MCIC Report/December 1971

Shot Peening for Improved Fatigue Properties and Stress-Corrosion Resistance

J. E. Campbell, Associate Fellow
Materials Information Division
Battelle-Columbus
Columbus, Ohio

MCIC-71-02

METALS AND CERAMICS INFORMATION CENTER

ACKNOWLEDGEMENT

This document was prepared by the Metals and Ceramics Information Center (MCIC), Battelle's Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201. MCIC's objective is to provide a comprehensive current resource of technical information on the development and utilization of advanced metal- or ceramic-base materials.

The Center is operated by Battelle-Columbus under contract to the U. S. Defense Supply Agency; technical aspects of MCIC operations are monitored by the Air Force Materials Laboratory. The support of these sponsor organizations is gratefully acknowledged.

Library of Congress Catalog No. 71-187960

TABLE OF CONTENTS

SHOT PEENING FOR IMPROVED FATIGUE PROPERTIES AND STRESS-CORROSION RESISTANCE

SUMMARY

Shot peening procedures developed over the past 40 years have resulted in substantial improvements in fatigue properties and stress corrosion resistance of high-strength alloys. These improvements have been observed in shot-peened specimens and components of high-strength steels, aluminum alloys, titanium alloys, and other engineering alloys. This report contains information on peening procedures that have been used in processing specimens and components to achieve these improvements in performance. Certain precautions are pointed out that should be observed in order to obtain the improved properties that have been attributed to the peening process.

The beneficial effects of shot peening are attributed primarily to the presence of residual compressive stresses at or near the surface. These compressive stresses can be very effective in prolonging fatigue life and in minimizing stress corrosion failures, so long as they are not reduced significantly by the service conditions. Their effectiveness can be impaired considerably by (a) exposure to temperatures at which significant stress relaxation can occur, (b) fatigue cycling at *R* values (minimum stress/maximum stress ratio) approaching -1, where the residual stress pattern tends to fade with increasing numbers of cycles, or (c) exposure to environments that chemically attack the surface, thereby changing the residual stress pattern.

The effectiveness of peening depends in large measure on the peening intensity. The latter is a function of numerous variables, including workpiece material, shot material, shot size, type of peening machine, and time of peening. Intensities are measured by peening specified flat strip specimens of steel (referred to as Almen test strips) and measuring the arc height of the curvature that results from the residual stress pattern achieved by peening. This height, in inches, is the Almen intensity. The extent of peening coverage also can be important. Generally, peening to obtain complete coverage or even redundant coverage is preferred to partial coverage.

Sizes and types of shot to be selected for a certain peening application depend on the material to be peened, desired peening intensity, fillet size, hole size, etc. For most peening applications, the shot material is chilled cast iron, cast steel, cut steel wire, or glass beads. Each shot material is recommended for specific applications. Nonferrous shot of various compositions is sometimes used.

Some of the peening programs cited in this report indicate the peening intensities that resulted in the greatest benefit in performance based on test data covering a range of intensities, shot sizes, and other variables. Optimum performance from peened components can be achieved only by conducting a preliminary testing program to evaluate the effects of the peening variables on the performance of the components. When optimum conditions are established, control of the peening process must be maintained to assure consistent benefits.

This report is intended to provide background information on peening for those who are concerned with obtaining maximum performance from highly-stressed components.

INTRODUCTION

The pattern of inquiries on various aspects of shot peening to the Defense Metals Information Center (MCIC's predecessor) over the past few years indicated a growing interest in the application of peening procedures to improve the performance of critical aerospace components. To satisfy the developing need, this summary of current peening procedures, methods of control, and improvements in performance that may be achieved by using these procedures was prepared, based on reports of U. S. Government-sponsored research and in the open literature.

In general, the peening processes produce residual compressive stresses in the surface layers of treated components. When these components subsequently are loaded in tension or in bending to a stress level in the range below that required for yield, the actual tensile stress at the surface is lower than that calculated on the basis of load and cross-sectional area. Most fatigue failures and stress-corrosion failures normally start at or near the surfaces stressed in tension. Thus, processes that produce residual surface compressive stresses in components usually enhance the resistance to fatigue and stress corrosion failure. The effects of shot peening on a material's resistance to these two types of failure is discussed in detail in this report.

The use of shot peening for sheet-metal forming, reduction of cavitation damage, testing the adherence of electroplated coating, and for removing surface contamination (cleaning) of metal components are not discussed in the report.

SHOT PEENING PROCEDURES

Specifications

Specifications for shot peening procedures, shot, and methods for measuring and controlling intensity have been developed by the Society of Automotive Engineers (SAE). The Aerospace Material Specification for "Shot Peening" (AMS 2430 F) was revised on May 1, 1969. Since then, AMS 2431 on "Mechanized Shot Peening and Peen Forming" has been prepared by the AMS Division of SAE. Federal Specification MIL-S-13165 also covers shot peening procedures.

SAE Recommended Practices J441, J444, and J827* deal with cut-wire shot, cast shot size numbers, and cast steel shot, respectively. SAE Recommended Practices J442 and J443 describe Almen test strips and use of these strips for measuring and controlling peening intensity. SAE J445a describes a method for mechanical testing of metallic shot.

Many companies in the aerospace industry have their own specifications for shot peening processes, which often are designed specifically for certain products such as landing gears or springs.

For production operations, details of the peening process for each part should be attached to the shop drawing of that part. The details should include:

- Type of peening machine (compressed air or wheel type)
- Air pressure or wheel speed
- Rate of metering of shot to the nozzle or wheel
- Type and size of shot or beads
- Speed of work movement through the machine and/or rotational speed of round components
- Time of exposure to the shot stream
- Number, size, angle, movement, and work distance of nozzles or wheels and locations of deflection plates and test specimens
- Peening intensity based on Almen test strips
- Peening coverage in percent
- Details of masking parts
- Sequence of peening procedures if parts are subjected to more than one peening cycle
- Dimensional tolerances for peened components.

The most effective method for establishing the details of the preferred peening procedure for a certain component is to evaluate a systematic series of the components peened to various intensities and tested under conditions of simulated service loading. This procedure has been used to set standards for peening of leaf springs, coil springs, torsion bars, connecting rods, crank shafts and other high-production parts. When such approach cannot be justified, it is advisable to have someone who is experienced in shot peening procedures recommend shot sizes, nozzle distances, intensities, etc. "Procedures for Using Standard Shot Peening Test Strip", SAE J443, is recommended for use in establishing the exposure times necessary to obtain specific peening intensities for a given peening application.

*SAE Recommended Practices are presented in the SAE Handbook.(1)

Shot Peening Equipment

In commercial shot peening equipment, the shot is propelled by a high-pressure air stream in a nozzle or by a high-speed rotating wheel. Factors that control the peening intensity are:

- Air pressure at the nozzle or wheel speed
- Distance of nozzle or wheel from the surfaces being peened
- Angle between the shot path and the surface being peened
- Rate of feed of shot to the nozzle or wheel
- Type and size of shot or beads
- Time of exposure to the shot stream.

Equipment of relatively small size may have one wheel or one nozzle, with some provision for moving the component in the shot stream or moving the nozzle to get uniform peening coverage of the component. Larger equipment may have multiple nozzle arrangements, with a mechanism for moving the components through the area subjected to the shot streams at a controlled speed to obtain the desired peening coverage. Many shot peening machines are of special design for peening certain specific parts, such as coil springs or leaf springs, and have special fixtures and nozzle arrangements for mechanized peening of these parts on a high-production basis.

The equipment must have some means for metering the shot to the nozzle or wheel to provide a steady and controlled supply of shot for peening. Air pressure to the nozzle should be regulated and the compressor capacity should be such that a constant air pressure can be maintained. For wheel-type machines, the driving power should be sufficient to maintain constant wheel speed during the blasting operation. Wear of the nozzles or wear of the impellers on the blasting wheel can cause variations in peening intensity, other factors being constant.

Some means also must be provided for retrieving the shot from the blast chamber, passing it through a cleaning chamber, through a separator to remove broken shot, and then into the storage hopper. The importance of efficient cleaning of the shot and removal of broken shot should not be underestimated, since the quality of the peened surfaces is dependent on the use of clean uniform shot for the peening operation.

Shot peening with metallic shot is always performed in the dry condition, but for some glass bead peening of nonrusting materials the glass beads may be in a water slurry. The slurry is metered to a high-pressure air nozzle which produces the blasting effect.

Portable peening equipment called Roto Peen by 3M Company is available for reworking, repair, and reconditioning of peened components.(2) The peening tool consists of cast steel shot or tungsten carbide shot bonded to polymeric flaps that extend from a slotted steel mandrel. When the tool is rotated at 2000 to 8000 rpm, the flaps are forced against the surface to be peened. Peening intensities to 0.020 Almen A* are claimed. When using this equipment, one must determine by experiment the required peening times for obtaining the specified peening intensities and extent of coverage. Use of the equipment would be advantageous for peening of repair welds and drilled holes down to 3/4 inch diameter.

Another rotary type of peening tool for peening in drilled holes has been developed by Northrop Norair.[3] Peening with this tool, called Norpeening, and results of stress-corrosion tests on specimens containing peened holes are discussed in a later section.

Types of Shot

Shot for peening is usually chilled cast iron, cast steel, cut wire, or glass beads. Cast shot is produced by atomizing a molten metal stream and quenching the atomized metal in water. The product is sized by screening. Cast steel shot contains 0.85 to 1.20 percent carbon and 0.60 to 1.20 percent manganese (SAE J827) and is heat treated to the hardness range 40 to 50 Rockwell C after quenching. Cast steel shot has less tendency for breakage than chilled cast iron shot. However, the latter usually is harder than cast steel shot and may produce a higher peening intensity, other factors being constant. Size ranges for cast shot are shown in Table 1. Modifications in the size ranges are being considered by the AMS Division, with a limited number of deformed shot in each size range. In designations of shot type and size, a prefix CS commonly is used for cast steel (or S for steel), P** for chilled cast iron shot, and CW for cut-wire shot. The prefix is followed by a number (see Table 1) indicating the nominal screen aperture. Thus CS330 indicates cast steel shot, most of which is retained on a screen of 0.0331-inch aperture in the standard screening analysis for shot.

Cut steel wire shot, as the name implies, is produced by cutting steel wire to lengths approximately equal to the diameter. The size is designated as the size of the wire from which it was cut. Thus, CW-54 shot would be obtained from steel wire of 0.054 inch nominal diameter. The composition, sizes, and hardnesses are designated in SAE Recommended Practice J441. Cut wire shot is conditioned to round off the cut corners before using it for peening. The conditioned shot is very uniform in size and has less tendency for fracturing than other types.

Glass beads for peening are designated by nominal screen size or diameter. For special peening applications, malleable iron or non-ferrous shot of various compositions (e.g., stainless steel or aluminum) may be used; however, information on use of special shot types is limited.

* Peening intensity is defined later.

**The P prefix is not covered in current specifications.

Measurement of Peening Intensity

Peening intensity is measured by means of Almen test strips as described in SAE J442 and J443. Three types of strips, designated N, A, and C, are 0.031-, 0.051-, and 0.094-inch thick, respectively. All strips are 0.745 to 0.750 inch wide and 3.000 ± 0.015 inches long. They are made of SAE 1070 cold-rolled spring steel, hardened, and heat set between flat plates for 2 hours at 800 F to obtain a hardness of 44 to 50 Rockwell C for A and C strips and 72 to 76 Rockwell A for the N strips. A test strip is held flat in a holder during exposure to the stream of shot. After exposure for the desired time period, the holder assembly is removed from the peening machine and the strip is removed from the holder. The difference in residual stresses between the peened surfaces and the bulk of the strip produces a curvature. An Almen gage (SAE J442) is used in measuring the arc height at the middle of the strip over a length of 1.250 inches. The arc height is a relative measurement of the curvature of the strip. A and C strips usually are used when peening with metallic shot and the N strip is usually used when peening with glass beads. Information for correlating intensities for each strip type is given in SAE J442. The standard method for designating peening intensity is to give the arc height or gage reading in inches followed by the letter designating the strip type, for example, 0.015A. Sometimes the designation is followed by -2 which means the number 2 gage was used in making the measurement (over a 1.250 inch span). For this report, it is assumed that all intensities were measured with a number 2 gage and the -2 will be omitted. The usual range of intensities for A strips is 0.006A to 0.024A. If the intensity is lower than this, the N strip should be used; if higher, the C strip should be used. A correlation between arc heights in A, C, and N strips when measured with a number 2 Almen gage is shown in Figure 1.

In certain instances, it may be desirable to determine the characteristic peening intensity for certain conditions of peening or to establish conditions to achieve a specified peening intensity. Almen test strips are used for these determinations. For specific peening conditions, i.e., specified air pressure, shot size, distance from nozzle to peened surface, etc., a series of Almen strips are peened for various time periods. Measuring the arc heights and plotting these values versus exposure times will yield a curve similar to that shown in Figure 2. Point A, where the curve tends to flatten out, represents the characteristic peening intensity for the specific peening conditions employed. Obviously, peening for time periods longer than the time period represented by point A will have only a limited effect.

