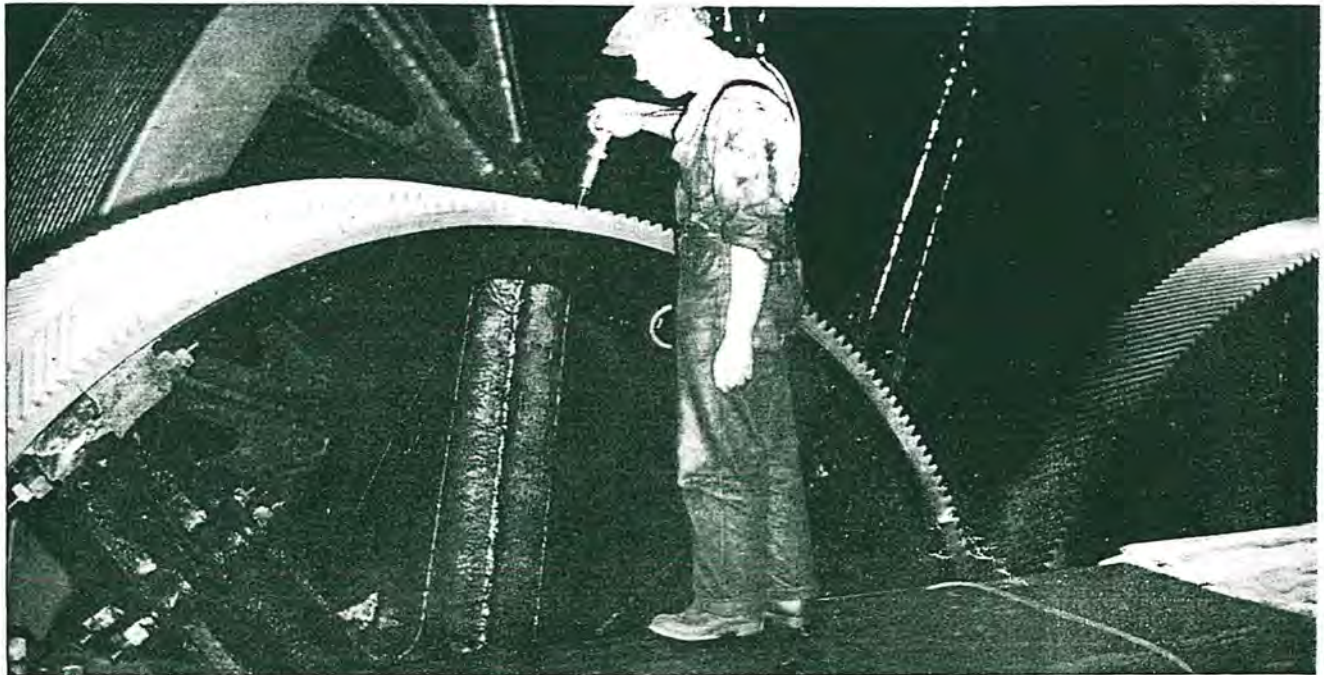

Brittle Structural Failures With Emphasis on Welded Ships

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Brittle Structural With Emphasis



SHIP FAILURES of the kind that have become all too frequent in recent years began, as is well known, with the introduction of welded hulls to replace the older and relatively trouble free riveted structures. It is apparent that some structural advantage offered by riveting was lost when welding was adopted; a loss so great that the ample factor of safety intended by the designers was reduced to less than unity.

One source of loss is the recognized ability of riveted joints to distribute the stress from otherwise concentrated loads by local plastic yielding of holes and rivets. Such adjustment of stress is not possible when adjacent plates are fused by welding. Load concentrations are inevitable and, when these loads act in the same direction as externally applied loads, the local residual stress may become very great.

Another and more general loss of strength arises from the residual stresses that are developed by welding. In joining two plates, the weld metal together with a considerable volume of metal on either side of the weld is heated to a high temperature and, being restrained by adjacent cold metal, cannot expand but must adjust in length by plastic compression to that of the cold metal. When the weld is completed and the metal cools, it seeks to contract. But being still restrained by the adjacent unheated metal, the cooling metal is residually stressed in biaxial tension with corresponding compressive stress in adjacent plate areas. Measurements indicate that this biaxial residual tensile stress developed by local heating may equal the static yield stress of the steel.

Both of these dangerous residual

stress systems, of course, may possibly occur in areas where stresses from external loads are concentrated to create an extra vulnerable structure.

The manner in which residual stresses decrease or increase the strength of a structure is not easily demonstrated by conventional laboratory tests. Long practice has shown, however, that it is desirable to reduce the magnitude of welding stresses. The purpose of the several stress relieving operations in common use is sometimes to reduce warpage but, more often, to produce a stronger structure.

In welding cast iron, pre-heating of the casting is usually necessary to avoid spontaneous cracking. Pre-heating reduces the residual tensile stress in the vicinity of the weld because the temperature gradient between the

Failures on Welded Ships

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Service experiences and results of pertinent experiments to support the theory that welded structures fabricated from ductile steel fail by brittle fracture. Data show that susceptibility to the several common causes of brittle fractures in ductile metal such as fatigue, stress corrosion cracking, and biaxial tension can be reduced by the development and retention of residual compressive stress in vulnerable areas. Simple and inexpensive methods for reducing harmful residual stresses. Since welded ships are fabricated from ductile steel and the fracture origins of failed ship plates are brittle in character, ship failures are suspected of developing from several causes.

Fig. 1—Prestressing gear teeth by air hammer peening developed sufficient residual compressive stress to avert further tooth failure in a 12 foot diameter cast steel mining hoist gear.

hot and cold metal is reduced. Many welded production items, including complete locomotive frames, are "stress relieved" by oven-heating after welding. Practical "stress relieving" by uniform heating does not, of course, eliminate residual stresses but they can be reduced to equal the yield stress of the metal of the annealing temperatures. Neither pre-heating nor annealing appears practical in large structures such as ships.

Local stress relieving is often practiced by experienced welders. In its simplest form this operation consists of striking the weld near its end with a hammer after the weld has become black. The effect is to induce a temporary state of residual compression by plastic deformation, thus reducing the final residual tension below the spontaneous fracture level.

Table I—Tensile Properties of Several Metals
in Shot Peened and Non-peened Conditions

Material and Condition	Shot Peened	Peening Intensity	Rockwell Hardness	Tensile Yield, 1000 psi	Tensile Ultimate, 1000 psi	Elongation, percent in 2 in.
SAE 4130, heat-treated to 175,000 psi	No	—	D53	178.0	195.0	5
	Yes	0.008-0.010A1	D55	167.5	192.5	5
SAE 4130, heat-treated to 125,000 psi	No	—	D50	130.0	139.2	10
	Yes	0.007-0.009A1	D48	121.0	139.0	10
Stainless "w", condition A	No	—	D46	109.0	139.5	8
	Yes	0.007-0.009A1	D46	111.5	141.5	6
Stainless "w", condition D	No	—	D53	152.5	167.0	8
	Yes	0.007-0.009A1	D54	154.0	176.0	9
Alclad 24S-T	No	—	E 96	49.0	64.7	16
	Yes	0.004-0.006A1	E 96	48.7	64.7	16
Magnesium alloy FS1H	No	—	E 81	31.6	43.0	5
	Yes	0.004A1	E 75	34.3	42.7	9

LABORATORY TESTS INADEQUATE

Attempts to measure the effects of residual stresses by conventional laboratory tests cannot succeed because, regardless of the magnitude and orientation, such stresses have little or no effect on the static tensile or impact strength of ordinary structural materials. The reason is that, since ordinary materials are ductile, sufficient general yielding occurs during laboratory tests to dissipate any residual stresses that may originally have been present in the region of the specimen where fracture is initiated. As long as they are judged by conventional static tests,

the true significance of the effects of residual stresses will be misunderstood.

