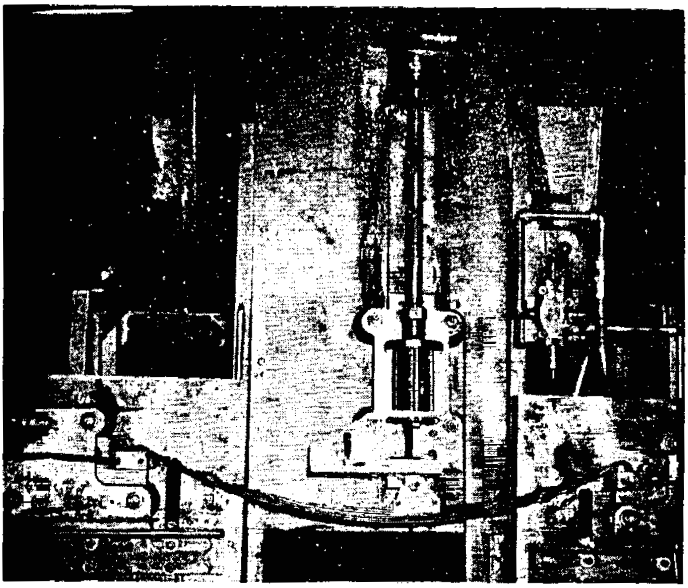


Fig. 9.2 Automotive leaf spring undergoing treatment in a prestressing machine for the purpose of inducing residual stresses.

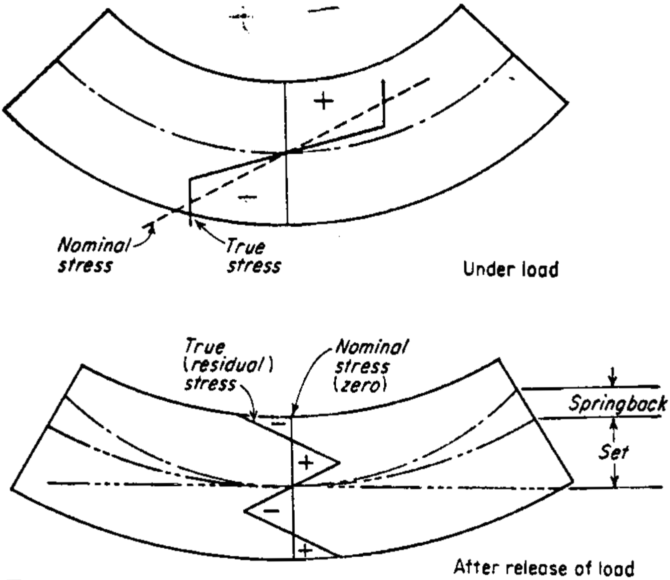


Fig. 9.3 Residual stresses produced by bending beyond yield.

is applied, the highly stressed surface layers yield. When the bulldozing load is removed, elastic recovery brings the spring part of the way back toward its original shape. In the new free shape those surfaces which yielded in tension now are stressed in compression, and surfaces which yielded in compression now are stressed in tension. Core stresses are opposed to the adjacent surface stresses. When loads are again applied, the residual stresses oppose the load stresses in the highly stressed regions; they add to the load stresses in the regions of low stress. Analyses of these effects were given by Upton[11] and by Timoshenko;[10] Figs. 9.3 and 9.4 illustrate the analyses. The same principle is applied in the manufacture of torsion-bar springs. A comparison of residual torsional stresses measured after fatigue cycles with residual stresses derived by Upton's method from presetting data is shown in Fig. 9.5. An older application of the same principle is used in the manufacture of gun tubes, where it is called autofrettage. The thick-walled tube is subjected to high internal pressure which expands it and leaves residual compressive stresses on the surface of the bore. (Figure 9.6 shows the approximate stress history of the process.) Overstressing is also used in the assembly

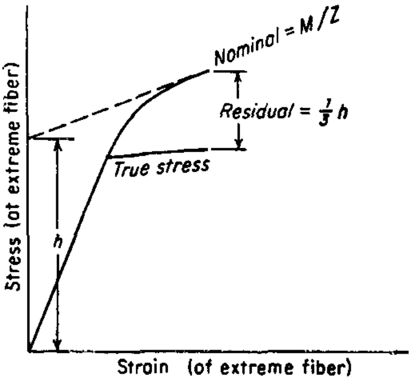


Fig. 9.4 Residual stress produced by bending beyond yield, derived from load-deflection curve for rectangular prism.

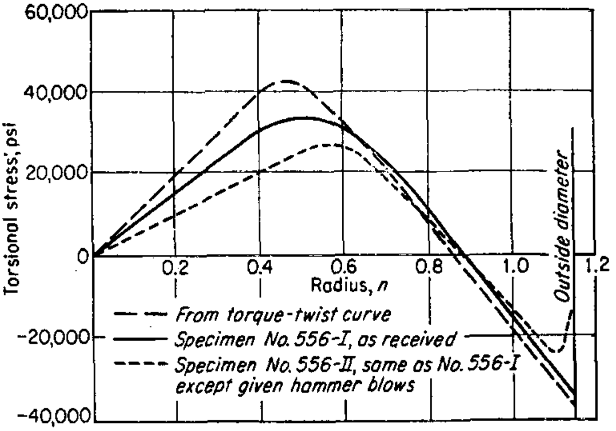
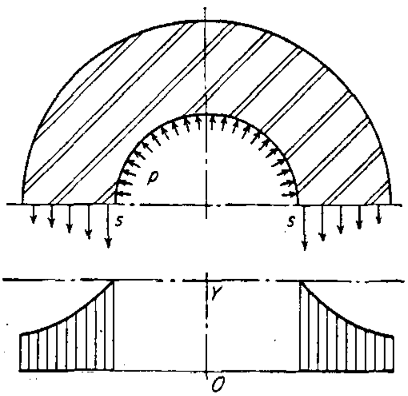


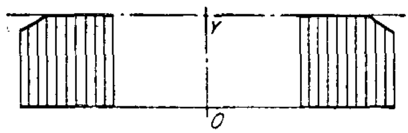
Fig. 9.5 Residual stresses produced by twisting, predicted and measured.[23]

of railroad wheels and in overspeeding turbine disks before putting them in service.

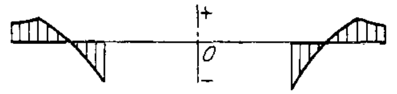
The use of overstressing is limited by the ductility of the highly stressed region. Ductile yielding results from a difference between the principal stresses, e.g., high tension along one axis and low tension or compression normal to that axis; fracture results from excessive tensile stress.



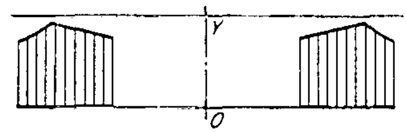
(a) Distribution of stresses in a gun barrel from low internal pressure



(b) During overstressing (or autofrettage)



(c) After autofrettage, showing residual stresses



(d) During firing after autofrettage

Fig. 9.6 Approximate stress history of the autofrettage process.[24]

In applying overstressing to counteract stress concentrations in sharp grooves, one must keep in mind that near the bottom of the groove the material may be subject to tension along all three principal axes and therefore may have no ductility. In applying overstressing to springs, one observes that much higher overloads can be used in torsion than in tension. The different ratio of maximum shear stress to maximum tension stress explains this difference. In hardened torsion bars it was necessary to shot-peen before overstressing; the resulting compressive stress decreased tension and thereby increased ductility.

Although overstressing is used to avoid fatigue, its chief purpose usually is to increase the ability to carry loads in one direction. The science of limit design is concerned with this use.[12]

In limit design, the unequal distribution of elastic load stresses is equalized by yielding the part or structure, so that under load the stress is evenly distributed and without load the parts are under residual stress: negative on the sections with high stress range and positive on the sections with low stress range.

The beneficial results of overstressing apply only to loads which are much higher in one direction than in the opposite direction, such as centrifugal loads and spring loads. In reversed loading, the effect is lost. This must be kept in mind when setting up tests; the results of reversed-load fatigue tests will not apply to service where the load is mainly in one direction.

9.7 Straightening and Cold Forming

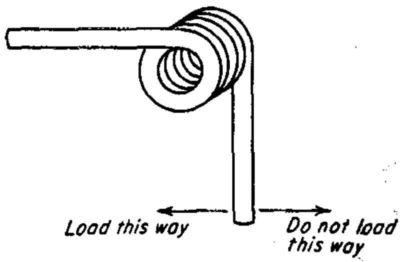


Fig. 9.7 Direction of forming should be the same as direction of loading.