If the peening intensity represented by point A is lower than desired, it can be increased by increasing the shot velocity and/or increasing the shot size. If the characteristic intensity is too high, it may be decreased by decreasing the shot velocity and/or decreasing the shot size. After changing the peening conditions, a new series of Almen strips should

TABLE 1. CAST SHOT SIZE NUMBERS FROM SAE J444[1]

Screen No.	Screen Opening Size	Maximum and Minimum Cumulative Percentages Allowed on Corresponding Screens for SAE Shot Number:													
		S1320	S1110	S930	S780	S660	S550	S460	S390	S330	S280	S230	S170	S110	S7(
4	0.187	All Pass	--	--	--	--	--	--	--	--	--	--	--	--	--
5	0.157	--	All Pass	--	--	--	--	--	--	--	--	--	--	--	--
6	0.132	90% min	--	All Pass	--	--	--	--	--	--	--	--	--	--	--
7	0.111	97% min	90% min	--	All Pass	--	--	--	--	--	--	--	--	--	--
8	0.0937	--	97% min	90% min	--	All Pass	--	--	--	--	--	--	--	--	--
10	0.0787	--	--	97% min	85% min	--	All Pass	All Pass	--	--	--	--	--	--	--
12	0.0661	--	--	--	97% min	85% min	--	5% max	All Pass	--	--	--	--	--	--
14	0.0555	--	--	--	--	97% min	85% min	--	5% max	All Pass	--	--	--	--	--
16	0.0469	--	--	--	--	--	97% min	85% min	--	5% max	All Pass	--	--	--	--
18	0.0394	--	--	--	--	--	--	96% min	85% min	--	5% max	All Pass	--	--	--
20	0.0331	--	--	--	--	--	--	--	96% min	85% min	--	10% max	All Pass	--	--
25	0.0280	--	--	--	--	--	--	--	--	96% min	85% min	--	10% max	--	--
30	0.0232	--	--	--	--	--	--	--	--	--	96% min	85% min	--	All Pass	--
35	0.0197	--	--	--	--	--	--	--	--	--	--	97% min	--	10% max	--
40	0.0165	--	--	--	--	--	--	--	--	--	--	--	85% min	--	All Pass
45	0.0138	--	--	--	--	--	--	--	--	--	--	--	97% min	--	10% max
50	0.0117	--	--	--	--	--	--	--	--	--	--	--	--	80% min	--
80	0.007	--	--	--	--	--	--	--	--	--	--	--	--	90% min	80% min
120	0.0049	--	--	--	--	--	--	--	--	--	--	--	--	--	90% min
200	0.0029	--	--	--	--	--	--	--	--	--	--	--	--	--	--

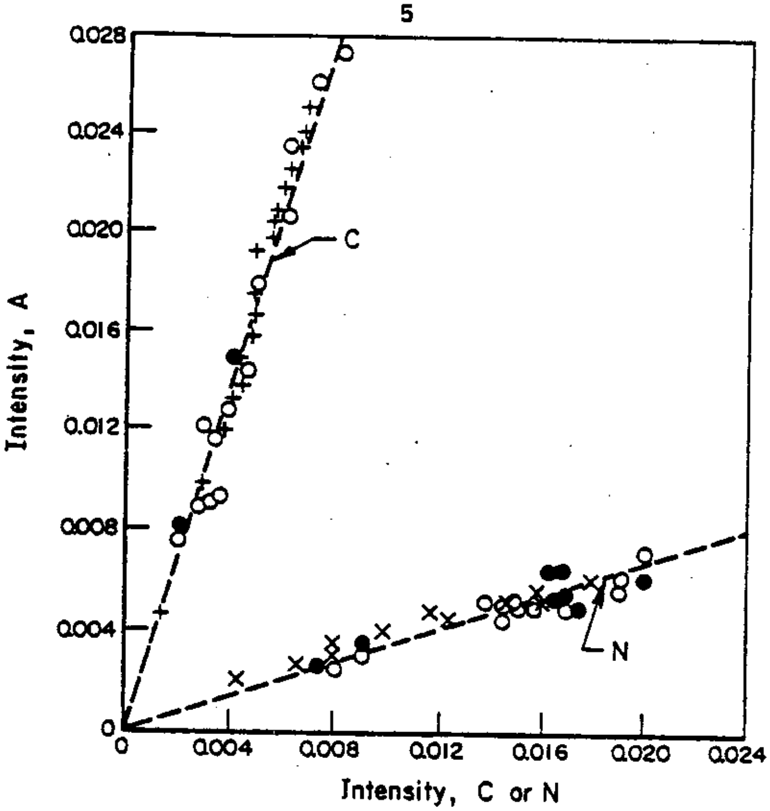


FIGURE 1. CORRELATION OF A, N, AND C STRIPS AS CHECKED ON AN ALMEN GAGE No. 2[1]

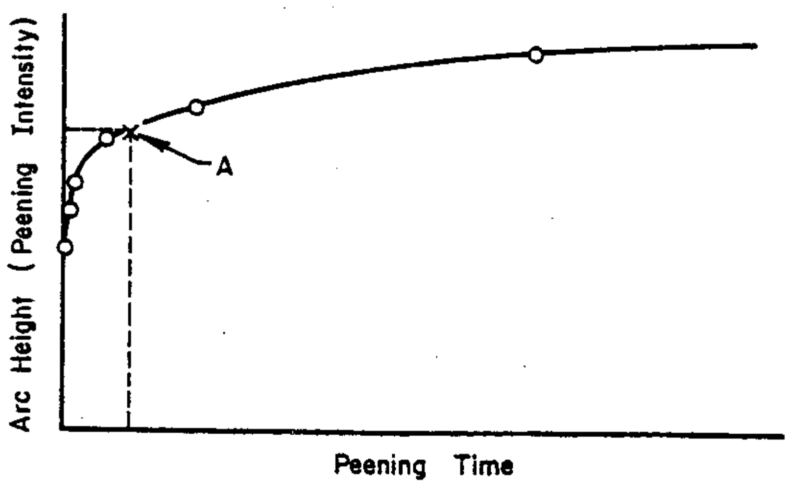


FIGURE 2. CHARACTERISTIC INTENSITY DETERMINATION CURVE (FROM SAE J443)[1]

again be exposed to the shot stream for various lengths of time to determine the characteristic intensity under the new conditions.

When aluminum alloys or other nonferrous metals are peened, the intensities normally are specified by the Almen arc heights of standard steel strips. However, since the nonferrous alloys usually are softer than the steel used for the Almen strips, the peening impressions are deeper in the nonferrous components. Because of this, 100 percent coverage is obtained on the nonferrous materials in a shorter time than on the Almen strips. Furthermore, the work-hardening characteristics of ferrous and nonferrous materials are not the same. In order to obtain a correlation between the intensities designated by Almen (steel) strips and those of 2024-T3 aluminum alloy, strips of each material were peened under controlled conditions at Metal Improvement Company.[4] The results are summarized in Figure 3. The correlation is between Almen A and C strips and strips of 2024-T3 aluminum alloy 0.100 and 0.188 inch thick. Four sizes of steel shot were used in establishing the correlation curves: 0.019, 0.033, 0.055, and 0.093 inch nominal diameters. To illustrate the application of the curves in Figure 3, the reader should note, for example, that the same arc height on 2024-T3 strips can be obtained by peening to the following Almen intensities:

0.008A with 0.093 steel shot
0.011A with 0.055 steel shot
0.017A with 0.033 steel shot.

Another factor that should be considered in the measurement of peening intensities is the different hardnesses of the different types of shot. To avoid any confusion in obtaining the desired peening intensity, one should specify the type of shot as well as the preferred shot size for peening aluminum alloys and other nonferrous metals. If there is a choice of sizes of shot for peening aluminum alloys, experience has indicated that the largest size, consistent with fillet and hole sizes, is most preferable.

In addition to establishing conditions for the characteristic peening intensity, one must determine the extent of coverage to be achieved in a given time period under given peening conditions. This may be accomplished with Almen strips if they are polished metallographically before being exposed to the shot stream. The procedure for obtaining a magnified image of the peened surface and plotting the area of the peening impressions with a planimeter is discussed in SAE J443. An accurate measurement of the percent of coverage is not practical above about 98 percent, hence the conditions for 98 percent coverage arbitrarily represent full coverage. However, for applications where coverage in excess of 98 percent is desired, the peening time often is expressed as a multiple of the time required to obtain 98 percent coverage; e.g., 1.5 coverage refers to peening for 1.5 times as long as the period required for 98 percent coverage.

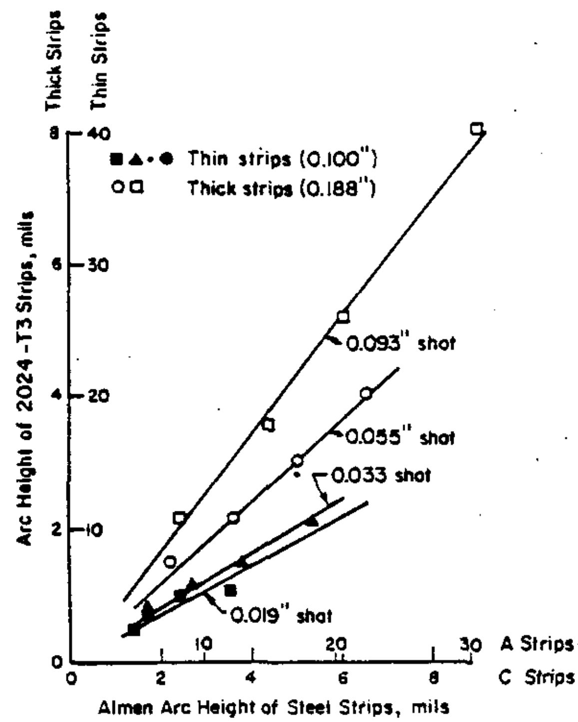


FIGURE 3. CORRELATION BETWEEN ARC HEIGHTS OF ALUMINUM AND ALMEN (STEEL) STRIPS[4]

The described techniques provide for a considerable degree of control of the peening processes. However, attention should be given to producing the desired intensities at all parts of the surfaces of the actual parts. This may present some problems if there are complex surface contours. Periodic examination of the surfaces at critical locations with the aid of a magnifying glass will help in controlling the degree of coverage being obtained.

For more detailed information on shot peening procedures, refer to the section on Shot Peening in ASM Metals Handbook, Volume 2, Heat Treating, Cleaning and Finishing, American Society for Metals, 1964.

SURFACE EFFECTS PRODUCED BY SHOT PEENING

Shot peening tends to work harden the surface layers of metal components and to produce compressive residual stresses in these surface layers. The work hardening effect at the surfaces may be detected by means of a microhardness survey across the polished cross section of a peened specimen.

Residual stress magnitudes in shot-peened surface layers have been measured by several different techniques at a number of laboratories. Among the techniques is the x-ray method used extensively at Boeing[5] and other laboratories and the method of measuring curvatures after removing thin layers from the surface by etching. The latter method was used at the University of Illinois in a program for studying peening stresses.[6] Each of the references cited refers to many other sources of information on the subject.

At Boeing, a program was conducted in which AISI 4130 steel fatigue specimens, 8 x 1.0 x 0.125 inch, heat treated to a tensile strength in the range 150 to 170 ksi, were peened to an intensity of 0.020A.[5] Cast steel shot of 0.033 inch nominal diameter was used in a air-blast machine operated at 95 ksi air pressure through a 3/8-inch nozzle. The residual stresses induced by peening and measured by the x-ray method to a depth of 0.020 inch below the surface are shown in Figure 4 by the solid square points. The residual stress pattern illustrated by the points, typical of peened specimens, indicates that the maximum residual stress in compression is a few mils below the surface. After 28,000 cycles of tension-tension stressing between 4,380 psi and 73,000 psi, the <u>surface</u> residual stresses dropped from about 90,000 psi in compression to about 75,000 psi in compression. This is indicative of the "fading" of the residual stresses on tension-tension fatigue loading. References 5 and 6 describe in detail how the surface stresses fade as the specimens are subjected to cyclic loading.

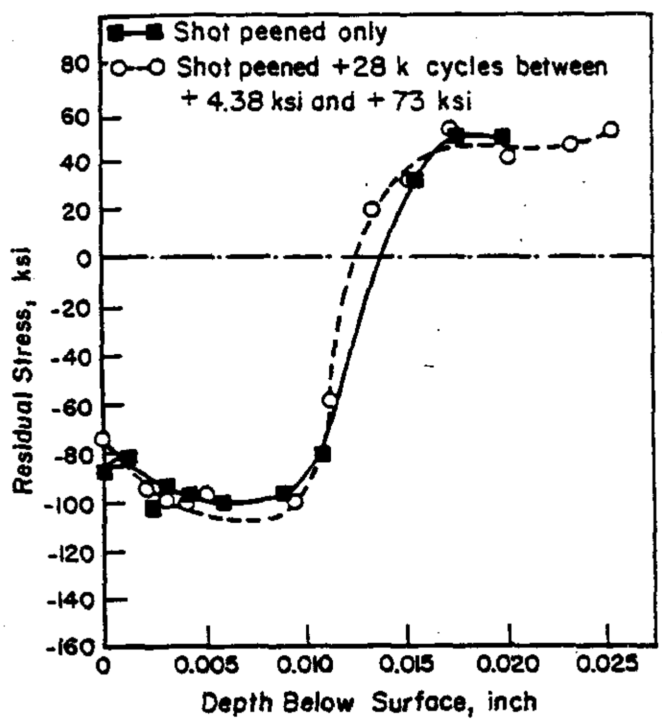


FIGURE 4. RESIDUAL STRESSES NEAR THE SURFACE IN SHOT PEENED SPECIMENS OF HEAT TREATED 4130 STEEL[5]

In a study of the influence of shot size on the residual stress distribution, fatigue specimens of SAE 5160 steel were peened with shot of different sizes and subjected to residual stress analysis by the x-ray diffraction method at the Chrysler Corporation.[7] The specimens were heat treated to a hardness of 50 Rockwell C and finish ground to 0.610 inch diameter in the test section before peening. Cast steel shot of four sizes (CS 230, CS 390, CS 550, and CS 660) was used in the peening operations. The peening procedure and peening time were the same for all specimens (no peening intensity data were reported). Since the processing was intended to be representative of that applied to obtain maximum resistance to failure on torsion fatigue loading, the specimens were prestressed in torsion to 175 ksi surface shear stress. The residual stresses were determined at the surface in the tangential direction and at 45 degrees to the tangential direction for maximum tensile and maximum compressive loading resulting from prestressing. However, there was no substantial difference between the residual stress curves in the direction of maximum applied tensile loading for shot peened and prestressed and those for shot-peened-only specimens.

