This is the first third of a notable paper read before the Detroit Chapter, ⊕, November 1942 meeting, on the general subject of "Fatigue of Metals as Influenced by Design and Internal Stresses". The author is head of the Mechanical Engineering Dept. 1 of G.M.'s Research Laboratories, and has had long experience in diagnosing service failures, and devising proper cures. Subsequent installments will describe some experiences with bolts, studs and gears, and finally the general problem of endurance under loads higher than the "true" fatigue limit will be expounded

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PEENED SURFACES IMPROVE ENDURANCE OF MACHINE PARTS

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FULLY 90% of all fatigue failures occurring in service or during laboratory and road tests are traceable to design and production defects, and only the remaining 10% are primarily the responsibility of the metallurgist as defects in material, material specification or heat treatment. While this ratio is not a measure of the quality of workmanship contributed by each department, there can be no doubt that the metallurgist has a better appreciation of his responsibility for fatigue failures than has the designer, the engineer, or the man in the production department — in fact, it contributes to the relative irresponsibility of the engineer by over-willingness of the metallurgist to accept the blame when things go wrong.

Being metallurgists you are familiar with the routine followed when a broken part is received. The fracture is examined and is found to be due to fatigue, the material is analyzed for composition, sections are studied for all of the many things that are metallurgically important, and a report is written describing the things that are and are not up to par. But no matter how many possible metallurgical causes of trouble are found, such examination is far from sufficient unless the failure is also examined for design faults and bad fabrication and assembly practice. Most of the failed parts should not be sent to the metallurgist at all but, unfortunately, very few engineers or production men are adequately trained in diagnosing fatigue trouble, and failures are therefore seldom examined for contributing mechanical causes. Like the cowbird who lays her eggs in the nests of other birds, most of our engineers pass all fatigue problems on to the metallurgical department with the implication that something must be wrong with the material or with the heat treatment. The metallurgist does his metallurgical best and in the process frequently destroys the evidence of mechanical faults!

The study of fatigue of materials is properly the joint duty of the metallurgical, engineering and production departments. Unless all have an understanding of fatigue phenomena and the factors that promote fatigue, they cannot recognize their individual responsibilities. There is no definite line of demarcation between mechanical and metallurgical factors that contribute to fatigue and there must, therefore, be very close cooperation between the metallurgist and the engineering fatigue specialist, if such there is, or the metallurgist must possess the combined qualifications of metallurgist, designer and machinist. This overlapping of responsibility is not sufficiently understood in industry and hence the engineers are constantly demanding new metallurgical miracles instead of correcting their own faults. Until metallurgists insist on a competent examination for mechanical causes of fatigue failures, we cannot hope to make full use of our engineering materials.

Service Conditions Are Not Reproducible — The development of engineering materials, designs, and processes requires that we conduct laboratory to devise a reliable laboratory test is far from simple. The common belief that we can reproduce the conditions of service in a laboratory test is wholly erroneous. By the time the laboratory investigator has provided for all of the conditions that occur in service, he will, in the case of automobile parts, find himself on the road with a complete automobile, and even then he will not represent the type of driver who most severely taxes the strength of the machine.

Compromise Treatments — Many materials and processes have been graded and are still being graded by laboratory tests which are now known to have been very costly to the automobile industry (and to other industries as well). For example, the fiction that a carburized part should have a hard case to resist wear, and a tough core to resist breakage, arose from laboratory impact tests. In these tests the strength of the part was judged by the number or intensity of hammer blows it would withstand before fracture. Since gear teeth resisted impact fracture in accordance with the physical properties of the core, it seemed logical to specify heat treatments to bring out the best compromise between the imagined requirements of the case and the core. Being compromises, these heat treatments were not the best for either region.

If, instead of counting the number of impacts or measuring the intensity of hammer blows to produce fracture, the gear tooth had been examined after the first impact, the tooth would have been found bent and, therefore, ruined, and it would make no difference how many more blows were required to fracture the tooth.

This compromise heat treatment resulted in reducing the quality of many millions of gears before it was realized that gear teeth fail by fatigue and that fatigue failure, for the usual depth of carburization, always originates at the surface of the case. From this evidence it became clear that the heat treatment should consider the requirements of the carburized case only, and that the properties of the core were relatively unimportant, because, in bending and in torsion, the core serves mainly as a stuffing for the case.