Many static tests have been made to compare the yield strength and tensile strength of normal specimens not prestressed and specimens prestressed by shot peening. The results of a few such tests made by Consolidated Vultee Aircraft Company (Ref. 1) in cooperation with the Research Laboratories Division of the General Motors Corporation are given in Table I. In the several pairs of specimens tested, there is no significant difference in ultimate tensile strength or

in yield strength, and the differences in elongation are no greater than may be expected from any two specimens of similar material and heat-treatments.

It is probable that the surfaces of all tensile specimens are residually stressed in compression whether or not they are intentionally prestressed. Measurements of residual stress in tensile specimens (Ref. 2) that had been loaded slightly above their elastic limits showed the surfaces to be stressed in compression as a result of greater plastic extension of their surfaces than of their cores.

SPECIMENS UNAVOIDABLY PRESTRESSED

Numerous comparisons have also been made between the strength of shot peened and non-peened impact specimens, which included gun parts, carburized starter gears, and standard laboratory specimens of the bending and torsional types. In all these specimens, the applied stress caused sufficient local yielding to dissipate the residual stress induced by peening. One series of four Charpy keyhole specimens made of SAE 4640 steel was heat-treated to give Rockwell C 32-36 hardness, tensile strength 148,000 psi, reduction of area 54 percent, and elongation 19.5 percent. As would be expected, none of these specimens showed significant changes that resulted from shot peening because sufficient plastic yielding preceded fracture to dissipate the residual stress induced by peening. The angle of swing for each of the two non-peened Charpy specimens was 116 deg and for the shot peened Charpy specimens the angles were 115 to 116.5 degrees.

New systems of residual stresses are developed in tensile specimens during tests, as has been described, because

plastic deformation is not uniform with respect to strain through the deformed section. A similar effect is no doubt observable in impact specimens, but since these new stresses result from the test loads and not directly from stress initially in the material, they will not be discussed further.

Due attention must be given, however, to any increase or decrease in initial residual stress by plastic yielding under normal loads or occasional overloads occurring in service. Such changes can and do result in deterioration or improvement of structure strength.

More precise knowledge of material behavior than is afforded by the usual laboratory tests is required in the design of structures in which material must be used efficiently such as aircraft and automobiles, or in which factors of safety are dissipated by fabrication processes such as in welded ships, or in which favorable residual stresses are lost and unfavorable residual stresses are developed by service deterioration such as in railroad rails and wheels. Such structures are characterized by more or less frequent failure in service, even though the ma-

terial conforms to the most rigid specifications.

When the strength of materials is measured by tests in which plastic flow approaches zero, residual stresses are partially or entirely retained and their effects approximate the effect of stresses from external sources having the same magnitude and direction. Under low plastic yielding, therefore, the original residual stresses that are retained will increase or decrease the effective strength of a structure, depending mainly upon whether their tensile components act in the same or in the opposite direction to the tensile stresses from the external loads.

Accelerated fatigue tests in which fractures develop in less than 100,000 load applications usually mean that the test stresses are so great that extensive plastic yielding occurs. Such tests cannot be used to evaluate residual stresses resulting from prestressing operations because under reversed loading much or all of the prestress is lost, while under unidirectional loading the favorable residual stresses are increased somewhat as occurs in static strength tests.

SOURCES OF RELIABLE DATA

Data from arbitrary laboratory tests on arbitrary specimens are not only unreliable, but little confidence can be placed on data from so-called "simulated" tests. Service conditions cannot be reproduced in the laboratory even though the specimens are faithful copies of full scale structural elements. It is axiomatic that nothing can be learned relative to the ultimate strength of any particular structure, except from tests to failure.

The only source of reliable data is the "scrap pile". There, first hand studies may be made of true service failures in complete structures and under actual service operating conditions. "Scrap pile" data include the results of all manner of mistakes, accidents, and random experiences. The realistic interpretation of such data is the most fruitful source of new discoveries in engineering processes and of new knowledge for testing the validity of

machine design formulas. It is in the scrap pile where clues are found that lead to the solution of many vexing problems and the foundations for more accurate theories.

Unfortunately, little use is made of the most productive source of reliable data. Instead, remedies for service troubles are almost invariably sought, at great expense, in laboratories through unreliable and misleading "simulated" tests.

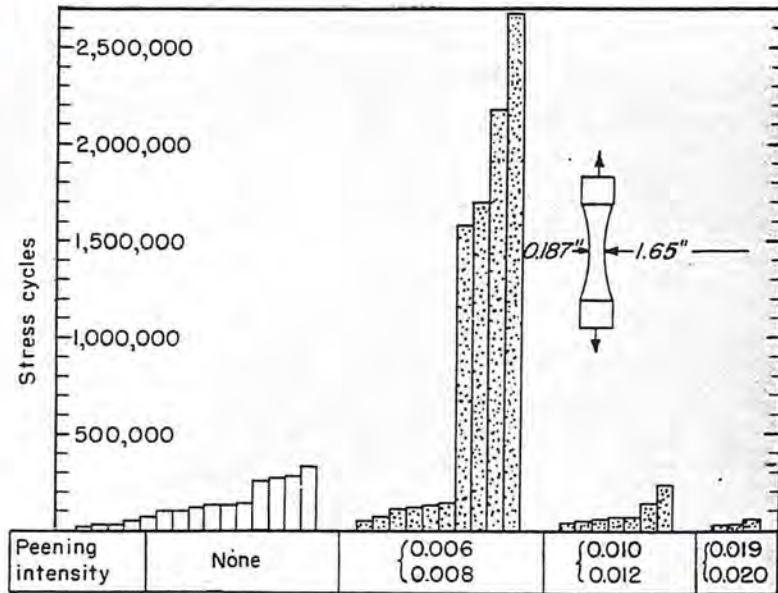
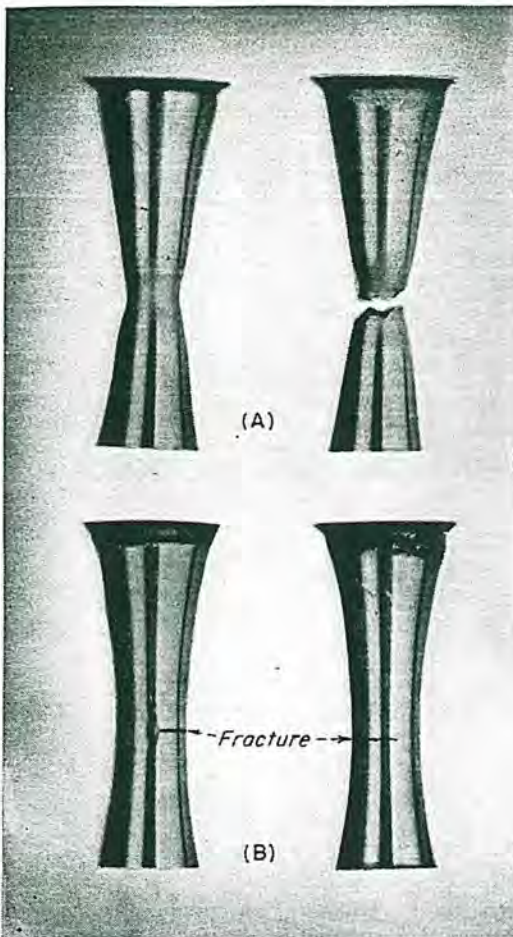


Fig. 2 — Typical tensile stress fractures in SAE 4340 steel specimens of 32-36 R_c hardness. (A) Static tensile stress; plastic flow occurred before fracture. (B) Tensile fatigue; no apparent yield before fracture.

Fig. 3 — Relation between tension fatigue durability and shot peening intensity, as indicated by pull-pull fatigue tests on SAE 4340 steel specimens hardened and tempered to 33-36 R_c hardness.

SHIP FAILURES ARE BRITTLE FAILURES

Studies seeking to determine the causes of and remedies for the numerous catastrophic failures that have occurred in welded ships have followed conventional laboratory methods. Test procedures have been based on erroneous concepts of causes of failure and little if any realistic correlation has been attempted between competent field observation and laboratory tests.

