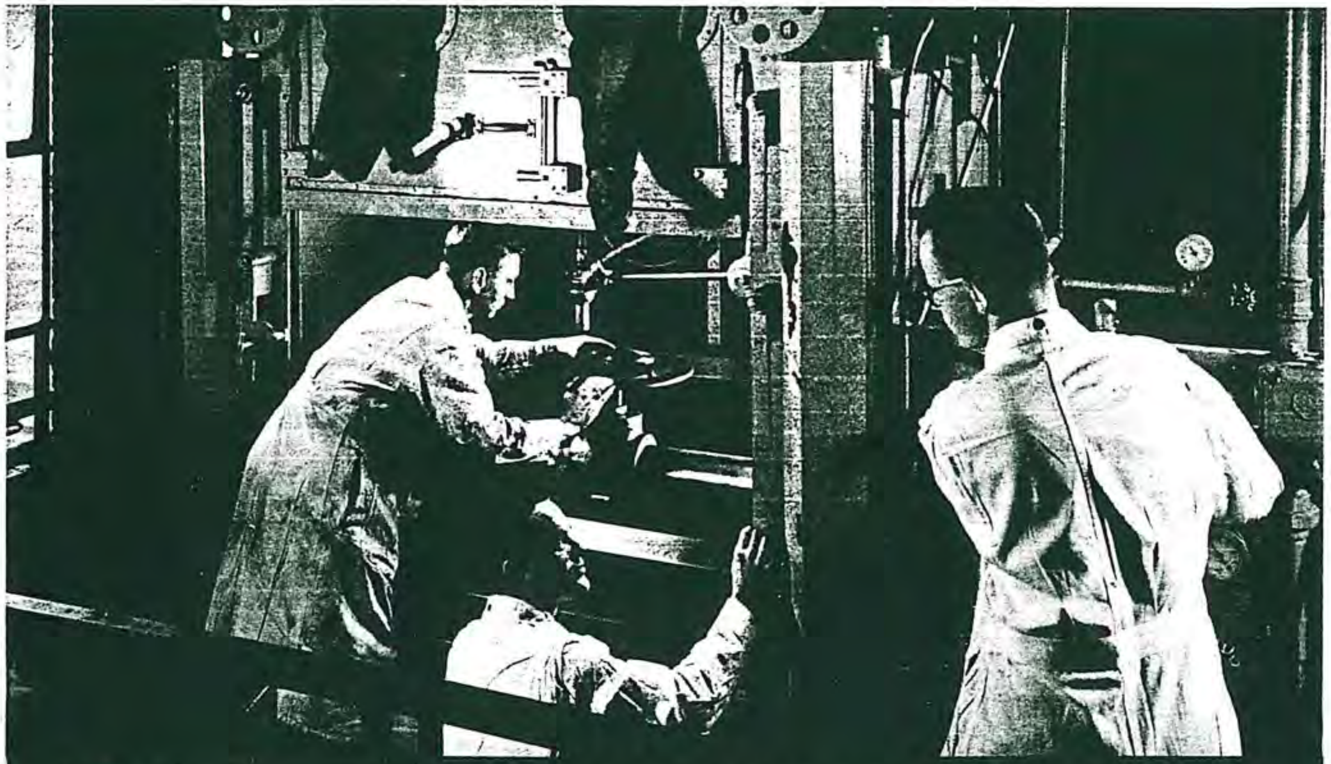


Fig. 1—Laboratory set up used in projects for determining effect of shot blasting on the fatigue life of automotive parts.

Prestressing Processes and Fracture Barriers

UNEXPECTED and unrecognized improvement in fatigue strength of metal products is often obtained from processes that are applied for other purposes. Engineers, often unknowingly, have long made use of the fact that fatigue fractures cannot originate (Ref. 1) and cracks cannot propagate in compressively stressed material.

Railway car wheel failures would be more frequent if fatigue barriers, in the form of residual compressive stresses, were not present in the rims of the wheels. These essential stresses are induced during fabrication by operations that are intended to harden the wheel surfaces and thus obtain wear resistance.

CARBURIZING, nitriding, and other case hardening operations are immunizing treatments against fatigue fractures. Although usually specified to increase resistance to wear, abrasion, or corrosion, case hardening also increases the fatigue strength of the surface hardened part. Though usually attributed to the toughness of the core, the superior fatigue strength of such parts actually results from the fracture barriers that are established by residual compressive stresses in the hardened surfaces.

Mechanical cold working processes such as shot peening, surface rolling, and stressing beyond the yield strength of the material as is commonly done in pre-setting springs, are applied because the cold worked metal is known to resist fatigue failures. Actually, the improved fatigue strength results from the protection afforded the metal surface by the residual compressive stress induced by the cold working (Ref. 2). Even laboratory fatigue specimens profit greatly from the relatively minute cold work of polishing. The residual compressive stress that results from polishing increases the fatigue strength of most laboratory specimens to such an extent that the purpose of the polishing the specimen is defeated.

Explanations of the behavior of fatigue specimens are usually incomplete, misleading, and erroneous when the fact is neglected that cold working, and many other processing operations, develop beneficial residual stresses in the treated metal. The concept that residual stresses can be beneficial also runs counter to the generally accepted theories of failure (Ref. 3). In static tests, failure is measured by extensive plastic deformation of the test specimens; and such failures will result from tension, compression, or shear stresses.

Information obtained from dissection stress measurements (Ref. 3, 4, and 5) of fatigue specimens permits interpretation of data in terms of residual stress.

Re-interpretation of old test data in terms of residual stresses, in numerous instances, have completely changed the significance of the test.

Criteria for Carburizing

The customary criteria for carburizing are incomplete and misleading as far as fatigue strength is concerned. Among the important factors that affect fatigue life are:

1. Magnitude of the residual compressive stress in the carburized case. This stress is a measure of the protection against surface weakness.

2. Compressive elastic limit of the hardened case. If compression yielding occurs residual compressive stress will be lost.

3. Area of the case in relation to the area of the core. Premature internal fractures in the core can develop from excessive residual tension.

One serious problem in the production of Allison engines during World War II was the large number of carburized main reduction gears that were scrapped because magnetic particle inspection revealed cracks in the tooth surfaces. The cracks were caused by the residual tensile stress developed in the surface layers of the teeth by finish grinding.

During grinding, the temperature of a very thin layer of the metal immediately under the grinding wheel increased greatly causing thermal expansion of this layer and at the same time reduced its yield strength. Being restrained by the underlying cold metal, the hot layer became compressively stressed above its elastic strength, whereupon it adjusted to its restrained dimensions. Upon cooling, the heated layer contracted, and cracks appeared on the tooth surfaces when the resulting residual tensile stress exceeded the ultimate strength of the metal.

When magnetic particle inspection revealed such cracks, the almost completely machined gears were scrapped as useless, since any surface defect increases the local stress and hastens fatigue failure. Also, grinding cracks in carburized gear teeth were presumed to be particularly harmful, because the local stress increases as the metal hardness is increased and as the surface notch become sharper.

So many gears were scrapped that gears containing numerous grinding cracks were tested for fatigue strength and thus measure the extent of damage caused by the cracks. The gears were tested in a fixture employing the closed circuit system, in which two main reduction gear sets were coupled to oppose one another and the torque to be transmitted was controlled by a suitable wind-up mechanism. The gears were rotated by an electric motor through the low speed shaft.

During the test periodic magnetic particle examinations were made of the gear teeth. Also at these times, adhesive tape transfer prints of all the teeth were made to record any increase in number or growth of surface cracks between examination intervals.

A succession of transparent ad-

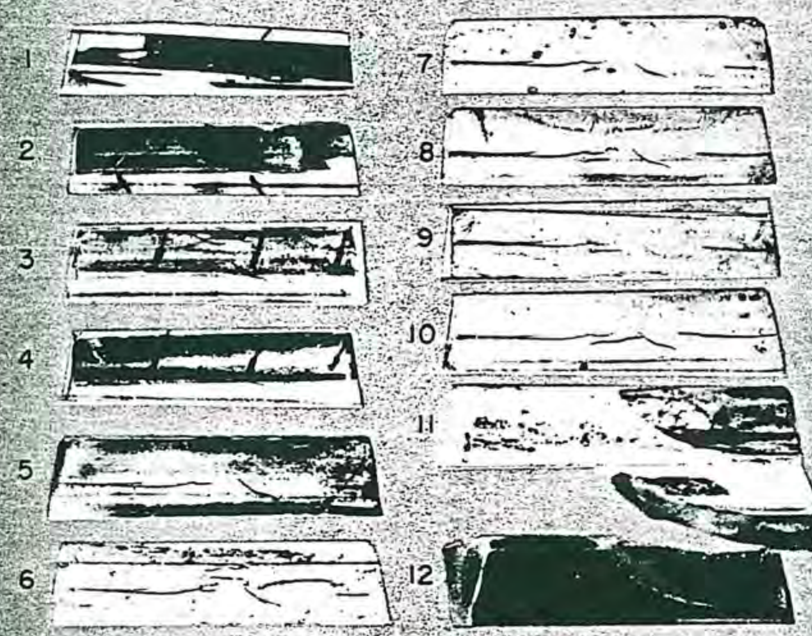


Fig. 2 — Succession of transfer prints of magnetic particle markings on one cracked gear tooth.

Table I—Test Data on Carburized and Ground Main Reduction Gear

Note: Print Numbers refer to series shown in Fig. 2.
Test loads are stated in percent of take-off torque.

Print Number	Test Load	Stress Cycles Between Readings	Total Cycles at Time of Print	Total Number of Cracks
1	None		None	1
2	100	1,830,000	1,830,000	2
3	100	2,850,000	4,680,000	3
4	100	4,420,000	9,100,000	3
5	100	5,740,000	14,840,000	3
6	100	3,010,000	17,850,000	3
7	100	17,950,000	35,800,000	4
8	100	14,350,000	50,150,000	4
9	122	2,500,000	52,750,000	4
10	122	4,170,000	56,920,000	4
	122	6,450,000		
	144	18,750,000		
11	166	18,800,000	100,920,000	4
12	Broken tooth after a total of 100,920,000 stress cycles.			

hesive tape transfer prints of the magnetic particle markings on one cracked tooth from a gear used in one fatigue test is shown in Fig. 2. These prints are made by placing transparent adhesive tape upon the tooth surface after the cracks have been revealed by magnetic particles. The magnetic particles marking the cracks adhere to the tape, which thus becomes a faithful copy of the actual crack pattern. After removal from the gear tooth, the tape is attached to a white background to increase the contrast for photographic purposes. To avoid smudging, the tape should not be placed on the gear tooth until the surface is thoroughly dry.

The particular tooth shown in Fig. 2 was selected for illustration because it is the only one in the gear undergoing fatigue test that finally failed. The upper left-hand print was made before the test commenced. The early prints, particularly the first, second, and fourth, are not clear because of inexperience with the adhesive tape method of transferring the magnetic particle indications. A few markings can be distinguished, however, that show that grinding cracks increase from one in the first print to two in the second and three in the third. No additional cracks appear in succeeding prints in that column.

The numbers in the first column of Table I refer to the prints of Fig. 2. The test loads applied to the gear and the number of stress cycles (revolutions) completed at the time each print was made are given in Table I; the test loads are stated in percent of take-off torque, that is, the torque at the maximum engine output that may be used for short periods only.

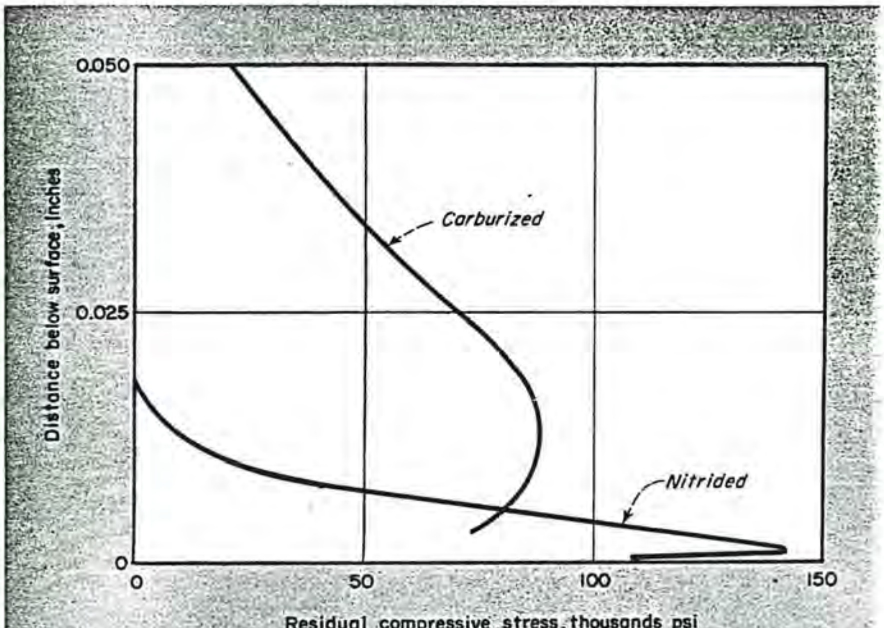


Fig. 3 — Residual stress in carburized case of gear tooth (not ground) as measured by dissection method.

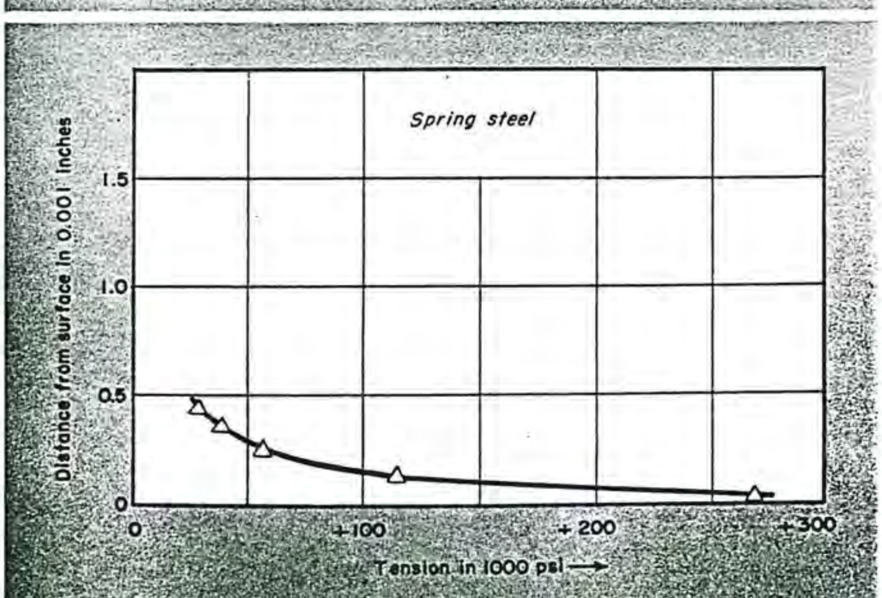


Fig. 4 — Residual stress in a high carbon steel specimen caused by grinding.

Note that there is an increase in the number of cracks during the early part of the test, as is indicated in the last column of Table I, and that a fourth crack appears in Print 7. A slow increase in length is seen to occur in all the cracks except the original diagonal crack, which appears to the right of center. Prints 9 and 10 were made after the test load had been increased to 122 percent of take-off torque. The final transfer print, Print 11, was made after the tooth had failed as the result of being subjected to more than 100 million stress cycles at various loads; the last 18.8 million of which were 166 percent of take-off torque.

Fracture of the tooth occurred after a total of 100,920,000 stress cycles had been applied for reasons other than the extension in depth or in length of grinding cracks. Extensive surface pitting occurred to the right of the original inclined crack, as may be seen in Print 12, which is a photograph and not a transfer print. This pitting may have contributed to the final fracture or the fracture could have originated at the root of the tooth near its outer end. For the present purpose, the important fact is that the grinding cracks did not grow in depth as would be expected from this severe type of stress raiser.

