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Trapped Stresses

. . . how they can be created to improve the performance of machine parts

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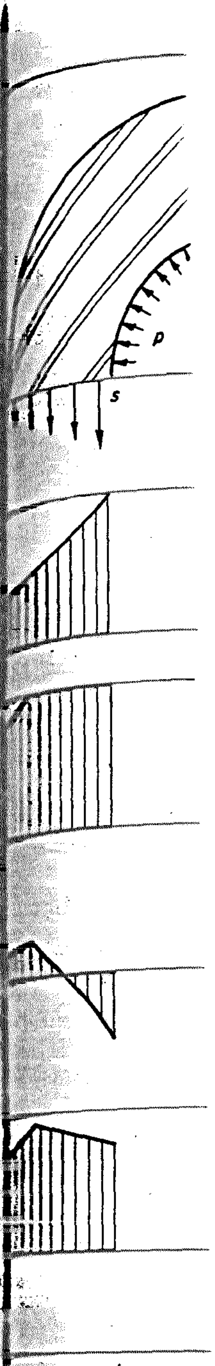
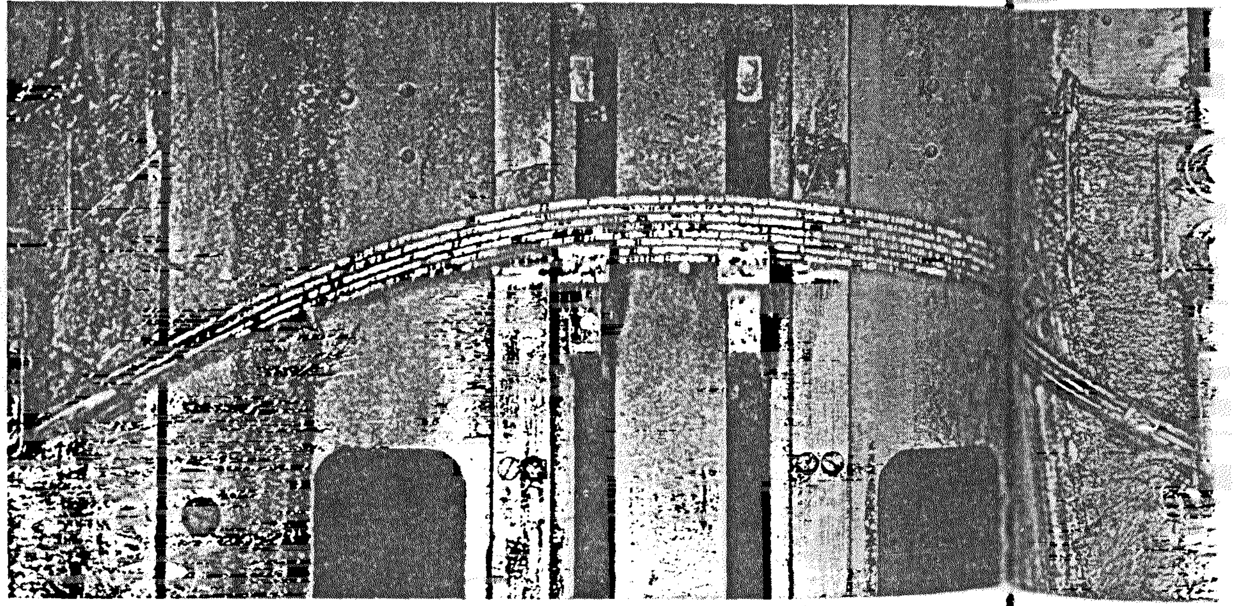
Most designers and all good shop men are aware of quench cracks and of the distortions which accompany welds. As is well known, such cracks and distortions are caused by stresses set up within a piece when one part cools more rapidly than another. As a result of this knowledge, stress-relief annealing is often specified for complicated weldments and castings, and special high-temperature quenching is used in heat treatment.

Only in the last few years has the knowledge of this type of stress, which may best be called "trapped stress" but is also known as residual stress, been applied consciously to serve a useful purpose. Trapped stresses, deliberately produced by heat treatment, shotpeening, overstressing (*Fig.* 1) or other methods, help to carry loads and to increase the strength of parts against static and, especi fatigue failure.