Alloy Steels — Similarly, gear steels and steels for many other parts have long been selected by false standards that are based only upon arbitrary laboratory tests, among which are fatigue tests of ideal specimens. For many years industry has paid premium prices for alloy steels because of fancied advantages. Fatigue tests on actual have shown that there is no detectable difference between the high priced alloy steels and many of the low priced alloy steels when used in many machine elements. (This was demonstrated by A. L. Boegehold and the writer in a 1935 A.S.T.M. paper on rear axle gears.) Machine parts are so far removed from the ideal laboratory fatigue specimens that the latter are misleading as measures of worth. This is indicated by the relative slopes of the fatigue curves (as will be demonstrated later in this article) since the slopes of fatigue curves for machine parts under high loadings are always steeper than the slopes of fatigue curves for the preferred laboratory specimens by which materials are usually selected. In all probability there are real differences in the fatigue characteristics of the various alloys, but these differences are often so small in comparison with the mechanical fatigue hazards introduced by the design and fabrication of the machine part as to be negligible.

Fig. 1 — Transfer Print of Magnaflux Markings on Side of a Gear Tooth That Failed by Spalling, Undoubtedly Originating in Grinding Cracks

Mechanical Causes of Fatigue

It is possible to discuss only a few of the many mechanical causes of fatigue in the available space. The subjects selected are those which have not been given the attention they deserve in recent publications, or that may be somewhat differently interpreted. For a thorough and comprehensive review of fatigue literature, the recent book on "Prevention of the Failure of Metals Under Repeated Stress" by the staff of Battelle Memorial Institute is highly to be recommended.

Surface Finishes — Efforts to improve products by improving surface finish may sometimes have the opposite effect. Highly finished surfaces and fillets may lead to a false sense of security if, as the result of machining or straightening operations, the parts have high internal stresses of the wrong kind. In ground surfaces, such as shafts, wrist pins and gear teeth, the grinding operations may introduce high surface tension stresses and thus promote fatigue failures. More harm than good often results from the grinding of machine parts. The surface tension stresses from grinding are often so great as to produce visible or magnaflux surface cracks — but, whether detectable or not, surface tension due to finishing operations is frequently very serious.

For example, Fig. 1 is a magnaflux transfer print on transparent cellulose tape showing surface fractures in a ground gear tooth. This tooth these surface fractures. Since fatigue cracks start on the side of the gear tooth that is loaded in tension, the effective stress is the grinding pre-stress plus the working stress.

Frequently we find that a hardened part will show a file-soft skin after grinding, a surface which not only promotes fatigue but is also susceptible to seizure and galling.

Internal Stresses of the wrong kind are perhaps the most insidious of all fatigue hazards because we can seldom know their magnitude, or the pattern in which they are distributed within the material, or even whether they are alike for all commercially identical machine parts. Internal stresses may be the result of operating conditions such as occur in brake drums, clutch plates or other friction surfaces where the instantaneous temperature in a thin layer is so great that the surface layer is stressed by thermal expansion beyond its yield point in compression. When the source of heat is removed from such a part the heated surface layer is quenched by the adjacent cool metal and, under thermal contraction, it is so severely stressed in tension that fractures occur. This is, of course, the same thing that happens in grinding unless great care is used.

An estimate of the magnitude of the surface tension stresses set up by normal grinding practice was made in the following way:

A specimen of annealed spring stock 0.062 in. thick, 1 in. wide and 7 in. long was ground to a depth of cut of 0.002 in. After grinding the straight specimen was found to be curved concave on the ground side, indicating tension stress therein. Very thin layers were then removed from the ground surface by hand honing until the specimen regained its initial straightness. Measurements of the change in curvature with each thin be calculated, as follows:

Distance From Surface	Tension Stress
0.00005 in.	270,000 psi.
0.00013	110,000
0.00025	57,500
0.00035	37,500
0.00045	27,500

Obviously a stress of 270,000 psi., a stress just below the fracture point of full hard steel, could not be supported by the steel in the annealed state, from which it follows that the stressed layer was hardened by the heat of grinding to not less than Rockwell C-55. The extreme thinness of the hardened layer presents an interesting problem in hardness measurement, the unground and ground surfaces testing as follows:

	Unground	Ground
Rockwell B scale	88	89
Rockwell C scale	5	5
Vickers Brinell	193	199

These figures demonstrate the futility of our normal hardness measuring technique for measuring the hardness of the most significant portion of our machine parts, namely, the surface layer.