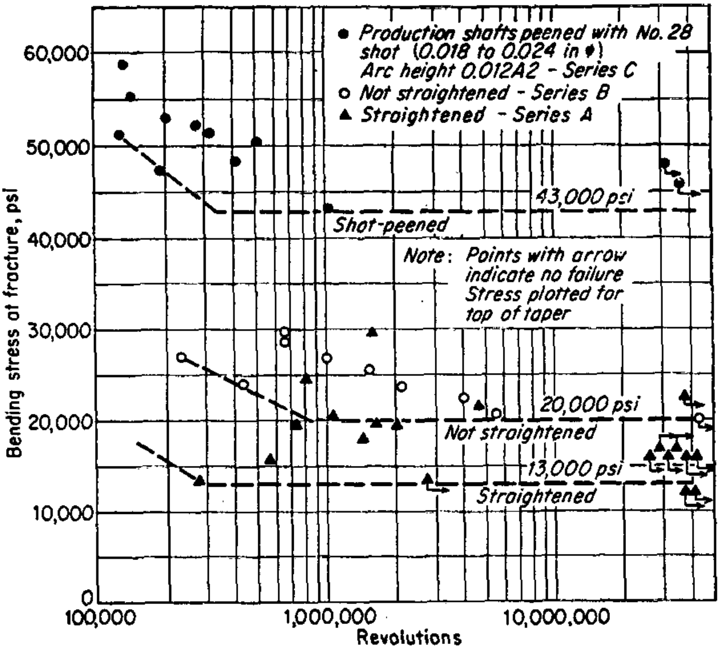


Fig. 9.8 Straightening decreases the fatigue life of axle shafts; peening increases it.[33]

The residual stresses set up by straightening or by cold forming have the same distribution over the cross section as those set up by overstressing, and they may have similar beneficial effects if the forming load is applied in the same direction as the service load. Unfortunately, the direction of forming loads is usually not related to service loads, and severe damage to fatigue life may result from forming loads. Helical torsion springs and clock springs are well-known examples of this relation: they should be loaded in service in the same direction as the winding load, i.e., in the direction which tightens the coil (Fig. 9.7). The effects of straightening automotive rear axles were investigated by Horger and Lipson.[33] They found that cold straightening reduced the endurance limit from 20,000 psi to as low as 13,000 psi. The endurance limit of cold-straightened axles was raised to above 43,000 psi by using the favorable but shallow residual stresses produced by shot peening (Fig. 9.8). The technique has been used since 1935.[46] The Horger and Lipson investigation very graphically demonstrates the overwhelming importance of surface stresses in fatigue and the great economic importance of residual stresses. Similar results on crankshafts were obtained by Schmidt.[41]

Fig. 9.9 Hammer peening a shaft.

Any cold-forming operation creates residual stresses. The ones trapped by bending a rectangular bar without stress concentration may be up to 50 per cent of the yield strength, as shown by analysis of the equilibrium. Strain hardening will increase the trapped stress to somewhere between 50 per cent of the original yield strength and 50 per cent of the final strain-hardened yield strength.

9.8 Peening

The crankshafts investigated by Schmidt[41] were straightened either by bending or by hammer peening, with the peen-straightened shafts carrying at least 20 per cent more bending moment without fatigue failure. Results of hammer peening on a large gear were mentioned in Sec. 9.4. Figure 9.9 shows the setup used for hammer peening the drive shafts of

Fig. 9.10 Views of a hammer-peened shaft.

Fig. 9.10. Here hammer peening is used to overcome the stress concentration and the unfavorable residual stress created by plug-welding a sleeve to a cold-finished shaft.

Peening with rotary hammers is also used, particularly to overcome the damaging effect of small transverse holes. The hammers are actuated by a rapidly rotating eccentric weight, as indicated in Fig. 9.11.

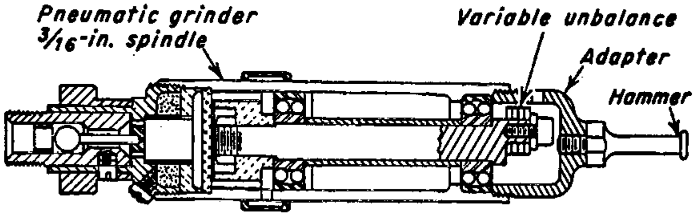


Fig. 9.11 Standard pneumatic portable grinder converted to a peening tool by incorporating a centrifugal unbalance on the shaft. (Research Laboratories Division, General Motors Corporation, Ref. 4.)

9.9 Mechanism of Peening

Peening produces a crack-resistant layer of compressively stressed material by forming indentations or dimples which overlap and eventually cover the surface. In forming a dimple, the peening tool squeezes the material plastically depthwise and stretches it along the surface, radially away from the tool. When the tool is removed, the material expands normal to the surface; the elastic core produces contraction along the surface. The contraction will now squeeze the stretched surface of the dimple, producing a compressive residual stress; the expansion normal to the surface cannot produce a residual stress because there can be no stresses normal to a free surface. (When the tool was applied, the surface was not free and stresses could exist.)

In a very thin sheet the compressed layer under a single dimple could conceivably extend all the way through the material, held in equilibrium by a stretched ring around the dimple. With continued peening, the entire sheet would stretch, leaving very little residual stress. In thicker material, tension below the surface balances the residual compression in the surface. The compressed surface layer has a higher tolerance for alternating stresses (as shown in Chap. 7) and prevents cracks from growing even when they have been started by surface corrosion, by cracked plating material, or by fatigue of a shallow decarburized skin.[40]

Figure 9.12 shows the distribution of residual stresses in a hammer-peened specimen of annealed 1030 steel, $1\frac{3}{4}$ in. square. The maximum residual stress is 42,000 psi, about $\frac{1}{8}$ in. below the surface. The compressive stress changes to tensile about $\frac{5}{16}$ in. below the surface.

Usually, when the peening tool is a ball or has a spherical radius, the depth of the compressed layer is about the same as the diameter of the dimples, and the highest compressive stress in this layer is about half the yield strength. This depth will be found if the material is homogeneous and the peening tool considerably harder than the peened material. The stress will be found to be half the yield strength if there is little or no strain hardening. In the example of Fig. 9.12 the depth of $\frac{5}{16}$ in. is about equal to the diameter of the dimples. The stress of 42,000 psi is about 80 per cent of the original yield strength of the annealed 1030 specimen; the yield strength has been increased by the severe deformation.

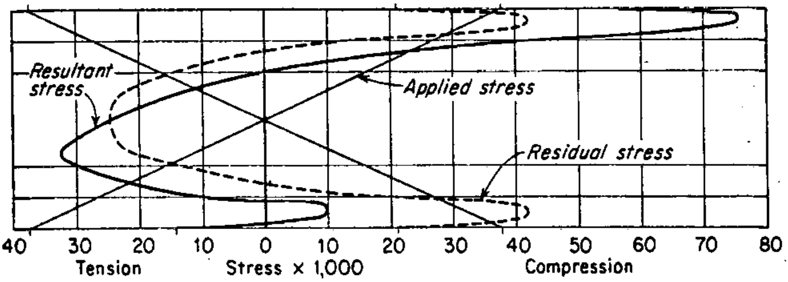


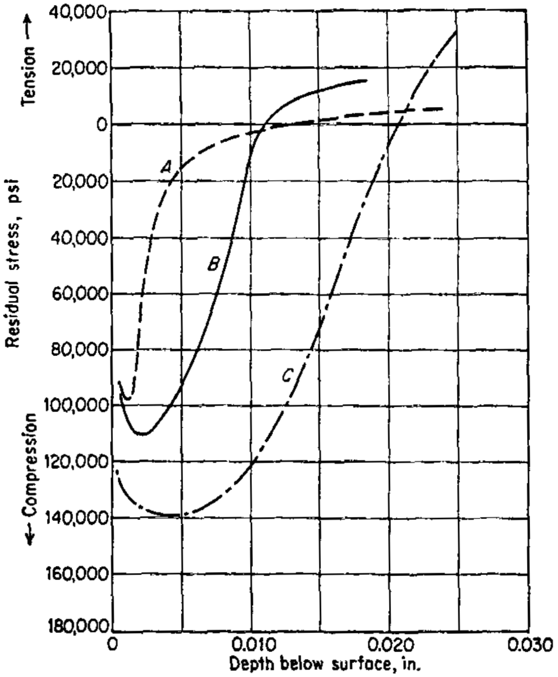
Fig. 9.12 The residual stresses induced in SAE 1030 annealed-steel specimen by hammer peening; also resulting stresses acting at the start of fatigue test.[20]

9.10 Shot Peening

Shot peening is accomplished by small round shot impinging on the surface with high velocity. This is the most versatile of surface-stressing techniques, applicable to all metals and to all shapes excepting only the insides of closed vessels, which cannot be reached by the shot.

Sizes of shot range from about 0.007 to about 0.175 in. diameter, with the extremes more difficult to handle than the intermediate sizes. Large shot sizes are used to produce deep layers of compressive stress; small shot sizes are used to reach into small radii. Shot velocities are of the order of 100 to 200 ft/sec. The depth of the resulting compressed layer is between a few thousandths and a few hundreths of an inch, depending on shot size and velocity; in this layer the maximum stress occurs slightly below the surface. Figure 9.13 shows typical residual stresses measured in shot-peened samples of automobile leaf-spring stock of hardness Rockwell C-48. The magnitude of the maximum compressive stress is about half the strain-hardened yield strength. If the part is externally loaded while being peened, the residual compressive stress will be higher. For instance, on leaf-spring specimens of hardness Rockwell C-47 to C-50, maximum residual compressive stresses of specimens peened free were from 96,000 to 120,000 psi. When peened under an applied strain of 0.54 per cent, the maximum residual stresses were 134,000 to 147,000 psi. Figure 9.14 compares residual stresses induced in various materials.