In the absence of data that could have been accumulated by trained observers, it is necessary for those who seek to prevent failures of welded ships to base their diagnosis on service and laboratory failures of other structures having similar characteristics.

Structural materials in the ordinary range of ductility fail by brittle fracture (low plastic yielding) when subjected to certain conditions that often prevail in service. These conditions are: (1) Repeated load (fatigue); (2) biaxial and triaxial tension; (3) simple tension in corrosive environment (stress corrosion cracking); and (4) tensile loads across sharp notches. In such situations residual stresses, depending upon whether they are tensile

or compressive, can increase or decrease the effective stress tending to cause failures.

Ships and other welded structures are fabricated from ductile steel and since the fracture origins are brittle in character, their failures are suspected of developing from one or more of the foregoing enumerated causes.

Tensile fractures in SAE 4340 steel specimens heat-treated to hardness 32-36 R_c are shown in Fig. 2, (Ref. 3). The two specimens at the left were subjected to a static tensile stress and show extensive plastic yielding prior to fracture. Any residual stress in these specimens prior to testing would, of course, have been dissipated before fracture. The specimen strength would therefore be substantially the same whether or not they had been residually stressed. The two specimens at the right in Fig. 2 also show tensile fractures, but these were subjected to repeated tensile loads ranging from 32,000 psi nominal minimum stress to 150,000 psi nominal maximum stress.

The bar chart Fig. 3 gives the re-

sults of pull-pull fatigue tests on 0.187 in. dia non-peened and shot peened SAE 4340 steel specimens hardened and tempered to 33-36 R_c hardness.

These specimens were subjected to a calculated stress cycle of plus 32,500 psi to plus 150,000 psi. This maximum stress, which is slightly less than the static yield strength of the steel, was selected to assure that the peened specimens would fail in a short time. As stated in a previous article (Ref. 4), such short duration fatigue tests require the application of stresses well above the dynamic elastic limit.

As shown in Fig. 3, the cycles to failure in the group of non-peened specimens ranged from 25,000 to 320,000; the plastic extension averaged 0.0005 inch.

Plastic yielding, however, was not sufficient to dissipate the residual compressive stress induced in the surface of the ten specimens that were subjected to a light peening with chilled iron shot of 0.006 to 0.008 in. dia. The cycles to failure of four of these specimens ranged from 1,500,000 to more than 2,500,000. The greater

average fatigue durability of these specimens indicates the retention of some of the original residual compressive stress.

Lest this increased fatigue durability should be attributed to work hardening by the peening, note that more intense peening, and therefore greater work hardening, did not increase the fatigue durability of the specimens in groups three and four. The lesser effect of more intense peening appears to result from the greater loss of the residual compressive stress induced by the peening because, as the depth of the compressively stressed peened layer is increased, the residual tensile stress in the core is necessarily increased and the core area is decreased. As a result, plastic extension of the core increased and surface residual compressive stress decreased under the same applied load.

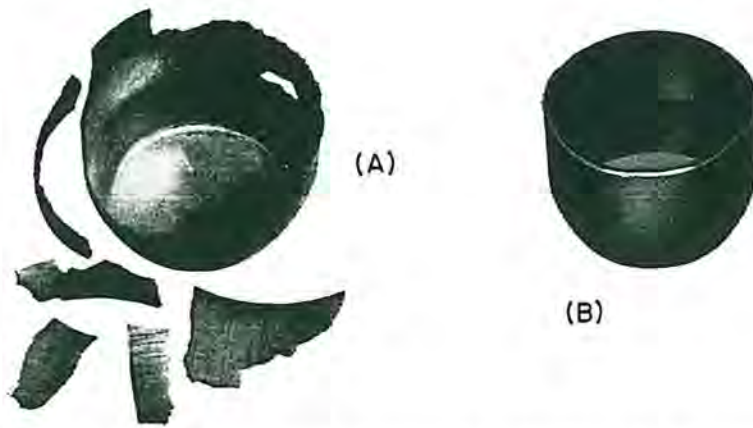


Fig. 4—Specimens, which were residually stressed by the dies in forming, used in studying season cracking in brass. (A) Non-peened brass case failed in 2½ hours in ammonia atmosphere. Stress corrosion cracking occurs only in tension stressed areas. (B) Undamaged lightly peened case after 100 hours exposure in ammonia atmosphere. Cracking is prevented when thin surface layer is compressively stressed.

SEASON CRACKING OF SHELL CASES

The brass cups shown in Fig. 4 are specimens that were used in studies to obtain a remedy for brittle cracking of shell and cartridge cases. The Research Laboratories Division of the General Motors Corporation; the Bureau of Ordnance, Navy Department; and the Springfield Armory (Ref. 5 and 6) cooperated in these studies.

These cups were residually stressed by the forming dies. Brittle fracture developed in the non-peened specimen, Fig. 4(A), after exposure in an ammonia atmosphere for 2½ hours.

That this stress corrosion cracking (known as "season cracking" when occurring in brass) resulted from residual tensile stress is shown by the protection afforded the specimen, Fig. 4(B), by light shot peening. The thin layer of compressively stressed metal developed by the peening prevented failure although this cup was exposed in an atmosphere of ammonia for 100 hours.

This experiment was repeated many times with fracture occurring also in peened cups but only after prolonged

exposure. Reason for failure was non-uniform peening; overpeening one portion of a cup developed tensile residual stress in some other region. When only one surface was peened fracture always developed in the unpeened surface.

Shot peening also prevented accelerated season cracking on unused shell cases, but the protective residual compressive stress was lost by the stress and heat of subsequent firing, after which the cases were again subject to season cracking.

STRESS CORROSION CRACKING OF MAGNESIUM

Shot peened and non-peened magnesium specimens have been tested to compare their resistance to stress corrosion cracking (Ref. 7 and 8). These tests were a part of a cooperative investigation by the Research Laboratories Division of the General Motors Corporation and the Aluminum Company of America. The specimens were of the strip form shown in Fig. 5. They were notched at the ends and were longer than the distance between the end lugs of the I-shaped magnesium holder, so that when assembled in the holder the strips were stressed in bending. The holder together with a non-peened and a peened specimen was immersed in a solution of 20 grams potassium chromate and 35 grams sodium chloride per liter of water and time to fracture measured.

The lower specimen, Fig. 5, which had been shot peened with small glass spheres, was still intact after twelve

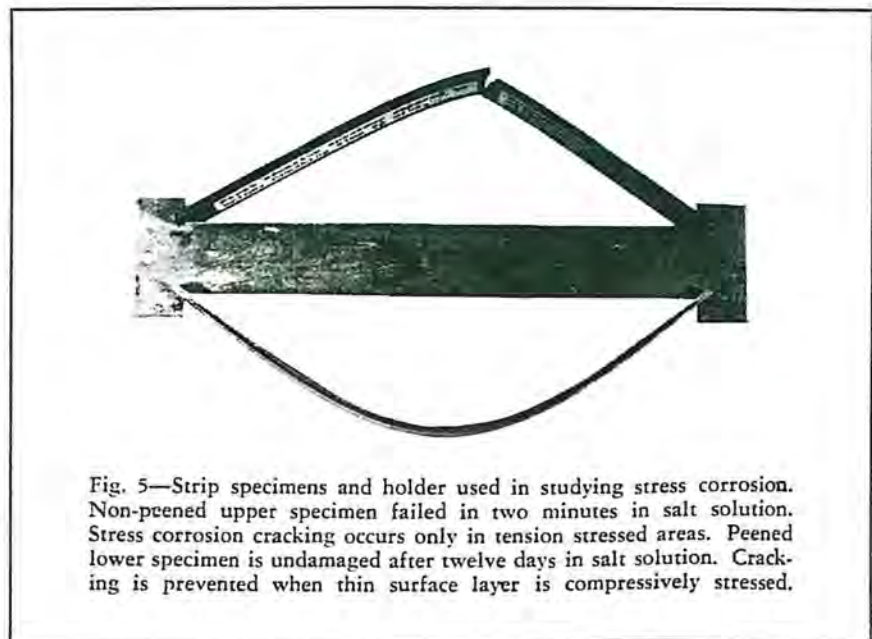


Fig. 5—Strip specimens and holder used in studying stress corrosion. Non-peened upper specimen failed in two minutes in salt solution. Stress corrosion cracking occurs only in tension stressed areas. Peened lower specimen is undamaged after twelve days in salt solution. Cracking is prevented when thin surface layer is compressively stressed.

days immersion. The non-peened upper specimen failed from a crack originating on its tensile stressed surface after two minutes in the salt solution.