Residual Stresses From Processing — Internal stresses often result from the cooling of castings and forgings, or from the vigorous heat transfer of heat treating. Many parts, such as crankshafts, axle shafts, and camshafts require straightening, and since this is usually done at room temperature and the part rarely stress relieved after straightening, the result is severe internal stresses. In turning, milling and other machining operations, it is necessary that metal be removed at a minimum cost and therefore the cutting tools often take deep cuts at high feed rates. Since metal cutting is more accurately described as a metal tearing operation so far as stresses are concerned, we need not be surprised to find serious internal stresses to considerable depths after machining. When metal cutting has been unusually severe or after operations such as punching and shearing, we often find that the surfaces are actually fractured. Finish machining or grinding rarely goes deep enough to remove the internally stressed metal from previous rough machining — and these operations add stresses of their own.

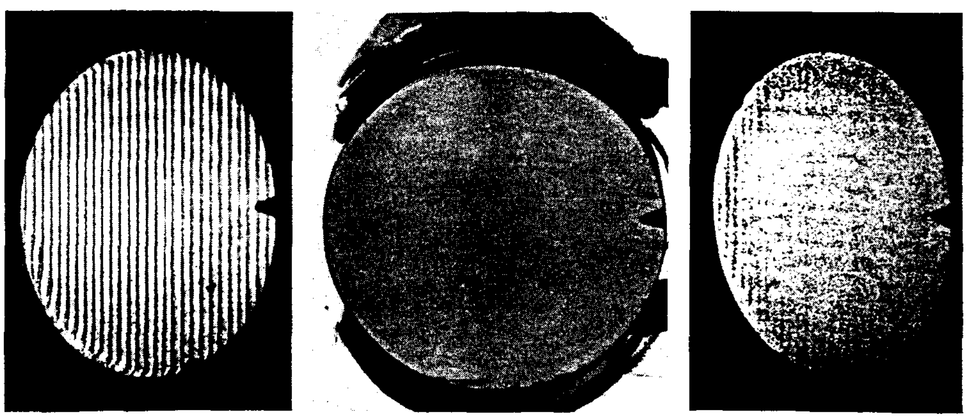

Fig. 2 — Views Showing Deep Seated Disturbance by Rough Machining. Left: Bar end after rough machining on shaper. Center: Same after carburizing, grinding smooth and lapping — all in a direction perpendicular to machining. Right — Shot-blasted surface shows traces of both the machining and the grinding marks

Whenever it is economically practicable, internal stresses that produce tension in any surface layer subjected to cyclic tension stress should be reduced or removed — or, better still, converted to compressive stress by suitable treatment, for all fatigue failures are due to *tension* stresses.

The layer of metal "injured" by machining is undoubtedly deeper than is generally believed, nor does it "recover" after heating for long periods at high temperatures. For example, the left view in Fig. 2 on page 211 shows a bar of 4615 steel after rough machining on a shaper. This piece was then carburized for 8 hr. at 1700° F., cooled in the box, reheated to 1500° F., quenched in oil and drawn at 300° F. for 1 hr. The machined surface was then ground in a direction at right angles to the shaper marks to a depth of 0.0055 in. below the last visible tool mark. It was then polished and lapped to a "perfectly smooth" surface as shown in the center. Finally, the polished surface was shot blasted, whereupon the machining marks (vertical lines) and the grinder marks (horizontal lines) reappeared as shown in Fig. 2 at the right. This shows that the material was not uniform in resisting the shot blasting, notwithstanding the long period at carburizing temperature.

There is no evidence at present that the effect brought out by this experiment is significant in fatigue; it is presented here merely to emphasize that there is much that is not known about our materials and processes.