The fatigue-life improvement and endurance-limit increases which result from shot peening may reach very high figures. The results on rear-axle shafts where the endurance limit was raised from 13,000 to over

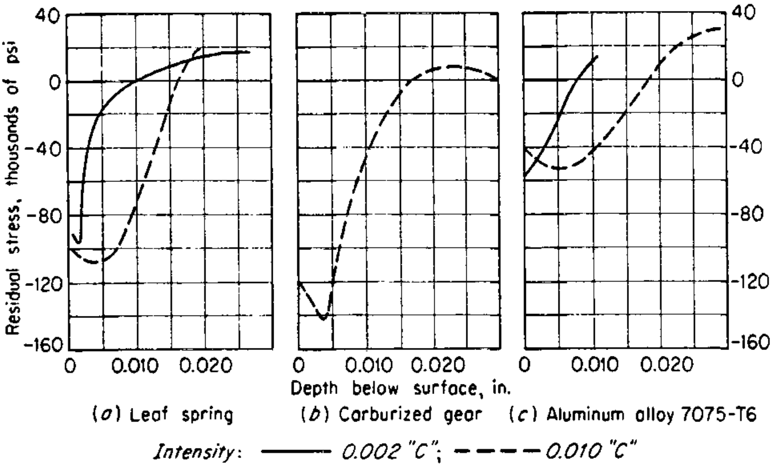


Specimen	Hardness, Rockwell C	Shot size	Intensity	Strain while peening
A	48.5	230	0.0049C	None
B	49.7	230	0.0067C	None
C	47.2	660	0.0091C	0.0054

Fig. 9.13 Residual stresses in shot-peened leaf springs.[39]

43,000 psi were quoted above in connection with straightening. On coil springs, the safe stress range may in some cases be increased from 75,000 to 125,000 psi.[43] These are high figures selected from the extensive literature. The actual permissible increase of load or the expected extension of life depends, of course, on the application. There is evidence that the residual peening stress may be subtracted from the load stress, provided the total maximum "net" stress does not exceed the dynamic repeated-load yield strength at either end of the load cycle.

The economic importance of shot peening results not only from the increase in permissible load, but also from the reduction in processing cost because it eliminates the need for costly fine finishing. A poor surface after shot peening is superior in fatigue life to an expensive high-grade surface without shot peening. Forged and shot-peened connecting rods are superior to polished connecting rods, as shown in Fig. 9.15. Severe grinding followed by peening is superior to the more expensive gentle grinding, as shown in Fig. 9.16, provided, of course, that the



(*a*) Leaf spring (*b*) Carburized gear (*c*) Aluminum alloy 7075-T6

Intensity: ——— 0.002 "C"; – – – – 0.010 "C"

Fig. 9.14 Residual stresses induced by shot peening various materials.

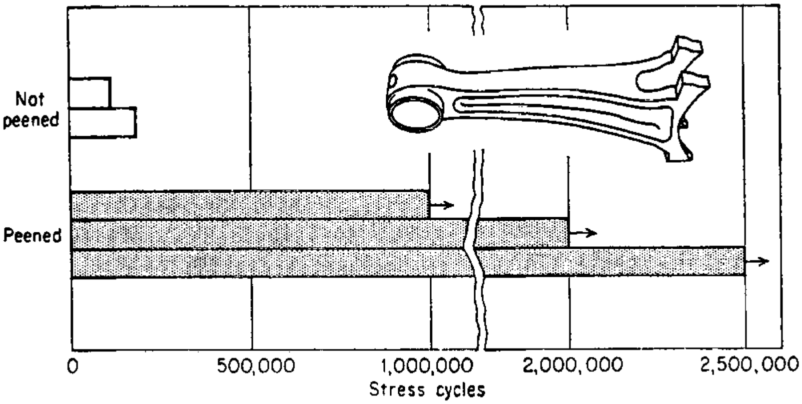


Fig. 9.15 Fatigue durability of polished vs. rough-finish and shot-peened forked connecting rods.[38]

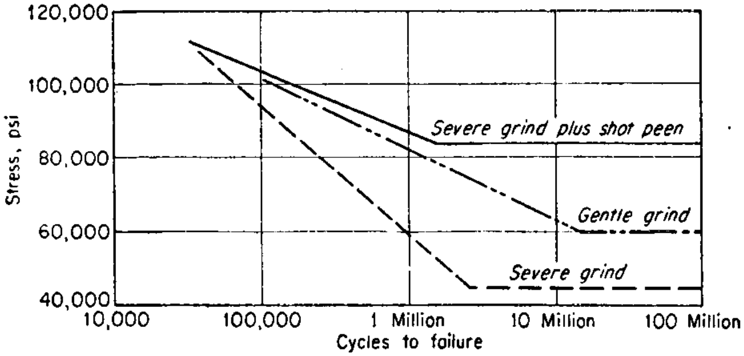


Fig. 9.16 The effect of grinding and peening on reverse-bending fatigue strengths of flat steel bars, Rockwell hardness C-45.[42]

grinding was not so severe that the surface actually cracked. Shallow decarburized layers which otherwise would cut fatigue life short can be tolerated if the surface has been peened.[40]

9.11 Shot-peening Equipment

The shot used in peening are thrown either by air pressure or by an impeller wheel. Figures 9.17 and 9.18 show examples of the two types

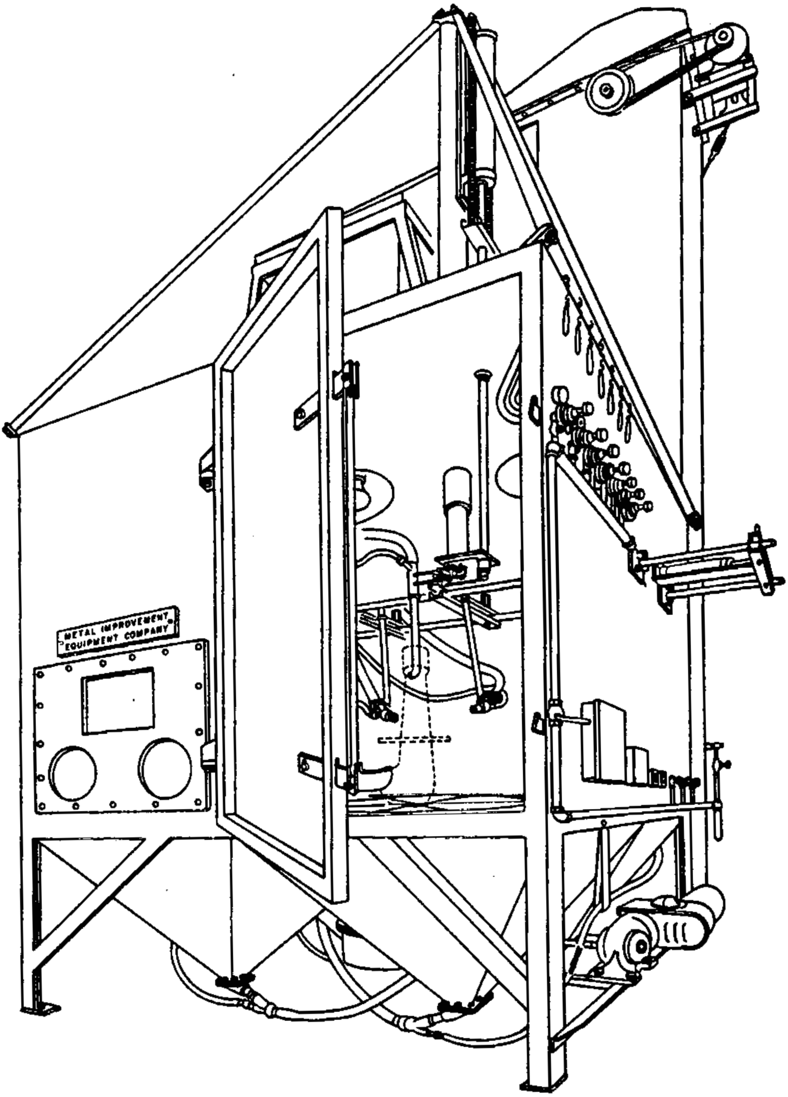


Fig. 9.17 Air-blast peening machine. (*Courtesy of Metal Improvement Equipment Company.*)

of equipment. The wheel method is generally used for large production applications, where it is more economical than the air method. The air method is more flexible and, therefore, preferred where different kinds of parts are peened in one machine. A wheel will throw about 100 to 500 lb of shot per minute; a single air nozzle will throw about one-tenth as much but can concentrate it on a smaller area. In most applications, the work is moved under the shot stream by suitable automatic devices such as conveyors, rotating fixtures, turntables with or without planet tables, rollers, or carriages. Small parts may be peened in a barrel where they are tumbled in the shot stream. It may be necessary to protect certain areas such as oil holes, fine threads, or journal surfaces from the shot stream. These areas are masked off by a resilient material such as rubber cups or tape.

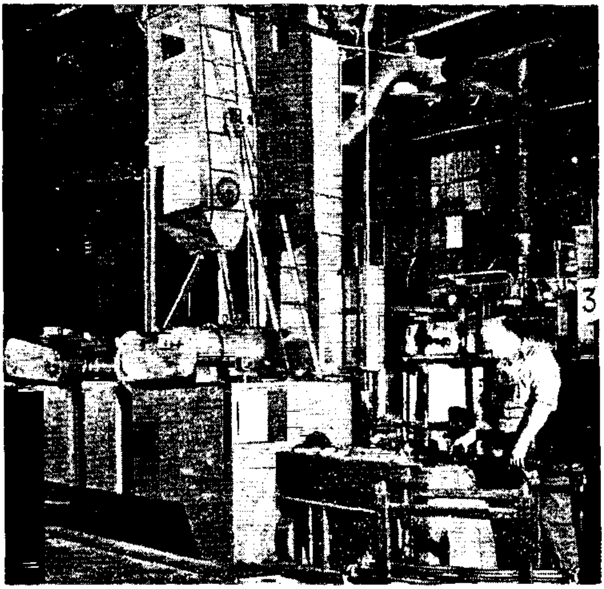


Fig. 9.18 Airless shot-peening machine. (*Courtesy of the Wheelabrator Corp.*)

After being thrown at the work, the shot falls into a hopper and is returned by elevators for further throwing.