It should not be assumed that the peened specimen was better than the non-peened by the ratio of 12 days to 2 minutes. The yield stress of magnesium under prolonged strain is indefinite, therefore, the effective peening stress decreased by plastic creep of the underlying metal. It was necessary to immerse the stressed specimens within a reasonable time after assembly in the fixture because, if too long

delayed, enough of the peening stress was lost by plastic creep to interfere with the experiment.

Because of the creep characteristics of magnesium, and to a lesser degree aluminum, shot peening is not an effective preventive against (tension) stress corrosion cracking when these metals are tested under conditions of constant load, instead of constant strain as described for this experiment in which the magnesium strips were subjected to bending in the holder. When tested under constant load, the stress remains unaltered regardless of

creep; whereas under constant strain, the stress decreases with creep. Under sustained load the protective compressive stress induced by peening is soon lost, and as creep continues the vulnerable surfaces become stressed in tension whereupon cracking proceeds as if peening had not been applied.

This experiment, supported by many similar ones, shows that stress corrosion cracking, which is in fact tensile corrosion cracking, is prevented as long as the magnesium surface is protected by a thin layer of compressively stressed metal.

STRESS CORROSION FAILURES IN STEEL

Similar accelerated stress corrosion experiments comparing peened and non-peened mild steel specimens and stainless steel specimens have been made by the Illinois Institute of Technology in cooperation with the Research Laboratories Division of General Motors Corporation.

These specimens were heat-treated after being bent to the form shown in Fig. 6. A number of specimens from each of several groups were then shot peened, after which test loads were applied by tie bolts adapted to bend the arms of the U-specimens

toward one another, thereby stressing the outer surfaces in tension.

MILD STEEL SPECIMENS. The test loads in percent of static yield stress for each of the mild steel specimens (Ref. 9) are given in Fig. 7. The length of the respective bars indicate the relative time required to fracture the loaded peened and non-peened specimens when immersed in a boiling solution of

Ca(N₃O)₂ 4H₂O 1800 gm
NH₄NO₃ 100 gm
Distilled water 1200 gm

STAINLESS STEEL SPECIMENS. In testing the peened and non-peened stainless steel specimens (Ref. 10), the following test solutions for the corresponding groups of specimens shown in Fig. 8 were used:

Group A. 60 percent hydrated magnesium chloride, no acidification, pH 5.4, boiling point 114C.

Group B. 60 percent hydrated magnesium chloride, acidified with 1.5 percent citric acid pH3, boiling point 114C.

Group C. 60 percent hydrated magnesium chloride, acidified daily with

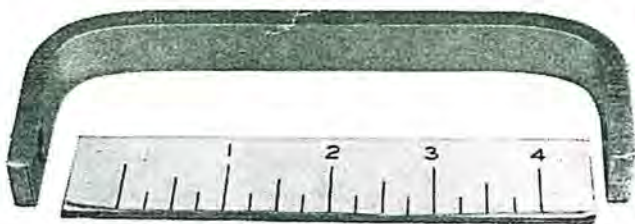
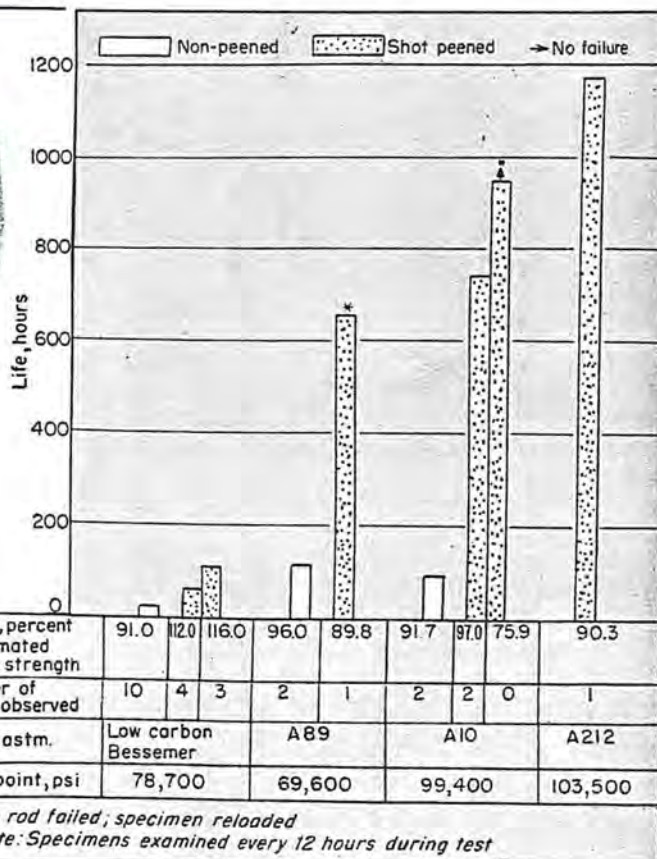


Fig. 6—Form of specimens used to study stress corrosion failures in steel. Specimens were heat-treated after being bent to the form shown. Test loads were applied by tie bolts that bent the arms of the U-shaped specimen inward, thereby stressing the outer surfaces in tension.

Fig. 7—Relative durabilities of mild steel U-specimens when immersed in a boiling solution of ammonium nitrate, calcium nitrate, and distilled water. The length of the respective bars indicate the relative time required to fracture the loaded peened and non-peened specimens.



N/10 hydrochloric acid to pH 2.2, boiling point 114C.

Groups D and E. 42 percent anhydrous magnesium chloride, no acidification, boiling point 140C.

One half of the shot peened specimens in each of the five groups A to E were peened after the external stress was applied by tightening the tie bolts (strain peening) and in the remaining half the external stress was applied after peening. The nominal test stress in all specimens was calculated to be 90 percent of yield stress. SAE steel 30915 was used for all specimens except those in the E group, which were of SAE 30805 steel. The relative durabilities of the specimens are indicated in chart, Fig. 8.

Strain peening was not more effective in resisting stress corrosion cracking in these statically loaded specimens than normal peening, because either process provided a "skin" that was residually stressed in compression and therefore impervious to intergranular corrosion. Under greater external static loads or in fatigue, strain peening (Ref. 11) can be superior to normal peening because the greater residual compressive stress will counteract greater applied tensile stresses when the latter are unidirectional or biased.