The significant point is that the maximum compressive stress was located farther from the surface for specimens peened with the larger shot. This is shown in Figure 5. The shot size had little effect on the residual compressive stress at the surface. As a result of these tests, one may conclude that the smaller size shot should be used for hardened steel components with relatively smooth surfaces which are free from defects such as pits, laps, and seams. Smaller shot roughens the surface less than does larger shot. For components with surface defects, a larger shot size is preferred, since the deeper residual compressive stresses minimize the stress-raiser effect of the defects.

Benefits from shot peening have been attributed to both the work hardening effect and to the compressive residual stresses in the surface layers. An in-depth review of the relative contributions of these effects is outside the scope of this discussion. From a practical standpoint, the usual peening operations produce both effects simultaneously. No satisfactory technique has been devised for showing which effect is more important in a specific application.

Peening also tends to roughen surfaces. The amount and type of roughening depend on the size of shot used for the peening operation and other factors. There is no general requirement for surface conditions prior to peening other than that the surface be free of grease, oil, dirt, corrosion products, corrosion-preventive coatings, and paint. However, individual companies may have their own surface finish requirements for surfaces to be peened. A relatively smooth as-machined surface is preferred to avoid traces of machine marks in the peened surfaces. Additionally, in steel parts the surface should not be decarburized.

The ideal peened surface contains a series of rounded impressions in at least 98 percent of the surface area. To minimize the occurrence of irregular dents in the peened surface, broken shot should be separated from the bulk of the shot during cycling in the peening machine.

If roughness in the peened surfaces is objectionable, as it may be for bearing surfaces or for gear teeth, the surfaces may be honed, lapped, or polished after peening. However, the depth of surface metal removed by these processes should not be more than 10 percent of the minimum arc height in

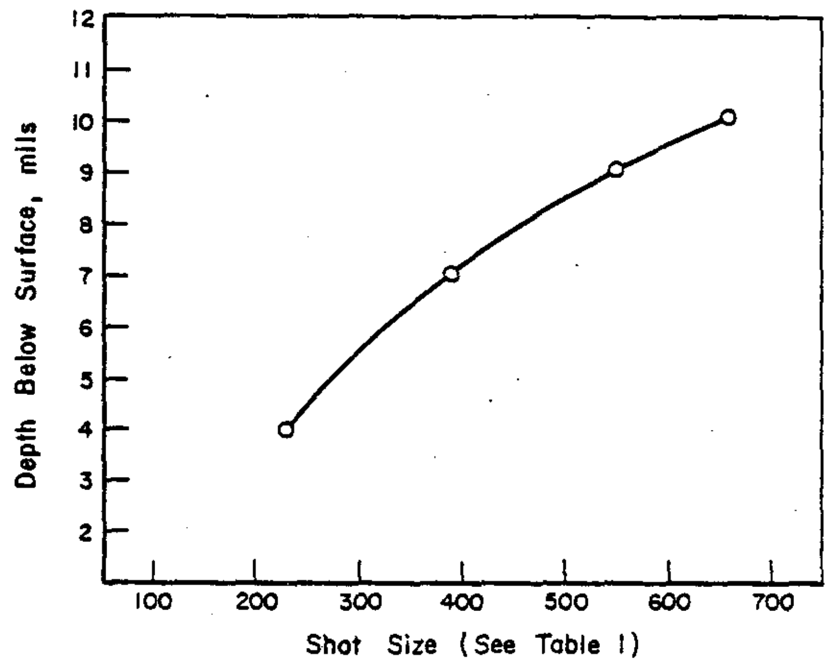


FIGURE 5. DEPTH TO MAXIMUM RESIDUAL COMPRESSIVE STRESS VERSUS SHOT SIZE FOR SAE 5160 STEEL AT 50 RC HARDNESS[7]

inches when specified for A or C Almen test strips and not more than 3 percent of the minimum arc height for N test strips. In some instances, the surface metal may be machined off to the bottoms of the peened impressions. Information on the residual stress pattern would be beneficial in determining the limitations for removal of surface metal.

Temperatures to which the peened components are exposed during machining or other processing should not be so high that the residual stresses are affected significantly. For most steels and titanium alloys, the temperature should not exceed 475 F; for stainless steels, it should not exceed 550 F; and for aluminum and magnesium alloys, it should not exceed 200 F, according to the proposed AMS 2431 on Mechanized Shot Peening and Peen Forming (May 7, 1969). The effect of exposure temperature may be determined by exposing a series of peened test strips of the alloy to various temperatures. Decreases in arc height following exposures will indicate that the residual stresses have been relaxed during heating.

SHOT PEENING FOR IMPROVED FATIGUE RESISTANCE

One of the earliest industrial applications of modern shot peening techniques (circa 1940) was developed to improve the fatigue life of valve springs.[8] With the development of proper control methods, shot peening was effective in practically eliminating valve spring failures in automobile engines. The optimum peening conditions were established by testing the peened springs in simulated service-type testing equipment.

Shot peening techniques soon were developed for peening leaf springs and Belleville washers to minimize fatigue failures. The result was improved performance of automotive suspensions and clutches. Special fixtures and techniques were developed to obtain optimum peening effectiveness under simulated service-type testing. Improvement in fatigue resistance of other engine and suspension components, such as connecting rods, crankshafts, coil springs, and torsion rods, also was achieved by shot peening.

In many peening applications, it may not be feasible to use full size components to evaluate the effectiveness of shot peening. However, if service failures occur by fatigue, some form of fatigue testing procedure should be devised using specimens of the same material heat treated to the same strength level and stressed in a manner similar to that experienced by the component. Such tests are needed to evaluate the advantages of shot peening before assuming that it will be beneficial in improving the fatigue life of the components.

Shot peening also may be advantageous for minimizing fatigue failures in components that are redesigned to reduce weight. The redesigned components usually are subjected to higher service stresses than the components of original design. If the stress levels in the redesigned components are such that failures occur by fatigue, shot peening should be considered for minimizing this problem.

For evaluation of shot peening procedures, peened specimens often are subjected to various fatigue cycling tests such as rotating-beam, reversed-bending, tension-compression, tension-tension, or reversed-torsion. In fatigue tests where the R* value is -1, such as rotating-beam tests, the extent of improvement in fatigue life resulting from shot peening usually is not as obvious as in those where $0 \leq R < 1$, (tension-tension tests, for example). Residual compressive stresses developed by peening tend to be diminished more rapidly by cyclic compressive stresses than by cyclic tensile stresses on fatigue loading.

The most effective improvement in fatigue resistance by shot peening is achieved in components that are subjected to tension-tension loading in service. Leaf springs usually are subjected to this type of loading (considering surface stresses on one side only). Early tests on automotive leaf springs indicated that peening was necessary only on the tension side. The improvement in fatigue resistance that peening provided made it feasible to use fewer leaves in the suspensions and resulted in better spring characteristics. The fatigue resistance of leaf springs and similar components can be enhanced by deforming them elastically in special fixtures during shot peening, as discussed later.

Even though shot peening has been effective in minimizing fatigue failures in many structural components, it is not necessarily a cure-all for all structures that are subject to fatigue failure. When such failure is observed in a component, a complete review of the material selection, processing specifications, stress analysis, fracture appearance, metallographic structure, and component history should be considered in deciding what to do to minimize the problem in future components of the same type. If the failed component has been shot peened, an examination of the peened surface and an evaluation of the residual surface stresses would be helpful in analyzing the effectiveness of the peening operation. If shot peening is recommended as a preventive measure to minimize further problems with fatigue failure, a testing program should be conducted to verify statistically the improvement in fatigue life that may be expected from the peening operation.

Because of the residual stresses produced by shot peening, yield strengths of peened tensile specimens usually are lower than those of corresponding unpeened specimens. This occurs because the bulk of the material in a peened tensile specimen at depths greater than 0.015 inch, in heat treated 4130 steel, for example, (Figure 4) is already under residual tensile stress. The combination of tensile stress in the bulk with residual compressive stress in material near the surface, results in a low elastic modulus and yielding at gross stresses that are lower than those for unpeened specimens. The effect of the surface compressive stress is retained until general yielding occurs across the test section as a result of the tensile load. Beyond this point, results of the tensile test are the same as those for an unpeened specimen. The ultimate tensile strengths of peened and unpeened specimens of the same material are the same.

*R value is the ratio of minimum stress to maximum stress on fatigue cycling.

Shot Peening Carbon and Alloy Steels

Shot peening of steel components to improve fatigue properties usually involves high-strength carbon and alloy steels. Applications include all types of springs and torsion bars, engine components such as connecting rods and crankshafts, and landing gear components. Because these components are subjected to repeated high stresses in service, they are shot peened as one of the final operations in manufacture.

As noted previously, valve springs for automotive engines represent one of the earliest products for which a systematic study was conducted to establish optimum peening procedures.[8] In the study, springs of 1-7/8-inch free length and 1-7/32-inch O.D. were coiled from 0.162-inch diameter valve spring wire (average composition 0.65% C, 0.58% Mn). The springs were heated to 750 F after coiling. Maximum spring stress* for no failure in 10 million cycles in unpeened springs was in the range 20,000 to 95,000 psi. To establish optimum time for peening by an established procedure, batches of springs were peened for 7, 10, 15, and 20 minutes. All of the peened springs were heated for 20 minutes at 500 F -- the maximum temperature that permits retention of maximum fatigue resistance. Heating to this temperature before use in an engine minimizes changes that might occur at operating temperatures. Fatigue tests on the springs indicated that those peened for 10, 15, and 20 minutes could be stressed to 135,000 psi during cycling (20,000 psi minimum stress) for 10 million cycles without failure -- representing a 42 percent average increase in endurance limit.

Heating of springs to 825 F for 20 minutes after peening completely eliminated the effect of the peening on the fatigue properties. In the investigation of other variables, 1/16-inch diameter and 3/64-inch diameter steel shot were used for peening springs made from 0.148-inch diameter and 0.187-inch-diameter wire. At high fatigue stress levels, the springs of smaller wire performed better when peened with the smaller shot, while the springs made from the larger wire performed better when peened with the larger shot. Peening with the smaller shot did not roughen the surface as much as did peening with the larger shot. Peened springs made of decarburized wire or wire containing scratches and large inclusions failed at substantially lower stresses when cycled up to 10 million times than peened springs made of satisfactory wire, tested in the same way.

*Maximum spring stress was determined by the Wahl formula and is a summation of the torsional and shearing stresses:

$$\text{Maximum stress} = \frac{16\,Pr\,(4c-1)}{\pi d^3\,(4c-1)} + \frac{0.615}{c}$$

where P = axial load in pounds, r = 1/2 mean diameter of the spring, d = wire diameter, and c = 2 r/d, i.e., ratio of mean diameter to wire diameter.

The same equipment was used in a later program to fatigue test peened and unpeened valve springs over the temperature range -75 to 650 F.[9]

The later program was concerned with peening of wire springs made from:

Pretempered carbon steel
Pretempered chromium-vanadium steel
Pretempered chromium-silicon steel
Pretempered high-manganese steel
Patented music wire
Hard-drawn 18 Cr-8Ni stainless steel
High-speed steel wire, heat treated after coiling.

Wire for these springs was of 0.135 to 0.148-inch diameter. All of the pretempered steel springs and the patented music wire springs were tempered at 750 F for 1/2 hour after coiling. The stainless steel springs were coiled on a lathe, oil quenched from 2250 F, and tempered at 1050 F for 3 hours and at 1150 F for 3 hours. Springs were shot peened for 1/2 hour and then tempered at 450 F for 1/2 hour. Additional information on the peening operation is not available.

Furnaces were positioned around the springs on the fatigue-testing machine for the elevated temperature tests. Maximum operating stresses and temperatures for 10 million cycles without failure are shown for each spring type in Figure 6. Effect of the peening in increasing the allowable service stress under the conditions of fatigue loading is evident from these curves. The benefit from peening tended to decrease at the elevated temperatures but the overall effect was dependent on the composition and treatment of the wires. The upper curve in each set represents the maximum stress on the springs as installed in the engine while the lower curve represents the maximum stress for a lifetime of 10 million cycles, in springs that already had been run continuously in a test engine for 96 hours. The figure indicates that some relaxation had taken place in the engine-tested springs.

Results of the fatigue tests on springs of five types of wire at -75 F are shown in Table 2. The benefit of shot peening for springs tested at -75 F was about the same as for those of the same material tested at room temperature.

One of the early investigations in which the influence of shot size, shot velocity, and peening time were analyzed with respect to peening intensity, residual-stress patters, and fatigue properties was that reported by Mattson and Coleman.[10] The specimens, of SAE 5147 steel, were similar to sub-size leaf springs (0.192 x 1.5 x 12 inches). These specimens were heated to 1600 F, clamped in a curved fixture immediately upon removal from the furnace, and quenched in oil while in the fixture. Then they were removed from the fixture and tempered at 725 to 760 F for 70 minutes to a hardness of 48 Rockwell C. All of the specimens subjected to fatigue tests were preset before peening to a nominal 220,000 psi surface stress or 10 percent above the test stress of 200,000 psi. The specimens were either sandblasted or peened on the tension side. Chilled iron shot was used for peening in a compressed-air type machine while each specimen was clamped in a fixture which was rotated and moved laterally under the air-blast nozzle. Almen strips were fastened to the fixture.