Similar results were obtained from check tests conducted by the Allison Division on another carburized reduction gear, which was also damaged in grinding to the extent that actual cracks were detected in several teeth. In fatigue tests, this gear was subjected to various loads; tests were continued to 82 million stress cycles, the last 18 million of which were under a load of 166 percent of take-off torque. During the tests a few new cracks appeared and the length of cracks increased, but when the test was stopped failure had not occurred in any tooth.

These tests are cases in which numerous severe stress raisers in very hard, and therefore notch sensitive, steel did not weaken any of a large number of cantilever beam test specimens. Their behavior is contrary to all normal expectations; and the explanation is not to be found among the recognized physical properties or in the microstructure of the material.

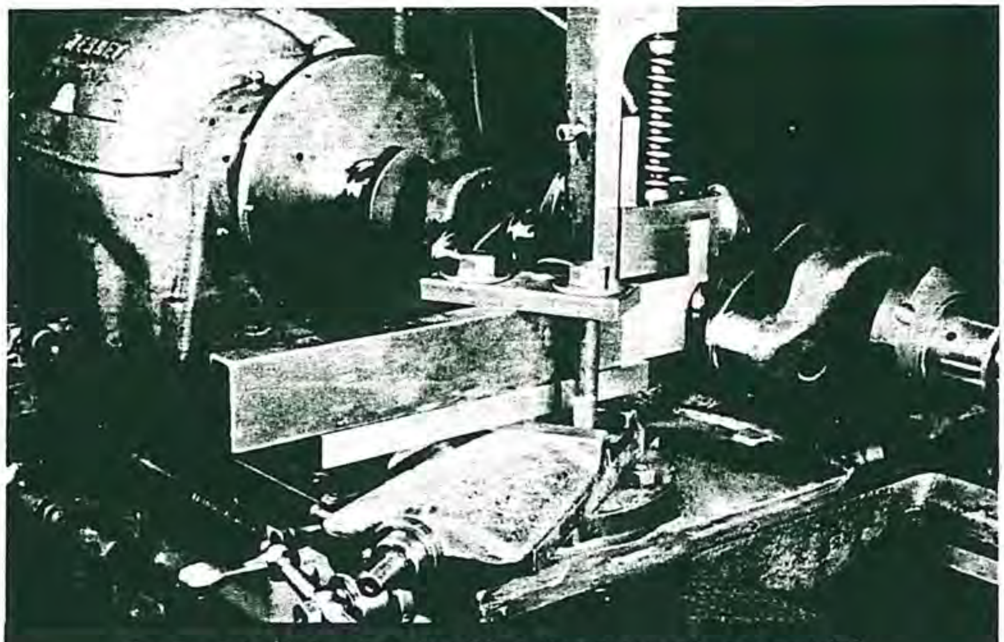


Fig. 5 — Lathe fixture for rolling fillets of crank journals on a crankshaft.

Cracks Cannot Propagate in Compressively Stressed Metal

Dissection measurements, made by the General Motors Research Laboratories (Ref. 1 and 2), of the residual stress in the carburized case of an Allison reduction gear tooth that was not ground yielded the data shown in Fig. 3. The surface residual stress is compressive and its magnitude approaches 100,000 psi. This stress developed as a result of the dilation that occurs in the carburized case during the hardening transformation. The case seeks to expand and to occupy more space (Ref. 6) but since the low carbon steel in the core does not harden, and therefore does not expand, the case is restrained by the core. The case thus becomes residually stressed in compression and the resisting core becomes residually stressed in tension.

Measurements of the residual stress that resulted from grinding a high carbon steel specimen (Ref. 1 and 2) are shown in Fig. 4. These show that the surface residual stress developed by grinding is tensile, that the stress magnitude is approximately 25,000 psi, and that its maximum depth is 0.0005 inch.

It is probable that the surface residual stresses developed by grinding in the Allison gear teeth were of similar depths and similar or greater magnitudes. The residual compressive stresses in the deeper layers of the carburized case were probably of similar magnitude and depth as the measured stress in the carburized gear tooth, Fig. 3, because this specimen was taken from another Allison gear having the same dimensions, material and heat-treatment. The residual tensile stress from grinding that is shown in Fig. 4 is also shown extending leftward in Fig. 3, but with exaggerated depth. The combination is presented for the purpose of indicating the probable stress pattern in the Allison gear teeth.

Since in the Allison teeth the surface grinding cracks overlay the hard and compressively stressed case, the cracks could not extend in depth unless the tensile stress from the test load was considerably greater than the residual compressive stress. But since this tensile stress did not greatly exceed the residual compressive stress, the grinding cracks were therefore harmless as far as tooth fracture was concerned.

Cracks can perhaps contribute to the formation of surface pits by generating high pressures in the oil within the cracks as described by Way (Ref. 7). Way found that the surfaces of contacting rollers were more severely damaged when lubricated than when dry. He suggested the damage was caused by hydrostatic pressure within the oil filled cracks when passing through the zone of high contact pressure.

Cracks Penetrate Carburized Layer

In a third fatigue test, conducted by the Allison Division, on a gear in which grinding cracks had developed in the root portions as well as on the active involute profile surfaces of the teeth, a tooth failed by complete fracture after 3.15 million stress cycles; the first 900 thousand of which was at take-off torque and the final 2.25 million at 115 percent take-off torque.

In this third test, the metal in the region of the grinding cracks at the roots of the teeth was more highly stressed by the bending load, at any externally applied load level, than was the metal in the vicinity of the cracks in the active areas of the gear teeth in the first two fatigue tests. The increased stress was caused by the greater bending moment and by stress concentration in the tooth fillets, plus reduced residual compressive stress through the loss of thickness of the carburized case by excessive removal of metal during grinding.

The normal case depth measured 0.051 in., but the depth of case in the fractured teeth measured 0.030 in.; indicating that the case thickness had been reduced 0.021 in. by grinding. From Fig. 3 it is seen that the peak of the residual compressive stress in the case was removed, and a further loss of effective case thickness occurred by the relatively deep layer that was residually stressed in tension by the severe grinding.

Augmented by the severe stress raiser in the form of grinding crack, the increased tensile stress from the applied load was sufficient to overcome the less than normal compressive stress of the case. The progress of the crack, however, was greatly retarded by the remaining barrier since failure did not occur until after 3 million stress cycles.

In all the ground gears, the tooth

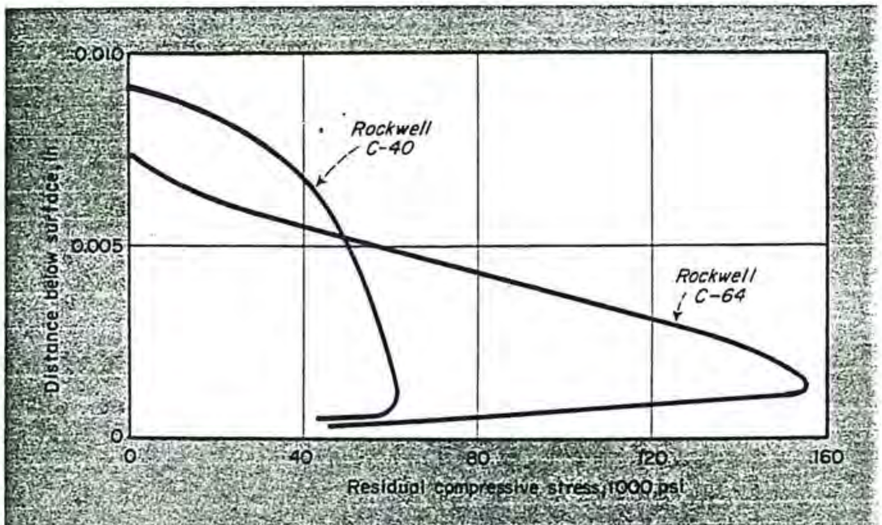


Fig. 6 — Residual compressive stress induced by identical shot peening in steel specimens of different hardness.

surface areas in which no cracks occurred were still severely afflicted by the residual tensile stress that resulted from the grinding operation. In these areas, the stress was only slightly less in magnitude than the ultimate tensile strength of the steel. This residual tensile stress in the active tooth surfaces was augmented by tensile stress from the test loads.

The magnitude of the residual tensile grinding stress was gradually reduced, and eventually became converted to residual compressive stress, by the mutual cold working of the contacting teeth. The combined high unit pressure and the sliding motion caused plastic displacement of the surface metal. This displacement induced residual compressive stress in the same manner as it is induced by the high unit pressure of impacting shot during shot peening and by the high unit pressure from surface rolling.

Hard Steel Is Ductile

Steel of highest hardness is still sufficiently ductile to flow by mutual cold work under the pressures occurring between contacting teeth; and the magnitude of the residual stress induced increases with the hardness of the cold worked surfaces.

In Fig. 6 are shown measurements, by the Research Division of the General Motors Corporation, of the residual compressive stress induced by identical shot peening in two steel specimens that differed in hardness. The maximum residual compressive stress induced in the specimen having a Rockwell C hardness of 40 was dissection measured as 60,000 psi. Whereas in the specimen having a Rockwell C hardness of 64, the peening residual stress was measured as 155,000 psi. These values respectively are roughly one-half the nominal yield stress of the specimens.

The residual compressive stress that was induced in the Allison carburized gear teeth by plastic flow of the surface metal was not measured, and no direct evidence was taken to show that plastic flow had occurred. Such plastic displacement, however, is shown in Fig. 7, which is a section at high magnification through a carburized spiral bevel gear tooth having hardness of Rockwell C 62 (Ref. 4). The flow lines of the plastically displaced metal are clearly shown.

Because of cold working of this character and the resulting residual compressive stress, new cracks did not appear after the test had progressed for some time, although the test load was increased by sixty-six percent. Because of the hydrostatic pressure of the oil within the cracks, the extension in length of grinding cracks may continue, even after the surface residual stress has been converted from tension to compression by the cold working of contacting teeth.

Measurements of the residual stress in another gear tooth are shown in Fig. 8. This tooth was taken from a large marine gear in which the teeth were cut after heat-treatment. The tooth surface, therefore, was substantially free from residual stress except that which may have been induced by the machining processes (Ref. 4). The dissection measurements were made in the direction of the tooth width after prolonged tests of the gear at high load.

Note that the residual stress in-

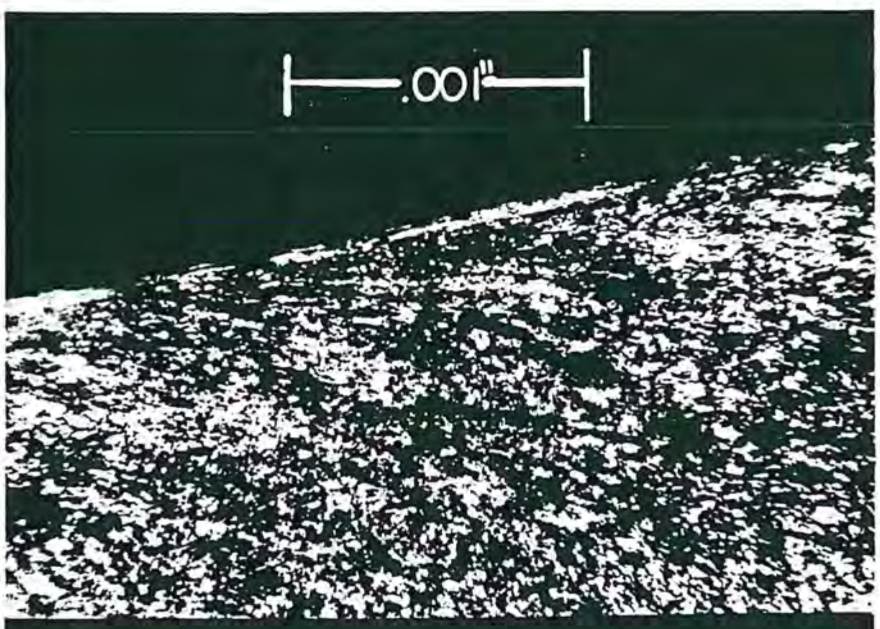


Fig. 7— Plastic flow of hard steel, Rc 62, in carburized bevel gear tooth.

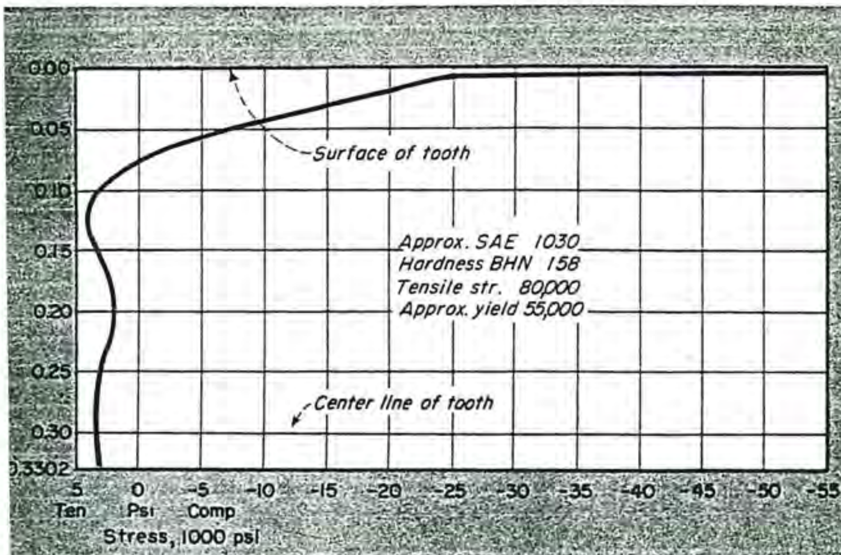


Fig. 8 — Residual stress in tooth of a large marine gear that was cut after heat-treatment.

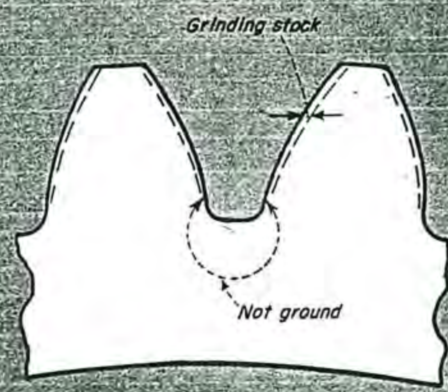


Fig. 9 — Exaggerated form of involute gear tooth cut with a protuberance hob. Involute profiles can be ground without grinding vulnerable root areas.

duced in the cold worked surface is compressive, and that it is approximately equal to the nominal yield strength of the steel. (This statement conflicts with the earlier statement that the residual stress from shot peening is approximately equal to one-half the nominal yield strength of the peened metal. The explanation is: (a) Shot peening residual stress is the average of the stress from many independent local areas of stress, whereas gear tooth contact is more nearly continuous; and (b) the duration of the treatments is not comparable. If shot peening should be continued for a period similar to the operating time of the gear teeth the peened surface would be worn away more rapidly than the residual stress could be increased.) Hence, cold worked areas of gear teeth acquire a degree of immunity in normal operation.

This effect has long been recognized by industrial and marine gear manufacturers as "corrective pitting." This term means that the pits, which often form on the loaded surfaces of the teeth after a relatively short time in service, cease to develop as normal operation continues. It has been assumed heretofore that the early pits were caused by excessive local compressive stress upon projecting areas on the newly cut surfaces, and that the pitting would stop when the elevated areas were sufficiently reduced by wear. Actually, pitting stops because of the protection that develops in the form of surface residual compressive stress.

In the hardened case of carburized gear teeth, the residual compressive stress is similarly effective in preventing shallow surface fatigue pits from acting as stress raisers, and thereby reduces this type of tooth fatigue fracture.