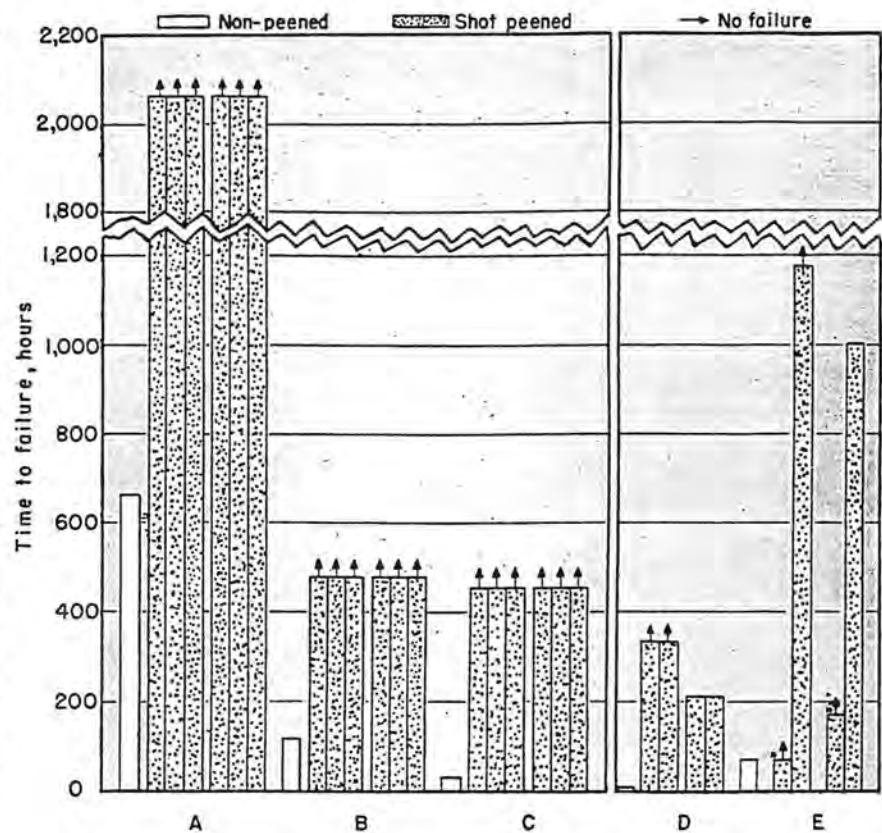


Fig. 8—Relative durabilities of stainless steel specimens when immersed in various boiling solutions. Tie bolts failed in two specimens of E group marked by asterisks.

STRESS CORROSION FREQUENT IN SERVICE

Numerous instances are recorded in which tension stress corrosion cracking has caused extensive trouble (Ref. 12) in service. These range from watch springs to suspension bridges. Watch spring strength was once thought to be affected by lightning because failures were most frequent in the season of thunderstorms. It was soon realized, however, that high humidity and therefore greater corrosion activity coincided with thunderstorms and that these frequently occurring failures were actually caused by stress corrosion cracking.

Similar frequent failures have occurred in such items as split lock washers, door lock springs and parts in which the metal is loaded at a sustained high stress. Only recently I found the spring of my seldom used bow pin broken. At McCook Field, Dayton, Ohio, about thirty years ago I observed the sudden collapse of an airplane parked unattended on the field. The welded landing gear had failed for no reason apparent at that time. A few instances of similar spontaneous failures will be given in which a reasonably accurate history of the failed specimens are known.

In the spring of 1929, numerous

failures of wires were discovered in the cables of the 1200 foot span of the Mount Hope suspension bridge in Rhode Island and also in the cables of the 1850 foot span of the Ambassador suspension bridge between Detroit, Mich., and Windsor, Ontario. Both bridges were under construction at the time. The Mount Hope bridge cables had been completed and preparations were being made to lay the roadway. The Ambassador bridge cables were still being placed when the failures were discovered.

The method of construction was such that the tensile stresses from the applied load were augmented by bending stresses that approached or exceeded the elastic limit of the steel. As a result, brittle fractures developed from stress corrosion cracking in regions of high tensile stress. It was necessary, at great cost, to dismantle both bridges and to replace the original wire with wire more resistant to stress corrosion cracking.

Regardless of other prior induced mechanical or thermal residual stresses, a cold formed spring is residually stressed because the metal must be strained well above its yield strength when bending the wire to form a per-

manent arc. At the outside diameter of the coil, a layer of metal parallel with the neutral plane of the wire must be stressed beyond the yield strength in tension; also, at the inside diameter of the coil the metal in a similar layer must be likewise overstressed in compression. The bending stress in the metal between these overstressed outer and inner layers is proportional to the distance from the neutral plane of the wire and ranges from the yield strength of the material to zero. Although this layer is not plastically deformed, it contributes to the residual stress.

On release of the bending load, the radius of curvature of the coils increases to establish equilibrium between clockwise and counterclockwise residual stress moments about the axis of the spring. One result of this elastic recovery (springback) that the layer of metal near the outer diameter of the spring, which yielded in tension, becomes residually stressed in compression; and the layer near the inner diameter, for a similar reason, becomes residually stressed in tension. These effects are easily observed by wrapping a wire (a straightened paper clip will do) around a pencil.

RESIDUAL STRESS FROM COLD FORMING

The residual stress in a cold formed spring is qualitatively indicated in the diagram, Fig. 9, in which a beam supported near its lower ends is loaded in a downward direction at O . The upper surface of this beam, which is stressed in compression by the downward acting load, represents the inner diameter of the coil spring. The lower surface, which is stressed in tension by the applied load, represents the outer diameter of the coil spring.

The nominal stress in the plane OO' of the beam is represented by the horizontal distance from OO' to the diagonal line $N_t N_c$. The nominal compressive stress on the upper surface of this beam from the applied load is indicated by the distance ON_c . The nominal tensile stress on the lower surface is indicated by the corresponding distance $O'N_t$. Nominal stresses at intermediate points are proportional to the distances from a central horizontal plane passing through the point O'' and the respective points.

The compressive and tensile yield

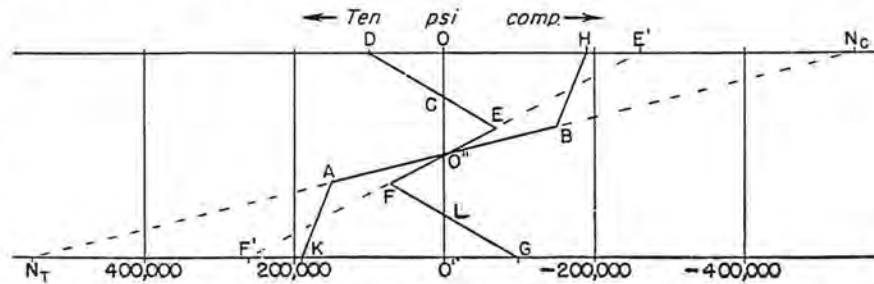


Fig. 9—Diagram of nominal stresses and residual stresses developed in cold forming a wire spring. Plastic bending develops dangerous longitudinal residual tensile stresses.

stresses are indicated by the lines HB and KA respectively. These lines are arbitrarily slanted to indicate greater yield stresses at the surfaces because of greater cold working of the material nearer the surface. The nominal compressive stress ON_c on the upper surface exceeds the yield stress of the material by an amount HN_c . The nominal surface tensile stress $O'N_t$ exceeds the tensile yield stress by the amount KN_t . Since the stress is limited by the yield strength of the material, the actual stress from the applied

load is indicated by the Z-shaped line $KABH$.

Upon removal of the downward acting load at O , the beam will recover elastically until a balance is established between the tensile and compressive acting residual stresses as is indicated by the Z-shaped line $DEFG$, Fig. 9. Equilibrium conditions are satisfied when the clockwise moments represented by the areas $CO''E$ and $LO''F$ are equal to the counterclockwise moments represented by the areas DOC and $GO''L$.

CRACKING OF COLD FORMED MEMBERS

A transverse brittle crack on the inner diameter of a coil taken from a multi-coiled cold formed spring is shown in Fig. 10. The spring was coiled from SAE 1365 steel wire having a diameter of $\frac{7}{8}$ in. The wire was heat-treated prior to forming to Rockwell C 42 to 48 and tempered after coiling to 550 to 600 F for 20 minutes. The crack shown in Fig. 10 is typical of hundreds of other such cracks that developed while cold formed springs were in a pickling bath or that developed in a short time after they were removed from bath.

This crack resulted from the residual tensile stress that was developed during cold forming as described in the preceding paragraphs and as shown in Fig. 9. The wire section at the right in Fig. 10 shows the crack depth to be approximately 25 percent of the wire diameter.