For fatigue testing, the specimens were supported at each end and loaded at the middle on the convex surface. The loading "shoe" was designed with a curvature that produced a nominal surface stress of 200,000 psi surface stress in tension at maximum deflection of the specimen.

As shown in Figure 7, nonpeened specimens failed in 4500 to 5900 cycles, or about 5000 cycles. Sandblasting the specimens for 1 to 4 minutes with the air pressure at 80 psi extended the fatigue life significantly. Effects of peening with 130 chilled iron shot (0.013-inch diameter) at air pressures of 25, 50, and 75 psi and for times of 0.5 to 30 minutes are also shown in Figure 7. Maximum fatigue life apparently was achieved by peening for 1 to 4 minutes with an air pressure of 50 psi for the fixturing used in this peening program. Specimens peened for only 1/2 minute had much shorter lifetimes. Peening for times up to 30 minutes did not improve the fatigue lives of the specimens over those which were peened for 4 minutes, but on the other hand, 30 minutes of peening did not prove to be very detrimental. Peening for 5 minutes with an air pressure of 25 psi apparently failed to produce the desired depth of compressive stresses near the surfaces of the specimens.

When larger shot (660) was used in peening another series of specimens, the fatigue properties obtained were less satisfactory than those obtained with the 130 shot. The results are shown in Figure 8. As before, peening for too short a time period provided only marginal improvement in the fatigue life, but over-peening did not appear to damage the surface.

Similar data for a third series of specimens peened with 230 shot, representing an intermediate size, are shown in Figure 9. Minimum conditions for achieving near-optimum life are, for example, 5 minutes peening time at 55 psi air pressure or 15 minutes peening time at 25 psi air pressure. Again, overpeening within the conditions shown in Figure 9 did not degrade the fatigue properties of the specimens.

Correlation of fatigue test data with arc heights of Almen C strips is show in Figure 10. The larger shot has the capability for producing greater arc heights corresponding to extended peening times. However, for the specimens used in these tests (0.192 inch thick), it was not necessary to obtain large arc heights to obtain maximum resistance to fatigue failure. Good coverage with the smaller shot size was more effective, since it was accomplished in a shorter time for the smaller shot with the shot metering arrangement used in these tests.

Residual stress patterns near the surfaces of specimens peened with 230 chilled iron shot are shown in Figure 11. For the range of peening conditions shown, the depth of the compressive stresses is greater as the corresponding arc height (peening intensity) is increased. The residual stress pattern was about the same for specimens peened 5 minutes with 130 shot using 50 psi air pressure as it was for those peened with 230 shot for 15 minutes at 20 psi pressure (curves numbered D and E in Figure 11). Greater depths of compressive stresses were noted for specimens peened with the 660 chilled iron shot than for those peened with shot of smaller sizes.

Strain peening (peening during deformation) also can be used for various types of springs to improve their fatigue properties. To show the effect of strain peening, Mattson and Coleman bent additional specimens of 5147 steel elastically in a fixture to a predetermined curvature while the tensile-stressed surface was peened. These specimens were then fatigue tested by the same procedure used for the other peened specimens. Results of the tests are shown in Figure 12. Maximum fatigue life was obtained for specimens strained during peening to about 0.0045 inch/inch or greater for the smaller sizes of shot. Total surface strain at the yield strength was about 0.0069 inch/inch. The improvement in fatigue life for the strain-peened specimens is about 10 times that for unstrained specimens peened according to the same procedure but without prestraining. Strain peening produces a greater depth of residual compressive stress near the surface than that in peened but unstrained specimens, and the magnitude of the compressive stress is greater just below the surface in the strain-peened specimens.

The data plotted in Figure 13 indicate the effect on the fatigue life of heating after peening. These data indicate that heating to 200 F can cause some reduction in fatigue life. Further reductions occur as the exposure temperatures are increased. The reductions are caused by partial relief of the compressive residual stresses near the surfaces.

Additional one-directional bend testing of strain-peened specimens has been conducted at General Motors on leaf-spring-type specimens of SAE 5160 spring steel.[11] The specimens were heat treated to 48 Rockwell C hardness and finish machined to a size of 0.215 x 1.750 x 12 inches. The flat blanks were preset by bending to develop a surface stress of 220 ksi (slightly above the yield strength) in the same bending direction that would be used in the fatigue tests. After presetting, the specimens were peened with 230 chilled iron shot to an intensity of 0.006C with complete coverage on the "tensile" side only.

The presetting treatment by itself produced a residual compressive surface stress of about 35 ksi and a resultant substantial increase in the endurance limit (128 ksi) over that for specimens in the as-heat-treated condition (about 90 ksi). S-N curves for specimens tested in the preset condition, after conventional shot peening, and after strain peening are shown in Figure 14. For strain peening, the applied strain of +0.30 and +0.60 represents applied tensile strain in the peened surface during peening and -0.30 and -0.60 percent represents applied compressive strain on the peened surface during peening. Straining the peened surfaces in tension developed increased compressive residual stresses in the surface layers, as shown in the figure, and resulted in increased endurance limits. Prestraining in compression during peening had the opposite effect.

Circumferentially notched round specimens of heat treated AISI 86B45 steel, peened and unpeened, have been tested in bending fatigue at Caterpillar Tractor Company.[12] The specimens were obtained from 3-3/8-inch bar stock which had been normalized at 1600 F. After rough machining, the specimens were austenitized at 1500 F for 2.5 hours, quenched in oil, and tempered at 550 F for 2 hours. They were then finish machined to 1.50 inch diameter at the root of a 0.250-inch radius annular notch. The stress concentration factor (K_t) was about 1.5. Separate series of specimens were retempered at 670, 1080, and 1280 F to yield hardnesses of 50, 35, and 20 Rockwell C, respectively. About 0.0025 inch was etched from the notch surface by electropolishing to eliminate the surface discoloration resulting from tempering. Some of the specimens from each series were shot peened in the notches to an Almen intensity of 0.024A using nominal 0.033-inch-diameter steel shot. Residual surface stresses were determined by the x-ray line broadening technique for each series of specimens. Reversed-bending fatigue tests were conducted in a specially constructed machine at 1800 cycles per minute, with R = -1.

Results of the fatigue tests are plotted in Figure 15. The surface residual stresses in the notches of the specimens for each condition are noted in the graphs. Residual stresses in the unpeened specimens are the result of the heat treatment (i.e., quenching stresses). The peening procedure was the same for all specimens but the average residual compressive stresses at the surface were 76,000 psi for the RC 50 specimens, 59,000 psi for the RC 35 specimens, and 45,000 psi for the RC 20 specimens. The fatigue life and endurance limit of each of the peened specimens were substantially greater than those in corresponding unpeened specimens. The data clearly show the advantage of shot peening of steels at high strength levels for minimizing fatigue failure problems.

In another experimental program at Caterpillar Tractor Company, further information on the effects of surface compressive stresses produced by heat treatment and by shot peening was obtained using similar bending fatigue tests on round notched specimens.[13] Longitudinal residual stresses were measured in the notches by an x-ray diffraction technique as before. Specimens were peened in the notches to intensities of 0.024A using S330 steel shot or to 0.016C using S550 steel shot.

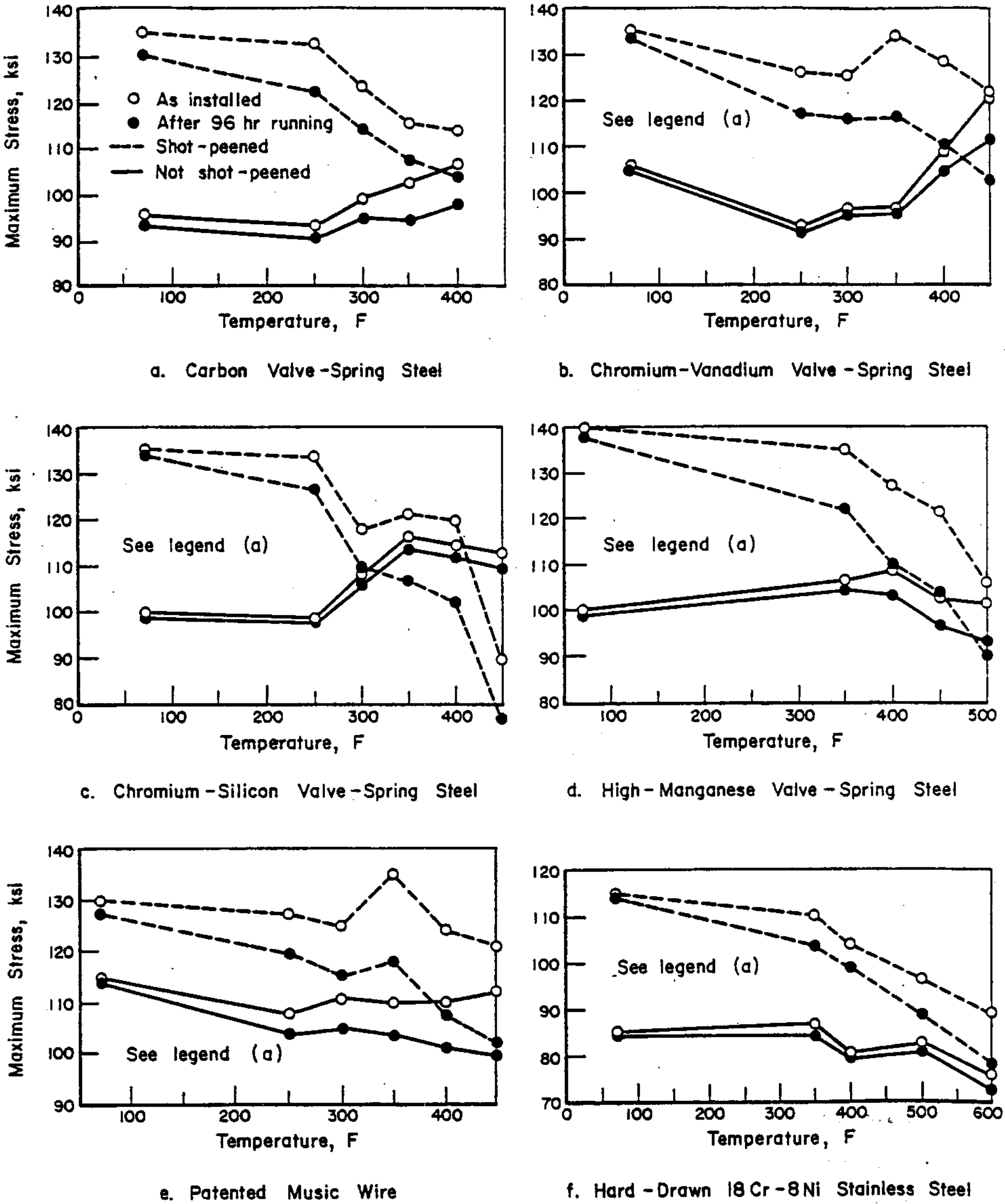
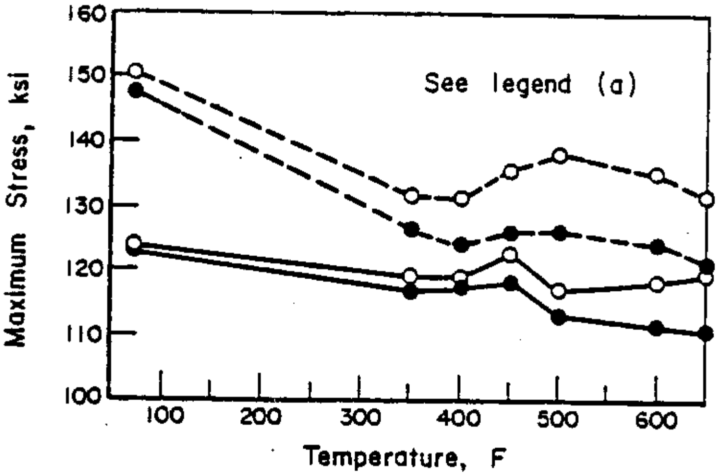


FIGURE 6. MAXIMUM STRESSES FOR 10 MILLION CYCLES IN FATIGUE TESTS OF VALVE SPRINGS AT ELEVATED TEMPERATURES(9)



g. High – Speed Steel

FIGURE 6. (Continued)

TABLE 2: MAXIMUM STRESSES FOR 10 MILLION CYCLES FOR FATIGUE TESTS OF VALVE SPRINGS AT -75F[9]

	Shot Peened Maximum Stress psi	Unpeened Maximum Stress, psi
Carbon Valve-Spring Steel	135,000	95,000
Chrome-Silicon Valve-Spring Steel	135,000	95,000
High-Manganese Valve-Spring Steel	140,000	100,000
18Cr-8Ni Stainless Valve-Spring Steel	105,000	85,000
Chrome-Vanadium Valve-Spring Steel	135,000	Not run

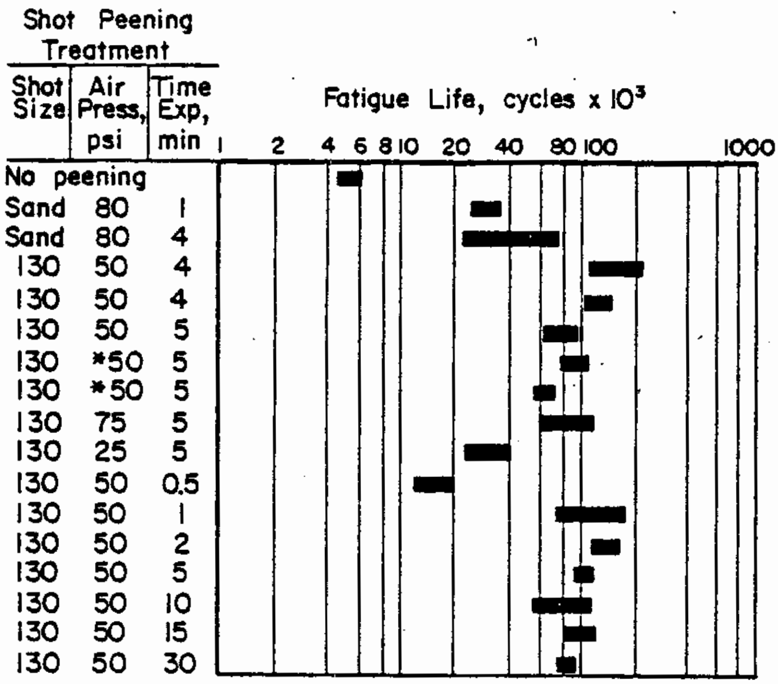


FIGURE 7. RESULTS OF BENDING FATIGUE TESTS ON SPECIMENS OF 5147 STEEL PEENED WITH 130 SHOT AND CYCLED TO A MAXIMUM STRESS OF 200,000 PSI [10]

*All specimens except these were from the same heat of steel.