Grinding Most Damaging at Tooth Roots

Mutual cold working does not extend to the root portions of contacting teeth, because tooth action is necessarily limited to the active involute profile. In the area below the active profile, the residual tensile stress from grinding remains undiminished except for the slow relaxation that occurs in unidirectional loading by dynamic yielding. Since the damaging grinding stress is retained at the roots of the teeth, where the tensile stress from the bending loads is usually greatest, the practice of grinding the root fillets of highly stressed gears is extra hazardous.

The residual stress in the gear tooth surfaces, however, can be converted from hazardous tensile stress to beneficial compressive stress by shot peening as a final operation. Shot peening is beneficial in increasing the bending fatigue strength whether or not the teeth are ground. In the case of ground fillets, however, shot peening is helpful only if deep surface grinding cracks are not present prior to the peening. If an initial crack is deeper than the depth of the residual compressive stress from shot peening, the residual stress will overlay the crack and the peening will therefore be ineffective.

In the carburized Allison gears described, grinding cracks did not occur in the root portions of the teeth of the first two test units, and the bending stress was not sufficient to cause cracks to develop in this region.

To avoid damaging the roots of teeth by grinding, the Allison Division later resorted to the use of protuberance hobs. These hobs undercut the teeth as shown in exaggerated form in Fig. 9. With the undercut, the involute profiles could be ground without grinding the vulnerable root areas. To further increase their strength, the teeth were shot peened in a final operation.

Low Temperature Annealing Ineffective

Damage to the fatigue strength of gear teeth caused by grinding cannot be overcome by the common practice of low temperature annealing. Such annealing can only reduce severe grinding tensile stress sufficiently to prevent spontaneous cracking of the ground areas while the gears are in storage. The effectiveness of low temperature annealing is usually demonstrated by showing that severely ground surfaces when not annealed will crack

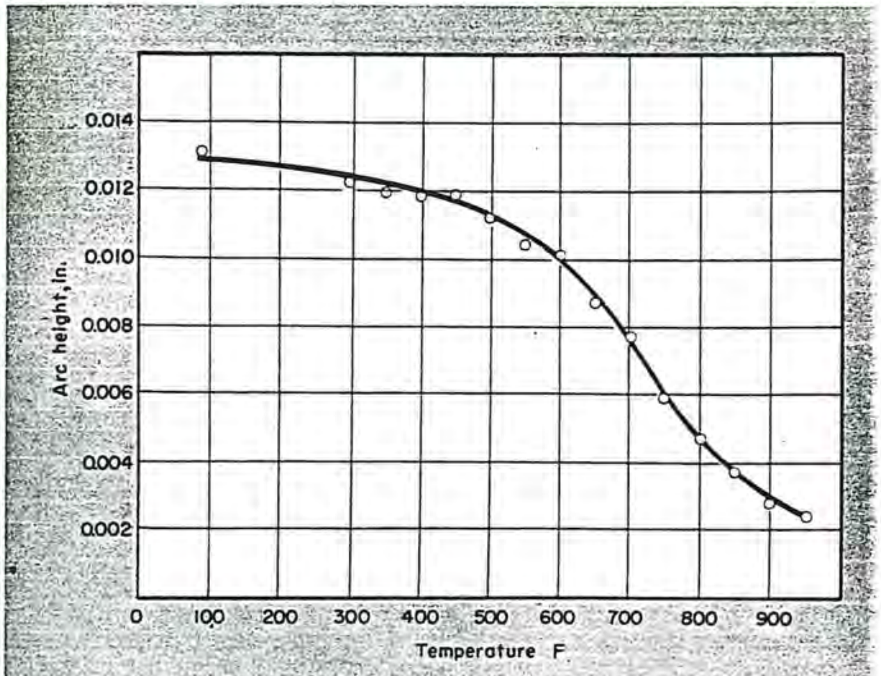


Fig. 10—Change of the arc height in a shot peened standard Almen peening specimen when held in a fixture at various temperatures.

when lightly etched, whereas, the same etching does not develop cracking after annealing. Actually, the etching as used is only an accelerator for spontaneous cracking, and is similar to other accelerators for developing stress corrosion cracking.

The relaxation of residual stress that can be obtained from annealing, of course, is measured by the stress the metal can sustain at the annealing temperature. Thus, if the initial grinding residual tensile stress in a carburized surface is 250,000 psi, and the yield strength of the steel at the annealing temperature is equal to or greater than 250,000 psi, no reduction of the residual tensile stress will occur.

Stress Relaxation Measured

The effect of relaxation of residual stress in a standard Almen peening intensity test strip by heating at various temperatures between 80 and 950 F is shown in Fig. 10. The strip, which was originally straight, was shot peened on one side while held flat by screws against a heavy hardened steel block. On release of the screws, the strip curved to an arc height of 0.013 in. on a 1.25 in. chord in response to the residual stress induced by the peening, as indicated in Fig. 10 by the test point at the upper left.

The strip was again attached to the heavy block and secured flat by the screws, and the assembly placed in a furnace and held at 300 F for one-half hour. Upon removal and release of the screws, measurements showed that arc height had been reduced from 0.013 to 0.012 in. through a slight relaxation of residual stress in the peened layer.

This process was repeated at temperature intervals of 50 deg F in the range from 300 to 950 F, as shown by the plotted points. After the 500 F treatment, the stress relaxation was only sufficient to reduce the arc height 0.002 in.; and considerable residual stress remained even after the 950 F treatment.

It is apparent that annealing in the range of 300 to 500 F is ineffective in removing the damaging tensile stress induced by normal commercial grinding. Effective annealing requires temperatures high enough to destroy many machine parts by reduction of hardness.

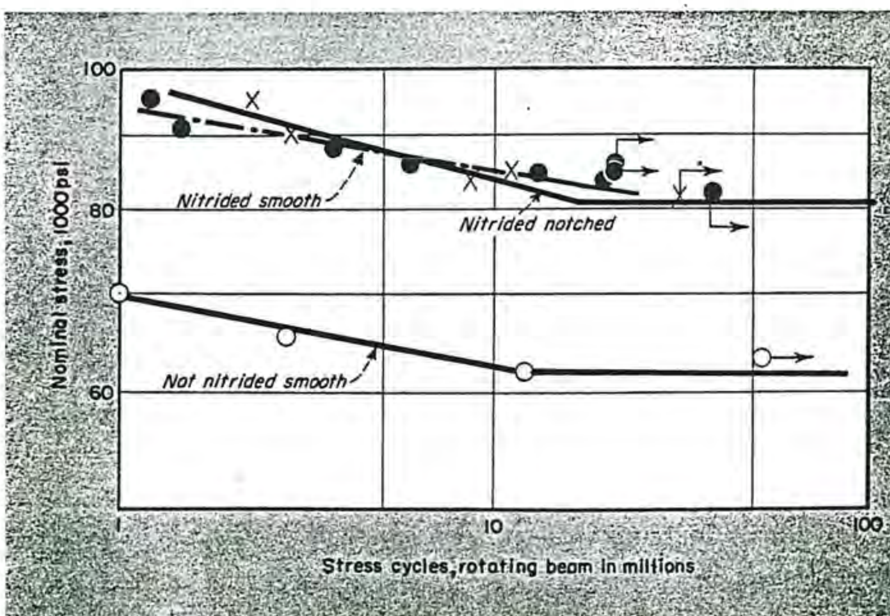


Fig. 11— Replot of Johnson and Oberg tests on smooth and notched specimens.

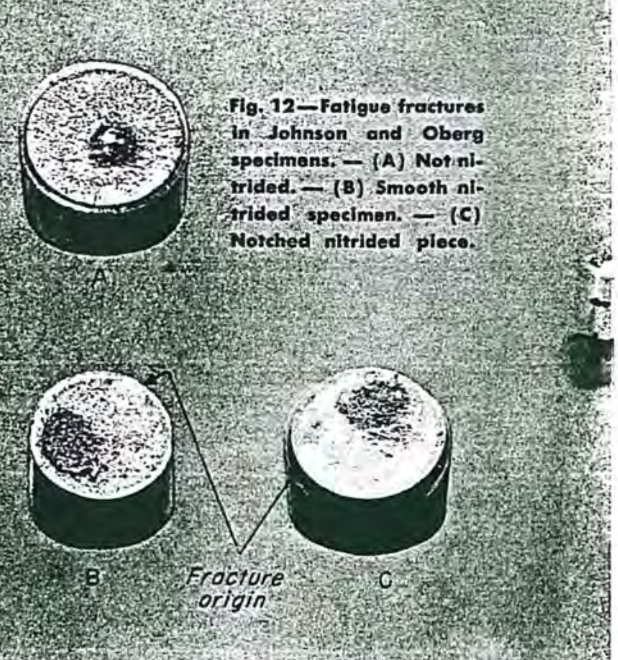


Fig. 12—Fatigue fractures in Johnson and Oberg specimens.— (A) Not nitrided.— (B) Smooth nitrided specimen. — (C) Notched nitrided piece.

Nitrided Layer Is Immunizing Layer

For the purpose of measuring the notch sensitivity of hard nitrided surfaces, Johnson and Oberg (Ref. 8) conducted comparative tests using smooth and notched nitrided specimens in a rotating beam fatigue testing machine. The notches were circumferential grooves formed by a grinding wheel, which produced side walls at 60 deg included angles and root radii of 0.008 inch.

The results of the Johnson and Oberg tests are replotted in the SN chart Fig. 11. A fractured smooth specimen is shown in Fig. 12*(B)*; a fractured notched specimen is shown in Fig. 12*(C)*. The origins of the fractures are within the light colored elliptical areas at the upper right in Fig. 12*(B)* and at the lower left in Fig. 12*(C)*. Both origins are in the core metal below the surface. Contrary to normal experience, notches of ordinary depth did not adversely affect the fatigue strength of the specimens.

In other Johnson and Oberg specimens the depth of groove was varied. In these when the depth of groove exceeded 0.012 in., which was approximately 70 percent of the case thickness, the fractures originated at the roots of the notches instead of in the core, and the fatigue strengths of the specimens were reduced.

The nitriding specifications given by Johnson and Oberg indicate that the residual stress in their specimens was of the same order of depth and magnitude as in the dissected nitrided specimen of Fig. 3. With the assumption that the nitrided residual stress from Fig. 3 applies to the diameter of specimen used by Johnson and Oberg, the stress diagram Fig. 13 was reconstructed to indicate the residual stress pattern within the Johnson and Oberg specimens. This composite diagram is sufficiently accurate to show how immunity to fatigue is bestowed by the fracture proof compressively stressed surface metal.

Note that the point of maximum tensile stress in the sub-surface metal corresponds to the points of origin of the fractures shown in Figs. 12*(B)* and *(C)*. Note also that the residual compressive stress in the nitrided case is so great that at no time, even under the maximum bending load applied during the test, did tension stress extend through the hard layer. Hence, fatigue failure originating in the case was impossible.

As in the Allison gear teeth, the notches in the nitrided case of the Johnson and Oberg specimens overlay compressively stressed metal. They were therefore harmless as long as the tensile stress from the external load acting at the bottom of the notches did not greatly exceed the residual compressive stress.

Experiments by Mailaender (Ref. 9) gave similar results. Mailaender sought to measure notch sensitivity of nitrided specimens having various types of grooves that were exposed to corrosive environments. These test results show again that the residual compressive stresses in nitrided surfaces rendered all notches harmless until their depths penetrated the immunizing layer.

The residual compressive stress that is developed in nitrided surfaces is a result of an increase in volume, similar to that which occurs during the hardening transformation in a carburized case.

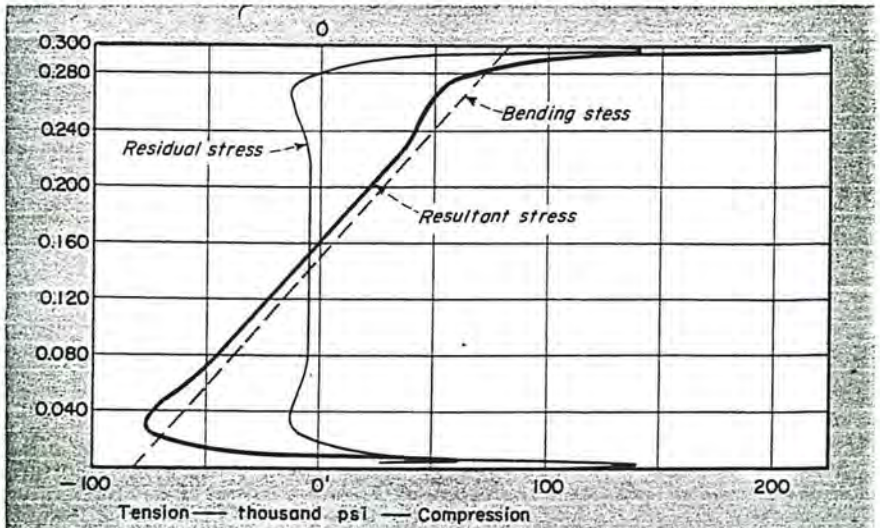


Fig. 13 — Composite diagram that indicates the residual stress pattern within the Johnson and Oberg specimens.

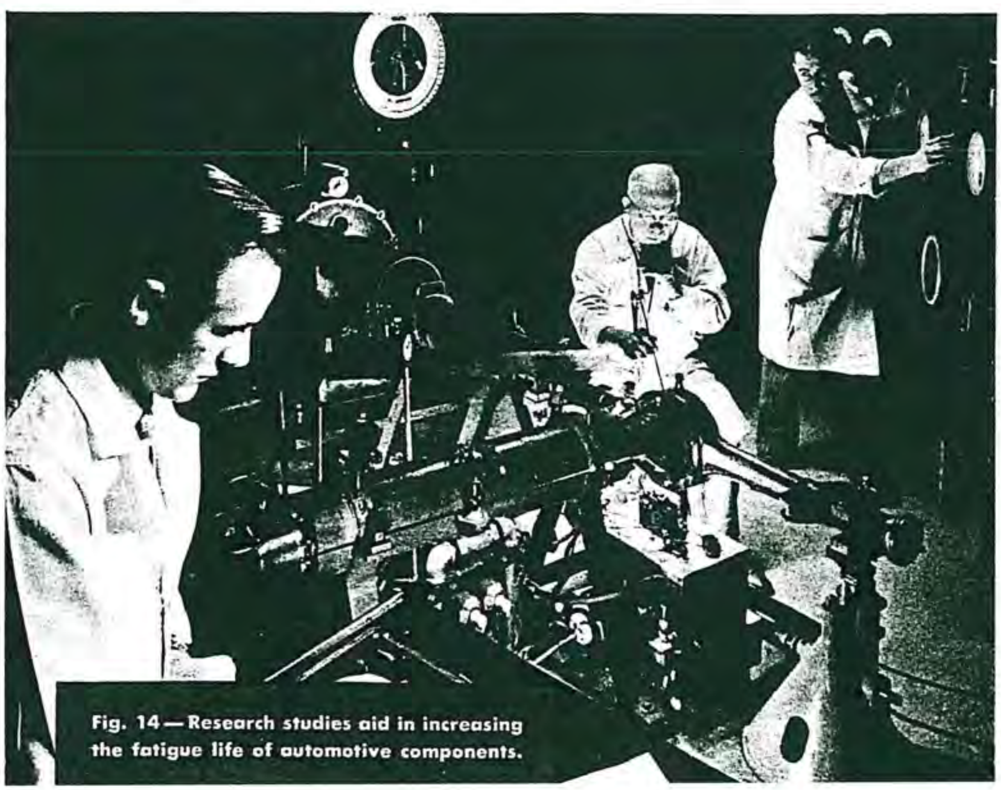


Fig. 14 — Research studies aid in increasing the fatigue life of automotive components.