9.12 Shot-peening Control

In view of the economic importance and relatively recent development of shot peening, a few words about specifications may be in order. We are interested in obtaining a compressed armor on the peened surfaces. The completeness of the armor can often be checked visually by making sure that the surface is well covered by shot impressions. However, peening works even when the shot is no harder than the surface to be peened, in which case it may not leave a visible dimple. The depth of the compressed layer and the amount of stress cannot be checked without destroying the piece, and the desired end result can be proved only by fatigue tests. To overcome these difficulties, the Almen gage is used.[7] Figure 9.19 shows the gage with a standard test strip in place under the anvil. One face of the standard test strip, made of flat steel hardened to Rockwell C-47 ±3, is exposed to the shot stream in the same manner as the surface for which peening is specified. As it is peened, compressive stresses are trapped in the exposed face. These stresses produce a bending or curvature of the strip. The curvature is measured in terms of the arc height, read on the gage. This arc height is the "Almen intensity."

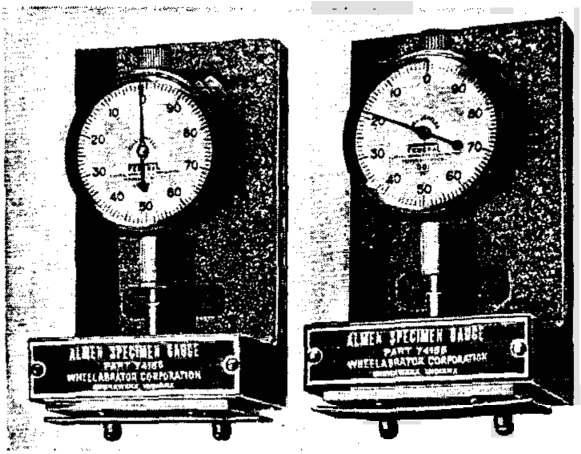


Fig. 9.19 Almen gage.

The Almen intensity is the best and most practical method of specifying shot peening, but by itself it does not fully define the process or the results. It measures, in effect, the bending moment of residual stresses set up in the standard test strip. Complete coverage of the surface by peen marks is tacitly required when an Almen intensity is given, as the same Almen intensity could be obtained by incomplete peening in a more severe blast. Equal Almen intensities can be obtained by small shot at high velocities or by larger shot with lower velocities. If the part to be peened is made of steel similar to the steel of the test strip, we may assume that equal Almen intensities mean equal peening results. On aluminum-alloy parts, it has been shown that, at equal Almen intensities, small shot produces less effect on the aluminum than larger shot, as measured by depth of compressed layer and amount of compressive stress. Nonstandard test strips, made of the same material as the peened part, are used by some to overcome this difficulty.

9.13 Surface Rolling

In certain cases surface rolling can be the most practical technique of trapping compressive stresses in a surface. This will be true when the parts can be surface-rolled in connection with some other necessary production process, or where very small regular radii must be reached, as in small screw threads, or where a very deep compressive layer is desired, as in railroad axles. Much work has been done[6] on surface rolling of railway axles and crankpins. Figure 9.20 shows a typical setup. Radii of rollers range from $\frac{1}{4}$ to $1\frac{1}{2}$ in., with roller pressures up to 10 tons. The depth of the compressed layer can be around $\frac{1}{2}$ in. Rolling can be specified in terms of fictitious Hertz stresses, i.e., in terms of the contact stresses which would be obtained if the material were elastic without yielding. These fictitious Hertz stresses are of the order of 200,000 to 800,000 psi, depending mainly on the hardness of the workpiece (Fig. 9.21).

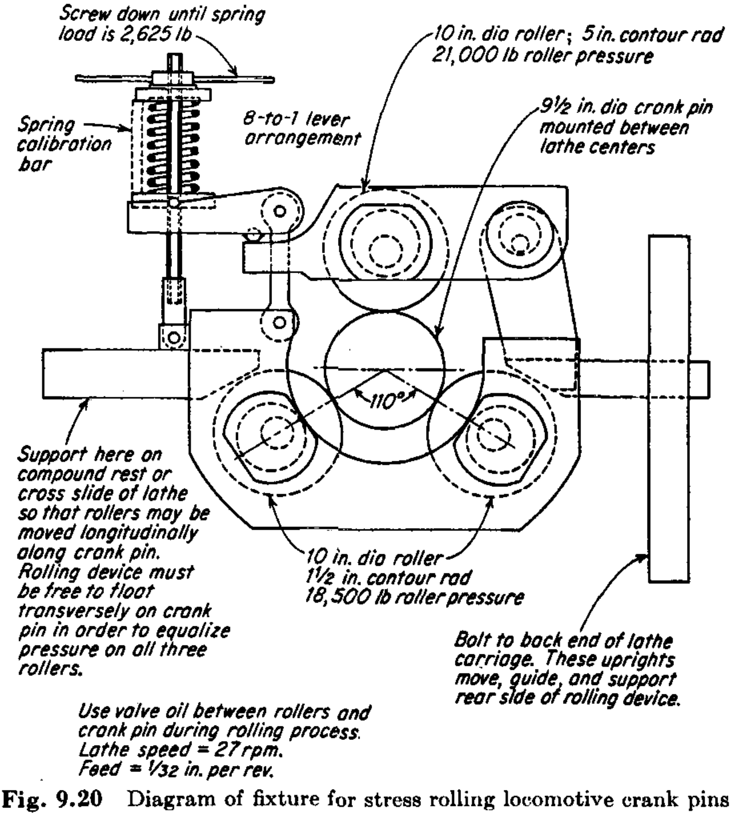


Fig. 9.20 Diagram of fixture for stress rolling locomotive crank pins.[6]

A particularly interesting fatigue-test result is summarized in Fig. 9.22. Here the depth of fatigue cracks in the press-fitted "root" of the crankpin, measured after 84 million cycles, is plotted over the applied bending stress. It can be seen that measurable cracks appear at stresses as low as 5,000 psi and that pins without surface rolling are broken at 11,000 psi. For crankpins similar in all respects except that they were surface-rolled, the cracks are only about one-tenth as deep for the same stress, and twice the "unrolled" limit of 11,000 psi is supported without breaking the pins. These crankpins were 9½ in. in diameter. For the interesting details see Ref. 6.

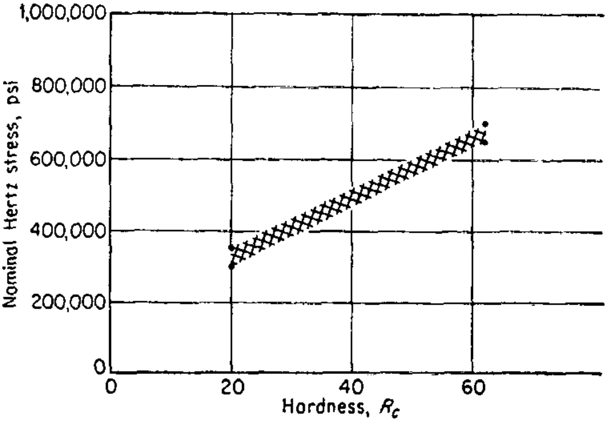


Fig. 9.21 Rolling pressure for fillets. (*Courtesy of J. O. Almen.*)

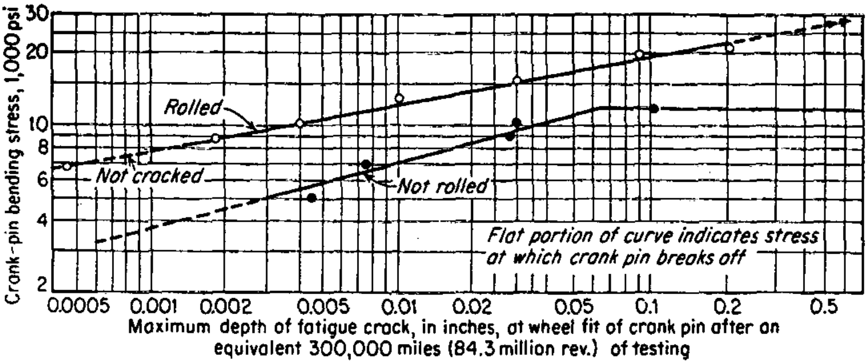


Fig. 9.22 Surface compression delays the growth of cracks.[6]

At the other end of the scale we find the roots of threads being rolled with rollers of ½ in. diameter, 5 mils (0.005 in.) tip radius, and 40 lb load. This treatment chased the failure from the thread root up into the fillet under the bolt head until this fillet was also rolled and failures were eliminated. A patented roller for fillets is shown in Fig. 9.23. The special shape of the roller is designed to cover the entire area of the fillet by increments without having to traverse the roller in an arc.