The manufacturer from whom these springs were obtained reported that such spontaneous failures occurred with alarming frequency and a quick commercial remedy was needed if possible, so that he could maintain his production schedule. Failures stopped

immediately when the spring manufacturer changed the cleaning operation prior to zinc plating from acid pickling alone to grit blasting before pickling.

Grit blasting, like shot peening, induces residual compressive stress in the treated surface. The depth of the compressively stressed layer varies with the particle size and velocity but is usually quite shallow. Principal difference between these processes is the abrasive action of the sharp particles. Grit blasting, rather than shot peening, is therefore used for removing scale and rust and similar cleaning operations.

As did the brass cups, Fig. 4, the magnesium strips, Fig. 5, and the various steel corrosion specimens, Fig. 6, the springs, Fig. 10, failed by stress corrosion cracking caused by high residual tensile stress.

Grit blasting the springs provided a surface layer or skin that was impervious to stress corrosion cracking by reversing the residual stress in a thin layer on the inner surface of the coils from tension to compression.

Acid pickling was as effective as before in cleaning the surface of the cold formed springs but the formation of a deep compressively stressed layer was prevented.

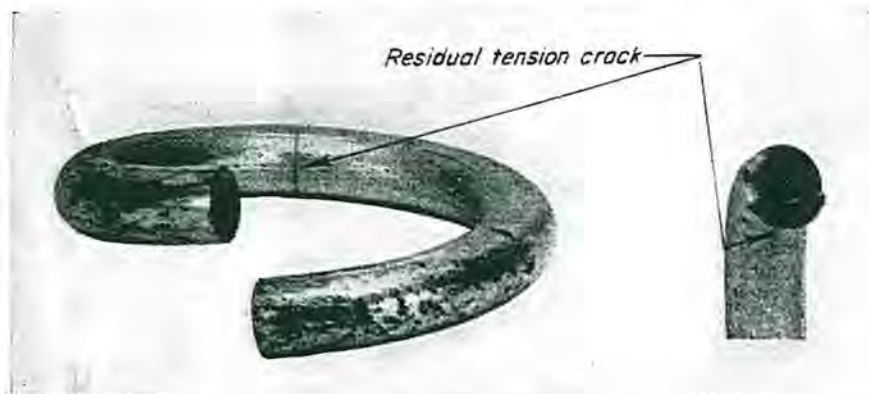


Fig. 10—Transverse fatigue crack on inner diameter of coil spring caused by residual tensile stress from spring-back after cold forming.

PISTON PIN RETAINER FAILURES

Spring retainer rings, such as are shown in Fig. 11 (A), were used in engine pistons to limit the endwise movement of floating piston pins. To assemble, the rings were elastically contracted sufficiently to enter grooves in the piston bosses. Since the free spring diameter exceeded the outer diameter of the grooves, the springs remained statically stressed after being inserted in their respective grooves.

This method is a common and very satisfactory one for restraining floating piston pins, but trouble developed in some engines that were placed in storage immediately after being operated through a run-in schedule. When again operated after long storage, a few engines were damaged because one or more of the retainer rings were broken and the piston pin would rub against the cylinder wall.

Examination of engines after storage, but before subsequent operation, showed that occasional retainer rings had failed while in storage in the manner shown in Fig. 11 (B). The fracture details are clearly shown in Fig. 11 (C), in which it is seen that two brittle transverse cracks originated in the outer tension stress metal, and that one crack continued inward to the mid section of the wire where branching occurred.

Sufficient moisture, apparently, was deposited between the retainer rings

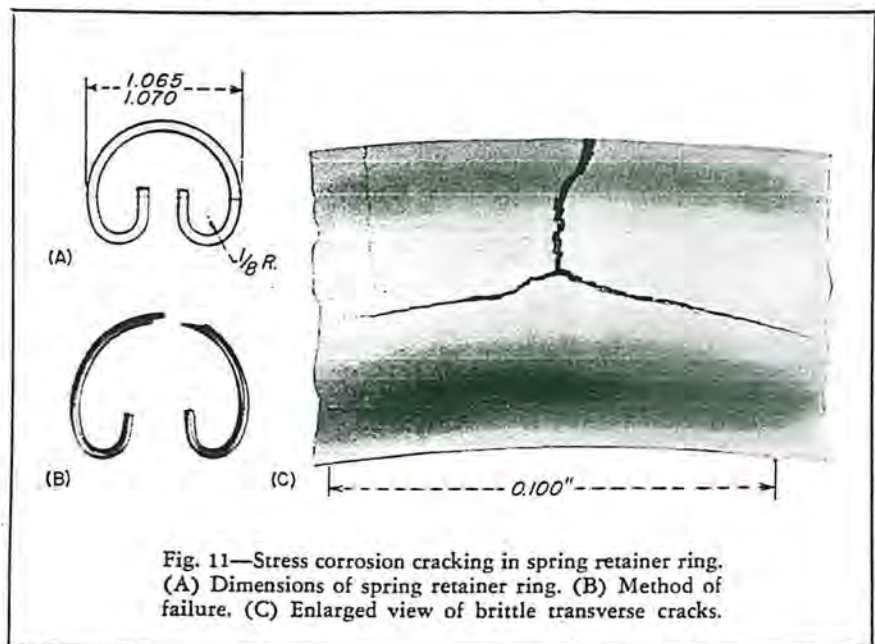


Fig. 11—Stress corrosion cracking in spring retainer ring. (A) Dimensions of spring retainer ring. (B) Method of failure. (C) Enlarged view of brittle transverse cracks.

and their grooves during the run-in period to initiate mild intergranular corrosion, not visible in the illustration, on the tension stressed outer surface of the spring retainer. It is known that the stress during storage was well below the nominal yield strength of the metal because during assembly the rings were contracted to less than their assembled dimensions. The stress and

corrosion action, however, were sufficient to cause stress corrosion cracking that originated on the tension stressed outer surfaces of the snap rings.

Such failures did not occur in engines that were not placed in storage, presumably because normal operating temperatures were great enough to dry the spring surface and to partially relieve the stress by slow annealing.

GRINDING CRACKS

The several cracks seen in the ground gear tooth, Fig. 12, are typical of delayed fracture in ground surfaces (Ref. 13). The metal in contact with the high velocity grinding wheel at any instant becomes very hot, but the usual oxide discoloration is not seen because formation of a visible oxide film requires time and the heated area, when good grinding practice is observed, is so shallow that it is cooled too quickly by adjacent cool metal or by liquid coolant.

The shallow heated area is plastically deformed in compression because thermal expansion is prevented

and this area must therefore conform to the dimensions of the underlying cold metal. Upon cooling and contracting, the heated layer becomes residually stressed in tension. The magnitude of this stress may exceed the ultimate strength of the metal, in which event a crack immediately appears. If the residual tension is less than the ultimate strength, the formation of cracks may be delayed until corrosion, usually not visible to the unaided eye, provides the necessary stress raisers.

Fractures such as are seen in Fig. 12 may therefore develop in ground sur-

faces at any time from the moment of grinding to a week or more in storage. As stated, the formation of cracks is often delayed until surface deterioration by atmospheric exposure, accelerated by high residual tensile stress, progresses sufficiently to initiate fracture.

In some factories, gears are annealed immediately after grinding to reduce surface residual tensile stress below that which will initiate stress corrosion cracks. The tensile stress in the surface after annealing, however, may still be so great as to be hazardous from the standpoint of fatigue, but the treatment is effective against spontaneous fracture if applied before actual cracks have appeared. The same protection against cracking can be had by immediate shot peening. This treatment is superior in that it converts the surface residual stress from tension to compression, thereby not only preventing tension stress corrosion cracking but also increasing the fatigue strength of the gear teeth.