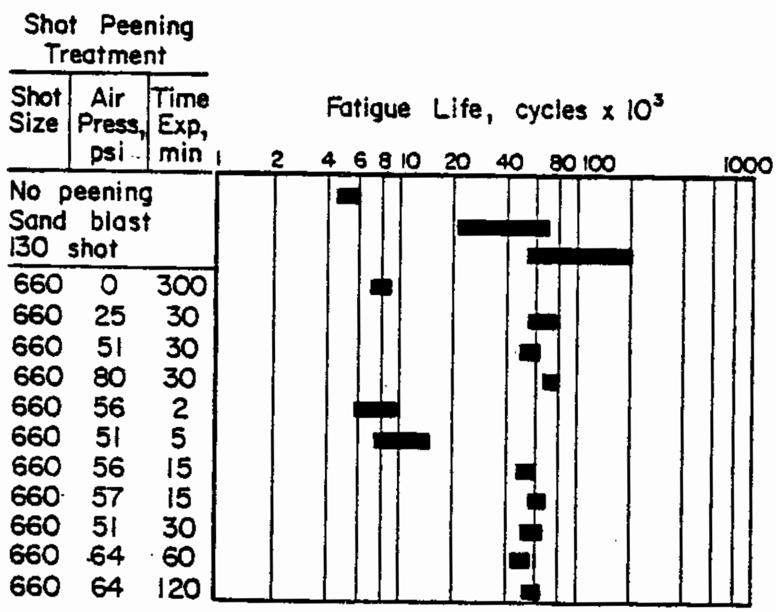


FIGURE 8. RESULTS OF BENDING FATIGUE TESTS ON SPECIMENS OF 5147 STEEL PEENED WITH 660 SHOT AND CYCLED TO A MAXIMUM STRESS OF 200,000 PSI [10]

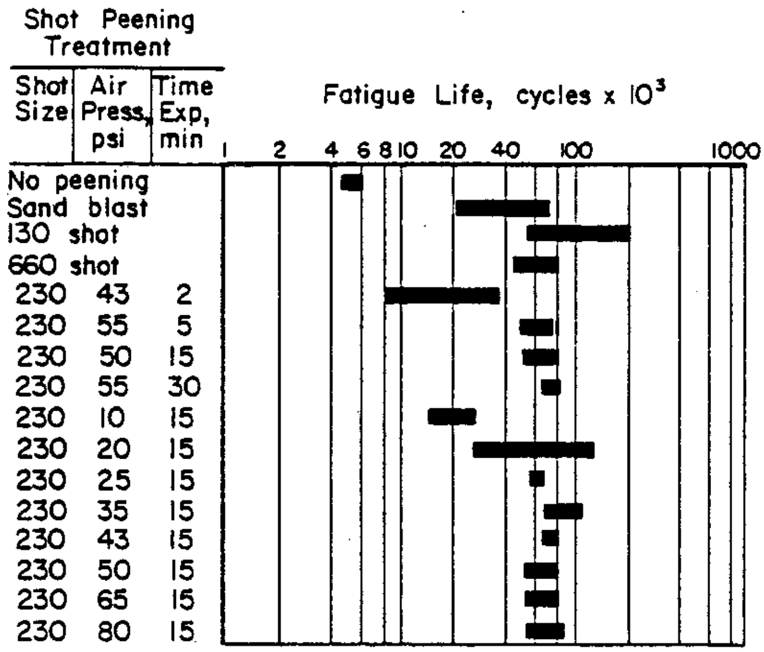


FIGURE 9. RESULTS OF BENDING FATIGUE TESTS ON SPECIMENS OF 5147 STEEL PEENED WITH 230 SHOT AND CYCLED TO A MAXIMUM STRESS OF 200,000 PSI [10]

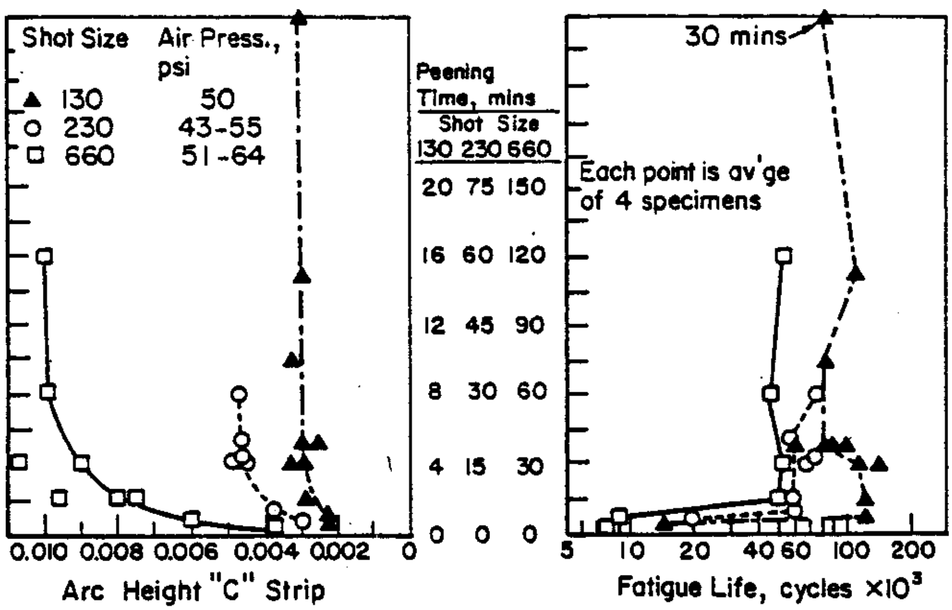


FIGURE 10. FATIGUE TEST DATA FOR SPECIMENS OF 5147 STEEL CORRELATED WITH ARC HEIGHTS OF ALMEN STRIPS [10]

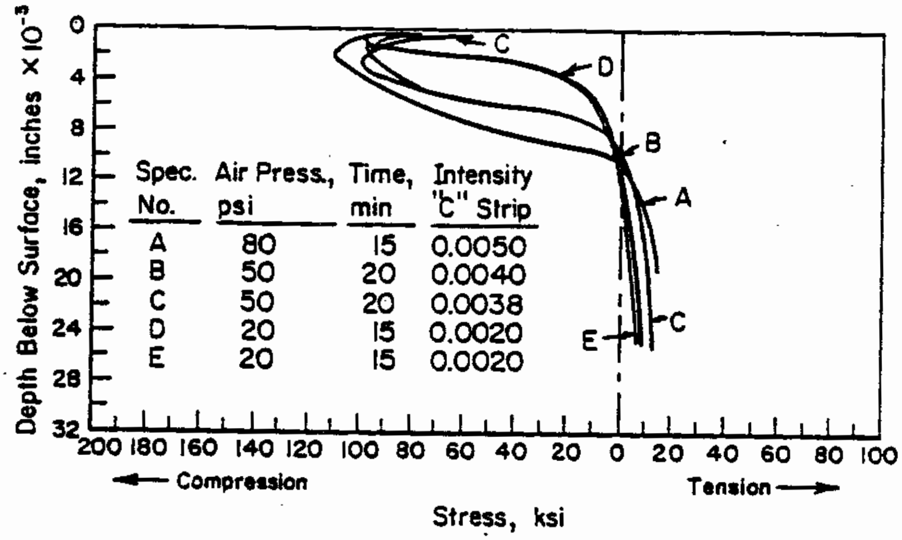


FIGURE 11. RESIDUAL STRESS PATTERNS NEAR THE SURFACES OF SPECIMENS OF 5147 STEEL PEENED WITH 230 CHILLED IRON SHOT[10]

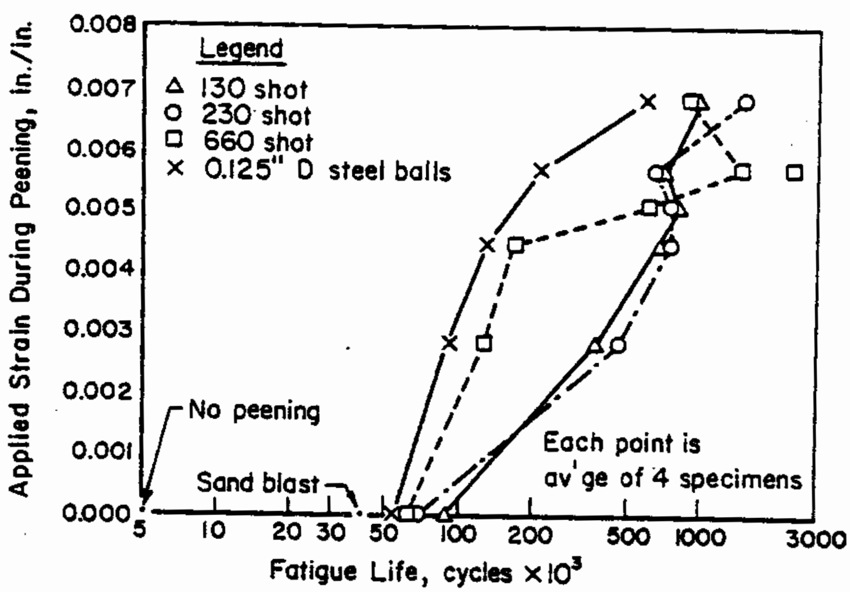


FIGURE 12. RESULTS OF BENDING FATIGUE TESTS ON STRAIN-PEENED SPECIMENS OF 5147 STEEL[10]

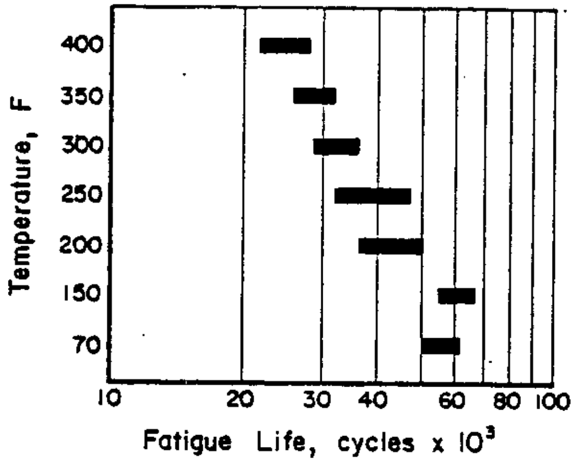
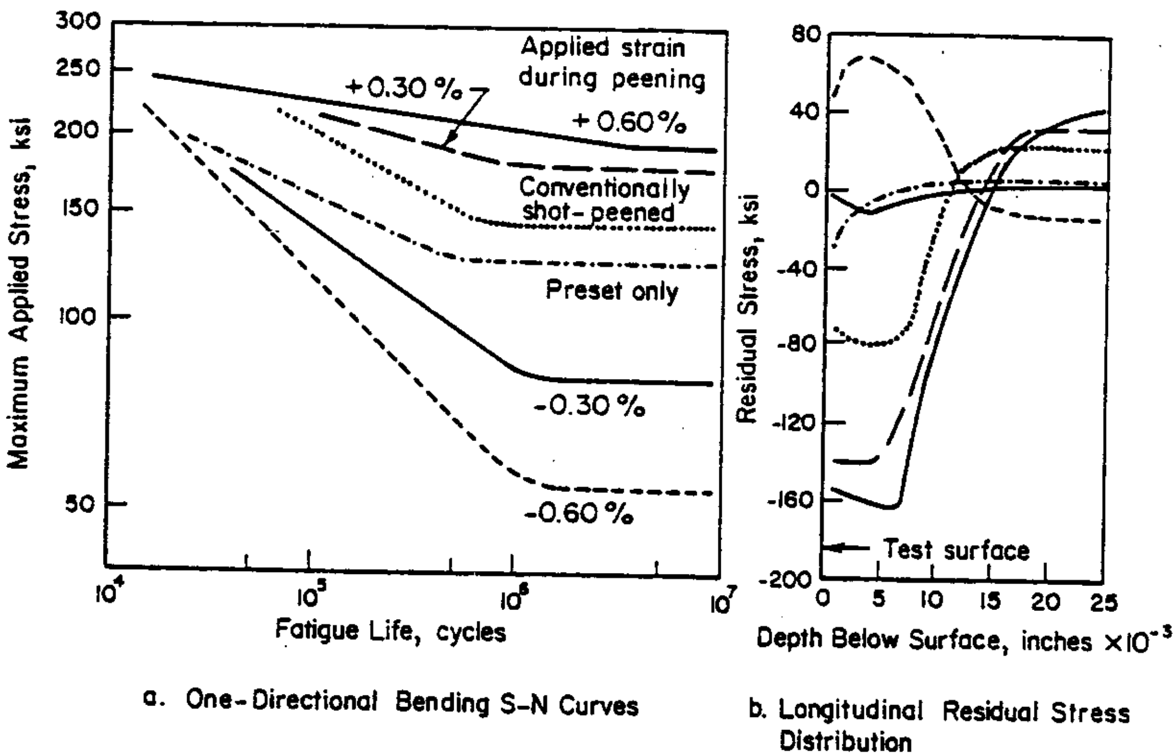