Stress analysis as taught in most schools and pra ticed in many engineering offices considers only stresses produced by external loads. Yet a part fail at a certain stress, no matter whether this stre is produced by external loads or trapped in it b some production process. Failure to give due consid eration to trapped stresses is one reason why th stress analyst is viewed with some suspicion by th practical shop man who knows that a spring ma operate very well at a calculated load stress abo the fatigue limit or even above the yield strength, a that a bracket bent cold can be opened up quite eas although it is hard to close it. Observations such a these check well with the theory of stresses if due





Photo, courtesy Eaton Mfg. Co

Fig. 1—Automotive leaf spring undergoing treatment in a prestressing machine for the purpose of inducing trapped stresses

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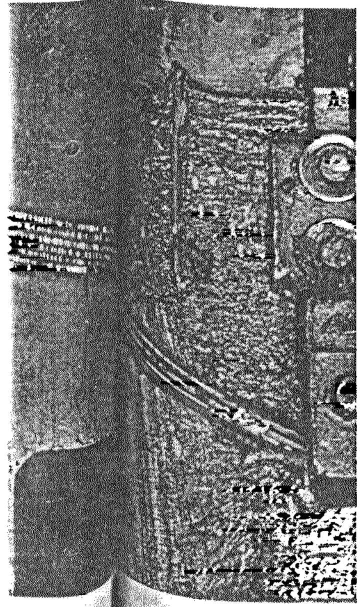


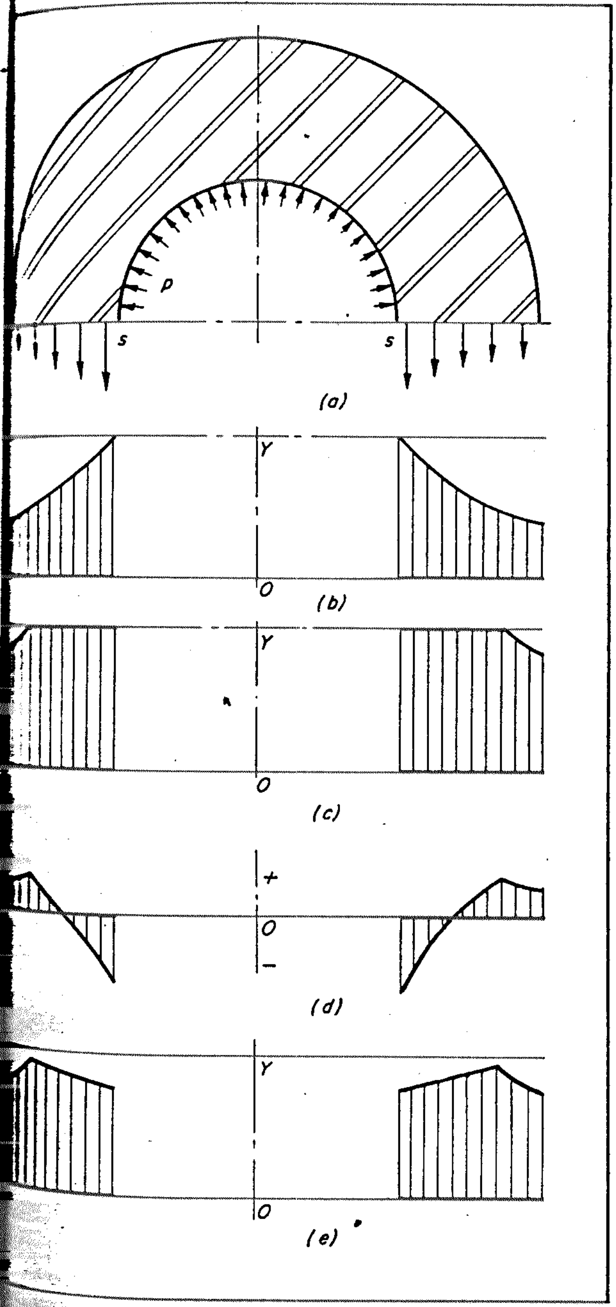


Fig. 2—Above—Distribution of stresses in a gun barrel (a) due to low internal pressure (b); during overstressing or autofrettage (c); after autofrettage, showing trapped stresses (d); and during firing after autofrettage (e)

lowance is made for the favorable or unfavorable effect of trapped stresses.