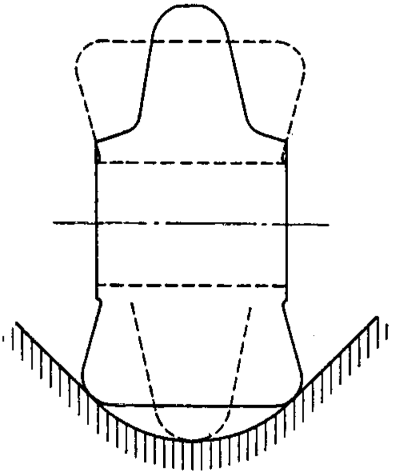


Fig. 9.23 Special roller for stressing fillets, schematic.

9.14 Coining

A protective armor of compressed material around a stress raiser such as a hole can be produced by coining the edge of the hole, i.e., by deforming the edge cold by pressing a cone into the hole. This was done, for instance, on clutch springs schematically shown in Fig. 9.24 to overcome the stress concentration at the holes between the fingers. Another method consisted of cold pressing round grooves into a shaft on both sides of a transverse hole. An increase in endurance limit from 15,000 to 20,000 psi has been obtained by this method on $7\frac{1}{4}$-in.-diameter shafts of 1050 steel, with 0.172-in.-diameter reamed oil holes (Horger[1]).

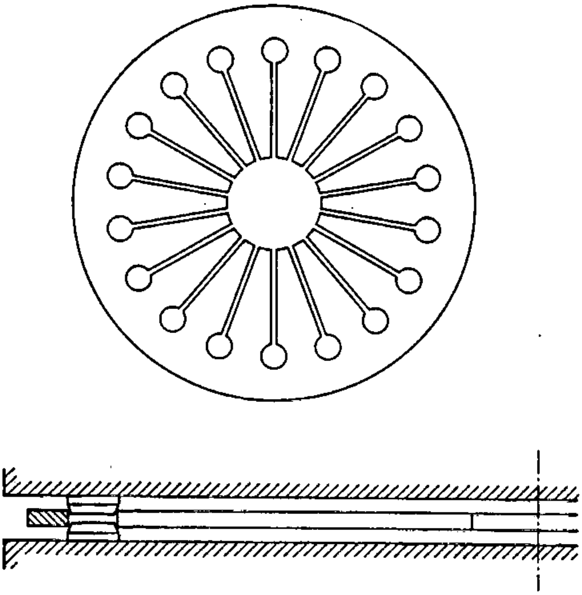


Fig. 9.24 Coining holes in Belleville-type spring to produce favorable residual stresses and thus prevent fatigue.

9.15 Surface Stressing in Finishing Operations

Surface stresses produced in cold forming were mentioned in Sec. 9.7, and grinding stresses will be discussed in connection with thermal contraction in Sec. 9.17.

In connection with peening, rolling, and coining, we are reminded of the various finishing operations which produce incidental stresses by similar cold deformations of the surface. Barrel finishing in tumbling barrels, where a load of parts is revolved together with stars, balls, or similar objects, will do some peening. Burnishing will compress surfaces in a manner similar to surface rolling. These effects are not as consistent or as deep as the effects of intentional surface stressing, but they will influence fatigue durability and should be considered in comparing parts produced by different shop procedures.

SURFACE STRESSING BY HOT LOCAL YIELDING

9.16 Heat Softening

In the cold-working techniques which were reviewed, the trick is to impose tensile strains which on the surface of the part exceed the yield strain, but in the interior remain below the elastic limit. Elastic recovery of the interior will then produce the desired residual compressive surface stresses.

In a variation of this technique, a steel shaft of 40,000 psi yield strength might be stretched 0.12 per cent, corresponding to a tension of 35,000 psi. While thus stretched, its skin would be heated (by induction or flame) to 600°F. At this temperature, the yield strength would be only 30,000 psi.

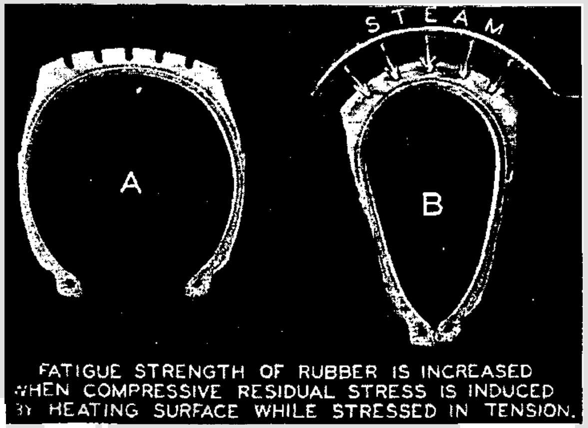
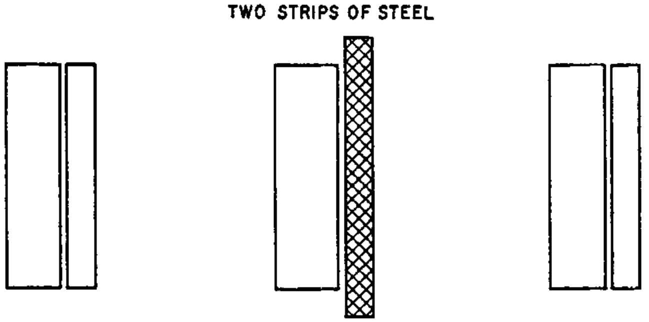


Fig. 9.25 Residual stress produced by heat softening. (*Courtesy of J. O. Almen.*)

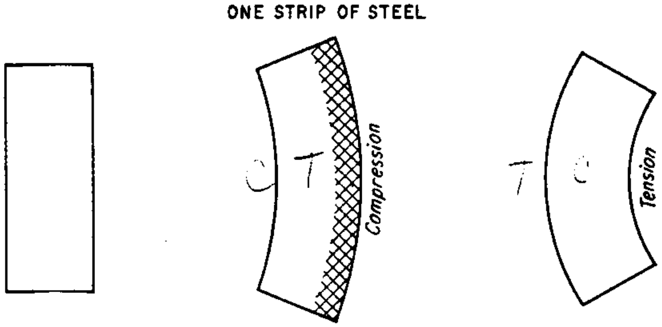
The skin would yield. If the piece were held in tension until cold and then released, the entire shaft would contract slightly less than 0.12 per cent, leaving a tensile stress of, say, 1,000 psi in the core and a compressive stress of 5,000 psi in the skin. This process is not practical for steel, but the tempering of rubber-tire treads is being carried out in such a manner by applying heat while the roots of the grooves are stretched (Fig. 9.25).

9.17 Thermal Contraction

Instead of imposing it mechanically, strain can be produced by nonuniform thermal expansion and contraction. If such a strain is combined with local variations in yield strength, which are produced by temporary thermal gradients, high residual stresses can be set up (see Fig. 8.2). This process can work for or against the designer.



(*a*) Both cold (*b*) Heated strip expands (*c*) Strip returns to original shape when cooled



(*d*) Cold (*e*) One side heated and upset (*f*) Cooled, upset side shrinks

Fig. 9.26 What cools last is in tension, unless there is a transformation with an expansion.

As materials usually contract and increase their yield strength in cooling (steel during quench hardening is a notable exception), the part which cools first will upset the warm and yielding remainder and will in turn be compressed elastically when the remainder cools and contracts. Conversely, the part which cools last will have been upset but will be prevented from further contraction by the stiff cold material near it. It will, therefore, be in tension. Figure 9.26 is a schematic illustration of this principle. As early as 1845, the residual stress from nonuniform cooling was used to produce compression on the inside of gun bores by casting them hollow and cooling from the inside, according to the Rodman patent of 1847.[36]

Tempered glass is an application of this technique. The surface of hot glass sheets is cooled by air jets. The surface cools first and will therefore have compressive residual stresses. Since glass is inherently strong, but has (like most materials) a surface vulnerable to tensile stresses; the strength level of the glass is raised by the full amount of the trapped compressive stress to several times the strength of the untreated glass.

The principle that what cools last is in tension explains many failures of machine parts: flame-cut surfaces are in tension and therefore weak; note, however, that flame-*hardened* surfaces are in compression, as explained in the next section. Grinding cracks are the result of high tensile cooling stresses. Weakness of ground surfaces in fatigue results from these same tensile stresses. As soon as the tensile residual stresses are overcome by the compressive residuals of peening, the weakness disappears (Fig. 9.16).

The importance of thermal stresses in welding has long been recognized, and techniques for their control by proper arrangement of the welds and proper sequences of welding operations have been worked out.

SURFACE STRESSING BY TRANSFORMATIONS

9.18 Quench-hardened Steel

The usual contraction of metals during cooling is reversed in the quench hardening of steel. The hard kind of steel, martensite, which is produced in quenching, takes up more space than the steel from which it is formed. The expansion takes place on cooling, at temperatures from 700°F and below, where the steel already has a high yield strength. The amount of linear expansion is of the order of 0.5 per cent, depending on composition and completeness of transformation. As a biaxial strain of 0.5 per cent corresponds to a biaxial stress of 200,000 psi (if the yield strength does not limit it to a lower value), it will be readily understood that in quenched steel we find high residual stresses.