FIGURE 13. RESULTS OF BENDING FATIGUE TESTS ON SPECIMENS OF 5147 STEEL THAT WERE PEENED, THEN HEATED FOR FOUR HOURS AT THE INDICATED TEMPERATURES[10]

Specimens were peened with 230 shot for 20 minutes at 50 psi air pressure to 0.003 C intensity.



a. One-Directional Bending S-N Curves

b. Longitudinal Residual Stress Distribution

FIGURE 14. S-N CURVES AND RESIDUAL STRESSES FOR SHOT PEENED LEAF-SPRING-TYPE SPECIMENS OF SAE 5160 STEEL AT 48 RC HARDNESS[11]

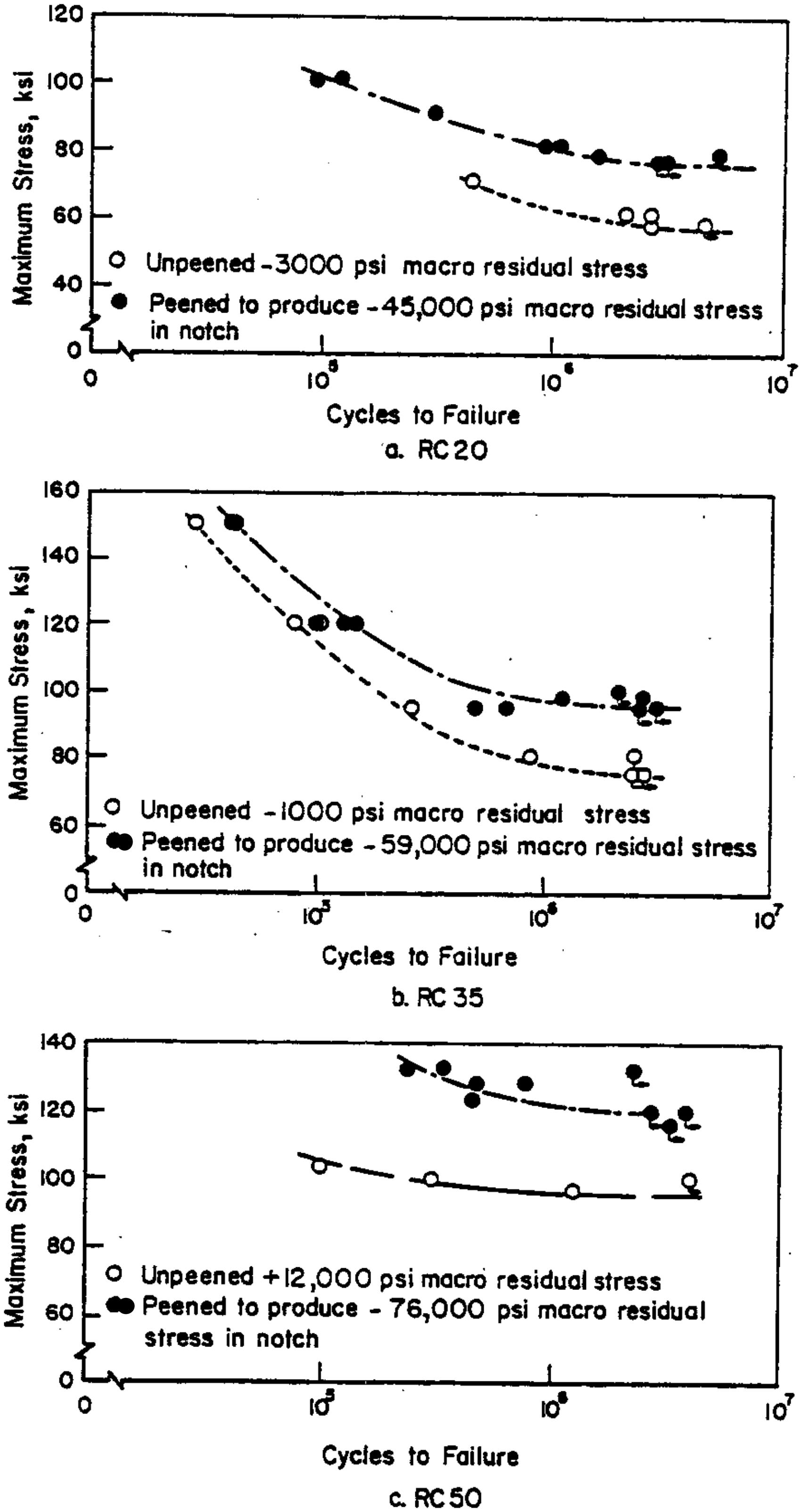


FIGURE 15. S-N CURVES FOR BENDING FATIGUE TESTS ON NOTCHED SPECIMENS OF AISI 86B45 STEEL HEAT TREATED TO (a) 20, (b) 35 and (c) 50 ROCKWELL C WITH AND WITHOUT PEENING[12]

In evaluating the effect of surface residual compressive stresses obtained by water quenching carbon steel specimens in the as-quenched condition and after peening, the investigators at Caterpillar observed that peening to a given intensity tended to produce a specific surface compressive stress depending on hardness but with negligible influence from the initial residual stress pattern. Thus peening "wiped out" any effect of the original surface residual stresses developed by water quenching. For water-quenched specimens of SAE 1045 steel, the residual stress pattern (from the surface to a depth of 0.040 inch) was more favorable for extended fatigue life than was the pattern associated with the quenched-and-peened specimens (Figure 16). In Figure 17, the data point for the fatigue limit of SAE 1045 at a hardness of 63 RC (water quenched, unpeened) indicates an extreme condition for fatigue properties. Peening similar specimens reduced the fatigue limit as well as the residual compressive stresses at the surface.

Fatigue data also are shown in Figure 17 for peened and and unpeened specimens of SAE 86B45. Surface residual stresses in these specimens, which were oil quenched, were near zero or slightly tensile after heat treatment. Peening, therefore, increased the fatigue limits for the specimens of SAE 86B45 steel as shown in the figure.

Although specimens in these tests were not tempered, commercial use of as-quenched untempered steel components is not recommended. One objective of the study at Caterpillar was to determine effects of carbon contents and residual stress patterns on fatigue properties without considering other factors that apply to commercial components. The results indicate that there is a good correlation between carbon content, surface residual stress, and fatigue properties, and peening is one of the variables that can be applied to establish favorable surface residual stresses.

Shot Peening Nickel-Plated Steel Specimens

The fatigue properties of nickel plated alloy steel specimens usually are much lower than those of similar specimens without the nickel plating. This change in properties is caused primarily by residual tensile stresses in the nickel plating. By making certain modifications in the plating bath and the procedure and maintaining good control of these conditions, a nickel plate having residual compressive stresses can be produced, as discussed in Reference 14. However, in many instances, it is more feasible to develop the compressive stresses by shot peening or by other mechanical methods.

S-N curves for tests of rotating-beam specimens that had been peened either before or after nickel plating are shown in Figure 18. The endurance limit of the polished and unplated specimens was 45,000 psi. Applying a nickel plate, which produced a high surface residual tensile stress, reduced the endurance limit to less than 20,000 psi. Shot peening prior to nickel plating eliminated most of the detrimental effect of the plating, but peening after plating further improved the fatigue properties. One-eighth-inch-diameter polished-steel bearing balls were used for peening to an intensity of 0.006A to 0.008A. In addition to improving fatigue properties, peening after plating will tend to reveal any problems with respect to adherence of the plating.

Shot Peening Chromium-Plated Steel Specimens

Chromium plating also tends to develop residual tensile stresses at the surfaces of plated components. This and other factors associated with plating cause a reduction in the endurance limit. Typical S-N curves for chromium-plated and shot-peened rotating-beam specimens of the same alloy steel used in the nickel plating studies discussed above are shown in Figure 19.[14] The endurance limit of the chromium plated specimens is substantially lower than that for the polished and unplated specimens. When the specimens were shot peened and then chromium plated, the endurance limit exceeded that for the polished and unplated specimens. Peening intensity supposedly was equivalent to that for the nickel plated specimens discussed above.

Earlier studies at Wright-Patterson Air Force Base also showed the beneficial effect of shot peening prior to chromium plating for high-strength steel components.[15] On this program, R. R. Moore type rotating beam fatigue specimens were produced from SAE 4340 steel and heat treated to a hardness of 46 RC (220 ksi tensile strength) or to 53 RC (280 ksi tensile strength). All specimens were finish machined and polished after heat treating. During peening, the specimens were rotated to produce a uniformly peened surface of 0.010A intensity in the test sections. Specimens were plated in a conventional chromium plating bath containing 33 ounces/gallon of chromic acid and a CrO_3/SO_4 ratio of 100:1. They were plated at a current density of 2 amperes per square inch for 3 hours with the bath at 130 F to obtain a plating thickness of about 3.5 mils. Some of the specimens were baked at 375 F for 3 hours while the others were tested as plated.

Endurance limits for rotating beam fatigue tests on these specimens were as follows:

SAE 4340 Steel, 46 RC	Endurance Limit, psi
Polished (control)	109,000*
Chromium plated	57,000*
Chromium plated and baked	39,000*
Polished (control for shot peening)	83,000
Shot peened and chromium plated	93,000
Shot peened, chromium plated, and baked	98,000

*Data from earlier program, using a different heat of steel.[16]

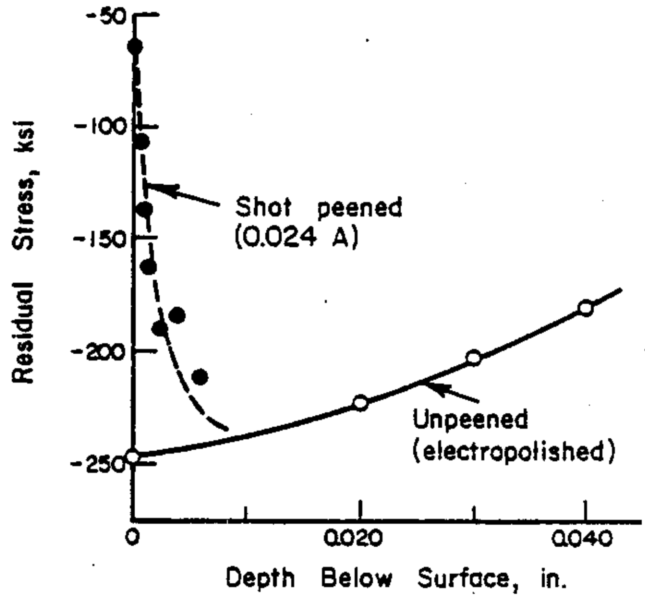


FIGURE 16. RESIDUAL COMPRESSIVE STRESSES FOR SPECIMENS OF SAE 1045 STEEL AS WATER QUENCHED (RC 63) AND AS WATER QUENCHED AND SHOT PEENED[13]

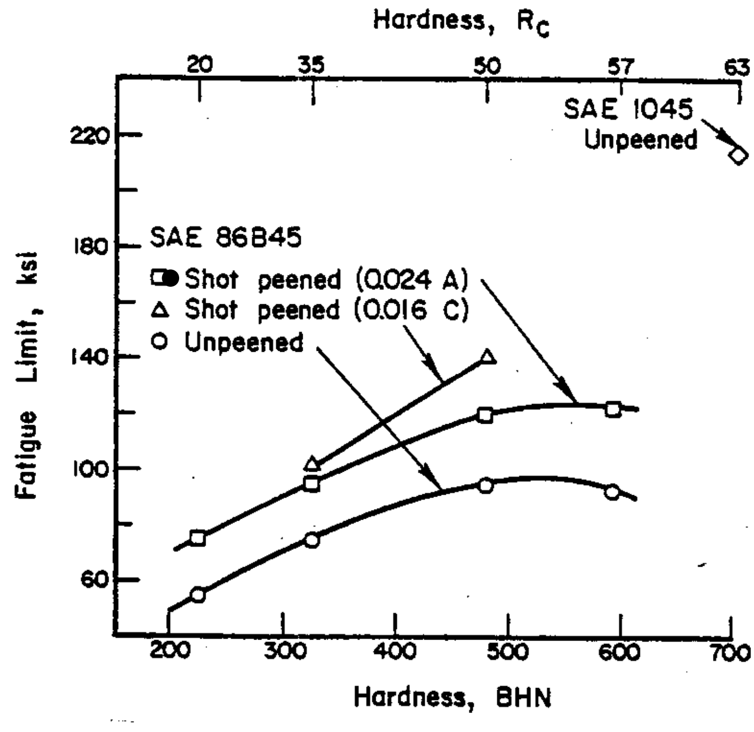


FIGURE 17. FATIGUE LIMITS VERSUS SURFACE HARDNESS FOR HARDENED AND SHOT PEENED SPECIMENS OF SAE 1045 AND 86B45 STEELS BASED ON BENDING FATIGUE TESTS WITH ZERO MEAN STRESS[13]