GUNS: A fairly old example of the deliberate use of trapped stresses is found in the manufacture of guns. Gun barrels are essentially thick-walled tubes. Ability to carry high internal pressures is highly desirable because it enables the gun to shoot farther and more accurately than the enemy's. However, the internal pressures which can be used are limited by the stresses which the gun barrel steel will withstand. These stresses cannot be decreased effectively by using barrels with thicker walls, the distribution of stresses in thick-walled tubes being such that the outer layers carry only a small part of the load and are relatively inefficient, *Fig. 2b*. The highest stress is at the bore which, in addition, is subjected to the intense heat of the firing.

Improving Conditions at Bore

The destructive stress in the gun barrel is tensile. Thus the gun can withstand higher pressures if compressive stress is trapped near the bore, where the load stress is high and temperature conditions severe. Since equilibrium conditions must be satisfied (you can't get something for nothing) this will result in a tensile trapped stress at some other region of the barrel—the outside. But the load stress is low near the outside and the temperature conditions are more

Photo, courtesy Ford Motor Co.

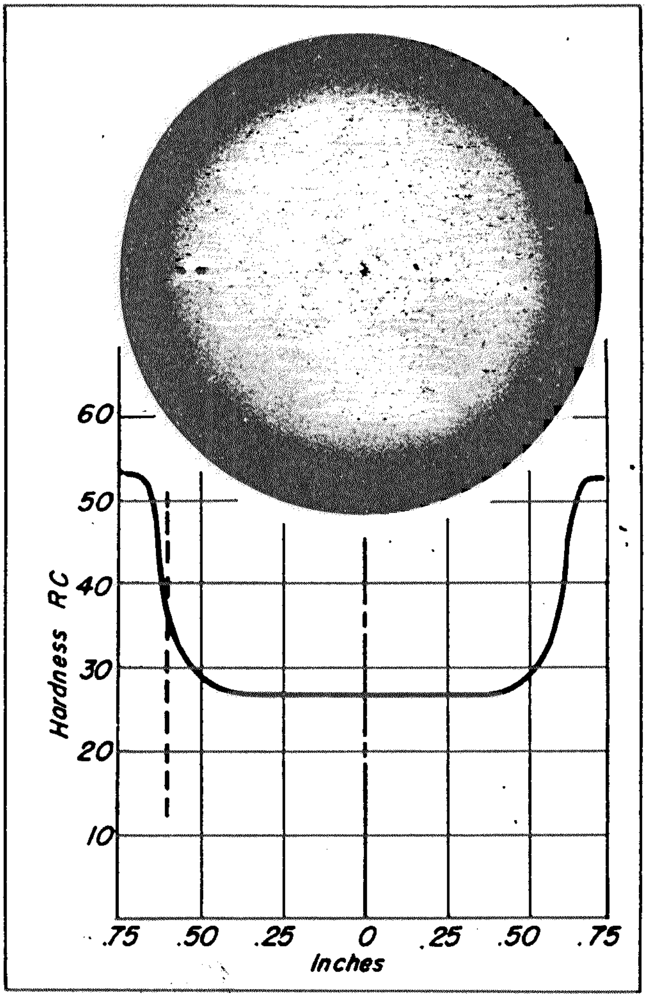


Fig. 3 — Right — Cross section through shallow-hardened truck axle showing 0.18-inch deep hard zone. Diagram shows hardness variation across section

favorable so that this added tensile stress is not harmful. The net effect of the trapped stress—compressive near the bore, tensile near the outside—is to combine with the unequally distributed load stress to give a more uniform total stress, *Fig. 2e.*