Quench cracks are a striking indication of such stresses. They occur most readily at points of section change when the core transforms after the skin has already hardened. In quench-hardened steel, the rule that what cools last is in tension does not hold; what cools last may well be what last transforms to martensite and may, therefore, be in compression. In tubes quenched from inside, the outside skin (which transforms last) will be in compression. Tempering at high temperatures will relieve the high residual stresses; it is the traditional method of achieving fatigue resistance. More recent methods make use of the residual stresses to obtain compression on the critical surfaces and a fatigue resistance far above the standard of a "stress-free" specimen.

9.19 Shallow Quenching

A shaft of 2 in. diameter made of plain carbon steel (1046) will harden to Rockwell C-60 on the surface if quenched severely. Toward the center the hardness will fall off rapidly to Rockwell C-30 at ¼ in. below the surface, and slightly less at the center. The steel is shallow quenching (Fig. 9.27). The residual-stress pattern will be high compression in the skin—mainly because of the expansion in hardening—and tension in the core, a very desirable distribution. Such shafts have been extensively used for severe service such as automotive rear axles and tank torsion bars. The correct application of residual transformation stresses has permitted the use of plain carbon steel where more conventional practice would require deep-hardening alloy steels. Figure 9.28 shows fatigue-test results for axle shafts of deep-hardening alloy steel and of shallow-hardening carbon steel.

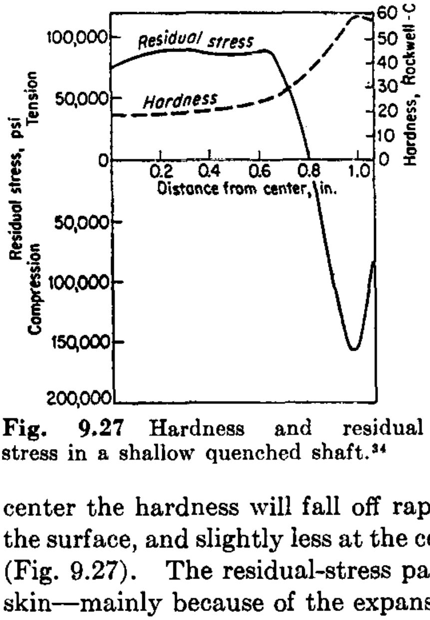


Fig. 9.27 Hardness and residual stress in a shallow quenched shaft.[34]

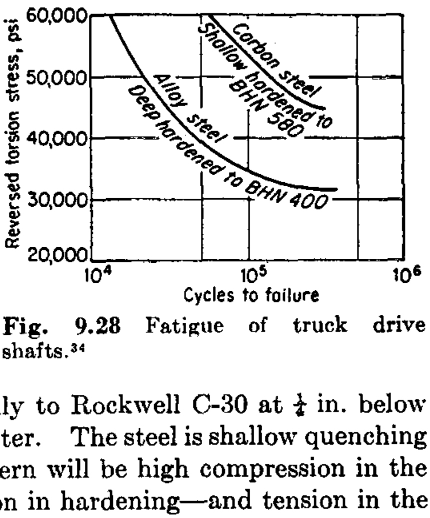


Fig. 9.28 Fatigue of truck drive shafts.[34]

9.20 Shallow Heating

Transformation of the skin to martensite, with the core remaining soft, and the resulting benefits of compressive residual stresses in the surface can be obtained by rapid heating of the surface immediately

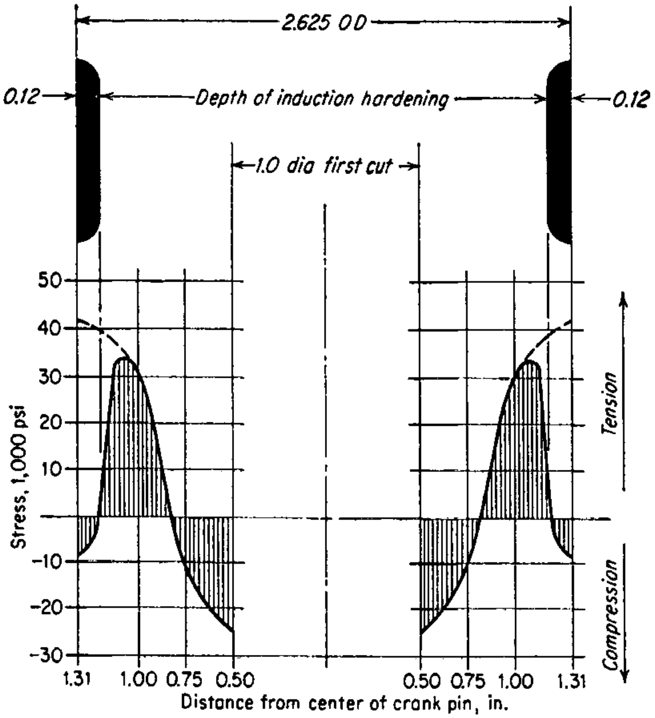


Fig. 9.29 Surface compression and subsurface tension produced by induction hardening.

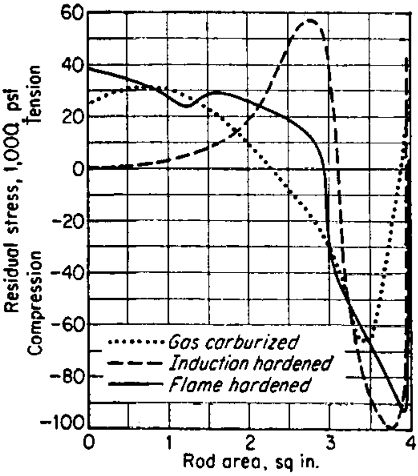
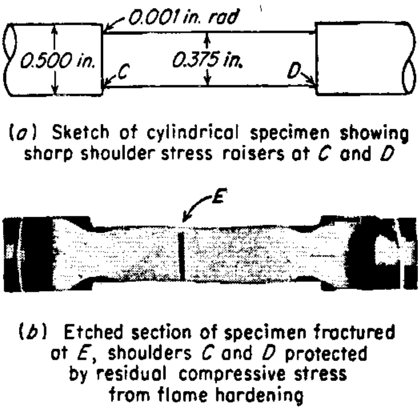


Fig. 9.30 Residual stresses in rods surface-hardened by three methods.[27]



(*a*) Sketch of cylindrical specimen showing sharp shoulder stress raisers at *C* and *D*

(*b*) Etched section of specimen fractured at *E*, shoulders *C* and *D* protected by residual compressive stress from flame hardening

Fig. 9.31 Surface compression by shallow hardening.[44]

followed by quenching, so that the core has no time to get hot enough to transform before the surface is already quenched. This requires high heat flow into the surface; it is achieved in production by either induction hardening or flame hardening.[44,85]

In considering the residual stresses produced by these shallow-heating methods, it must be kept in mind that only the expansion on transformation can produce compression. The contraction on cooling without transformation produces tension, just as flame cutting does. Somewhere between the hardened skin and the cool core there may be a layer which was heated enough to upset it but not enough to transform it, and this layer will be in tension. Figures 9.29 and 9.30 show residual stresses measured in induction-hardened parts. The tensile layer beneath the skin is evident in both. Figure 9.30 also shows residual stresses measured in a flame-hardened part similar to the induction-hardened rods of the same figure. A striking demonstration of fatigue improvement by flame hardening was given by J. H. Zimmerman,[44] who prepared specimens with intentional stress raisers (Fig. 9.31) and tested them for endurance after various treatments. The results are listed in Table 9.1. The most graphic demonstration of the effect of residual compressive stress is given by the tests in series C, where the failures occurred in the smooth body of the bar, and not in the very sharp fillets which had been flame-hardened.

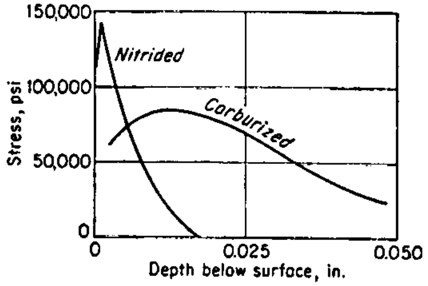


Fig. 9.32 Residual stresses in surface-hardened steel.[14]

Table 9.1

Series	Treatment	Endurance limit in terms of nominal stress, psi	Location of failure
A	None	18,000	Fillet
B	Oil-quenched and tempered	28,000	Fillet
C	Fillets only flame-hardened	32,000	Body
D	Flame-hardened all over	52,000	Fillet

9.21 Diffusion Hardening

Carburizing and nitriding produce high compressive stresses in the hardened surface. The core cannot harden because it lacks the hardening elements which are diffused into the surface in the carburizing or nitriding process. In quenching a carburized part, the surface will be compressively stressed by the two effects of expansion in transforming to martensite and by contraction of the core, which cools last and is therefore in tension. Measured residuals in the cases of gear teeth are shown in Fig. 9.32. The residual compression in the nitrided surface is particularly high. These stresses contribute to the fatigue durability of such parts over and above the effects of hardness or high tensile strength.

It is well known that high tensile strength alone is accompanied by notch-sensitivity and that the fatigue durability of machine parts may be reduced by excessive hardness unless the hardness is accompanied by compressive surface stresses. Carburizing and nitriding are two of the processes by which a combination of high hardness and compressive residual stresses is achieved on the skin of parts. The combination of a "hard skin on a tough core" by itself is not sufficient to explain the success of these processes. What good would the tough core of a gear tooth be after the skin had cracked? The combination of a hard skin with a core which is in tension and thereby compresses the skin is the key to the fatigue durability of gear teeth and similar parts, as has been shown by J. O. Almen.