Surface Vulnerable to Fatigue

The surfaces of repeatedly stressed specimens, no matter how perfectly they are finished, are much more vulnerable to fatigue than the deeper layers. It has long been appreciated that the vulnerability to fatigue increases as the surface roughness is increased, particularly if the roughness consists of sharp notches and more particularly if the notches are oriented at right angles to the principal stress. The practice of carefully finishing fatigue test specimens is, of course, a recognition of this vulnerability insofar as visible marks or scratches are concerned. These precautions are known to be effective in increasing the fatigue strength of specimens, and specimens finished in this manner have therefore come to be known as "par" bars. This name implies that fatigue specimens approaching perfection in finish give the highest possible fatigue endurance for any particular material, and that they accurately measure the ultimate fatigue properties of that material.

It can be shown, however, that the so-called "par" bars are not the best specimens, but that influences akin to notches, so far as fatigue vulnerability is concerned, are retained by them. It seems that the specimen surface is highly vulnerable simply *because it is a surface* — that there is an extra hazard in the surface layer not shared by the deeper layers. This extra surface hazard may be due to sub-microscopic notch effects, or to the fact that the outer crystals are unsupported on their outer faces. Whatever the reason, the evidence for surface vulnerability is strong.

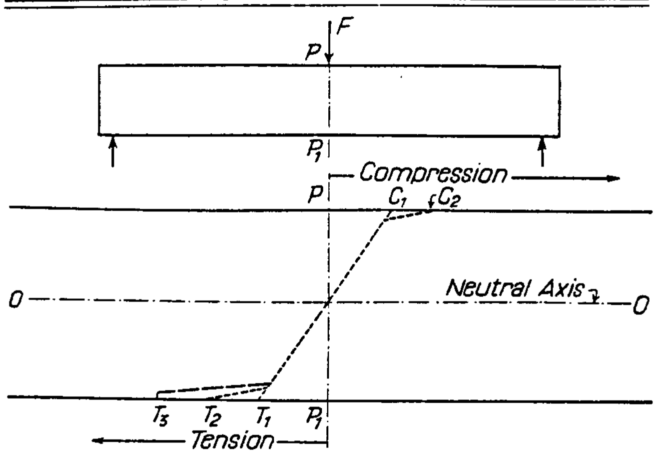

Fig. 4 — Conventional Linear Representation of Stress (C_1-T_1) in a Beam Modified by Lines C_1-C_2, T_1-T_2 and T_1-T_3, Additive Stresses Due to Surface Condition

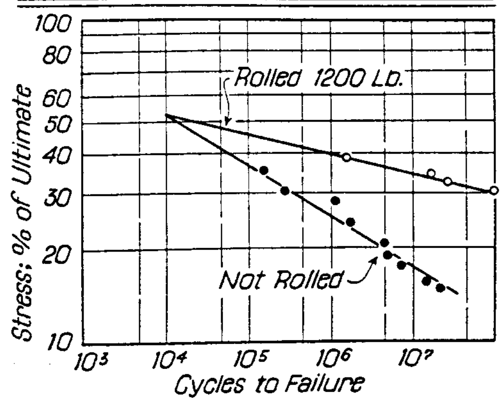

Fig. 3 — O. J. Horger's Experiments on Full Sized Railroad Axles Show Better Endurance When Normally Machined Journals Are Burnished by Cold Rolling. Diagram from A.S.M.E. Transactions, *1936*

Compression Lessens Surface Vulnerability — The fatigue strength of the most carefully prepared specimen will be increased if a thin surface layer is pre-stressed in compression by a peening operation such as hammering, swaging, shot blasting, tumbling, or by pressure operations by balls or rollers. This increase in fatigue strength, resulting from the surface layer being stressed in compression, is clearly shown by the *S-N* curves, Fig. 3, which compare normally finished railway axles with axles that had been subjected to a rolling operation. These and other tests show that the surface, stressed in compression, is effective either on highly finished specimens or those with comparatively rough surfaces.