How Stresses Are Trapped

Various methods have been used to achieve the foregoing result. Winding wire under tension around the inner barrel is one (obsolete) method. Shrinking a hoop around the inner barrel is another. The most modern and most interesting method is called autofrettage. In this process the gun barrel is closed off at the ends, filled with liquid, and subjected to internal pressure until it expands so much that a permanent set remains. In this operation the bore of the barrel first reaches the yield strength of the steel and then progressively larger zones yield until finally the entire material of the barrel has reached the plastic stage, *Fig. 2c.* In this stage, the stresses all across the gun are fairly uniform. When the pressure is released the stresses decrease much more near the bore than near the outside. The bore reaches the zero stress when the outside is still highly stressed, but the stresses must decrease still more to reach a condition of equilibrium. Near the bore they decrease into the negative range and in this way a negative or compressive stress is trapped near the bore, *Fig. 2d.*

The logic of prestressing a gun barrel is very simple. Tensile service stresses are offset in part by compressive trapped stresses. The trapped compressive stress in one section is held in equilibrium by a trapped tensile stress in another region of the part, where the service stress is low. This simple line of reasoning has been known for quite some time. It explains, among other things, the modulus of rupture which is usually much higher than the ultimate tensile strength.

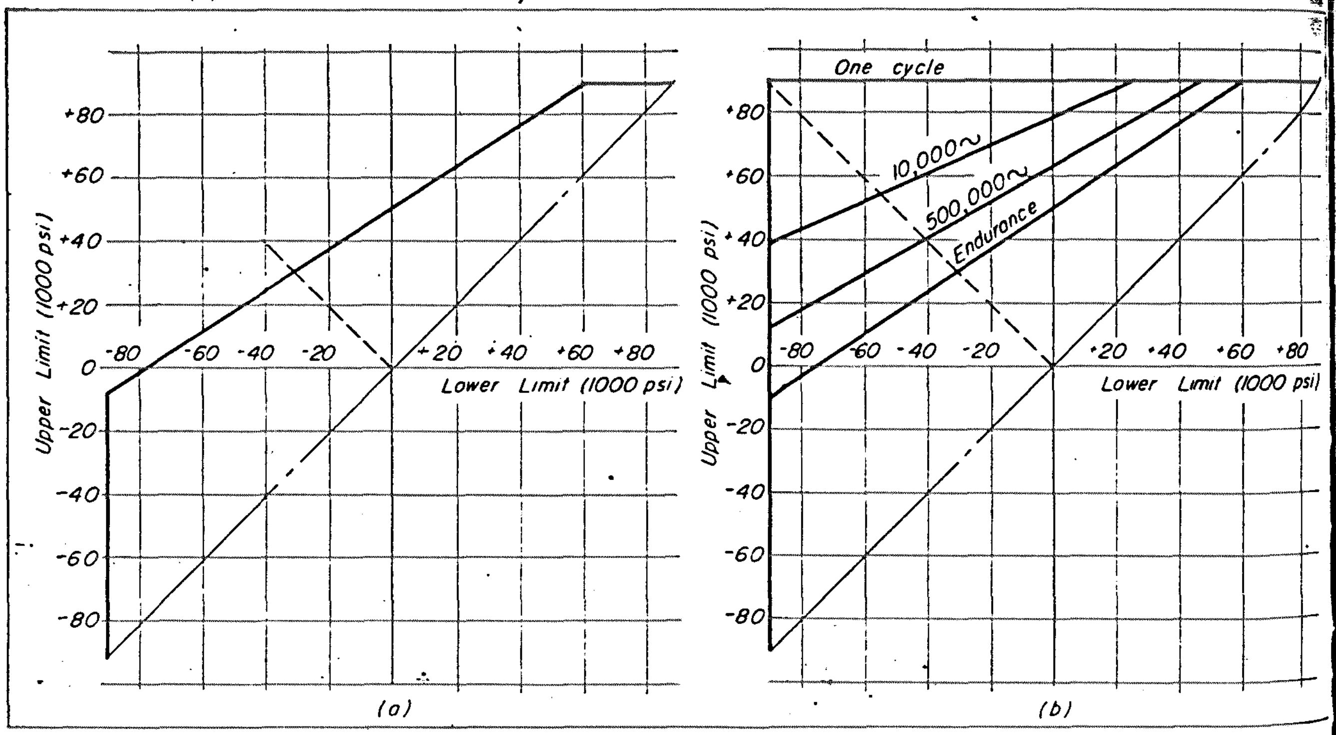
Axle Shafts: Newer and more interesting applications of trapped stresses are based on the knowledge that compressive stresses can be used to increase resistance against fully reversed service stresses, such as occur in the flexing of members or in the rotating beam test, and against torsional stresses such as those in coil springs. They can also be used to prevent brittleness by permitting local areas of incipient failure to yield and to adjust themselves without cracking.