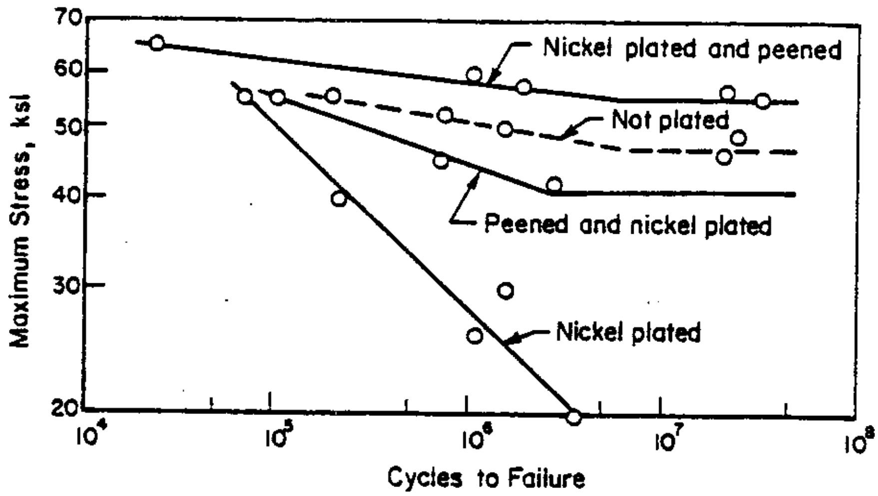


FIGURE 18. S-N CURVES FOR NICKEL PLATED AND SHOT PEENED ROTATING-BEAM SPECIMENS OF ALLOY STEEL[14]

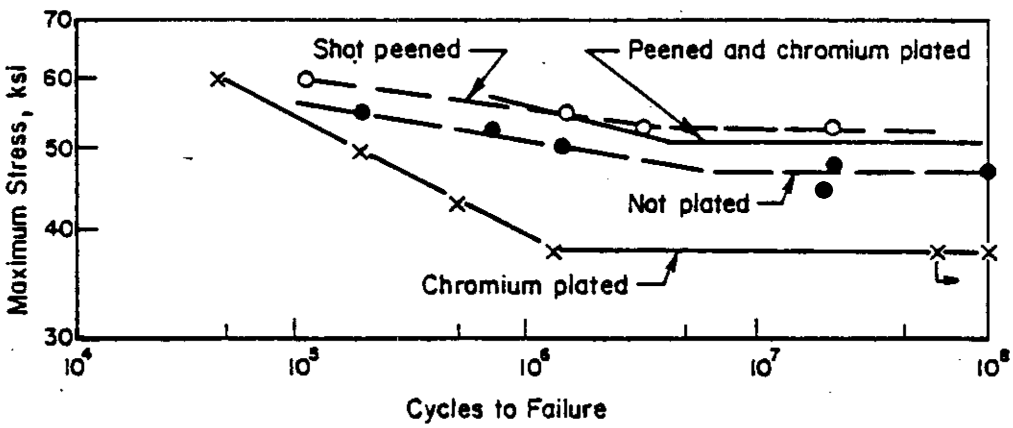


FIGURE 19. S-N CURVES FOR CHROMIUM PLATED AND SHOT PEENED ROTATING-BEAM SPECIMENS OF ALLOY STEEL[14]

SAE 4340 Steel, 53 RC	Endurance Limit, psi
Polished (control)	105,000
Chromium plated	55,000
Chromium plated and baked	55,000
Shot peened and chromium plated	100,000*
Shot peened, chromium plated, and baked	103,000

*Approximate value.

These data indicate that the endurance limits of the chromium plated specimens were about half of the corresponding endurance limits of the unplated specimens. Peening before plating, followed by baking after plating, overcame the effect of the plating itself on the endurance limits.

Effect of Peening Chromium-Plated and Fatigue-Stressed Specimens of AISI 4340 Steel

A program to evaluate the effects of shot peening on chromium plated and fatigue-stressed specimens of AISI 4340 steel was initiated at the Aeronautical Materials Laboratory of the Naval Air Engineering Center in order to determine if shot peening could be used to extend the service lives of components after they had been in service.[17] High-strength steel landing gear components have often been shot peened and chromium plated in the final stages of manufacture.

Rotating-beam specimens of AISI 4340 steel, 0.250-inch diameter at their midsections, heat treated to a tensile strength of 260 to 270 ksi, were prepared for this program. Shot peening was accomplished in a rotating-wheel type of machine using S110 shot to produce uniform coverage to an intensity of 0.009 to 0.010A. Plating was carried out in a chromic acid bath to a thickness of 0.002 inch. Initial data on the fatigue limits based on 20 million cycles and the fatigue strengths based on 100,000 cycles for rotating-beam specimens in four conditions were as follows:

Surface Preparation of Specimens	Fatigue Limit at 2×10^7 cycles		Fatigue Strength at 10^5 cycles	
	ksi	percent	ksi	percent
Polished (control)	96	100	130	100
Peened (not plated)	103	107	154	118
Plated (not peened)	66	69	90	69
Plated and peened	104	108	142	109

These data indicate that a modest improvement in the fatigue limit and fatigue strength occurred as a result of peening. However, the fatigue properties were significantly lower in the plated specimens than in the controls. Peening after plating restored the original peened fatigue limit. However, the rotating beam tests produce tension-compression fatigue loading (R = -1) with maximum stress at the surface. One would expect an even more significant improvement for peened specimens if tensile-tensile loading were used.

Based on S-N curves using the data above, certain damage criteria were established for cyclic prestressing of additional specimens. These damage criteria represent various stages of anticipated service life. Of the four S-N curves in Figure 20, one is for prestressed specimens and another is for prestressed and peened specimens. Prestressing for both of these sets of specimens involved fatigue stressing on the rotating beam machine for 3000 cycles at a maximum cyclic stress of 135 ksi. As expected, prestressing reduced the fatigue life in the low cycle range. However, peening the prestressed specimens caused a substantial increase in both the fatigue life in the low cycle range and in the endurance limit.

The S-N curves in Figure 21 represent tests similar to those illustrated by Figure 20; however, in the case of Figure 21, prestressing involved fatigue stressing on the rotating beam machine for 5000 cycles at 100 ksi maximum stress. Prestressing apparently had little effect on the fatigue properties of plated specimens although the plated specimens had a relatively low endurance limit. When plated and prestressed specimens were peened after prestressing, the endurance limit was increased to approximately that of the polished specimens. Highest fatigue properties for plated specimens were obtained when they were peened after plating. Additional data in the cited reference indicates that repeening of specimens that had been plated, peened, and prestressed did not improve their fatigue properties.

Effect of Peening Chromium-Plated Specimens of AISI H-11 Steel, With Effect of Elevated Temperature Exposure

Additional studies of chromium plating and peening processes were conducted at the Aeronautical Materials Laboratory on rotating-beam specimens of AISI H-11 tool steel.[18] Transverse specimens were obtained from two 6-inch square billets, one air melted and the other vacuum arc melted. All specimens were austenitized at 1850 F for 45 minutes, cooled in air to room temperature, and double tempered at 1050 F for 2 hours each time. The resultant tensile properties were as follows:

	Yield Strength, ksi	Tensile Strength, ksi	Elongation in 2 in., percent
Air Melted	222	264	7
Vacuum Arc Melted	228	272	7

Rotating beam fatigue tests were conducted on specimens in the following conditions: (a) polished, (b) plated, (c) peened, (d) plated and peened, and (e) peened and plated.

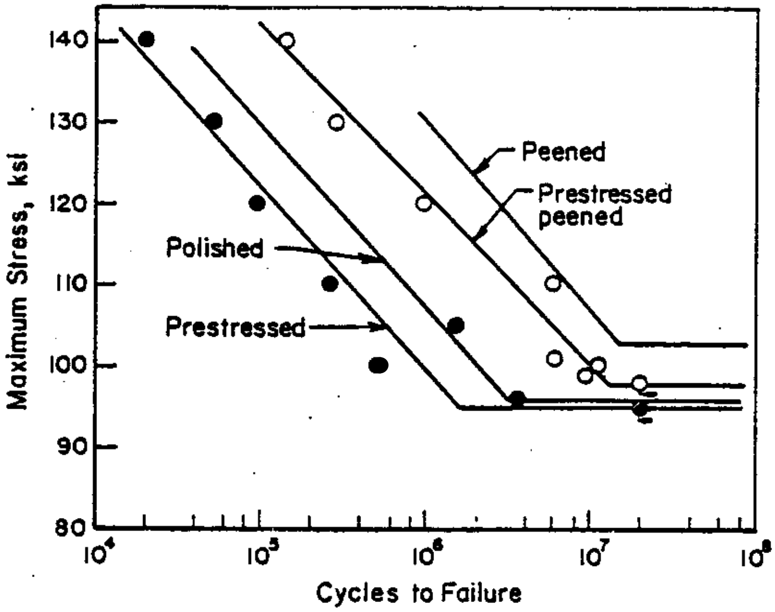


FIGURE 20. S-N CURVES FOR ROTATING-BEAM SPECIMENS OF AISI 4340 STEEL[17]

Prestressed specimens were fatigue stressed for 3000 cycles at 135 ksi maximum stress.

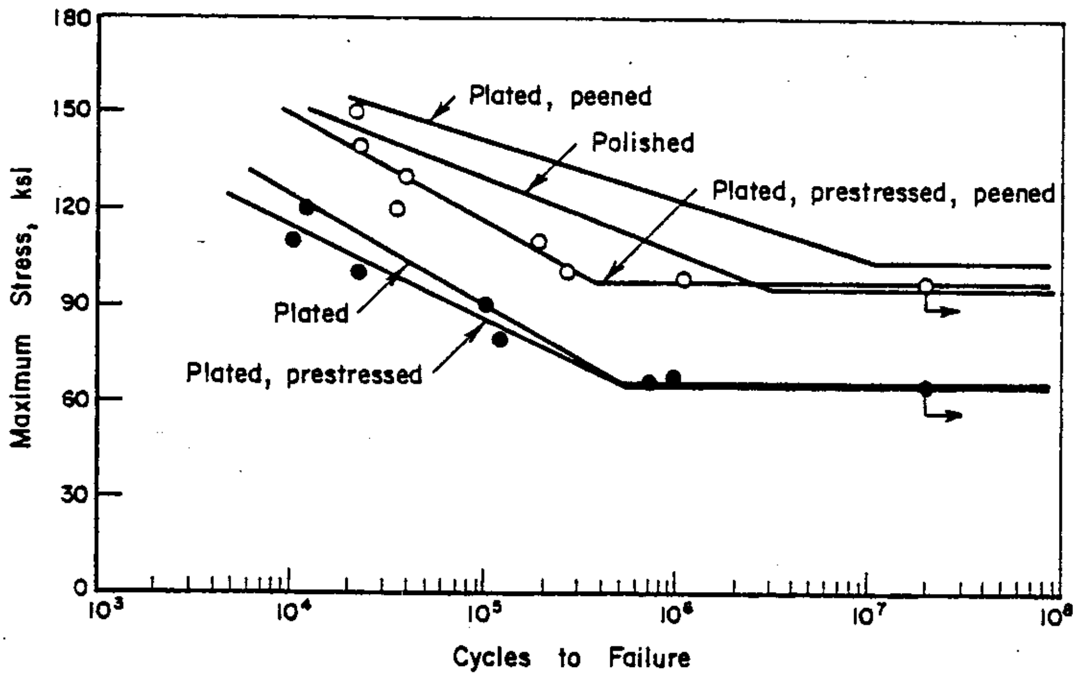


FIGURE 21. S-N CURVES FOR ROTATING-BEAM SPECIMENS OF AISI 4340 STEEL[17]

Prestressed specimens were fatigue stressed for 5000 cycles at 100 ksi maximum stress.

Peening of specimens involved 5 minutes in a rotating-wheel-type machine using S110 hardened steel shot. During peening, the specimens were rotated at 100 rpm to produce a uniform coverage equivalent to peening intensity of 0.009A to 0.010A. Plating to a thickness of 0.002 inch was accomplished in a chromic acid bath.

Specimens of each condition were heated at 375, 500, 750, 1000, or 1250 F for 4 hours prior to fatigue testing at room temperature, to determine the effect of elevated temperature exposure. Components in some applications become heated in service, and this program was conducted to establish whether damage occurs as a result of the elevated temperature exposure.

Fatigue strengths at 100,000 cycles for rotating-beam specimens of the H-11 steel are presented in Table 3. Exposure to 1000 F had no effect on the fatigue strength of the polished specimens. This result was expected, because the tempering temperature was 1050 F. Plating itself reduced the fatigue strength of the H-11 specimens much the same as for the AISI 4340 steel specimens discussed previously. However, the fatigue strengths were higher after the elevated temperature exposures of the plated specimens, presumably because the unfavorable plating stresses were lowered. Peening resulted in higher fatigue strength than that obtained on the polished specimens, and subsequent exposure at temperatures to 1000 F for 4 hours had little effect on the fatigue strength. Peening after plating brought the fatigue strengths up to the same level as that of the unplated peened specimens.

TABLE 3. FATIGUE STRENGTH OF VACUUM ARC MELTED AISI H-11 TOOL STEEL AFTER ELEVATED TEMPERATURE EXPOSURE[18]

Specimen Condition	Fatigue Strengths (ksi), of Rotating Beam Specimens after 10^5 Cycles When Tested at 75 F After Exposure at:				
	75 F	375 F	500 F	750 F	1000 F
Polished	130	132	132	132	130
Plated	78	96	98	114	112
Peened	138	138	140	138	142
Plated and Peened	140	142	140	140	142

Endurance limits for the same series of specimens are shown in Table 4. Endurance limits of the plated specimens (unpeened) increased as the exposure temperatures were increased. Peening by itself did not have an appreciable effect on the endurance limit as compared with that of polished specimens, but peening either before or after plating tended to overcome the effect of the plating.