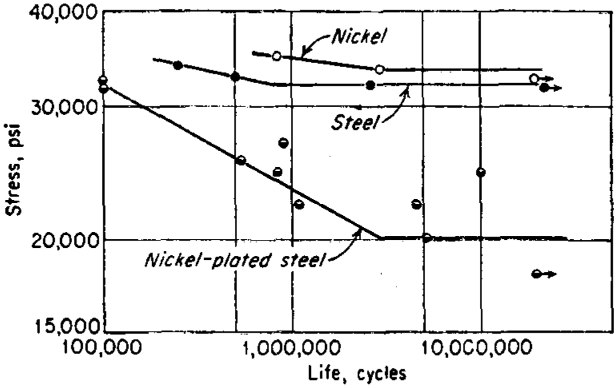


Fig. 9.33 Much of the fatigue strength of steel is lost when coated with electrodeposited nickel.[17]

9.22 Plating

Surface residual stresses created in plating have the same important effect on fatigue life as those created by other means. Without discussing the mechanism by which these stresses are set up, this section will merely list some typical effects and show how the damage of plating to fatigue life can be overcome.

For electrodeposited nickel as an example, Figs. 9.33 and 9.34 tell what can happen: Plating steel, which had an endurance limit of 32,000 psi, with nickel, which had an endurance limit of 34,000 psi, produced a composite nickel-plated steel of 20,000 psi. Residual stresses in the plated nickel may range from 70,000 psi tension to almost 10,000 psi compression, depending on the process. The data plotted in Fig. 9.34 show the effects of two nickel-plating procedures on the fatigue durability of steel with 45,000 psi endurance limit (polished). One procedure developed a tensile residual stress of 25,000 psi in the coating and decreased the endurance limit from 45,000 to 29,000 psi. The other procedure developed compressive residual stresses of 6,000 psi in the coating and increased the endurance slightly.

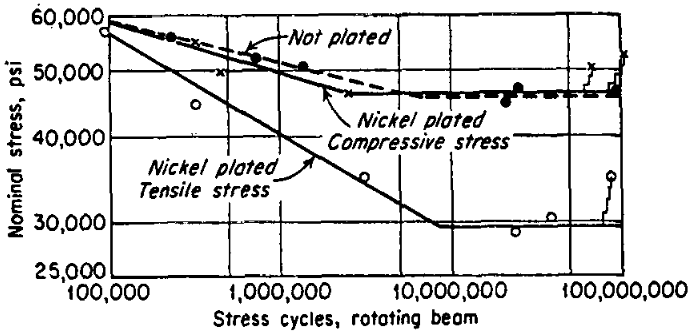


Fig. 9.34 Fatigue of nickel-plated steel; strength is greatly affected by the state of stress in the electrodeposited metal.[17]

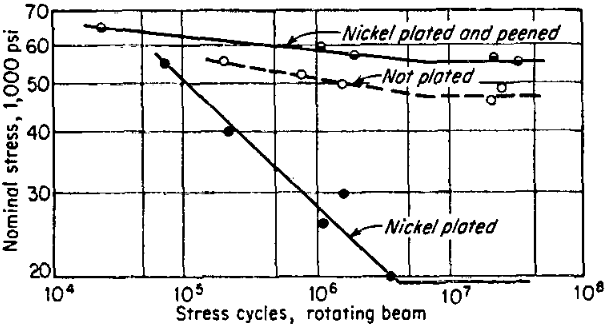


Fig. 9.35 Comparison of fatigue strengths of uncoated, nickel-plated, and nickel-plated and peened steel rotating-beam specimens.[17]

The more common way of avoiding fatigue damage by plating is indicated in Fig. 9.35. Here the plated coating itself was applied with the usual tensile residual stresses, but shot peening was used before plating to produce compressive residuals in the base metal just below the plate, with the result that the fatigue durability, which would have been ruined by plating (from 47,000 to 20,000 psi), was restored by shot peening.

Chrome plating is more widely used than nickel plating for highly stressed parts. It is common practice to specify shot peening before chrome plating where fatigue durability is a factor. Figure 9.36 indicates the reasons: chrome plating lost 20 per cent of the endurance value of polished specimens, while shot peening plus chrome plating increased the endurance limit slightly above that of the polished specimens.

It is interesting to note that the endurance limit of peened and plated specimens was practically the same as that of unplated peened specimens. The compressed armor of the peened specimens must have stopped the cracks in the plate from further penetration into the base metal.

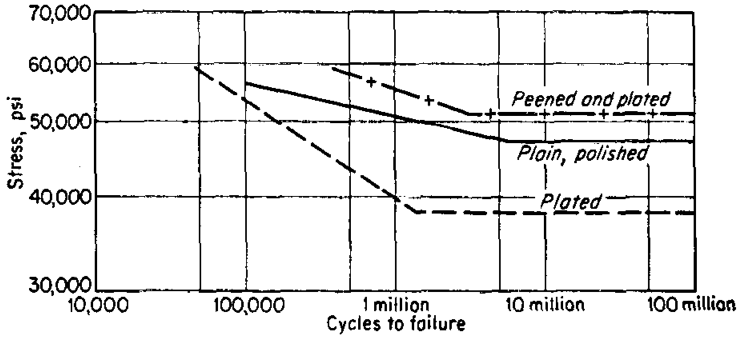


Fig. 9.36 Rotating-beam fatigue-test results showing the effect of chromium plating with and without shot peening.[17]

FEATURES COMMON TO THE TECHNIQUES

9.23 Dependence of Techniques on Local Differences

All surface-stressing techniques depend on *local differences* between one region of a part and another. Compressive stresses in the surface are balanced by tensile stresses in the core. Only different histories of the different regions can produce the residual stresses. To produce favorable residual stresses, we deliberately create nonuniform temperature distribution, as in surface-quenched safety glass; or nonuniform composition, as in nitrided steel parts; or nonuniform yielding, as in the autofrettage of guns or in peening.

9.24 Dependence of Techniques on Residual Stresses

All surface-stressing techniques depend on *residual stresses*, i.e., on stresses which remain after the external load has been removed. Other names for these stresses are trapped stresses, locked-in stresses, tessellated stresses, internal stresses, initial stresses, or prestresses. Such residual stresses have long been well known to craftsmen who can straighten or bend metal by peening or who have seen pieces crack in quenching.

They used to be feared or neglected by most engineers, who had been taught to think of stress in terms of applied load divided by area or section modulus. As far as fatigue is concerned, there is no difference between residual stresses and load stresses. What counts is the sum total of the stresses, regardless of their origin. To be convinced of this truth, one need only remember that a particle of metal has no way of knowing whether a stress is a residual or load stress; all it knows is that it is pushed, pulled, or distorted by neighboring particles. The main difference between load stresses and residual stresses is perhaps the difficulty with which the latter are measured and visualized, and our inability to compute them simply in advance.

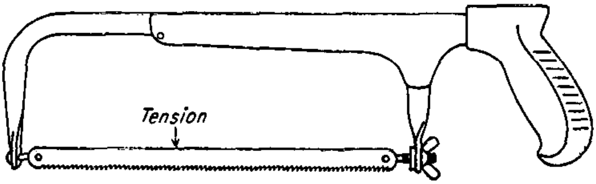


Fig. 9.37 Hacksaw with the blade in tension.

The blade of a hacksaw (Fig. 9.37) is stretched in mounting. Whether the resulting tension stress should be called residual because it does not depend on loads external to the saw or should be called a load stress (because it is caused by turning the thumbscrew) may be debatable. It does not matter. The important fact is that the stress exists; its origin has no influence on its results. The same is true of all residual stresses. They must be considered together with the load stresses.

9.25 Dependence of Techniques on Yielding

Most surface-stressing techniques depend on yielding or plastic deformation of the material. In overloading or in peening, the surface material is stretched beyond its tensile yield; when the stretching force is removed, the elastic core pulls the part back toward its original shape (elastic recovery or spring-back). The pull of the neighboring regions produces compression in the plastically deformed surface layer. In quenching (without martensite transformation), the skin cools and contracts while the hot core is still plastic; the core yields; and later the core contracts and imposes compression on the solidified skin.

In thinking about yielding or plastic deformations, the engineer must overcome a certain reluctance which is based on good reasons: the theory of elasticity is hundreds of years old, an imposing body of exact theory has been accumulated, the main results are available in clear elementary form in the texts on strength of materials, these texts are used in our engineering schools, and the student develops familiarity with the ideas of elasticity and confidence in their validity. The theory of plasticity is only a few dozen years old, and its main results have not yet been incorporated in our texts and handbooks in a simple form which would compare to the theory in the same way as "strength of materials" compares to "theory of elasticity." In the absence of simple accepted approximations, some mental pioneering is required of the engineer who wants to think about the effects of local plastic deformation. A most useful rough approach is to think in terms of strains rather than of stresses. The strains can be converted to stresses by using an approximate stress-strain curve.

9.26 Permanence of Residual Stresses

Whether residual surface stresses remain in a part during service has been a question; a theory and test data are given in Chap. 8. Briefly summarized, one can say that residual stresses do remain as long as the total stress, the sum of load stress and residual stress, does not exceed the yield strength. If the yield strength is exceeded, the residual stresses will be redistributed.