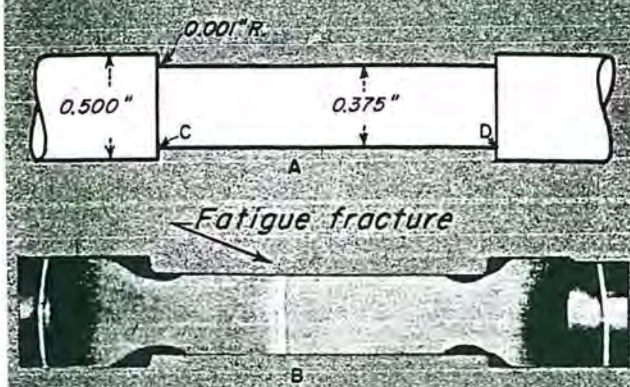
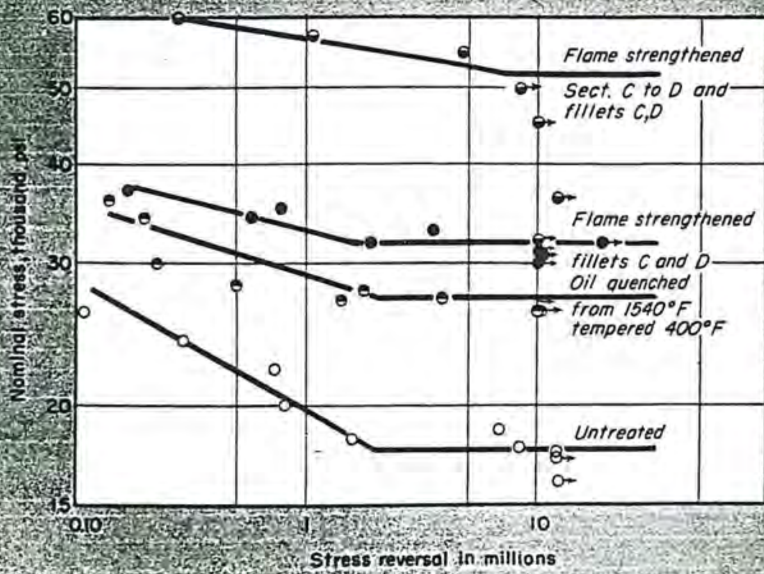


Fig. 15 — Flame strengthening specimen used by J. H. Zimmerman. — (A) Cylindrical specimen with sharp shoulder stress raisers. — (B) Etched section of fractured specimen.



Flame Strengthening

In a series of experiments, described as "Flame Strengthening" (Ref. 10), J. H. Zimmerman of Linde Air Products Company applied local flame hardening to regions of severe stress concentration, and thereby greatly increased the fatigue strength of rotating beam specimens. Fig. 15*(A)* shows the dimensions of the central portion of the specimens; Fig. 15*(B)* is a photograph of an etched section through one of the fractured specimens.

During the test, the entire central portion of the rotating specimens was subjected to uniform bending. But, because of variations in diameter of the loaded beam and intentional stress raisers in the form of abrupt section changes and sharp shoulders, the stress was far from uniform.

Assuming that smooth specimens of the untreated steel would have an endurance limit of 45,000 psi, the author concluded that the sharp shoulders increased the stress by a factor of 2.5. In the following discussion of the test data, the stress will always be given as the nominal calculated stress of the smaller diameter without regard to the local increase in stress introduced by the sharp shoulders.

Results of Zimmerman's tests are presented in Fig. 16, which shows S N curves of four series of specimens made of SAE 1045 steel variously heat-treated. The lowest curve records the fatigue strength of specimens made from the steel in the as received condition. The fatigue endurance limit of these specimens was approximately 18,000 psi nominal stress. In this group the sharp fillets *C* and *D*, Fig. 15*(A)*, were the points of fracture origin.

The second curve upward shows the fatigue strength of specimens that were oil quenched from 1540 F and drawn at 400 F. This treatment increased the fatigue endurance from a nominal stress of 18,000 psi to a nominal stress of 26,000 psi, with the fractures still originating in the same sharp fillets.

The third curve upward gives the results obtained from specimens identical with those used in the first series, except that the fillets *C* and *D* were flame hardened as shown in the etched section, Fig. 15*(B)*. This local treatment increased the fatigue endurance from a nominal stress of 18,000 psi to a nominal stress of approximately 32,000 psi. The origin of the fatigue fractures, as is shown in Fig. 15*(B)*, was also shifted from the sharp fillets to the smooth surface in the 0.375 in. dia portion of the specimen.

The great increase in the fatigue strength of the sharp fillets resulted from the residual compressive stress developed in the locally hardened regions by the increase in volume of the hardened steel during the hardening transformation. The surface hardness of the flame hardened metal is given as 485 BHN, as compared to 250 BHN for the heat-treated specimens and 130 BHN for the as received specimens.

Although the magnitude of the residual stress was not measured, it was sufficient to prevent fatigue fracture in severe stress raisers in hard and therefore notch sensitive steel. Note that failure did not occur in the fillets at twice the load that caused failure in the unprotected fillets in the previous series of tests.

The fourth curve upward in Fig. 16 shows the results of flame hardening a series of specimens that, like the third series, was not otherwise heat-treated. The hardening was applied to the sharp fillets in the same manner as in the third series, in addition to which the 0.375 in. dia portion of the specimens between *C* and *D* was flame hardened. The fatigue endurance of these specimens, still in terms of the nominal stress of the smaller diameter, is approximately 52,000 psi, and the fractures again occurred in one of the sharp fillets.

Like the Allison carburized gears and the Johnson and Oberg nitrided

Fig. 16 — Results of Zimmerman's tests on four series of SAE 1045 steel specimens variously heat-treated to improve their fatigue strength.

Fig. 17 — Sub-surface fatigue fracture that originated in tensile stressed layer of an induction hardened torsion bar suspension spring.

specimens, the Zimmerman flame hardened specimens demonstrate that severe stress raisers are harmless in fatigue as long as the notched metal is residually stressed in compression to a sufficient magnitude.

Flame Hardening Compared to Carburizing

Although flame and induction hardening of surfaces can provide the desired surface residual compressive stresses, it must not be assumed that the resulting gain in fatigue strength is equivalent to that obtainable by case hardening processes such as carburizing and nitriding (Ref. 11). Induction and flame hardening, which are advantageously applied to many machine parts, are accomplished by heating the surfaces while the core metal remains cold. The heated surface layers seek to expand, but being restrained by the underlying cold metal the hot surfaces become severely stressed in compression.

As a result of this transient compressive stress and the low yield strength of the heated metal, plastic yielding occurs. Upon cooling, the plastically deformed surface metal contracts and becomes residually stressed in tension, similar to that which occurs during grinding when the surface is heated by the grinding wheel. However, since in induction and flame heating treatments the surfaces are hardened, the expansion that occurs during the hardening transformation (Ref. 6) develops residual compressive stress in the hardened layer but only to a depth somewhat less than the depth of hardening.

The net effect is therefore a surface residual stress that is the algebraic sum of the tensile stress developed by plastic yielding of the heated metal and the compressive stress from the hardening transformation. This stress may be either tension or compression, depending upon the surface hardness attained but, as practiced, the surface residual stress is usually compressive. At best, the magnitude of the surface residual stress is less than that attainable by case hardening processes in which the temperature gradient is reversed, for example, as in carburizing in which the residual stress from both sources is compressive.

Immediately below the hardened layer, the metal is residually stressed in tension from two sources. The metal temperature decreases with depth until it no longer hardens upon quenching. As a consequence, this "second" layer escapes the residual compressive stress from the hardening transformation, and the residual stress is therefore tensile as a result of plastic yielding during heating. To this stress must be added the sub-surface tensile stress that is necessary to satisfy equilibrium conditions within the specimens.

Fatigue failures often occur when this doubly stressed "second" layer emerges to the surface, so that thereby the surface also becomes afflicted with surface weakness (Ref. 3). For this reason, fatigue failures frequently originate within the oil holes of induction hardened crankshafts (Ref. 12). This difficulty can usually be remedied by peening, or otherwise prestressing by cold working, the walls of the oil holes, and thus remove the hazard of surface fatigue weakness.

In induction and flame hardened specimens, the "second" layer remains a region of fatigue weakness as compared to the sub-surface fatigue strength of properly carburized specimens. Because of the relatively great residual tensile stress, sub-surface fractures will develop at lower nominal stress in induction and flame hardened steel than in carburized steel. In Fig. 17 is shown an early failure by sub-surface fatigue, which resulted from an attempt by a foreign manufacturer to develop torsion bar automobile suspension springs by induction hardening.

In this induction hardened torsion spring, the sub-surface fatigue fracture originated in a tensile stressed layer.

Fracture Barriers in Welded Structures

Many interesting case histories could be cited and discussed in detail, in which unexpected advantages are often obtained from manufacturing operations that were applied for other purposes. An outstanding example is one in which an unsuspected barrier to the progress of fatigue cracks was present in a welded structure. Dissection measurements and procedure revealed the unknown source of fatigue durability.

A reputable supplier to one of the General Motors Divisions produced a truck rear axle housing, in which the spring seats and torque reaction brackets were attached to the axle tube by welding.

Since the localized heat of welding develops severe residual tensile stresses in the vicinity of the welds, the completed housings were heat-treated for the purpose of dissipating these usually harmful stresses. In development testing the completed housings, the supplier discovered that for some unknown reason the fatigue durability of "as welded" structures was much greater than that of housings made by the standard procedure for highly stressed members.

During World War II, the Ordnance Department requested this General Motors Division to conduct tests of various components of two designs of transmissions, driving shafts, gears, and rear axle housings to determine their relative merits. The results of these tests confirmed the discovery made by the supplier regarding the harmful effects of stress relieving after welding.

Laboratory fatigue tests were made for determining the relative fatigue durability of welded axle housings and stress relieved axle housings, under identical loads repeatedly applied on the welded spring seat. The magnitude of the test load was determined as that which would produce failure of the axle housing tube after approximately 100,000 stress applications. This test was then repeated on axle housings that had escaped the stress relieving treatment after welding. It was found that, under the same load, these did not fail up to a million stress applications.

METALLOGRAPHIC EXAMINATIONS FAIL. A systematic search to discover the causes of this unusual and unexpected behavior ensued. Sections through the fractured regions were made; one of which, made from a stress relieved housing, is shown in Fig. 18. The fracture originated, from the repeated downward acting loads, in the vulnerable region where a weld metal joins the tubular portion of the axle housing and the torque reaction member. The fractured housing tubes were made from SAE 1045 steel measuring 3.5 in. O D and 7/16 in. wall thickness.

A careful examination of the material, workmanship, and processes used did not indicate the cause of the trouble. The welds were made in the usual manner, and the housings were carefully heat-treated after welding to remove welding stresses and to increase the strength of the structure.

The rectangle in Fig. 18, which encloses the origin of fracture, indicates the boundaries of Figs. 19 *(A)* and *(B)*, which were made from other axle housings. Figs. 18 and 19*(A)* are similar in that both specimens were stress relieved after welding, and both show the point of origin of the fracture and the unobstructed progress of the crack from the outer surface through the tubular members.

An etched section through the fatigued area of a housing that was not stress relieved after welding is shown in Fig. 19*(B)*. It is somewhat confusing in that a complete fatigue fracture is shown that extends diagonally through the weld metal. But this fracture is of negligible importance, since it does not extend into the axle tube and affects only a limited portion of the torque reaction member. It is significant, however, that this diagonal fracture did not occur until more than 900,000 load applications were completed at the same stress that caused failure of the stress relieved axle after 100,000 stress applications.

The important fact shown in Fig. 19*(B)* is that a shallow fatigue fracture appears in the same location as the catastrophic fatigue fracture shown in Figs. 18 and 19 *(A)*. This shallow fracture appeared early in the test but, as would nor-

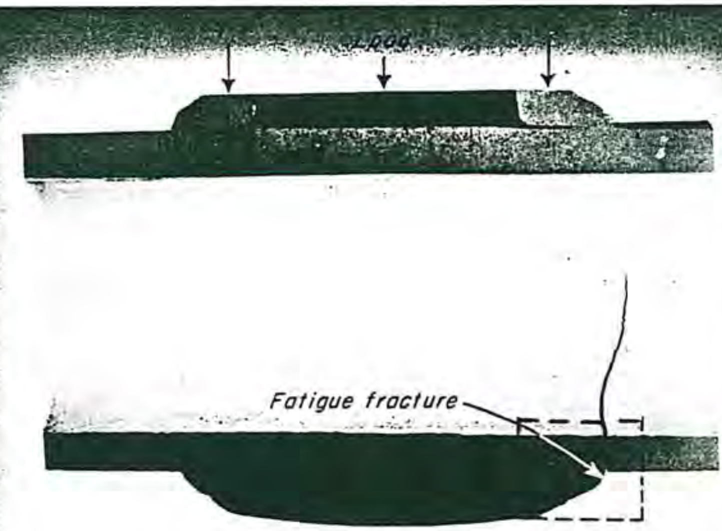


Fig. 18 — Section through a welded stress relieved axle housing. Tube is SAE 1045 steel.

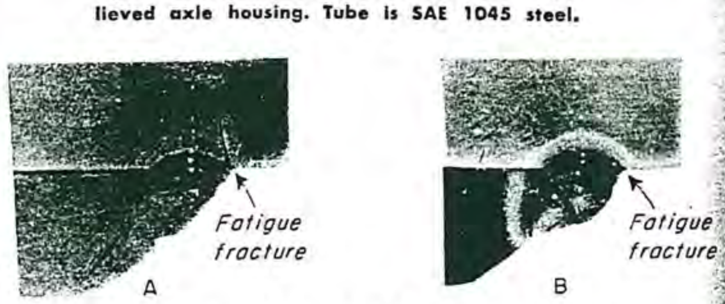


Fig. 19 — Boundaries of the failed axle areas (A) Heat-

mally be expected, it did not grow in depth as the test was continued.

The details in Fig. 19*(B)* of the metal structure, which are made visible by etching, confirm that this metal was not stress relieved after the welding operation. Since omission of the stress relieving operation appeared to be the only difference between the successful and unsuccessful axle housings, it was assumed that some unrecognized strengthening factor was removed during the final heat-treatment of the stress relieved axles.

Search Discloses Fracture Barrier

To discover the nature of this strengthening factor, a ring was cut from a housing that had not been heat-treated after welding. This ring was perpendicular to the tube axis. It included about ¼ in. of the weld metal and about one-half of this width outside of the weld metal, so as to include the section in which the fatigue cracks originated.

By cutting a gap in the ring 180 deg from the point of normal fracture origin, and measuring the change in the gap width as successive layers of metal were removed from the outer periphery of the ring, it was possible to reconstruct the original residual stress in each of the dissected layers.

Wherever possible dissection stress measurements should be made in a direction normal to the fatigue cracks. It should be therefore noted that because of the nature of this ring specimen, the stresses measured by this dissection procedure were acting parallel to the direction of the fractures. The character of the stresses acting normal to the fractures, however, could be deduced from these measurements with sufficient accuracy for the needs of the experiment.

Dissection Measurements Explain Fatigue Durability

A region of high magnitude, residual compressive stress was found to have developed about 1/32 to 3/32 in. below the outer surface of the tube. The metal external to this layer was residually stressed in tension, as was also the deeper metal in which the tension was relatively low. The greater tensile stress in the weld metal and in the adjacent outer tube metal resulted from the greater local heat of welding. The plastic deformation of this outer and hotter metal was greater, therefore, the thermal contraction upon cooling developed residual tensile stress of greater magnitude.

With discovery of the compressively stressed metal in the path of the crack it became clear why the fatigue fracture, Fig. 19 *(B)*, which commenced at the juncture of the weld metal and the tube metal, stopped at a depth of less than 1/32 in. without damage to the tube.

As is shown by the etching, the heat of welding was sufficient to develop a semi-circular area of martensite in the SAE 1045 steel of the tube. Since its volume increased during the hardening transformation, this hardened layer was compressively stressed just as carburized, nitrided and flame hardened layers are compressively stressed. The fracture could propagate only to a depth somewhat less than that at which the tensile stress from the external load was greater than the residual compressive stress in the hardened layer.