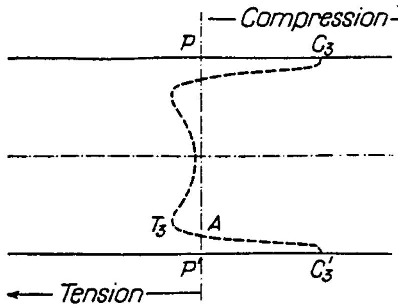

Fig. 5 — Pattern of Residual Stresses in Unloaded Beam That Has Had Its Surface Compressed by Peening

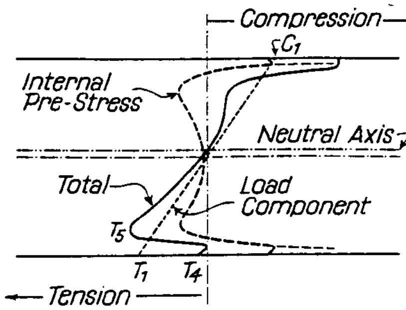

Fig. 6 — The Beam of Fig. 5 Has Been Loaded Once (External Load Equals T_1-C_1), and the Resultant Stresses Are Indicated by Full Line

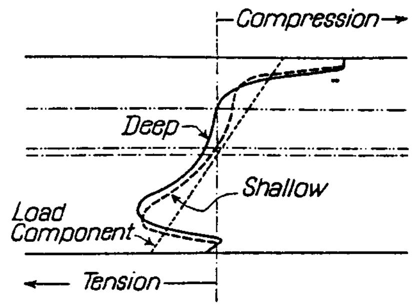

Fig. 7 — Depth of Pre-Stressed Layer Has Considerable Influence on the Working Stress Pattern and the Location of the Neutral Axis

We are all familiar with the improvement in fatigue that may be obtained by a few cycles of overload in such parts as springs. Local stresses from the overloads exceed the elastic limit of the material and, therefore, the tension stress at the working load is decreased. This treatment, which has long been practiced on many production items, is the equivalent of rolling or peening since, in the unloaded state, the member is stressed in compression in the areas where tension yield occurred during the overloading.

The most plausible explanation of the effectiveness of surface compression stress is that when a load is applied to such specimens the tension stress in the surface layer is reduced by the amount of the compression pre-stress, and since *fatigue failure starts only from tension stress* the fatigue durability of the surface layer is increased. However, the tension stress in the material *below* the pre-stressed layer is not reduced but may be actually increased, notwithstanding which the fatigue strength of the specimen is increased. It follows, therefore, that the lower layer is inherently stronger than the surface layer. The German investigator Föppl has shown that the fatigue fracture in cold rolled specimens does not originate at the surface but in the material below the pre-stressed layer, as would be expected if the surface is sufficiently pre-stressed in compression. Similar sub-surface fatigue failures, usually called fissures and attributed to faulty material, have long been known to occur in railroad rails in which the surface is stressed in compression from the cold work of heavily loaded locomotive and car wheels.

The situation can perhaps be clarified by the use of the conventional textbook stress diagram of a loaded beam, as illustrated in Fig. 4, in which a beam supported at the ends is loaded in the central plane, P-P_1. The stress at any point in the beam is measured by the horizontal distance from the plane P, in which the load is applied, to the diagonal line T_1-C_1. The distance P-C_1 represents the compressive stress at the upper surface, the stress at the neutral axis O-O is zero, and the tension at the lower surface is represented by T_1-P_1.

While this is a satisfactory enough stress diagram for static loads, it does not agree with the behavior of fatigue specimens. If we modify the diagram at the ends of the stress line so that T_1-T_2 represents an added increment of tension stress, we have a reasonable representation of the "surface fatigue vulnerability". For a sharply notched surface the additional stress increment T_1-T_2 is relatively great (something like T_1-T_3, where P_1-T_3 represents the yield point of the material). As the surface roughness is decreased the increment T_1-T_2 decreases, but no matter how well polished the specimen may be there still remains a considerable additional surface stress.