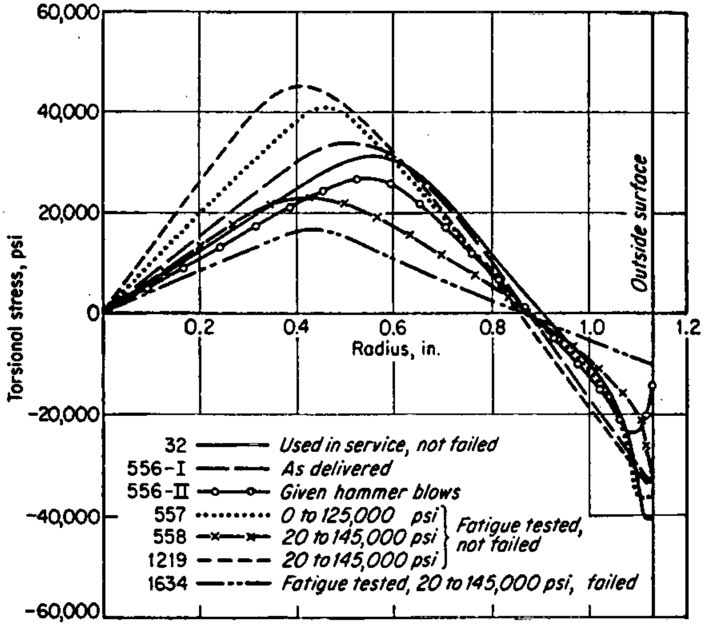


Fig. 9.38 Residual stresses measured on seven samples of torsion-bar springs.[33]

In applying this limitation, one must keep in mind that the yield strength for repeated loads is below the static value. Temperature increase will also reduce the yield strength. Experiments on preset torsion bars showed that the residual stresses did not fade out in service and during life tests, but were reduced by hammer blows and violent fracture (Fig. 9.38).

9.27 Note on Testing

So-called accelerated testing can be very misleading for parts strengthened by residual stresses. Figure 9.39 shows test results on generator shafts: at one load, the peened shafts were far superior to unpeened shafts. At a slightly higher load, the improvement disappeared. The higher load no doubt had dispersed or driven out the residual stresses by yielding. Because of this effect, it is very important to conduct fatigue tests of complete parts at stress levels equal to the service stresses without trying for quick test results by using higher stresses. The difference between reversed stresses and fluctuating stresses must be carefully observed and reproduced in tests. The beneficial effect of peening on leaf springs, for instance, is well known; but in a reversed-bending test it would not show as well because the compressive residual stresses on the tension side would be reduced by yielding if the tension side were subjected to compression in the reversed test cycle.

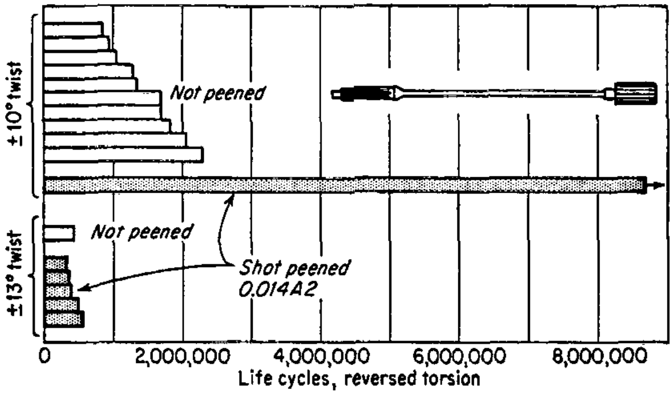


Fig. 9.39 Comparative tests at stresses exceeding the service stress may be very misleading. SAE 6150 steel at hardness Rockwell C-34 to C-38.[18]

9.28 Other Benefits of Surface Compression

Besides improving endurance, surface compression provides a number of other benefits. The compressively stressed surface layer prevents cracks from forming, delays the growth of cracks, or stops the growth of cracks. When the cracks result from fatigue, the result is a higher endurance limit or longer life, as shown by examples in the preceding sections.

Cracks may also be caused by stress corrosion or by cavitation. These are also prevented or delayed by the action of compressive residual stresses in the surface.[26] In a similar way, the presence of surface compression prevents the fatigue damage which accompanies frettage corrosion. Frettage corrosion occurs where highly loaded contacting surfaces (at the edge of a press fit, for instance) are subject to small motions such as may result from the elastic deformations of the mating parts; in steels a brown powder forms on the surfaces and is soon followed by fatigue cracks unless they are prevented by surface compression.

Compressive residual stresses work in an entirely different but equally important way in increasing ductility and thus indirectly increasing endurance by permitting the use of harder materials. It is well known that steels of very high tensile strength can be produced but that their use is limited by their "brittleness" and notch-sensitivity. Without surface compression the endurance of springs made of hot-rolled steel is highest at hardness levels around Rockwell C-45. The examples in the preceding sections showed only the endurance improvement without change of hardness, but a much greater improvement of endurance, together with greater resistance to static loads, is available by using higher levels of hardness together with surface compression, as indicated in Fig. 9.40.[32]

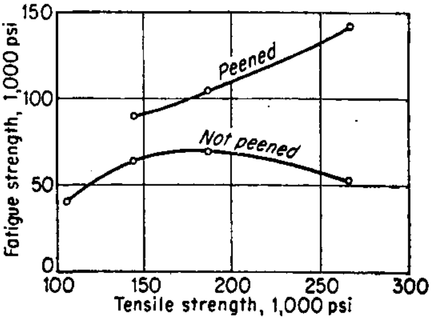


Fig. 9.40 Improvement by peening increases with hardness of steel.[32]

Springs of Rockwell hardness C-52 are entirely practical when protected by a shot-peened surface, and they are extensively used in torsion-bar suspensions. These springs are subjected to high static loads and to plastic deformation during presetting. The fatigue life of the springs was quite short when they were peened after presetting, but it was entirely satisfactory when they were peened before presetting.[18] We infer that, without peening, the tensile stresses produced in the surface during presetting had produced cracks. The compression of the peened layer prevented the cracks. We are reminded of Bridgman's experiments on plastic stretching of brittle materials under high lateral compression.[22] Another typical application is found in aircraft landing gears. Surface compression (obtained by shot peening) enabled the aircraft industry to use steel of 270,000 psi tensile strength (Rockwell C-52), which otherwise would be too "brittle" for such a critical application.

If brittleness of steel is measured by the transition temperature from ductile to brittle behavior, or by the strain velocity required to produce brittle fracture, the beneficial effect of surface compression can be expressed quantitatively. Grossman shows 60°F lower transition temperature, or twenty times higher strain rate, on specimens of 1020 steel after shot peening.[25] Brittleness and notch-sensitivity are overcome by surface compression because plastic adjustment can then take place without exceeding the highest bearable tensile stress.

9.29 Application to Limited Fatigue Life

A great number of fatigue tests comparing parts with and without compressed surface layers have been carried out. Some of the results are shown in preceding sections. All these data result in curves of the type shown in Fig. 9.41. The endurance limit is raised—often by the full amount of the residual compressive surface stress. At higher levels of stress range and correspondingly shorter lives, the increase in permissible load is smaller. The life extension obtained by surface compression at equal loads is very high at loads slightly above the endurance limit and is frequently the more decisive factor. At still higher load ranges, frequently at lives around 1,000 to 10,000 cycles, surface compression appears to bring no improvement.

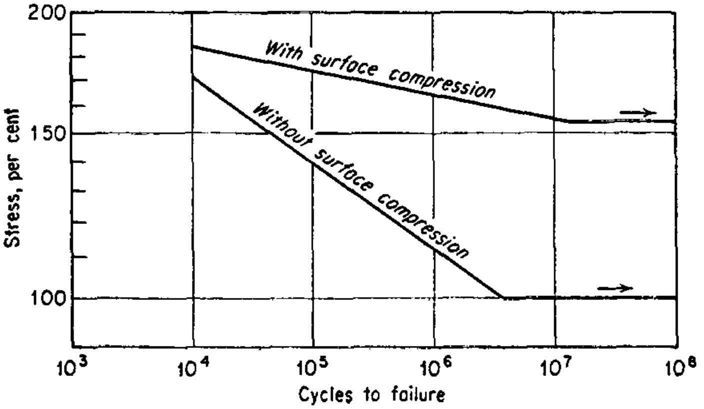


Fig. 9.41 Effect of surface compression on fatigue life at various stress levels.

In looking for an explanation, one might relate these data with the redistribution or fading of residual stresses when the total stress exceeds the dynamic yield strength or with "notch effect" of the uncompressed surface. In looking to the practical application, it would be a mistake to conclude that surface compression cannot improve the performance at life requirements of less than 10,000 cycles. Here the use of harder materials, protected against brittleness and notch-sensitivity by a compressed surface layer, will bring substantial improvements in fatigue life and load-carrying ability.

9.30 Summary

We have reviewed a number of techniques for improving fatigue resistance by surface stressing. In the main, these techniques consist of stretching or expanding the skin of parts without stretching or expanding the core. Skin hardening by heat treatment and skin stretching by peening are the two most common methods for producing a compressively stressed armor. Compressive stresses produced by these methods have been measured and found to be very substantial. Fatigue improvement is often startling, because the armored parts are far less sensitive to surface finish and small sharp notches. Commercially finished, compressively armored parts exceed the fatigue durability of polished specimens.

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