Again, because it was residually stressed in compression, a hard and notch sensitive steel formed an impassable barrier to the progress of a fatigue crack.

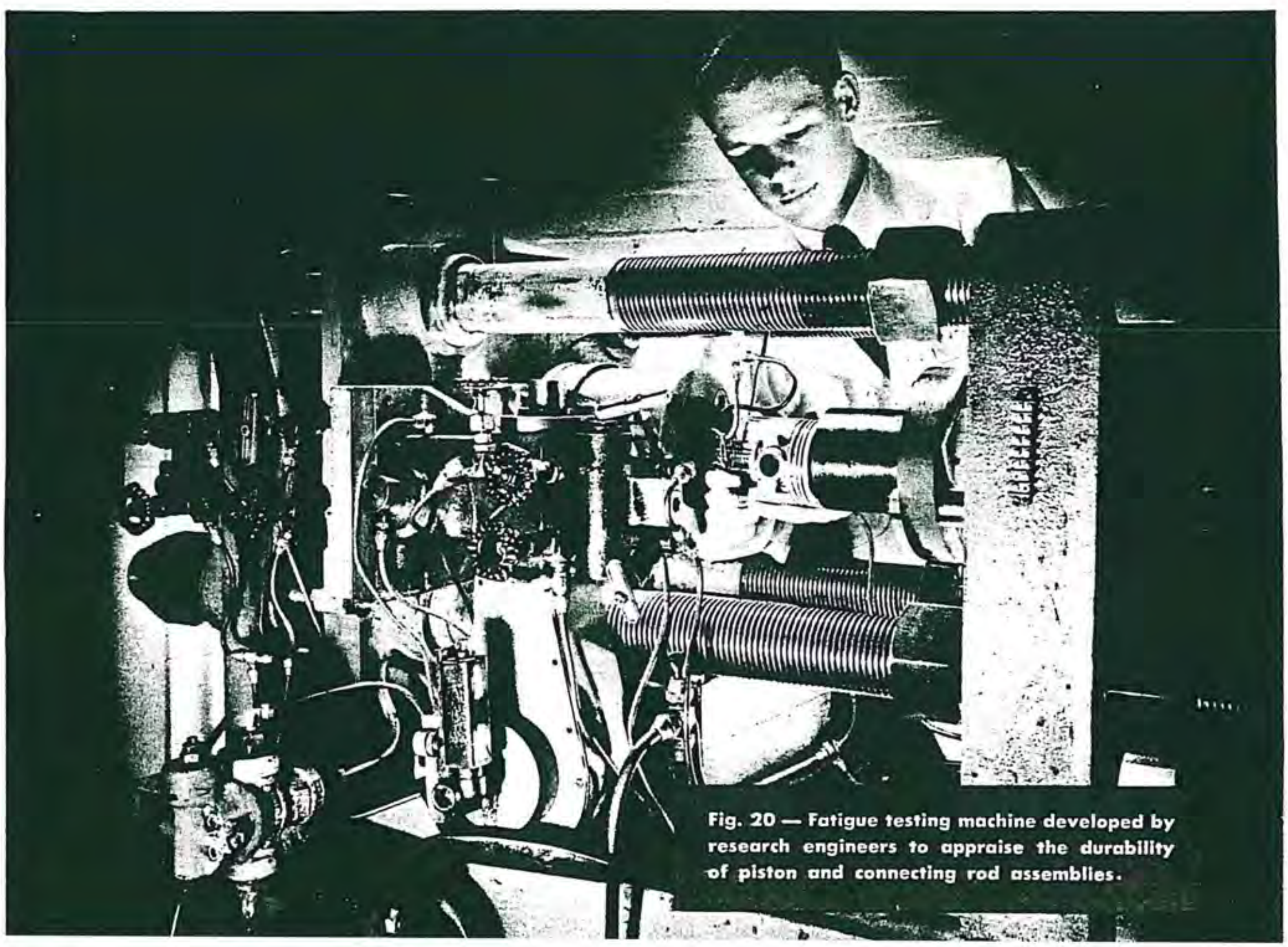


Fig. 20 — Fatigue testing machine developed by research engineers to appraise the durability of piston and connecting rod assemblies.

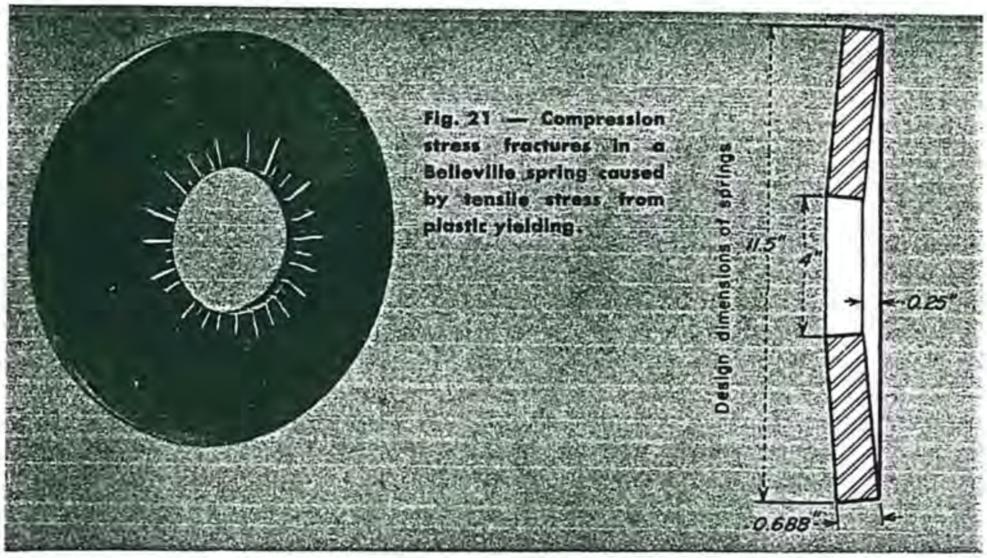


Fig. 21 — Compression stress fractures in a Belleville spring caused by tensile stress from plastic yielding.

Fatigue Failures From Nominal Compressive Stress

Fatigue fractures in many instances develop in areas in which the nominal stresses are always compressive. Among these are failures of Belleville type springs used by the American Locomotive Company in an industrial application. These springs developed numerous fatigue cracks after a relatively small number of load applications. As shown in Fig. 21 the cracks, which are made clearly visible by magnetic particles, occurred on the outer cone surface.

The cracks radiate outward from the central hole one-fourth or more of the ring width, and penetrate a similar portion of the metal thickness in the cylindrical surface of the hole. The loads applied to the springs deflected the cone toward a plane surface, therefore, the initial stress in the failed areas was unquestionably compressive.

These springs were peculiar in that after the fatigue cracks developed to the extent indicated, the springs continued to function quite satisfactorily without further extension of the cracks in length or in depth. Eventually complete failure occurred from new fractures that originated on the opposite surface of the spring; these failures always occurred when the springs were loaded.

From the dimensions, Fig. 21, the stress in the springs was calculated by a method (Ref. 14) that is probably as accurate as the formulas that are applied to other and simpler machine parts. On the outer surface of the disk at the edge of the hole, the compressive stress was calculated to be approximately 433,000 psi when the spring is deflected from a cone height of 0.25 in. to a plane surface.

Since this stress greatly exceeds the nominal yield strength of the steel, there can be no doubt that extensive plastic yielding occurred during the first deflection of the spring. It therefore appeared that the unusual behavior of the spring could be explained as a result of the local residual stresses that were developed by plastic deformation occurring in limited volumes of the highly stressed metal.

The local areas that yielded under compressive stress, from the external load, were residually stressed in tension after removal of the load when the spring elastically returned toward its original cone height. The magnitude of this residual tensile stress varied in proportion to the extent of compressive yielding. Since the extent of yielding decreased with depth and with radial distance from the edge of the hole on the outer surface, the observed fatigue cracks conformed to the intensity pattern of the residual tensile stress. The residual tensile stress that caused the cracks reached its maximum when the external load was at its minimum, and the minimum tensile stress in this area occurred when the external load was greatest.

IMPORTANT STAGES IN STRESS HISTORY. The three sets of diagrams, Figs. 22, 23, and 24, each represent an important stage in the stress history of the cone surface of the spring. A fourth diagram, Fig. 25, is devoted to the stress sequence on the cylindrical surface within the hole. In Figs. 22, 23, and 24 the stress diagrams for each of the two surfaces is placed opposite the corresponding face of the spring sketch that indicates the load. In the following discussion, the spring surfaces will be identified as the outer and inner corresponding to their respective positions on the outer and inner surfaces of the unloaded cone of the spring.

In Fig. 22 the spring is shown in the same attitude as it appears in Fig. 21, that is, the outer surface is at the left and the inner surface is at the right. The spring is shown deflected to a plane surface by a load that is uniformly distributed around the outer (left) edge of the central hole; the reaction load is uniformly distributed on the inner (right) conical surface near the outer edge. The load strains the outer surface of the spring in compression, as shown in diagram *A*. The magnitude of the tangential strain at any point on the spring surface is measured by the horizontal distance from the zero strain line *00'* to the curved lines *JK* and *J'K'*. In terms of stress, the tangential stress on the spring surface ranges from 100,000 psi *(OJ* and *O'J')* at the outer diameter to 433,000 psi *(LK* and *L'K')* at the edge of the central hole.

MATERIAL SPECIFICATION. The springs, as stated by the manufacturer, were made from ". . . about 0.55 carbon SAE 6100 chromium vanadium steel heat-treated to a Brinell hardness of about 429." Its yield stress was not measured, but steel of this hardness would be expected to have a nominal yield strength of approximately 185,000 psi. The probable dynamic elastic limit* is indicated by line Y_rH and $Y_r'H'$, the curved portions of which indicate the increase in yield strength developed by the plastic yielding during the first ten or twenty applications of the test load.

* The magnitude of plastic yielding under repeated stresses, particularly when the load is applied in one direction, is greater than the plastic yielding that is measured by static loads. Measurements indicate that plastic yielding continues at a decreasing rate throughout unidirectional fatigue tests. The stress indicated by the Dynamic Elastic Limit is therefore lower than the conventional Yield Stress, but it does not identify a limit of plastic yielding.

The estimated increase over the nominal yield stress ranges from zero, near the mid-width of the spring at U, to 35,000 psi at the edge of the hole at H. That is, the dynamic elastic limit is estimated to range from 185,000 psi where no cold working occurred to 220,000 psi in the region of maximum cold worked metal.

The triangular area $KHUK$ represents the surface metal that was plastically deformed by the initial loadings, in which the maximum yielding is indicated by the distance KH. In terms of stress, the greatest yielding is equal to 433,000 minus 220,000, or 213,000 psi. The extent of plastic yielding is also indicated by the darkened area in the sketch of the loaded spring, Fig. 22; this area also roughly indicates the depth as well as the radial width of the plastically deformed metal.

The strain that was applied on the inner surface of the spring by the initial load is shown in diagram B, Fig. 22. The tangential strain on this surface is tension; its magnitude ranges from the distance OM and $O'M'$ on the outer diameter to PN and $P'N'$ at the edge of the central hole. In terms of stress, this strain ranges from 157,000 to 320,000 psi. The estimated dynamic elastic limit is indicated by the lines Y_tT and $Y_t'T'$, which varies from the nominal yield stress of 185,000 psi at V to 216,000 psi at the edge of the central hole. Note that the assumed yield stress (216,000 psi) at T, diagram B, is less than the assumed yield stress (220,000 psi) at H, diagram A, because the extent of cold working by plastic yielding is less on the inner surface. The distance NT and $N'T'$, which equal 320,000 minus 216,000, or 104,000 psi, indicates the maximum yielding.

Plastic Yielding Causes Permanent Set. Upon release of the load, the spring returned to a cone shape but its free height, after ten or more load applications, was reduced to 0.22 in. As a result of the local plastic deformations that had occurred, the spring had suffered a permanent set in cone height of 0.03 inch.

Because of the permanent set, additional deflections from the new cone height to a plane surface strained the metal through a lower

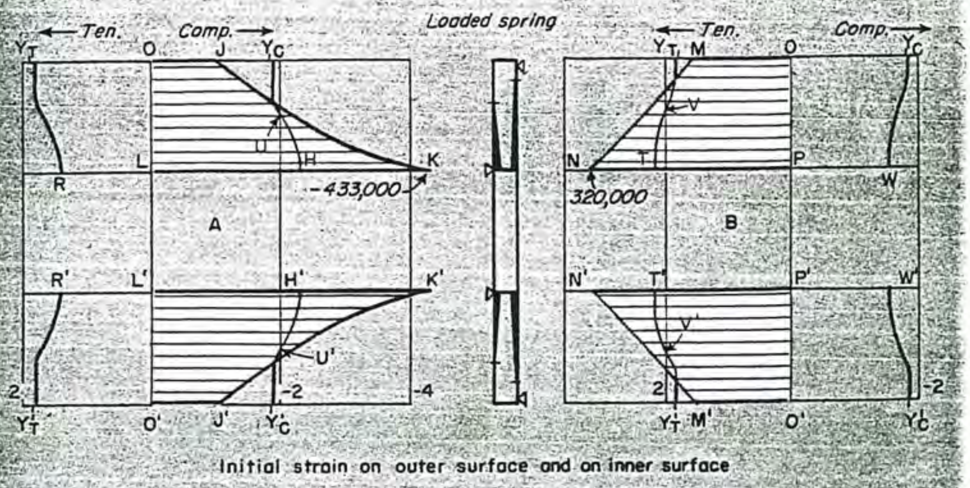


Fig. 22 — Strain distribution on surfaces of overloaded Belleville spring.

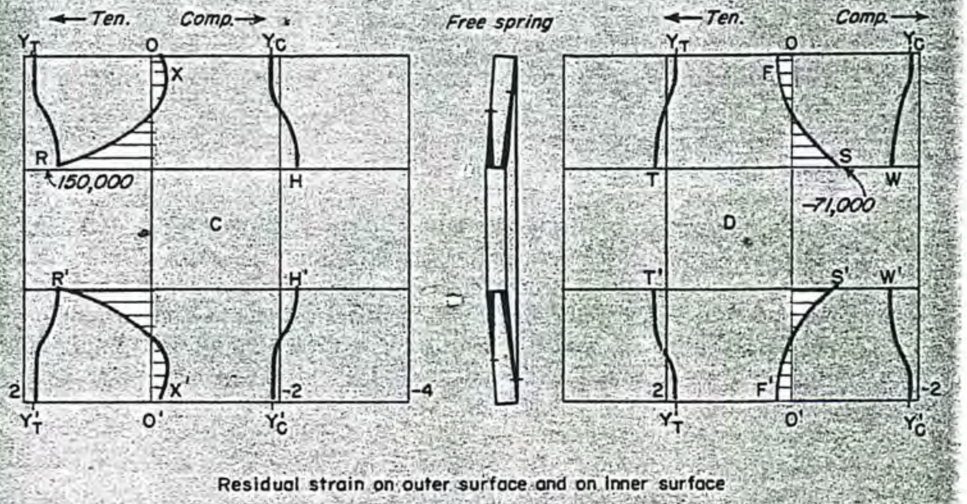


Fig. 23 — Residual stress distribution resulting from overloading of Belleville spring.