Endurance Limjt Raised 115 Per Cent

A remarkable example of this use has been reported by Horger and Lipson[1] who showed that the endurance limit of automotive rear axles, as measured in a rotating beam machine, was raised from 20,000 psi to 43,000 psi by shotpeening. In this process a relatively shallow surface layer, about 1/64-inch deep, is given a trapped compressive stress by peening with hard steel shot. The use of the same shot peening process to increase the endurance of coil springs, stressed in torsion, is standard practice in the automotive industry, for small valve springs as well as for large suspension springs.

It is interesting to note that one of the big three automobile manufacturers heat treats all rear axles to produce a compressive trapped stress near the surface by a different process. This process depends on the fact that, with a shallow-hardening steel, quenched drastically, the decrease of temperature near the center of the axle is too slow to produce a metallurgical transformation. However, near the surface, the

Fig. 4—Modified Goodman diagrams (a) for unlimited cycles and (b) for limited and unlimited cycles



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[1] References are tabulated at end of article

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a depth of somewhat over ⅛-inch, the temperature drops fast enough to induce hardening, *Fig.* 3. The transformation which produces hardness also produces an increase of volume, so that the surface layer, if it were not restrained, would expand. Expansion is prevented because the surface is tightly bonded to the core and a high compressive stress is the result of the inhibited expansion.

A similar result could of course have been obtained by carburizing. Although the good results of carburizing are usually ascribed to a hard, wear resistant skin on a tough core, the theory seems justified that carburizing works mainly by producing trapped stresses.

ENDURANCE FACTORS: To gain a better understanding of the fact that compressive trapped stresses increase endurance against load reversals, it must be considered that endurance is a function of both stress range and stress level. A stress cycle can be defined by its lower and upper limit. Since the upper and lower limit can be either tensile or compressive it is necessary to distinguish them by algebraic signs, plus for tension and minus for compression, and to remember that by "lower" is meant the algebraically lower stress. In other words, a stress cycle extending from 30,000 psi compression to 20,000 psi tension will have the lower limit minus 30,000 psi and the upper limit plus 20,000 psi.

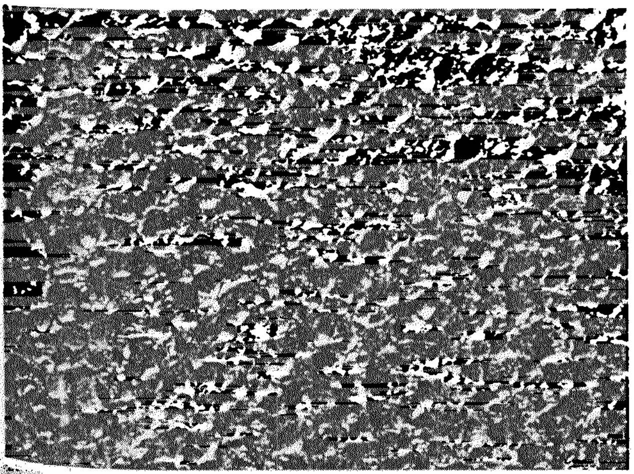
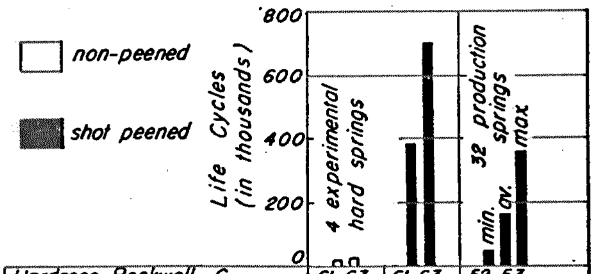

Photo, courtesy American Wheelabrator & Equipment Co.