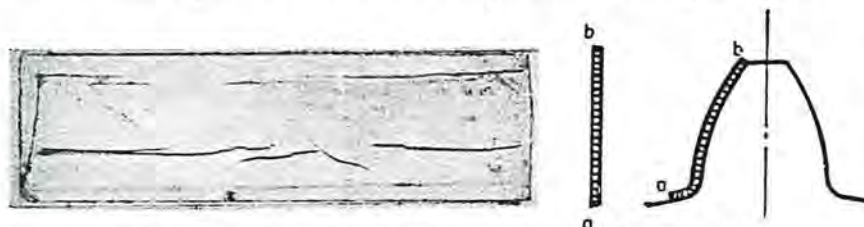


Fig. 12—Transfer print of magnetic particle markings of a gear tooth showing surface fractures that resulted from grinding.

WELD FAILURES

During a critical period in the late World War failures of welded cooling fans, which were being supplied to the Buick Motor Division of General Motors Corporation, for use in Buick-built tanks became so serious that tank shipments to the war theater could not be made. In the hope of finding a quick remedy, a cooperative investigation was undertaken (Ref. 14) by Buick and the Research Laboratories Division of General Motors Corporation.

With the expectation that shot peening was almost certain to overcome the difficulty, a special production shot peening machine was designed, built, and in operation in forty-eight hours. The results of shot peening the welded fillets are given in the bar charts, Fig. 13, which also shows the fan in question. The tests were not continued long enough to determine the magnitude of the improvement in fatigue durability because shipments had to be made as soon as it became apparent that adequate life was available.

Dynamometer operation at the critical speed caused failure of a non-peened fan in less than 100 hours, whereas the shot peened fan showed no distress when the test was stopped after more than 400 hours. Proving Ground tests gave similar results with no distress from the shot peened blades when the test was stopped after 3000 miles of test road operation.

The blades of these 34 in. dia fans were made of SAE 1025 steel. In all

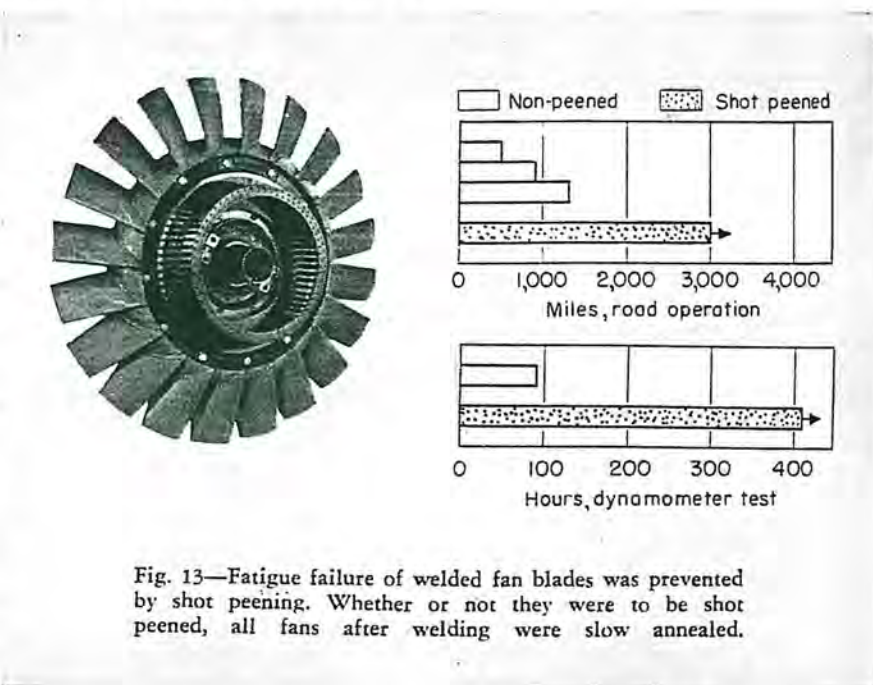


Fig. 13—Fatigue failure of welded fan blades was prevented by shot peening. Whether or not they were to be shot peened, all fans after welding were slow annealed.

cases the welding process was selected and applied to produce a ductile fillet. After welding, whether or not they were to be shot peened, the fans were stress relieved by slow annealing. Each assembled fan was placed in a furnace at 300 F and temperature then increased 100 deg F per hour to 1180 F. This temperature was maintained for two hours and then reduced 100 deg F per hour until the fan was removed at 300 F to cool in air.

Shot peening operation was performed by the American Sand Blasting Company of Detroit in accordance with instructions by the Research Laboratories Division, General Motors Corporation. The peening intensity was 15-18A using chilled iron shot of 0.016-0.020 in. diameter (SAE No. 110). Small diameter shot were used in order that the desired residual compressive stress would extend into the grooves and folds of the weld metal.

RESIDUAL STRESS FROM FLAME CUTTING

Residual stress patterns such as result from welding are developed by all processes that create steep temperature gradients. In flame cutting, the temperature gradient may be steeper than in welding and the resulting biaxial residual tensile stress in the surface of the cut may be correspondingly greater.

A one half inch wide strip sawed from a flame cut plate $\frac{3}{8}$ in. in thickness is shown in Fig. 14 clamped to a straight edge. The saw cut followed a straight line with respect to the plate but the severed strip is seen to be sharply curved concave in the flame cut surface. The observed curvature of the strip is a qualitative measure of the longitudinal residual stress that resulted from the localized heat during flame cutting. This demonstration does not indicate stress magnitude but only that longitudinal tension near the cut

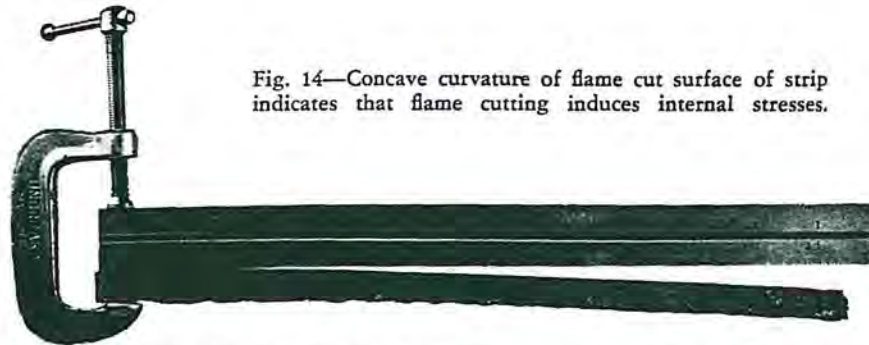


Fig. 14—Concave curvature of flame cut surface of strip indicates that flame cutting induces internal stresses.

surface was great enough to bend the strip, and in bending to develop residual tensile stress in and near the opposite surface as required to satisfy conditions of equilibrium.

Reliable residual stress measurements in flame cut surfaces have not been made, but it is highly probable that local tension equal to the yield strength of the metal is a common oc-

currence. It would not be surprising to find fractures originating in sharply notched flame cut surfaces that are exposed to corrosive environments, particularly when the residual tensile stress is augmented by tensile stresses from service loads. The probability of such fractures would be further increased if the external service load is of a recurring nature.

PRESTRESSING WITH HAMMER BLOWS

Prestressing by hammer peening, instead of by shot peening, is practiced when it is desired to develop residual compressive stress to a greater depth than is possible with shot; also, when peening must be applied to a portion of a complete machine.

An interesting example of the application of hammer peening is shown in Fig. 1. Early in World War II, broken gear teeth were found in one of three large hoist gears in a mine at Sudbury, Ontario, operated by the International Nickel Company (Ref. 15). These cast steel gears were 12 ft in dia, 30 in. face width, and had 288 herringbone teeth of 2 pitch.

Failure of teeth in these gears pre-

sented a most serious threat to the war effort. Nickel was in short supply and stoppage of the important Sudbury mine while new gears were being made would greatly reduce nickel production. Furthermore, since gear manufacturers were loaded to capacity with war orders, making new hoist gears would interfere with production of other important gears.

Through a cooperative effort by the Research Laboratories Division of General Motors Corporation and the International Nickel Company, the problem was solved by resorting to hammer peening. The portions of gear teeth that were cracked were removed, care being taken to cut away the entire

cracked length in each fatigued tooth. The remaining unbroken lengths of teeth, together with all other teeth in each gear were hammer peened at the roots using spherical ended punches $\frac{1}{4}$ in. in dia. This treatment was first applied to the damaged teeth and later, as time permitted, to all of the unfailed teeth.