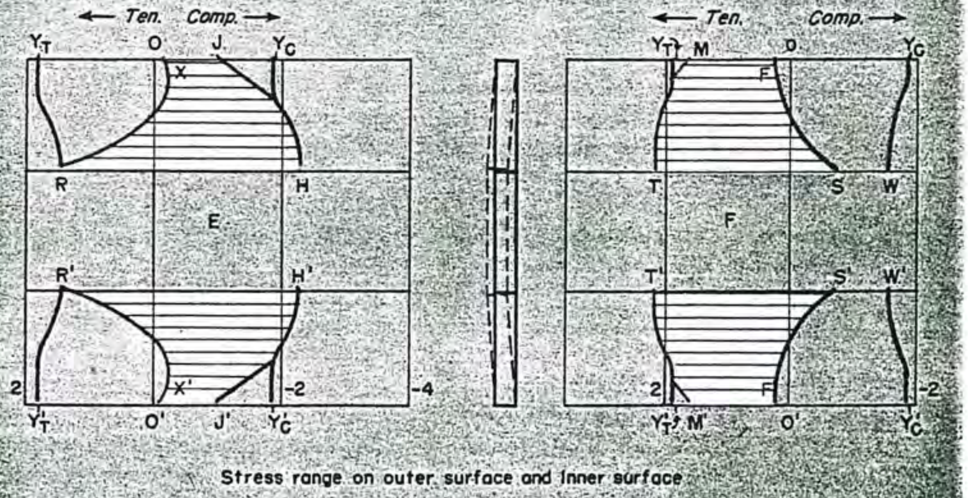


Fig. 24 — Stress range on surfaces of Belleville spring under service load.

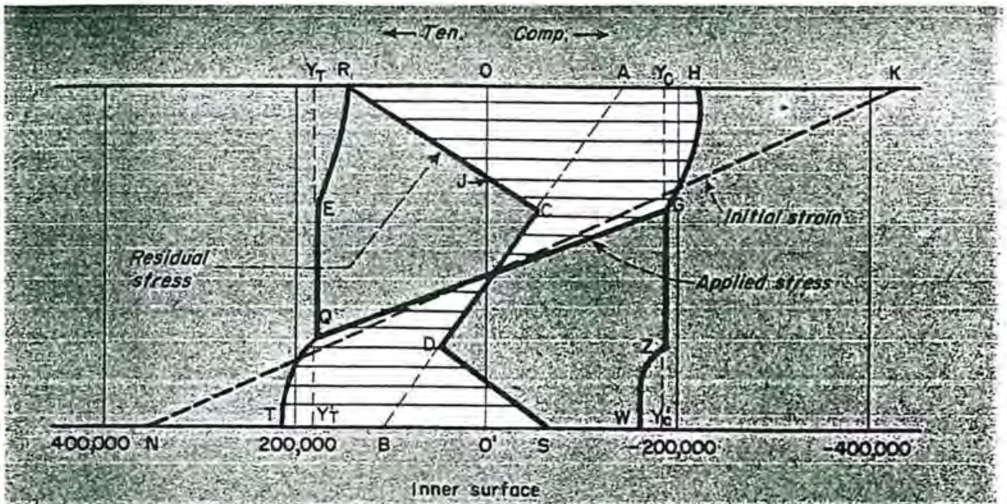


Fig. 25 — Probable stress range on surface of central hole in Belleville spring after a few applications of fatigue test load.

range. By calculation, deflecting the spring from a cone height of 0.22 in. strained the metal to corresponding values of 370,000 psi compression and 287,000 psi tension.

After the first ten or twenty applications, the stress in the spring at maximum deflection was not greatly altered by the permanent set, but residual stresses of large magnitude were present when the external load was removed.

The magnitude of these residual stresses is the difference between the stress under the maximum deflection and that produced by the elastic strain in deflecting the spring from its new free height to flat. At maximum deflection, the stress in the outer surface of the spring at the edge of the hole as shown in diagram *A*, Fig. 22, is 220,000 psi, which is the estimated dynamic elastic limit of the metal. The stress from deflecting the spring through 0.22 in. was found to be 370,000 psi, from which the residual stress at this point is 370,000 minus 220,000, or 150,000 psi. In like manner, the residual stress at the edge of the hole on the inner surface is 287,000 minus 216,000, or 71,000 psi.

Residual Stress From Plastic Yielding. Complete residual stress diagrams for both surfaces are shown in Fig. 23. Diagram *C* shows the residual stress on the outer surface of the cone. The residual stress is tension on the half of the spring toward the hole, and has a maximum value of 150,000 psi; on the remaining half the stress is compressive and of low magnitude, it results from the permanent set in the free height of the spring. It is, roughly, the stress that would result from deflecting the original spring through the distance of the permanent set of 0.03 in. The residual tensile stress is the result of the plastic yielding that occurred under compressive stress, as shown in diagram *A*, Fig. 22. As shown by the lines Y_tR and $Y_t'R'$, the maximum residual tensile stress is equal to the tensile elastic limit.

Note that the tensile elastic limit is shown as reduced by an amount equal to the increase in the compressive elastic limit by cold working of the metal that occurred during the plastic yielding under the initial loading. That is, the distance *RH* is made equal to Y_tY_c. Note also that *RH* is equal to the elastic strain of 370,000 psi when the spring is deflected 0.22 in., and that the estimated nominal elastic limit of 185,000 psi is equal to one-half of this strain.

The nice balance in these quantities, of course, is a result of the several assumed values of elastic limits each of which is subject to the usual errors. The purpose of the diagrams, however, does not require a high order of accuracy in these assumptions.

The residual stress on the inner surface of the cone is shown in diagram *D*, Fig. 23. This stress attains a maximum value of 71,000 psi in compression at the edge of the hole at *S* and *S'*, and decreases to zero near the mid-width of the surface. The remainder of the spring surface is stressed in tension as a result of the permanent set in the free height of the spring. The magnitude of this tensile stress is approximately that which resulted from deflecting the spring through the space of the permanent set.

Fatigue Stress Range. In diagrams *E* and *F*, Fig. 24, are shown the approximate stress range on each surface of the spring prior to the formation of fatigue cracks. These diagrams are constructed from the stresses shown in the diagrams of Figs. 22 and 23, and are designated by the same symbols. Diagram *E* shows the stress range on the outer surface of the cone upon each application and release of the test load.

According to diagram *E*, the metal at the edge of the hole was stressed from the elastic limit in tension at *R* to the elastic limit in compression at *H*. In view of the early formation of the fatigue cracks shown in Fig. 21, however, it is probable that the maximum stress exceeded the elastic limit with each application and release of the test load. The tensile stress and the stress range decreased rapidly toward the mid-width of the surface, where the stress became entirely compressive and fatigue failure in this area was therefore impossible.

Diagram *F* shows the stress range on the inner surface of the cone with each application and release of the test load. Because of the lower stress range on this surface the magnitude of the tensile stress could, and probably did, diminish by dynamic yielding continuously during the test with corresponding increase in the residual compressive stress. However, since the tensile stress was equal to the dynamic elastic limit, and since this high tensile stress extended almost entirely across the face of the spring, a fatigue crack once started quickly grew to complete failure.

Fatigue Cracks Fail to Grow in Depth. The fatigue cracks, as shown in Fig. 21, extended to a maximum depth of approximately one-fourth the thickness of the spring. Since these cracks developed after relatively few stress cycles, and then ceased to grow during the remainder of the test, it is necessary to find the reason for their failure to propagate in depth as well as in width.

From the stress range diagram

E, Fig. 24, it was found that the further extension of the cracks across the surface of the spring was prevented by the existence of a fracture barrier, in the form of diminishing tensile stress succeeded by compressive stress. The reason for the failure of the cracks to grow in depth is also shown by the orientation and magnitudes of the stresses transverse of spring.

In Fig. 25 is shown an approximation of the tangential stresses on the outer and the inner cylindrical surfaces of the hole in the spring. The upper surface of this diagram shows the stress at the outer edge of the hole; the stress magnitudes are therefore identical with the stresses shown in diagrams *A*, *C*, and *E*. The strain at *K* of Fig. 25 is the same as the strain at *K* in diagram *A*, Fig. 22. The stress at *H* in Fig. 25 is the same as the stress at *H* in diagram *A*, Fig. 22; and the stress at *R* in Fig. 25 is the same as the stress at *R* in diagram *C*, Fig. 23. The stress range on the upper surface of Fig. 25 is indicated by the distance *RH*, which is the same as the stress range *RH* that is shown in diagram *E*, Fig. 24.

Similarly, the stress magnitudes shown on the lower surface of the diagram, Fig. 25, correspond to the stresses that are indicated by the same symbols in Figs. 22, 23, and 24. The initial strain gradient across the spring thickness is represented by the diagonal line *KN*. The assumed nominal elastic limit of 185,000 psi is shown by the vertical line Y_cY_c' for compressive stress and by the vertical line Y_tY_t' for tensile stress. The probable elastic limits, as modified by the cold working from yielding, are indicated by the curved lines *HG* for compressive stress and *TQ* for tensile stress. Line *HGQT* represents the estimated stress resulting from the applied load, and line *RCDS* represents the residual stress.

STRESS RANGE. The tangential stress range across the thickness of the spring is shown by the series of horizontal lines between the applied stress and the residual stress. The diagonal line *AB* was coincident with the vertical line *OO'* before the initial load was applied. Its displaced position is the result of the extensive local yielding that occurred when the initial strain *KN* was applied, and is a measure of the local permanent set that resulted. The permanent set at the outer edge of the hole is represented by the distance *OA*, and the permanent set at the inner edge is represented by the distance *O'B*. The portion *CD* of the line *AB* represents metal that was not plastically deformed.

Residual tensile stress in the metal at the edge of the hole on the outer surface is represented by the distance *RO*. This stress decreases from a maximum of 150,000 psi at *R* to zero at a depth *OJ* from the outer surface. At greater depths the residual stress becomes compressive.

The conditions that prevented the fatigue cracks from growing in depth were therefore the same as those which set up the barrier against crack growth across the width of the spring. The cracks could progress only as far as the tensile stress, as amplified at the roots of the cracks, exceeded the fatigue strength of the steel. They could not extend into the compressively stressed metal. Since a compressively stressed layer underlay the cracked metal, the cracks were harmless, just as the grinding cracks in the Allison gear teeth were harmless.

With one exception, the length of the cracks on the spring surface in Fig. 21 do not exceed one-fourth of the spring width, although the tensile stress as shown in Diagram *C*, Fig. 23, and diagram *E*, Fig. 24, extends to one-half of the spring width. This discrepancy is accounted for by the probable errors in the plotted stress values, and the fact that growth of the cracks would stop before they reached the region of zero stress.

NUMEROUS FATIGUE CRACKS. The great number of fatigue cracks appearing on the outer surface of the spring is characteristic of fatigue specimens in which the growth of cracks is prevented or greatly retarded. In most laboratory fatigue specimens a single crack forms, and its growth is so rapid that complete failure of the specimen occurs before another crack appears in adjacent areas subjected to the same nominal stress.

In the case of this Belleville spring, relatively large areas were similarly stressed. A single crack developed from a point of greatest weakness that relieved the stress on either side of the fracture. Since the continued growth of the original crack was prevented by the underlying compressive stress, ample time was available for new cracks to form from successive points of high stress. Because the stress was relieved for a distance on either side of each fracture, a new crack could not form within the range of relieved stress. This relieving of stress accounts for the uniform

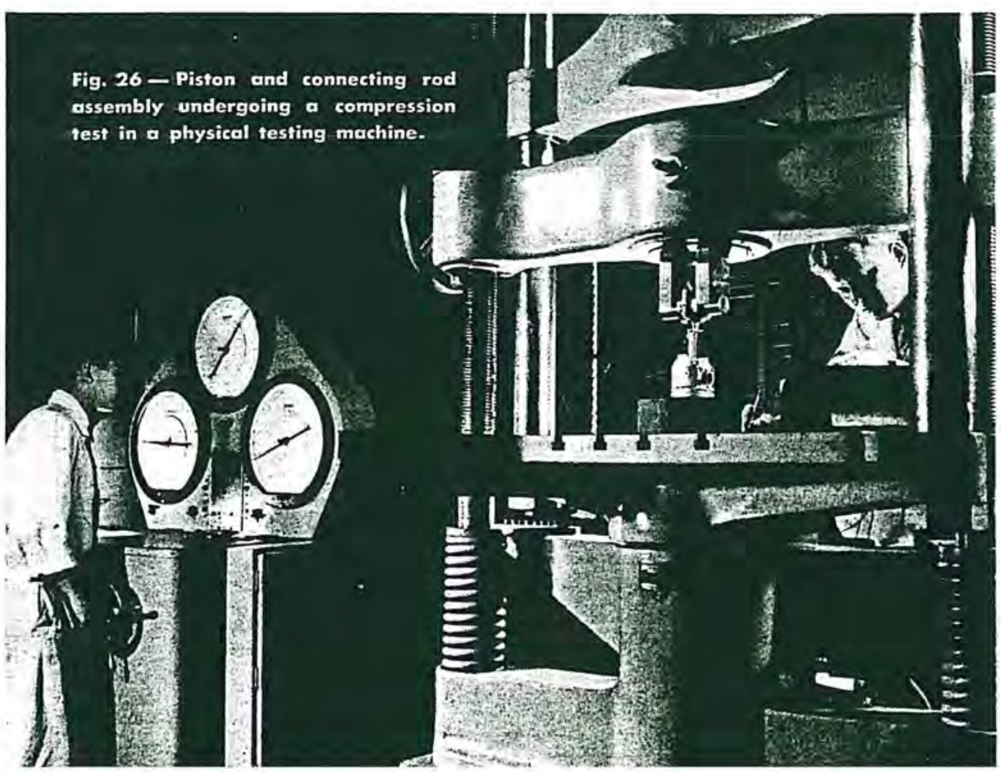


Fig. 26 — Piston and connecting rod assembly undergoing a compression test in a physical testing machine.

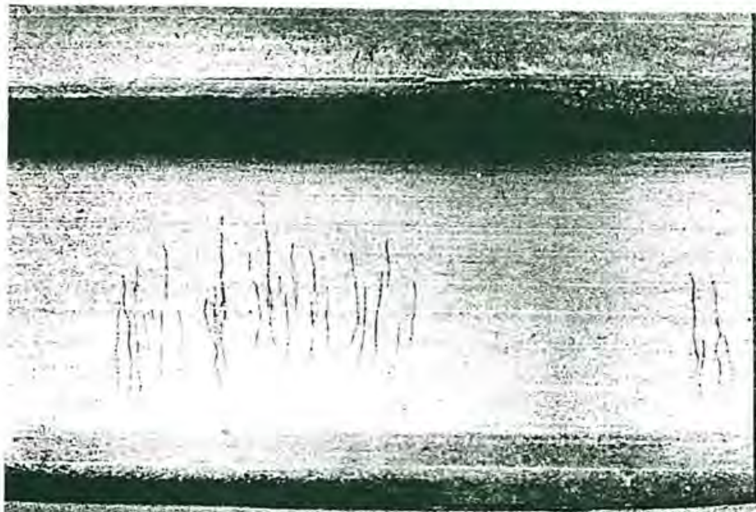


Fig. 27—Cracks in railway wheel rim. Thermal contraction of surface heated by brakes caused tensile stress sufficient to fracture rim.

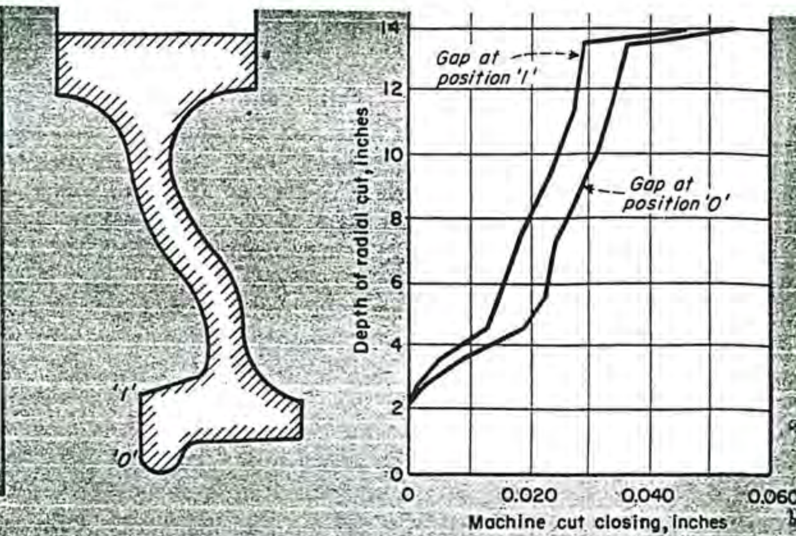


Fig. 28 — Residual compressive stresses in rim of wrought steel railroad car wheel as shown by contraction of cut.

spacing of the cracks, and for the short cracks that are frequently seen between long ones.