Fig. 5—Surface view of shot-peened steel at a magnification of approximately seven times actual size

It is a fact established by experience that for most materials the permissible stress range—difference between upper and lower limit of the cycles—is higher when the stresses are compressive than when they are tensile. One old rule of thumb states that compressive stresses are 5/6 as dangerous as tensile stresses; actually, it is believed that the difference is often greater than indicated by this rule. A practical application can be seen in the leaf springs of many cars, which are shaped in such a manner that the neutral axis is closer to the tension side, thus giving lower tensile stresses at the expense of somewhat higher compressive stresses. The shape of longbows and of skis—flat on the tension side and convex on the compression side—is evidence that old-time craftsmen had reached the same conclusions on the basis of long experience.



Hardness Rockwell C	61-63	61-63	52-53
Cold pressed	no	no	yes
Peening intensity	—	—	.012 A
Hot pressed 50 times at	300°F	300°F	575°F
Peening intensity	—	.018 A	—
Draw	no	no	to hardness

Operations arranged in sequence

Fig. 6—Effect of shot peening on fatigue durability of brittle springs compared with softer production springs

MODIFIED GOODMAN DIAGRAM: The modified Goodman diagram, *Fig.* 4, is one good way to gain an overall view of the various combinations of stress limits which can be used without leading to danger. Such a diagram is obtained by plotting the upper limit of the stress cycles as ordinate over the lower limit as abscissa. A curve of equally dangerous stress cycles results.

Interpreting the Diagram

Fig. 4*a* shows such a curve for the endurance limits of a particular steel. For zero lower limit the upper is 50,000 psi, meaning that the endurance limit for pulsating stresses varying from zero to tensile is 50,000 psi. Similarly the endurance limit for pulsating stresses varying from zero to compression is shown at the intersection of the diagram line with the horizontal axis, about 75,000 psi compression. The generally quoted endurance limit for fully reversed stresses is found where upper and lower limit are numerically equal, at the intersection of the diagram line with a 45-degree diagonal sloping upward to the left. It is shown as 30,000 psi, corresponding to a usable stress range of 60,000 psi.

Stress ranges corresponding to each point on the diagram may be visually indicated by vertical arrows extending down from the upper limit to the 45° diagonal sloping upward to the right. It will be seen that the usable stress ranges increase from right to left in the diagram, meaning that the fluctuating stress can safely be increased if the static stress is made more compressive or less tensile. The important point is that this static stress need not be a load stress: It can be a trapped stress. Compressive trapped stresses increase the permissible stress range in fatigue. This is true, as shown by experience with springs, for torsion as well as for tension and compression.

For limited life the incentive to use trapped compressive stresses becomes even greater, as indicated by *Fig.* 4*b*. Here the safe stress cycles are shown for certain limited numbers of cycles as well as for endurance and for single cycles. For single cycles the limits are given by the yield strengths in tension and compression, which are shown as 90,000 psi. In the case of single cycles, failure will occur as set rather than as fracture. For larger numbers of cycles, failure may either be set—if the combined trapped stresses and load stresses exceed the yield strength in tension or compression—or it may be fracture if the stresses exceed the safe limits indicated by the slanting lines of the diagram.

For other materials, or for steel of different hardness, or for a different surface condition of the test piece, a different diagram would be obtained. The diagrams given here are intended as a qualitative indication of well-established general behavior, not as exact design data. It is, of course, highly improbable that series of test points would fall exactly on the lines which are shown; the natural scatter of fatigue test points would be sufficient to prevent this. It is also likely that there is a transition region in which failure may be either by fracture or by set, depending in part on how small a set is considered permissible. This transition region would round off the sharp corners shown in the diagrams. But in view of present ignorance of the exact mechanism of fatigue, and of the lack of fatigue experiments with various limits and test conditions, it is better to get the general trends firmly established in the mind by simple lines than to check whether these lines are straight or perhaps parabolic.