In the beginning, peening was applied by hand hammers because air hammers were not available, but eventually air hammers were obtained and the work progressed more rapidly.

The hammer peening proved highly successful and the gears served throughout the war without recurrence of fatigue cracks.

HAMMER PEENING OF SOFT STEEL

As part of a study to prevent costly and time consuming fatigue failures of large forge hammer bases, fatigue specimens such as that shown in Fig. 15 were prepared and tested. The purpose of the experiments was to determine whether deep hammer peening of soft steel, such as is used for forge hammer bases, could be expected to increase fatigue durability and, if so, to determine the order of improvement that might result. Peening was applied by air hammer, actuated by 50-psi air pressure, using a one inch diameter spherical ended tip.

The specimens were made from SAE 1030 steel fully annealed to a hardness of Rockwell 65 B. The $1\frac{3}{4}$ in. square test sections were machined from larger rectangular bars $2\frac{1}{4} \times 2\frac{3}{4}$ in. in cross-section and $13\frac{1}{2}$ in. long. During testing they were loaded in reverse bending to $\pm 35,500$ psi. Under this loading, the unpeened specimen at

the left of Fig. 15 failed as shown after 130,000 stress reversals, the fracture being brittle in character despite the high ductility of the steel.

Under the same load conditions, the hammer peened specimen shown at the right of Fig. 15 completed 7,000,000 cycles of stress without failure although fine surface cracks appeared after 4,000,000 stress reversals. Note that the cracks, which in Fig. 15 have been broadened by pen, did not noticeably increase in depth during the 3,000,000 cycles of operation after they were first discovered. This is as would be expected unless much of the residual compressive stress induced by the peening had been dissipated by the reversed stresses from the applied loads. The cracks did not propagate; therefore, sufficient subsurface residual compressive stress remained to serve as a barrier to crack growth.

The peened specimen was later



Fig. 15—Non-peened and hammer peened reverse bending fatigue specimens made of SAE 1030 annealed steel that were used in a study of forge hammer base failures.

sawed from the side opposite the cracks until the remaining section could be broken to show the depth to which the cracks had penetrated. The depth was found to be approximately 0.030 inch.

DISSECTION STRESS ANALYSIS

To study further the effects of air hammer peening in inducing residual stresses in SAE 1030 annealed steel, dissection stress analysis was made of a specimen peened to the same intensity as the peened fatigue specimen of Fig. 15. The results of these stress measurements are indicated by the dash line in the diagram of Fig. 16. The induced residual compressive stress ranges from 21,000 psi at the surface to a maximum of 41,000 psi at a depth of 0.100 in. The residual tensile stress at the mid section is 24,000 psi. For purposes of dissection stress analysis, the surface of the speci-

men was assumed to be the bottom of the hammer depressions.

The two solid diagonal lightweight lines in the diagram represent respectively the plus and minus stresses from the externally applied bending loads. The heavy solid line represents the algebraic sum of the residual stress and the stress from the external load when acting to bend the beam concave on its upper surface as represented by the diagram.

The resultant stress near the upper surface of the diagram reaches a magnitude of 73,000 psi compression. If the resultant stress exceeded the mac-

rodynamic yield strength of the metal, plastic yielding occurred and the residual compressive stress was reduced by an amount equivalent to such yielding. The magnitude of the remaining residual stress at the time the test was stopped can be determined only by dissection stress measurements of a specimen after undergoing long fatigue testing at the particular load in question. This has not yet been done.

The resultant stress near the tension (lower) surface is seen to be compressive at depths between 0.03 and 0.2 in. So long as no plastic yielding occurs from stress reversals (see upper

part of diagram), this lower layer and a corresponding layer near the upper surface cannot fracture because they are never stressed in tension (Ref. 13). It is also seen that plastic yielding equivalent to 10,000 psi can occur and still leave a subsurface barrier to crack growth because it will not be stressed in tension.

Because of the lesser residual compressive stress near the surfaces together with the greater applied stresses, however, surface fatigue cracks can develop on and near the tension (lower) surface since, as is seen from the diagram, in this region the resultant stress is tensile. Shallow cracks can therefore develop just as was seen to happen after 4,000,000 load reversals. It is probable that the fatigue strength of a layer of metal near the surface was adversely affected by the very severe cold working that was applied and therefore relatively low tensile stress initiated the observed sur-

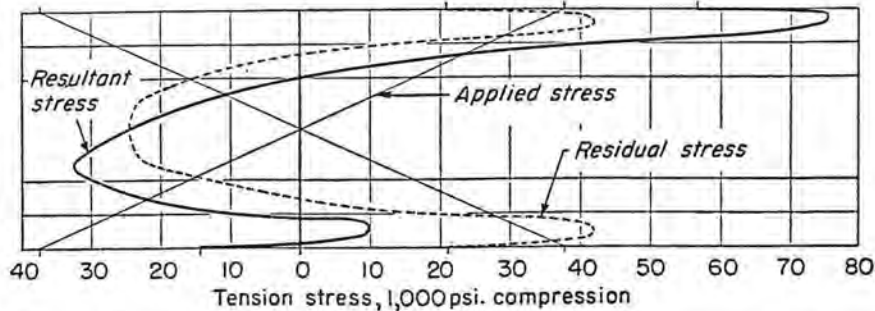


Fig. 16—Residual stresses induced in SAE 1030 annealed steel specimen by hammer peening, and resultant stresses acting at start of fatigue test.

face cracks. It is seen that the measured depth of the cracks (0.030 in.) is in agreement with the depth of the metal stressed in tension.

The greatest resultant tensile stress is seen to occur about $\frac{5}{8}$ in. below the surface and, unless the stress values shown in the diagram are markedly changed by yielding, disastrous sub-

surface fatigue cracks can originate at this distance from either surface when the specimen is subjected to reverse bending. The tensile stress required to initiate fracture in subsurface metal, however, must be greater than the fracture stress in sound surface metal because of the greater fatigue vulnerability of surfaces (Ref. 4).

SHIPS FAIL FROM RESIDUAL STRESSES

It is probable that the susceptibility of welded structures to brittle fracture is influenced in varying degrees by many factors such as material, welding technique, and design. This article has considered only residual stresses, which are the most important causes of failure, and the means whereby harmful residual stresses can be reduced or converted to beneficial stresses. The treatment that is required is simple.

The data that have been presented show that susceptibility to the several common causes of brittle fractures in ductile metal such as fatigue, stress corrosion cracking, and biaxial tension can be reduced or eliminated by the development and retention of residual compressive stress in vulnerable areas. The same treatment will ameliorate the detrimental effects of bad de-

sign, inferior materials, and even bad welding.

Successful peening will require the services of skilled workmen not now available, but the skill needed does not differ greatly from the well developed art of peening large saws.

The data presented include a number of specimens that differed greatly in hardness and therefore in notch sensitivity from the materials used in welded structures. Experience has shown that because of notch sensitivity, shot peening is even more effective on hard steels than on the softer more ductile grades. Note, for example, the effectiveness of the shallow residual compressive stress induced by grit blasting of the hard spring, Fig. 10. On the other hand, because of its greater notch sensitivity, hard steel is

more susceptible to stress corrosion cracking than soft steel. If the hardness is the result of nitriding or carburizing, however, hardened steel is not notch sensitive nor will it fail by stress corrosion cracking because its surface is compressively stressed by case hardening, thus giving the same effect as peening.

Brittle fractures from deep sharp notches are not easily prevented by normal peening because the peening cannot reach the bottom of such notches where the stress multiplication is very great. When deep sharp notches occur during fabrication, they must be widened to permit peening or a small hole must be drilled at the end of the notch. The inside of the hole must then be peened by hammers designed for the purpose.

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