DISSECTION CONFIRMS ANALYSIS. To verify the residual stress patterns shown in the diagrams, it was not possible to obtain for dissection stress analysis a spring specimen of the dimensions shown in Fig. 21. Other Belleville springs, however, in which the calculated stress was of similar magnitude, were supplied by Mr. Weber of the American Locomotive Company. One of these springs, which had been deflected 25 times from free cone height to a plane, was dissected for stress measurements. The reconstructed stress for the outer surface was found to be of the same pattern as shown in diagrams *C*, Figs. 23 and 25, that is, the metal on the half width adjacent to the hole was residually stressed in tension on the outer surface, and residual compressive stress was present on the inner surface.

Summary

1. The multiple fatigue cracks in Fig. 21, which formed in metal that was apparently subjected to compressive stress only, actually formed from residual tensile stress only.
2. The cracks did not grow in length or depth; in spite of the fact that the stress at the roots of the cracks ranged from low magnitude tensile stress to compressive stress of a magnitude equal to the compressive yield stress of the steel.
3. The springs eventually failed from unrelated fatigue cracks that developed on the side opposite to that where tensile stress extended across the face of the spring.

Heat Cracks in Railway Car Wheels

Numerous fissures, usually transverse of the rim, are frequently found on the rolling surfaces of railway car wheels. These cracks develop from the intense heat generated in the surface metal of the wheels by the brake shoes, in the same manner that cracks are developed by the intense heat generated in a metal surface by grinding wheels. The thin heated layer is restrained by the cold underlying metal from expanding in response to the increased temperature; the hot metal is therefore plastically deformed by the transient thermal compressive stress. Upon cooling the deformed metal contracts, whereupon the affected layer is residually stressed in tension.

Whenever this tensile stress becomes so great that it exceeds the ultimate strength of the metal, cracks will form. The more intense the heat, the greater will be the subsequent tensile stress, and the more numerous will be the cracks. Fig. 27 shows a short section of the rolling surface of a cast wheel from a freight car, in which numerous cracks have formed from severe brake shoe applications. Similar fissures from the same cause also appear in forged steel wheels.

Wheels having surface cracks are too common to excite interest. The cracks are regarded as undesirable because flat spots develop, which must eventually be removed by machining. But unless their depth becomes excessive, surface cracks are not considered to be hazardous from the standpoint of wheel strength.

Cracks in railway wheel rims, however, are stress raisers of the most severe type, and by ordinary experience they should continue to grow in depth. As in the occurrence of the grinding cracks in carburized gear teeth, and the greater fatigue durability of the truck rear axle housings that were not stress relieved, the fact that thermal cracks in car wheels do not propagate to complete and catastrophic failure requires an explanation. This explanation is found in the residual stress pattern developed in the wheel rim by normal processing operations and by plastic flow of rim surfaces in contact with the rails.

RESIDUAL COMPRESSIVE STRESS FROM PROCESSING. In casting, the periphery of car wheels are cast in a chill for the professed purpose of hardening the rolling surface. The chill causes the rim to solidify and strengthen while the central plate and hub are still plastic. The hot inner metal first conforms plastically to the dimensions of the colder rim, but as cooling continues the greater contraction of the hotter metals develops residual tensile stresses in the plate and hub with corresponding residual compressive stress in the rim.

A considerable percentage of

forged car wheels are similarly treated with the object of improving wear resistance of the wheel rim against the rails. The rims of forged wheels are water quenched from high temperatures, whereupon the rim contracts and plastically deforms the hot web or plate. As cooling progresses, the plate contracts and becomes residually stressed in tension with corresponding residual compressive stress in the rim. The internal stress pattern in both types of car wheels is substantially the same as that in a bicycle wheel, in which the rim is stressed in compression by the tensile stresses in the wire spokes.

STRESS MEASUREMENTS IN CAR WHEELS. Quantitative residual stress measurements in railway car wheels are not available. Also, residual stress measurements from other forms of quenched specimens are not reliable as indicating the probable stress magnitude in car wheels. Trapped stresses in quenched metal vary with: (a) Temperature gradient; (b) differences in surface to volume ratio; and (c) differences in quenching methods. Reliable stress measurements, therefore, will have to be obtained by the dissection method on actual production wheels.

Qualitative indications of the stress in car wheels are shown in Fig. 28, in which are plotted strain gage readings as reported by an A. A. R. Sub-Committee (Ref. 15). The readings were made as part of a study of the effects of rebuilding worn wheel flanges with weld metal.

A wheel of the form shown in Fig. 28 was cut by a saw from the rim toward the hub. Strain gage readings taken at points *O* and *I* recorded the change in the width of the cut as the saw progressed toward the hub. In response to the residual compressive stress in the rim and the tensile stress in the plate, the width of the cut closed rapidly as the saw penetrated the rim. It is not possible to reconstruct the residual stresses from such readings, but they may sometimes be used as indicating qualitative stresses.

LOSS OF RESIDUAL STRESS MAY BE FATAL. Heat cracks that form in the wheel surface by severe use of the brakes cannot propagate through the rim metal because of the barrier formed by the residual compressive stress. The conditions are similar to the conditions that prevailed in the carburized gear teeth and in the nitrided specimens, with the important difference that the protective residual stresses in car wheel rims can be and sometimes are lost. When this loss occurs, surface cracks can propagate through the rim, and a catastrophic failure follows.

The residual stress in wheel rims may be lost in whole or in part by the severe braking required on high speed trains operating on long mountain grades. The accumulated heat from the brake shoes raises the rim temperature, and the resulting thermal expansion tends to increase the diameter of the rim. The growth of the rim, however, is restrained by the cold plate and hub, with the result that the residual tensile stress in the plate and the residual compressive stress in the rim are increased.

If the compressive stress in the rim, from the thermal expansion plus the original compressive stress from the fabrication process, exceeds the compressive yield strength of the hot rim metal, plastic yielding will occur and the residual compressive stress will be reduced. When the brakes are released the rim metal cools and contracts and, depending upon the extent of the plastic yielding, the altered residual stress in the rim may be either tension or compression. In the former, if the residual tension is sufficiently great, surface cracks will propagate unhindered to complete wheel failure.

The conditions that are favorable to the loss of residual compressive stresses in wheel rims occur more frequently as train speed and severity of brake service are increased. That is why wheel failures are more common in high speed trains operating on long mountain grades. In modern locomotives, since the dynamic braking available per unit of train weight decreases as the number of cars is increased, wheel failures occur more frequently in proportion to the total number of wheels in long trains than in short trains.

ALTERNATING SURFACE STRESS. The residual surface stress in the portion of wheel rims that contact the rails alternates between compression and tension. The metal in rolling contact with the rails is cold worked, that is, the wheel metal in the instantaneous area of contact is plastically deformed by the compressive load. The metal flows away from the contact area in the same manner as occurred in the gear teeth (Ref. 4), Figs. 7 and 8, and as the metal of a peened surface is displaced in the area of impact by the shot or hammer.

As a result, the wheel surface and also the rail surface become residually stressed in compression. The depth and magnitude of the residual stress continue to grow with continued use. The occasional application of the brakes, however, reduces this relatively shallow residual stress in the wheel rims or converts this stress to tension, which as has been seen may become great enough to fracture the surface metal. The succeeding period of rolling restores the compressive stress.

The residual stress induced by the plastic flow of the surface metal establishes a barrier to the progress of thermal cracks; but the depth of this stress is not sufficient to prevent its complete loss during the next severe application of the brakes. This relatively shallow mechanically induced stress will be dissipated by moderately severe brake use, as may be judged by the depth of many thermal cracks.

It is important, therefore, to develop wheel processing that will provide the maximum residual compressive stress deep in the rim. The total rim compressive force must be consistent with the permissible residual tensile stress plus the tensile stress from the service load in the plate. To use the analogy of the bicycle wheel, a tolerable compressive stress in the rim may be great enough to fracture one or more spokes. The permissible residual tensile stress in the plate can be safely increased if the surfaces of the plate are shot peened or surface rolled as a final operation, since these operations (Ref. 3) will offset much of the inherent weakness of the surfaces to tension stresses.

The surface of the plate should not be interrupted by holes or ribs, since such section changes introduce high local stresses. The practice of forming the plate in the shape of a cone should be carefully studied as a probable source of dangerous bending stresses. The radial force, from the compressively stressed rim, loads the plate in tension and also in bending. The bending of the plate, which increases the dangerous tensile stress on the inner surface of the cone, can be avoided by using a flat plate.

RESIDUAL STRESS CAN BE RESTORED. The lost residual compressive stress within the rim of a car wheel can be restored by "tightening the spokes." This effect can be obtained by heating the plate while the rim is held at a relatively low temperature. The heated plate will attempt to expand thermally, but the restraint of the cold rim will cause the metal of the plate to yield plastically. Upon removal of the source of heat, the plastically deformed plate will cool and contract to a smaller diameter against the restraint offered by the rim.

Among the measures that may be taken to prevent loss of residual rim stresses are: (1) Use of metals having greater yield stress at somewhat elevated temperatures, and (2) Removal of the brake heat from the load supporting wheels by providing other surfaces for braking purposes. The latter expedient presents new and perhaps equally serious thermal stress problems, and the cost of the former alternative may be prohibitive. Possibly a combination of these measures can be applied.

Prestressing Not Always Beneficial

Improvement in fatigue strength expected from processes that induce residual compressive stress in the surfaces of specimens is sometimes not realized. In other instances, correctly applied prestressing is found to be detrimental to fatigue strength. These abnormal results are explained by such data as are shown in Fig. 29 in bar chart form.

This chart gives the results of fatigue tests on a series of spring plates made from 9260 SAE steel heat-treated to a specified hardness of Rockwell C 42-45. Each spring plate was 7 in. wide, 8.5 in. long, and 3/16 in. thick, and formed in a cylindrical arc having a height of approximately 1.1 in. Of the 45 springs tested, 21 were shot peened by Pangborn Corporation and 3 by the General Motors Research Laboratory Division. All were fatigue tested by the manufacturer, the Symington Gould Corporation. The test, (Ref. 16), was accomplished by applying repeated loads that bent the plates from their free arc height of 1.1 in. to an arc height of ¼ inch.

The fatigue durability of normal non-peened production springs was established by testing 21 springs to failure. The fatigue durability of each is shown by the length of the corresponding bar at the left of the chart. These bars show that the average life of the non-peened springs was approximately 2,000 stress cycles. This short fatigue life indicates that the stress from the applied load was excessive for the material and heat-treatment used.

PEENING REDUCES FATIGUE STRENGTH. Three groups of 7 specimens each, and one group of 3 specimens, were shot peened on the tension side to the intensities shown in Fig. 29 with shot of the various sizes, and then fatigue tested with results as shown at the right of the chart. The average durability of the peened specimens is not appreciably affected by the differences in shot size or in peening intensity, but the average life for each of the four groups was reduced to approximately 75 percent of the durability of non-peened springs.

The loss of fatigue strength from shot peening resulted because the stress from the test load greatly exceeded the elastic limit of the steel. Note that the arc height of the non-peened springs was reduced as much as 0.5 in. by the permnent set that occurred from one application of the test load. Even greater yielding occurred from a single load application on the first two peened groups, for which a permanent set of 0.06 in. is recorded. The extent of yielding for the third peened group was not reported.

The three specimens in the fourth group were subjected to two peening operations. After the first peening, these specimens were subjected to fifteen load cycles in which they were plastically deformed to permanent sets ranging from 0.098 to 0.125 in. After a second peening operation, a set of 0.02 in. was measured in these specimens.

During the fatigue test, since the dynamic elastic limit is much lower than the nominal elastic limit, the plastic extension of the sub-surface steel in the peened tension side of the springs was so great that much or all of the residual compressive stress induced by the peening was lost. With the loss of the protective compressive stress the stress raisers, in the form of cuts, indentations, folds, and bruises that were made by the impacting shot, became effective in reducing the fatigue strength of the peened springs.

Peening intensity		.012A2	.020A2	.024A2	.013A2
SAE Shot size		P 23	P 28	P 39	P 19
One stress cycle yield	0.050"	0.060"			0.020"

Fig. 29 — Results of fatigue tests on spring plates made from

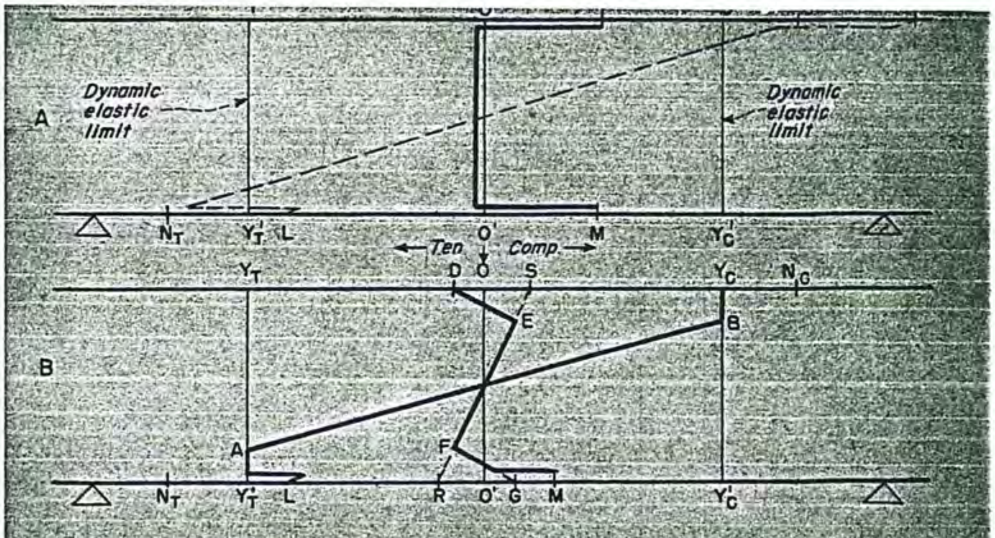


Fig. 30 — Idealized stress diagrams indicate how protective peening stress can be lost.

IMMUNIZING STRESS LOST. The manner in which the protective peening stress was lost is shown in the idealized stress diagrams *A* and *B* of Fig. 30. Diagram *A* shows a beam that has been shot peened on the upper and lower surfaces, as is indicated by the residual compressive stress *OJ* and *O'M*. Experience has shown (Ref. 3) that the magnitude of the residual stress induced by peening is approximately one-half of the dynamic elastic limit *OY*. A downward acting load at *O* exerts a nominal bending stress in the beam as indicated by the diagonal line N_TN_C. The sum of the nominal bending stress and the residual peening stress is represented by the line KN_TN_CL. However, since this nominal stress greatly exceeds the elastic limit of the material, extensive plastic yielding occurs near both surfaces; therefore, the line $Y_TBAY_C'L$ of diagram *B*, Fig. 30, represents the total stress.

PERMANENT SET MEASURED. Because of the plastic yielding, the beam will not return to its original height when the external load is removed, but will have a permanent set as was noted for the springs, Fig. 29. The local plastic yielding gives rise to the pattern of residual stress that is represented in Fig. 30 by the line *DEFGM*, which establishes the balance required between the residual clockwise and counterclockwise bending moments to satisfy equilibrium conditions within the unloaded beam. Areas *DSED* and *MRFM* represent metal that was permanently deformed by the plastic yielding. Line *EF* indicates the portion of the beam in which no plastic yielding occurred.

Prior to yielding, the line *SR* was coincident with the zero stress line *OO'*; its present displaced position is therefore a measure of the permanent set of the beam. That is, the permanent set is equal to the deflection of the original beam under an external load that stresses the upper surface to an amount *OS* in compression and the lower surface to an amount *O'R* in tension.