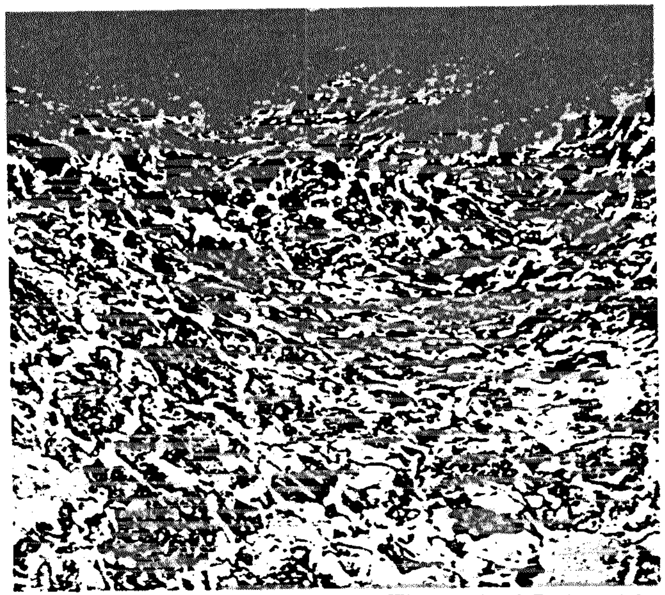

Photo, courtesy American Wheelabrator & Equipment Co.

Fig. 7—Cross section of shot-peened steel at a magnification of 200, showing compressively stressed skin

OTHER EFFECTS: The endurance diagram, *Fig.* 4*a*, shows an increase of stress range from 60,000 psi for fully reversed stresses to a little over 80,000 psi at the yield strength in compression. This increase can be obtained by superimposing a trapped compression stress upon the load stress in a rotating beam test, but no matter how liberal the interpretation, it is obviously not sufficient to explain the test data of Horger and Lipson, which showed that shot peening increased the safe fatigue load more than twofold. Surface improvement, workhardening, and increased ductility must be considered to obtain an adequate explanation.

Surface improvement is easily visualized as an ironing out of the multiple small defects in the as-forged surface of the axles by the overlapping peening marks left by the shot, *Fig.* 5. Similar results are obtained by surface rolling, burnishing, or polishing.

Cold Deformation Effects

Workhardening, or strainhardening, is not as easily pictured, but must be accepted as an experimental fact. It is well established that both yield strength and fatigue properties of steel and other materials are increased by cold deformation. The physical properties of cold-rolled steel are higher than those of hot-rolled steel. Hard-drawn spring wire obtains all its hardness and strength by cold drawing, and brass can be manufactured in various tempers, depending on the amount of cold reduction. The true tensile test diagram, in which stresses are calculated on the actual reduced section instead of the original section, shows strain hardening as the basic property it is. This effect is quite separate from, and in addition to, the effect of trapped stresses. One can workharden and offset the gain by introducing unfavorable trapped stresses, or one can introduce trapped stresses and their effect by controlled heating and cooling without any workhardening. Shotpeening, as a cold working process, introduces work hardening and trapped stresses together.

Local Yielding Distributes Load

Ductility: Finally, the trapped compressive stress increases ductility and thereby enables small areas of imperfection to yield and pass their share of the load to stronger neighboring areas without opening a crack which would form a nucleus for stress concentration and progressive fatigue failure. Plastic flow occurs when the shear stress at a point exceeds a certain value. Fracture occurs when the tensile stress at the point is excessive. Assuming that a point is in danger of showing a crack under the effect of high tensile stress, this danger will be decreased if a compressive stress can be deducted. Furthermore, if compressive stress in a direction at right angles to the highest tensile is introduced, the two combine to form a shear stress which may result in plastic flow, by which the load can be passed on to a neighboring area.

It is well known that a deep cup can be drawn from a flat sheet, while it is impossible to draw a long flange around a hole in a flat sheet. The difference between the two is this: When drawing a cup, the metal is drawn in from the outside, produc-

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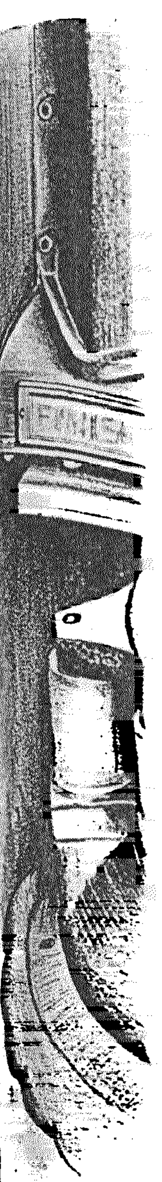