Stress Patterns — Figure 5 represents the residual stress pattern in an unloaded beam that has been rolled or peened, as has been described, in which C_3-P and C_3'-P' represent the magnitude of compressive pre-stresses and T_3-A represents the magnitude of the tension pre-stress to balance the compressed stresses in the surfaces. After this beam has been loaded from either side through one stress cycle (as in a reversed fatigue test) the compression pre-stress will be reduced if the applied load raises the total compression stress above the yield point. The stress diagram for such pre-stressed beam supporting an external load is shown in Fig. 6, in which the effective fatigue tension stress T_4 at the surface may be less than the stress T_5 below the surface, in which case failure would start below the surface as observed by Föppl. Note also that the neutral axis is displaced from the geometric center of the beam, and that the tension stress T_5 below the surface is greater than in the beam that had not been pre-stressed, as is shown by the dotted lines.

It seems evident that the improvement in fatigue strength by compressive pre-stress is due to the reduction in tension stress in the vulner-

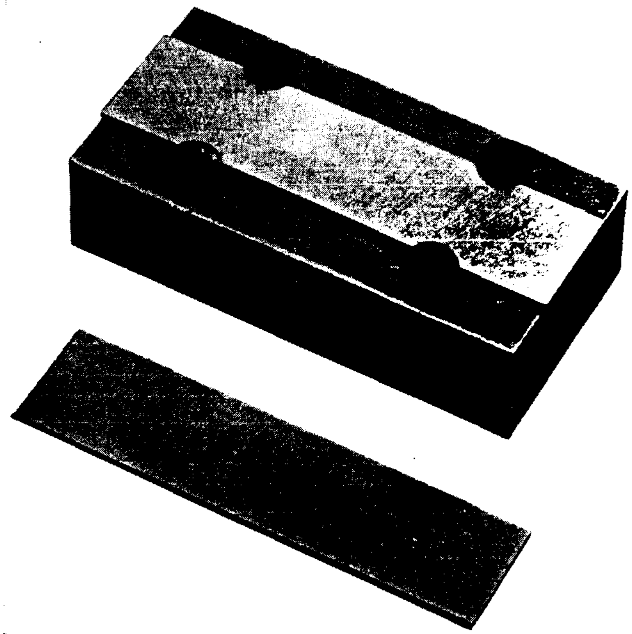

Fig. 8 — Flat Test Strip of Tempered (Stress Free) Steel, Held Down to Stiff Block by Screws so Only One Surface Is Exposed to Cold Working Treatment

able surface layer, and that the increased compressive stress in a specimen stressed from zero to a maximum in either direction does no harm — probably because the compression stress in the prestressed layer is adjusted by the yield of metal.

Further evidence of the extra vulnerability of the surface layer is found in the behavior of specimens having increased strength in a thin surface layer, as in thinly carburized specimens or in thinly nitrided specimens. Fatigue failures in such specimens also start below the surface and show greater fatigue strength than the same material in the unclad state. A nitrided specimen is probably superior to the other forms of hard cladding because, in addition to the higher physical properties of the surface layer, this thin layer is more highly stressed in compression and it is, therefore, less notch-sensitive.

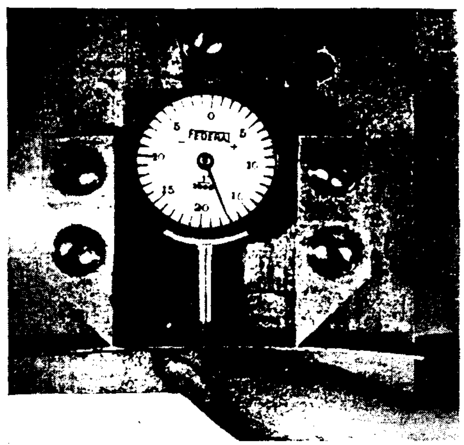

Fig. 9 — Dial Gage and Knife Edges for Measuring Curvature on Test Strips

While on the subject of beneficial residual stresses, mention should be made of surface compressive stress obtainable by heat treatment. By a rapid quench it is possible to trap compressive stress in the chilled surface and corresponding tension stress in the core, but this method is not so effective as the others discussed, possibly because of the low yield point of metal at heat treating temperatures.

First Use of Surface Compression

The idea of surface compression to improve the strength of steel is probably as old as steel itself. It has probably been discovered, forgotten and rediscovered many times. Certainly every village blacksmith knew and practiced the art in making wagon and buggy springs, axles and other heavily loaded parts. After these parts were forged into shape they were severely hammered to improve their strength and, no doubt, the same procedure was followed by the ancient sword makers. Likewise, mill and ship shafts were cold worked by the application of small rollers at high pressure, after machining, because of the greater strength that was known to result.