After plastic yielding of the peened beam, the stress range on the upper surface from the downward acting load is equal to DY_T, and on the lower surface to *ML*. This stress range occurs whether or not the upper surface was peened, since all of the peening stress on this surface was immediately lost by plastic yielding. If the beam was not peened on either surface, the stress range on the upper surface would still be DY_T, but on the lower it would be GY_C' instead of *ML*. The difference $Y_C'L$ is the remanent of *O'M*, the original residual peening stress.

STRESS RAISERS DOMINATE. If the gain in fatigue strength from this reduced residual compressive stress is less than the loss of fatigue strength from the stress raisers in the form of cuts, folds, and bruises, the fatigue strength of a peened beam under the assumed test load will be less than if peening is not applied.

The total yielding of the Symington Gould Springs, Fig. 29, was not measured; it is therefore impossible to construct diagrams to represent quantitative stress values in those specimens. Diagrams *A* and *B* of Fig. 30 are intended to illustrate, in a qualitative sense, the probable relationship of the residual stresses in the peened and non-peened springs, and to show that accelerated fatigue tests by unduly increasing the test load leads to invalid data.

The fatigue strength of the Symington Gould springs could have been increased by heat-treating to greater hardness, perhaps Rockwell C 50, to increase the elastic limit and thereby prevent or reduce the loss of the peening residual stress by sub-surface tensile plastic yielding. Brittle failure of high hardness

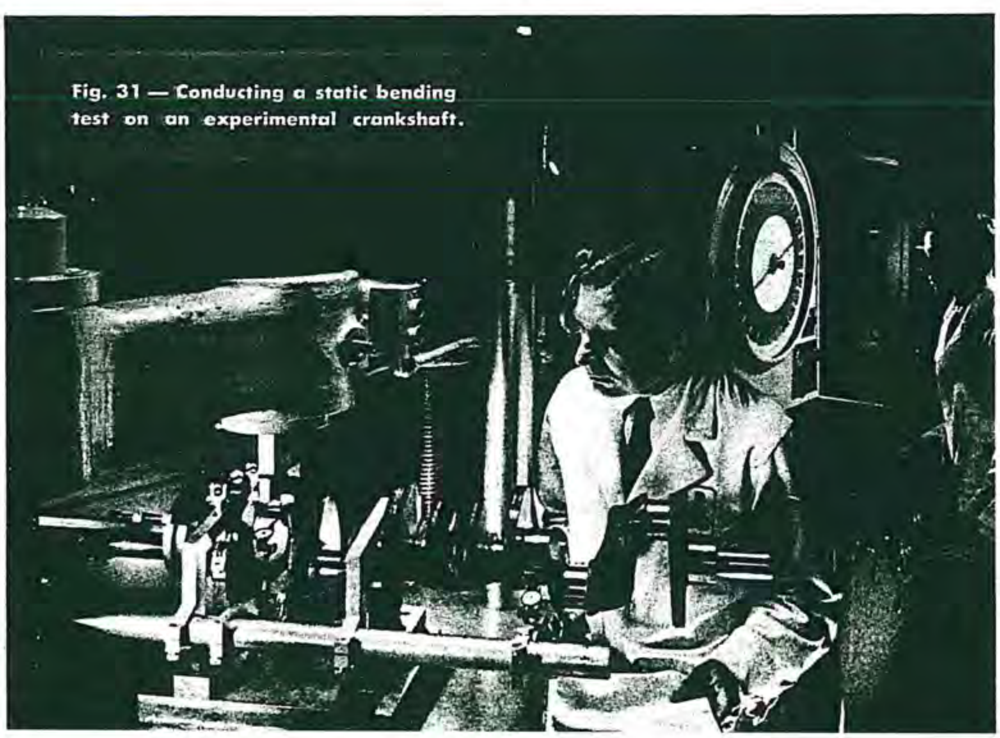
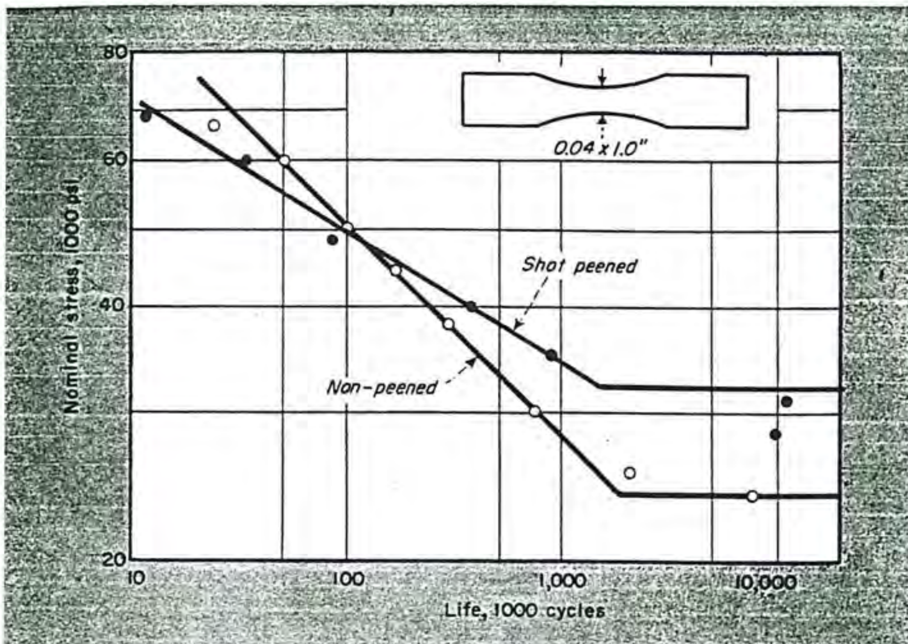
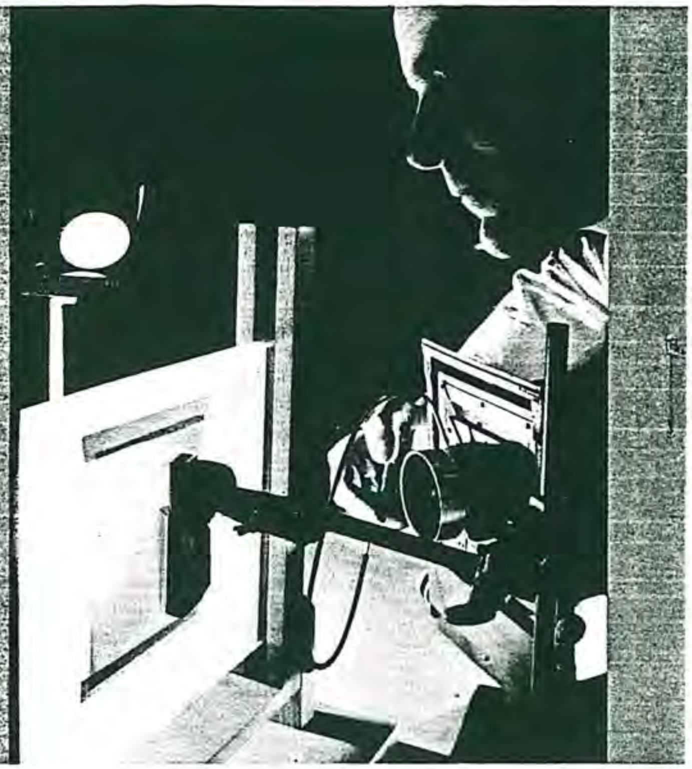


Fig. 31 — Conducting a static bending test on an experimental crankshaft.





Above. Fig. 32 — Results of fatigue tests on non-peened and shot peened 24ST Alclad aluminum sheet. *Right.* Fig. 33 — Irregularity of the shadows cast on the gear tooth is a measure of surface deterioration.

steel need not be feared if the surface of the part is residually stressed in compression to a sufficient magnitude.

It should be noted that there was no loss of whatever benefit may have been bestowed to the test springs by cold working in improving the "physical properties" of the steel. The yielding that dissipated the residual compressive stress on the side of the springs where fatigue originated resulted from the tensile plastic extension of sub-surface metal and the cold worked surface was not disturbed. It is apparent that the more important effects of shot peening cannot be credited to improved strength of the peened metal. In the absence of the residual stress, cold work by shot peening actually reduces the fatigue strength of the metal through the introduction of stress raisers.

Sub-Surface Tensile Plastic Yielding

Comparative tests have been made at the Battelle Memorial Institute (Ref. 17) of shot peened and non-peened fatigue specimens made from 24ST Alclad aluminum sheet. In these tests also, the surface residual compressive stress induced by shot peening was lost because of sub-surface tensile plastic yielding.

The form and dimensions of these specimens are given in Fig. 32. The shot peening was performed by the Research Laboratory Division of the General Motors Corporation using P66 shot propelled by gravity to produce an intensity of 0.002A2. These specimens were subjected to pull-pull loads whereby the nominal tensile stress range extended from the maximums shown in Fig. 32 to 25 percent of these maximums.

From Fig. 32 it is seen that the fatigue strength of the shot peened specimens was inferior to that of the non-peened specimens in the high load range; and as the maximum test stress was reduced that the fatigue strength of the peened specimens became superior.

These results would be expected; because, when external loads were great, all or most of the residual peening stress was lost by plastic extension of the core. With the loss or reduction of the surface immunizing stress, the stress raisers that were formed by the peening dominated, and the fatigue strength of the specimens was decreased. As the maximum applied tensile stress was reduced, a greater portion of the residual surface compressive stress was retained, and the immunizing effect began to overtake and dominate the effect of the peening stress raisers.

When the retained residual compressive stress exceeded the applied tensile stress as magnified by the peening stress raisers, the fatigue strength of the shot peened specimens was greater than that of the non-peened specimens. This gain in fatigue strength continued as the maximum test load was decreased until the plastic extension of the core was reduced to its minimum.

FATIGUE GAIN NOT THE RESULT OF COLD WORK. As in the Symington Gould Springs, any benefit resulting from improved "physical properties," which may have been imparted to the cold worked surface layers of the specimens by shot peening, remained substantially unaltered whether the test stress was great or small. The changes that occurred in the specimens as the test load was varied were confined to the core.

The observed variations in the relative fatigue strength of the peened and non-peened Battelle specimens cannot therefore be explained in terms of altered "physical properties" of the cold worked met-

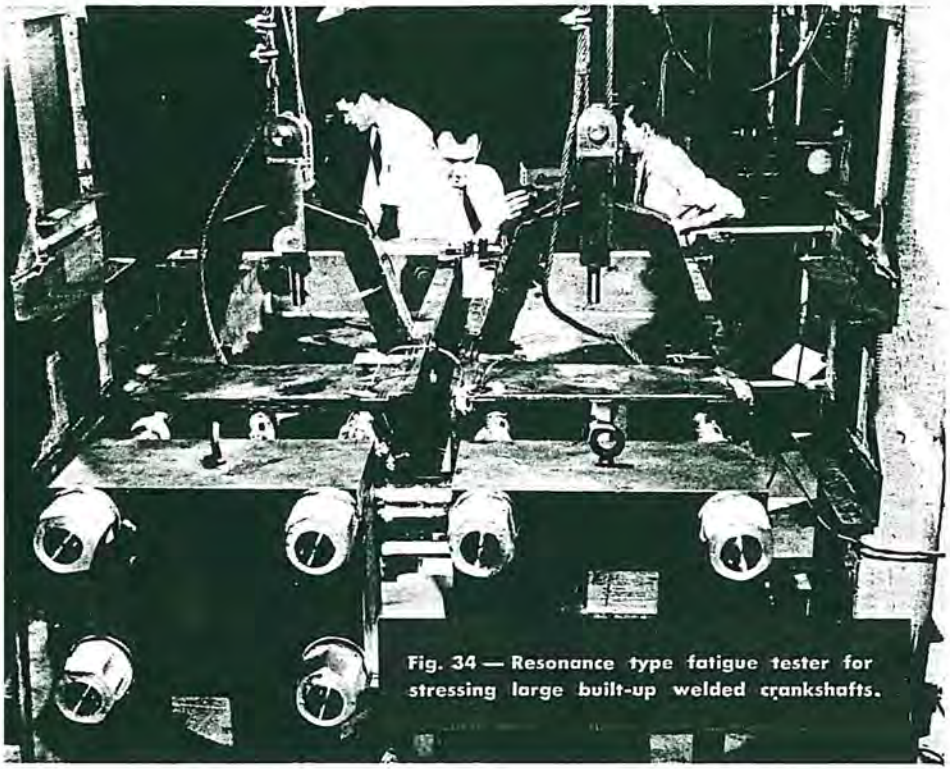


Fig. 34 — Resonance type fatigue tester for stressing large built-up welded crankshafts.

al, but they do conform to the variations in the surface residual stress. The losses in the fatigue strength of the peened specimens relative to the non-peened specimens occurred when the surface residual compressive stress was small, and the gain in fatigue strength occurred when the surface residual compressive stress was large.

Protecting Inherently Weak Surfaces

Surface residual compressive stresses are effective in increasing the fatigue strength of metals because: (a) the surfaces of structural metals are weaker in fatigue than sound sub-surface metal, and (b) the direct causes of all fatigue failures are tensile stresses.

In specimens that are loaded so as to stress any portion of the metal in tension, the magnitude of the tensile stress can be reduced by processing operations that will develop residual compressive stresses in the tensile stressed areas. Effective prestressing processes for increasing fatigue strength, therefore, are: (1) Those which protect inherently weak surfaces by adequate reduction of tensile stresses, which alone cause fatigue failures; and (2) those which reduce principal sub-surface tensile stresses, as, for example, by deep tensile plastic yielding.

Residual Stress Loss Must Be Avoided. In the protection of inherently weak surfaces, it is not enough to develop only the desired pattern of residual stress for any particular method of loading. Precautions must also be taken to assure that a reasonable portion of this residual stress pattern can be retained under the conditions of loading that will be experienced in laboratory or service use. As occurred in the Symington Gould Springs, Fig. 29, and in the Battelle specimens, Fig. 32, the surface residual compressive stresses that are intended to protect the fatigue vulnerable surfaces of the specimens may be lost by plastic tensile yielding of sub-surface metal.

A more common cause of loss of residual compressive stress is plastic yielding of the compressively stressed metal under additional compressive stress. An instance of this kind is the loss of residual compressive stress in railway car wheels as a result of local thermal compressive stress. The loss of residual compressive stress through compression yielding is particularly serious in rotating beam and other specimens loaded in bending, in which the stresses from external loads are reversed.

In such specimens, the residual compressive stress is added to the compressive stress from the bending load, and, since their sum exceeds the yield stress of the metal, residual stress is lost. For this reason, relatively little increase in fatigue strength can be had from mechanically induced residual compressive stress under conditions of reversed loading. When the surface residual compressive stresses are developed by nitriding, carburizing, and other case hardening treatments, large gains in fatigue strength are possible because the increased yield strength of the hard compressively stressed layers prevents loss of the surface protective stress through yielding.

Direction of Residual Stress. Only the stresses acting in the direction of the principal tensile stress as determined by the direction of external loads, by strain gage measurements, or by the direction of fatigue fractures have been considered in the foregoing discussions. No doubt the strength of many or all forms of fatigue specimens is affected by the stresses acting in other directions, but few data are available. Probably their greatest effect is to increase or decrease the effective yield strength of the metal in the direction of the principal tensile stress.

Any increase in the yield strength can be used to increase the fatigue strength. As has been discussed, this increase is possible because the sub-surface fatigue strength is approximately proportional to the dynamic yield strength, and because residual compressive stresses of greater magnitude can be retained to protect the inherently weak surfaces under adverse load conditions. Conversely, any decrease in yield strength results in reduced fatigue strength.

Editor's Note: In the April Number, Product Engineering will publish a sequel article in this series entitled "Fatigue Durability of Prestressed Screw Threads" by J. O. Almen.

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