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ing circumferential compression, at the same time as it is drawn down in an axial direction with tension. At the rim of the cup tension and compression combine to a high shear stress and plastic flow without cracks results. In the case of the flange, the stress is tensile around the circumference of the hole, and no compressive stress can be applied. Consequently the operation is difficult even for relatively shallow flanges. Bridgman has shown that even marble is plastic under conditions of simultaneous tension and compression.[2]

The compressive trapped stress produced by methods such as shotpeening or heat treatment acts in a similar fashion to prevent brittle failure. This is shown by *Fig.* 6, taken from the Mattson and Almen National Defense report.[3] The figure shows the test life of three types of springs. Production springs, drawn to Rockwell C-52 and shotpeened, gave an average life of about 160,000 cycles. Springs tested as quenched, without drawing or peening, lasted only about 20,000 cycles. They were too brittle, but the brittleness could be offset by shotpeening. The same springs, quenched to Rockwell C-62, not drawn, but peened, showed the remarkable life of almost 400,000 cycles for the poorer of two and about 700,000 cycles for the better of two.

Similar results have been obtained with parts which were brittle when cold. After peening, the impact value at low temperatures was increased to normal values.

This phase of the use of trapped stresses—their use to reduce brittleness—has been explored less than other applications, but it seems likely that great savings can be obtained when it is more fully understood how higher hardness, with corresponding higher yield strength, can be used without sacrifice in ductility and fatigue life of finished parts.

Practical Methods

PRODUCTION OF TRAPPED STRESSES: The useful effects of trapped compressive stresses would be of little interest if there were no practical means of producing such stresses. Fortunately there are many ways in which such stresses can be trapped so that the designer and manufacturer usually has a choice of methods.

Cold Work: One group of methods relies on cold deformation. They produce work hardening and small changes in surface besides the trapped stresses. Theoretically the simplest of these methods is overstressing. The autofrettage of guns is one example of overstressing. Overspeeding of turbine disks and presetting of springs are others. The fundamental principle in all overstressing operations is to produce a cold deformation by load applied in the same direction as the future service load. It is therefore suited to parts which in service are stressed in one direction only.

Shotpeening is the most universal method of producing trapped stresses. It results in a compressively stressed skin, *Fig.* 7. This method has been developed from an almost accidental discovery some twenty years ago to a well controlled production process used for parts as diverse as cutting tools and crankshafts. Ability to hit fillets and similar areas of stress concentration is one outstanding merit of this method. To this may be added freedom from distortion and improvement of surface.

Burnishing by rollers works in a way quite similar to shotpeening, but is limited in application to round parts of fairly regular shape.

Controlled Cooling: Another group of methods relies on controlled cooling to produce trapped stresses. As all metals, and most other materials, shrink when cooling, and at the same time become less plastic, the areas which cool first will be under compressive stress while the areas which cool last will be subject to tensile stresses. In welding, the trapped cooling stresses are often unfavorable. In castings they can be arranged in a favorable pattern by skilled use of chills. Tempered glass is an outstanding commercial example of the use of trapped stresses, produced by controlled cooling, to increase strength. The hot, plastic, sheet of glass is rapidly quenched on the surface. As the core cools more slowly it shrinks and pulls the surfaces together, leaving them in a state of compressive stress. The ability to resist loads and deflections is increased to several times its original value by this treatment. Shrink fits are a similar application of trapped stresses produced by different rates of cooling.

Methods For Trapping Stresses

Mechanical	**Thermal**	**Metallurgical**
Overloading	Selective quenching	Carburizing
Burnishing	Shrink fitting	Nitriding
Shotpeening		Shallow hardening

Metallurgical Methods: The last group of methods, apparently the most difficult and complicated, actually is one of the oldest. It relies on metallurgical phase change, which is accompanied by increase in volume, to produce compressive stresses in the surfaces of parts. Carburizing is one of these methods, shallow quenching another. In addition to producing high hardness, which can as well be obtained with through-hardening steel, these methods use the volumetric expansion which accompanies the martensitic transformation to set up compressive trapped stresses. The magnitude of these stresses can be guessed by anybody who has seen the quench-cracks produced by the same forces when they are not properly controlled.

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