Our technical language contains many words that vaguely describe properties or characteristics of materials or just symptoms that we do not understand. The oil technicians have the handy word "oiliness" for covering up many of the things they do not know about lubricants, the chemists have "catalysis" and the metallurgists have "cold work". We who are interested in fatigue have much to say about "cold work" without regard to the nature of the operation or to the effects that are produced. We often find that "cold work" and "work hardening" are used synonymously. These expressions serve well enough when applied to certain commercial fabrication processes, but engineers must be much more specific when they wish to measure the effect of cold work on fatigue strength.

Cold working of metals increases the hardness of most metals, including steel, at least in the range of low hardness. It usually results in internal stresses of varying degrees and patterns, it alters the physical properties and sometimes fractures the material. With the known sensitivity of materials to fatigue, we must learn how to control cold work just as we have learned how to control heat treatment, so we may benefit by the good effects and overcome the evil effects. We would not think of specifying a heat treatment without stating whether the temperature should be raised or lowered and to what extent, yet that is the way we now think of cold work. Cold working can be good or bad depending upon how it is done and for what purpose.

working the surface, so as to produce a layer stressed in compression, increases the fatigue strength of the parts to which it is applied, but we are not told the *amount* of the pre-stress or the *depth* of the pre-stressed layer. Both of these values are presumably important in obtaining optimum results for any particular specimen, but it is probable that the values should not be the same for all sizes of specimens, for all materials, or for hard and soft specimens.

When the layer is stressed in compression (by applying sufficient pressure on the work by rollers or by peening) to a degree exceeding the yield strength of the metal in compression, the *amount* of residual stress is presumably at least equal to this yield strength.

The *depth* of the stressed layer is probably roughly proportional to the instantaneous area over which the pressure is applied, and to the pressure intensity. The depth of the compression stressed layer in a railroad rail (as studied by E. J. Herbert and reported in the *Journal* of the British Iron and Steel Institute in 1927) should be greater than the depth of the compression stressed layer in the same material if small rollers at the same pressure intensity were used instead of large car wheels. Under these circumstances the initial point of fracture should appear at corresponding depths. Such evidence as is available indicates this to be true.

The magnitude of the sub-surface tension stress in a loaded beam having compression pre-stressed surfaces will vary with the amount of compression pre-stress and with the depth of the pre-stressed layer. Figure 7 shows that the sub-surface tension stress may sometimes be greater for a deeply pre-stressed layer than for a layer of lesser depth. It would therefore seem important to control the compression stressed layer, as to stress magnitude and depth, with considerable accuracy by proper selection of the curvature of the rolling or peening instruments and by the pressure that is applied.

Measuring the Pre-Stressed Layer

A simple and practical method for measuring the magnitude and depth of residual stress in the compression stressed layer consists of a thin flat strip, attached to the heavy base shown in Fig. 8. This strip is rolled or peened with the same intensity that is given to the machine part and when it is removed from the base it will be found to be curved, with the convex surface on the cold worked side. Curvature of the strip may be measured by an indicator, as shown in Fig. 9, which can then be interpreted as a measure of the imposed residual stress.

Figure 10 records as a dashed line and as a full line the stress magnitude and the depth of the stressed layer at constant cold work intensity of two such test strips. To determine the magnitudes the cold worked surfaces of these strips, whose Rockwell hardness was respectively C-64 and C-40, were honed away in small increments and the curvature measured after each thin layer was removed. Because of the higher yield point, the harder specimen was found to be more highly stressed than the softer specimen.

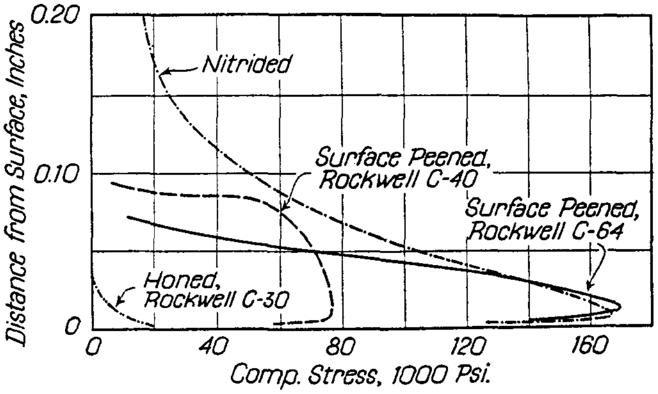

Fig. 10 — Stress Imposed by Various Treatments

Also shown in this chart is the surface compressive stress set up by nitriding. Procedure for this experiment was the same except that the face of the specimen that was in contact with the heavy base was tin plated to prevent nitriding. On removal from the base the strip was curved convex on the nitrided side. It seems, therefore, that the well known resistance of nitrided specimens to fatigue is primarily due to the compressively stressed surface layer.

Residual Stress From Honing — While the above described peened specimens were being honed it was found that the strips did not fully recover their original flat form. To determine if this residual curvature was due to a "set" in the material, or was the result of honing, other flat strips that had not been peened were honed. These strips developed the same curvature as the residual curvature in the peened specimens, demonstrating that honing produces a compressively stressed layer. The approximate magnitude of this stress is also shown in Fig. 10. This observation raises a question as to the state of surface stress in the carefully prepared and lapped specimens favored for laboratory fatigue tests, since additional tests have shown that lapping also introduces surface compressive stress.

The Carburized Layer in a carburized part is stressed in compression, as is shown in a simple test. Two opposite faces of a ½-in. square specimen were carburized while the other two faces were protected by copper plating. The specimen was quenched and tempered *(Continued on p. 270)*

PEENED SURFACES

(From page 215) in the usual manner, after which it was split longitudinally with a saw. The two parts curved, convex on the outer faces, indicating compressive stresses in these carburized faces. Analysis of the internal stresses in another carburized member by the method already described indicated the internal stress pattern shown in Fig. 11. Of interest here is the magnitude of the compressive stress in the carburized layer and the reduced stress (possibly even tension) in an extremely thin surface layer.

When carburized parts such as bearing races, wrist pins and gear teeth are ground we may expect the surface to be stressed in tension, as is indicated by the dotted line in Fig. 11.

The residual compressive stress in the carburized layer may be a hazard for members stressed in tension, because the tension stress in the core is equal to the working stress plus the tension stress due to the compressive pre-load of the case. For members stressed in bending and in torsion the internal compressive stress in the carburized case improves the fatigue strength of the part, except for the thin surface layer which, especially after grinding, is severely stressed in tension. It is, however, a simple matter to convert this thin tension stressed layer into stress in compression by a suitable peening or rolling operation.

With internal stresses of the magnitude shown in Fig. 11 we can readily understand why carburized parts are prone to warp during heat treatment, especially if the design is not symmetrical with respect to the internal stresses.

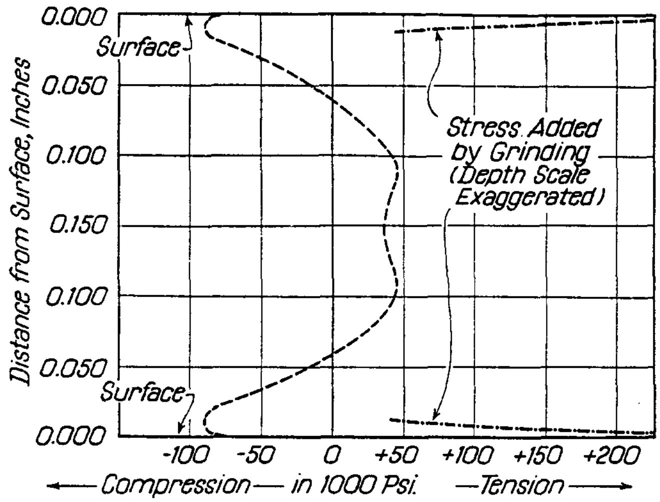

Fig. 11 — Dashed Line Showing Residual Stress in Steel Part Due to Carburizing and Hardening. Tension stresses added at very surface due to grinding are indicated by dotted lines