TABLE 4. ENDURANCE LIMITS OF ROTATING-BEAM SPECIMENS OF AISI H-11 TOOL STEEL AFTER ELEVATED TEMPERATURE EXPOSURE[18]

Condition[a]	Endurance Limits (ksi) for Tests at 75 F After Exposure at:					
	75 F	375 F	500 F	750 F	1000 F	1250 F
Polished, AM	91	91	88	85	81	64
Polished, VM	94	93	90	90	90	80
Plated, AM	54	--	--	74	80	--
Plated, VM	56	60	63	80	87	--
Peened, AM	90	87	--	--	82	66
Peened, VM	96	94	90	89	89	80
Plated and Peened AM	89	88	87	83	76	72
Plated and Peened VM	96	94	90	89	88	80
Peened and Plated, VM	96	--	--	--	87	--

(a) AM -- Air melted; VM -- Vacuum arc melted.

Glass Bead Peening Steels

The effect of glass bead peening on the fatigue properties of rotating beam specimens of AISI H-11 tool steel were studied in a program at North American Aviation.[19] The specimens were austenitized at 1850 F for one hour in a neutral salt bath, cooled in air to room temperature, double tempered at 975 F for two hours each time, and tempered again at 1025 F for two hours. Hardness of the specimens was 55 to 56 Rockwell C. Tensile properties of similarly treated specimens were: tensile strength 308 ksi, yield strength 257 ksi, and elongation 9.2 percent. The heat-treated specimens were finish machined and polished in the test sections to a minimum diameter of 0.190 inch. Some of these were glass bead peened to an intensity of 0.010A. Rotating-beam fatigue tests were conducted at 5000 rpm in laboratory air. The resulting S-N curves, shown in Figure 22, indicate that glass bead peening on these very hard steel specimens substantially increased the endurance limit. Information from other sources also indicates improved fatigue properties for glass-bead-peened alloy steel specimens but the available data are not complete.

Shot Peening Maraging Steels

Maraging steels have been used for certain components that are subjected to fatigue loading at relatively high stress levels. Data from the few fatigue testing programs that have been conducted on maraging steels have shown considerable scatter. A program was initiated at International Nickel to determine preferred processing conditions for developing optimum fatigue properties.[20] Fatigue curves were determined for rotating-beam specimens subjected to several processing variables including shot peening. These specimens were prepared from one heat of 18 Ni, 250 grade, consumable electrode vacuum melted, cross-rolled plate (1/2-inch thick). The long axis of the specimen was parallel to the final rolling direction. Data for both as-polished and as-peened specimens are shown in Table 5 for tests in which the specimens were subjected to a maximum cyclic loading stress of 130 ksi. Note the effect of the different processing sequences (age, grind, and polish and grind, polish, and age), as well as the effect of peening on the fatigue life.

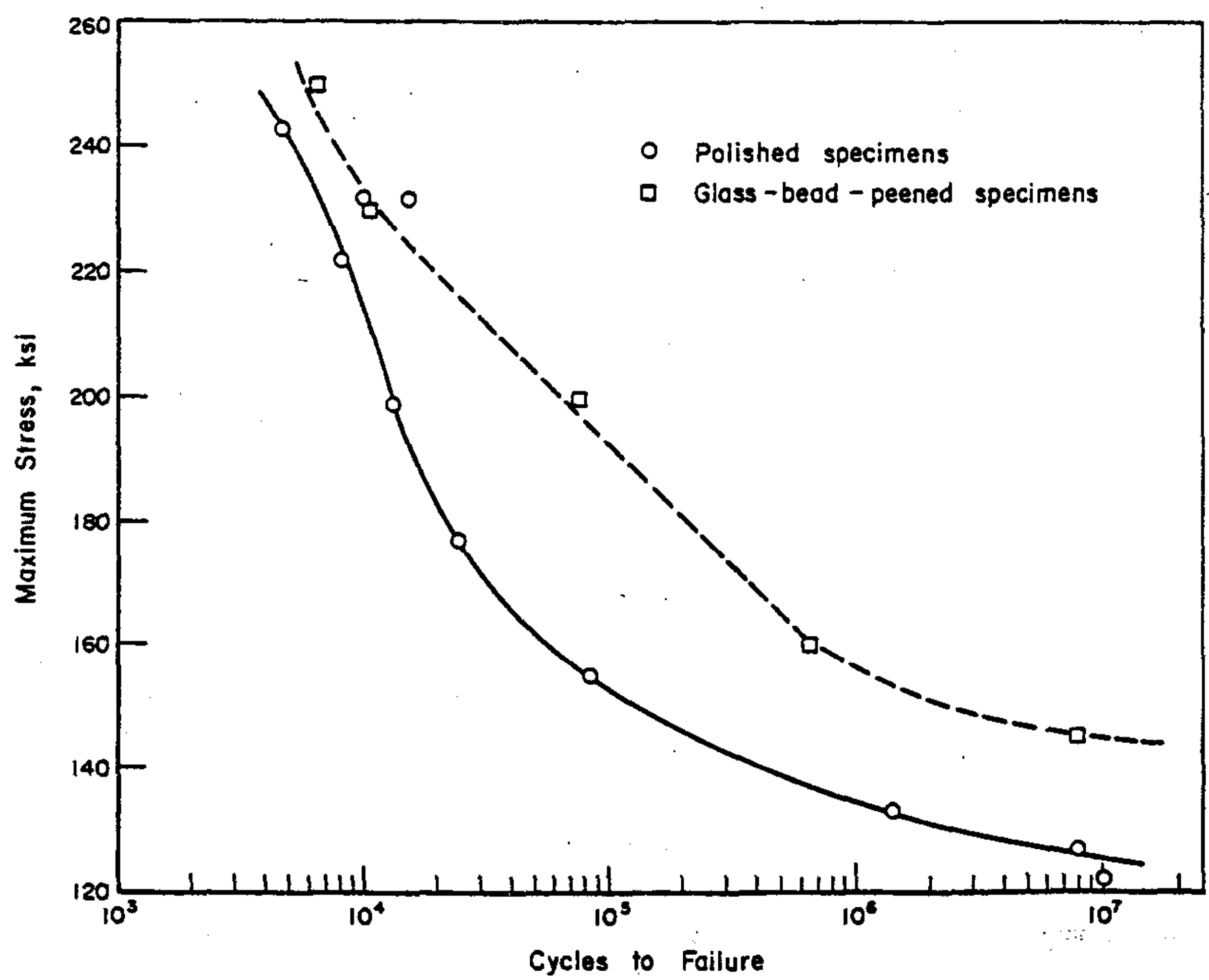


FIGURE 22. S-N CURVES FOR ROTATING-BEAM SPECIMENS OF AISI H-11 TOOL STEEL SHOWING EFFECT OF GLASS BEAD PEENING[19]

TABLE 5. EFFECT OF SEVERAL PROCESSING TREATMENTS ON FATIGUE LIFE OF 18 Ni MARAGING STEEL SPECIMENS[20]

Treatment	Yield Strength, 0.2% Offset, ksi	Tensile Strength, ksi	Elongation, percent	Reduction of Area, percent	Fatigue Life,(a) 1000 Cycles	Mean Fatigue Life, 1000 Cycles
1500 F/1 hr, AC, age 900 F 3 hr, grind, and polish	250	256	10	51.0	411 361 468	413
Same as above with shot peening after polishing	261	266	9	54.5	2245 4567 4699	3837
1500 F/1 hr, AC, grind, polish, and age 900 F/ 3 hr	251	259	11	55.0	136 132 160	143
Same as above with shot peening after aging	--	--	--	--	705 4582 981	2089

(a) Specimens cycled to 130 ksi maximum fiber stress in rotating-beam testing machine.

For the aged, ground, polished, and peened specimens, the average life based on triplicate tests was more than nine times the average life of unpeened specimens when cycled to a maximum fiber stress of 130 ksi. The shot peening treatment produced an intensity of 0.005A to 0.007A with S70 shot. It was estimated that this peening treatment produced a compressive stress of 132 ksi in the surface layers of the specimens. Under these conditions, peening can be very beneficial in improving the fatigue life of maraging steel components.

Maraging steel plate and welded specimens have been subjected to fatigue tests after shot peening at the Royal Armament Research and Development Establishment to determine the effects of peening.[21] The 18Ni 200-grade maraging steel plate used in the tests was 3/16-inch thick. The tensile properties of specimens aged at 900 F for 3 hours were:

Yield strength -- 197 ksi
Tensile strength -- 201 ksi
Elongation in 2 inches -- 10.1 percent

Fatigue specimens were prepared of parent metal plate, butt-welded plate (with the weld transverse in the center of the test section), and plate in which two pieces were joined edge to edge by two cover plates and welded by load-carrying fillet welds. Some of the specimens of each type were shot peened to an intensity of 0.012A using 0.170 inch diameter steel shot. A rotating-wheel type peening machine was used at 2250 rpm. The specimens were tested under tension-tension fatigue loading with a minimum stress of zero and a frequency of 33 cycles per second. Average S-N curves for the six series of specimens are shown in Figure 23.

Peening substantially increased the fatigue life of specimens of the parent metal plate and the butt welded specimens over the entire stress range. Peening of the fillet-weld specimens improved their fatigue life in the high-stress region. Peening tended to change the location of failure in the fillet welded specimens.

Shot Peening PH Stainless Steels

Fatigue specimens of 15-5PH stainless steel in the H-900 condition and the slightly overaged H-1050 condition were tested at Boeing to determine the effect of shot peening.[22] Standard R. R. Moore rotating-beam specimens were machined 0.020 inch oversize from 1/2 inch-diameter bar stock in the solution annealed condition (Condition A). The H-900 condition was obtained by aging at 900 F for 1 hour and the H-1050 condition by aging at 1050 F for 4 hours. Rockwell C hardness values were 46 and 37, respectively. All specimens were finish machined after aging. During shot peening, each specimen was rotated at 20 rpm, but shot peening was done in the test sections only. Two nozzles were positioned straddling the longitudinal axis of the specimen and 60 degrees to the horizontal specimen plane. They were automatically oscillated parallel to the specimen to produce a uniform peening intensity of 0.010A with S170 shot.

The effect of this peening treatment on the fatigue life is shown in Figure 24. The S-N curves indicate substantial

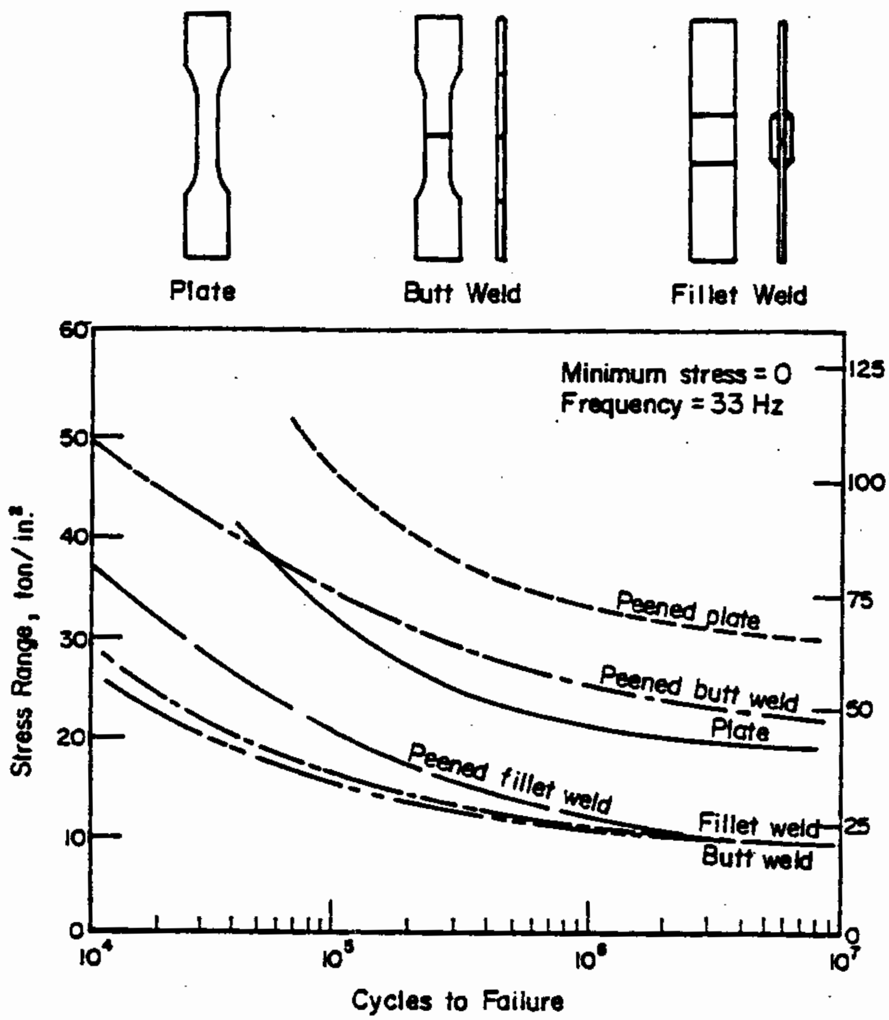


FIGURE 23. S-N CURVES FOR TENSION-TENSION FATIGUE TESTS ON PARENT METAL AND WELDED SPECIMENS OF 18NI(200) MARAGING STEEL[21]

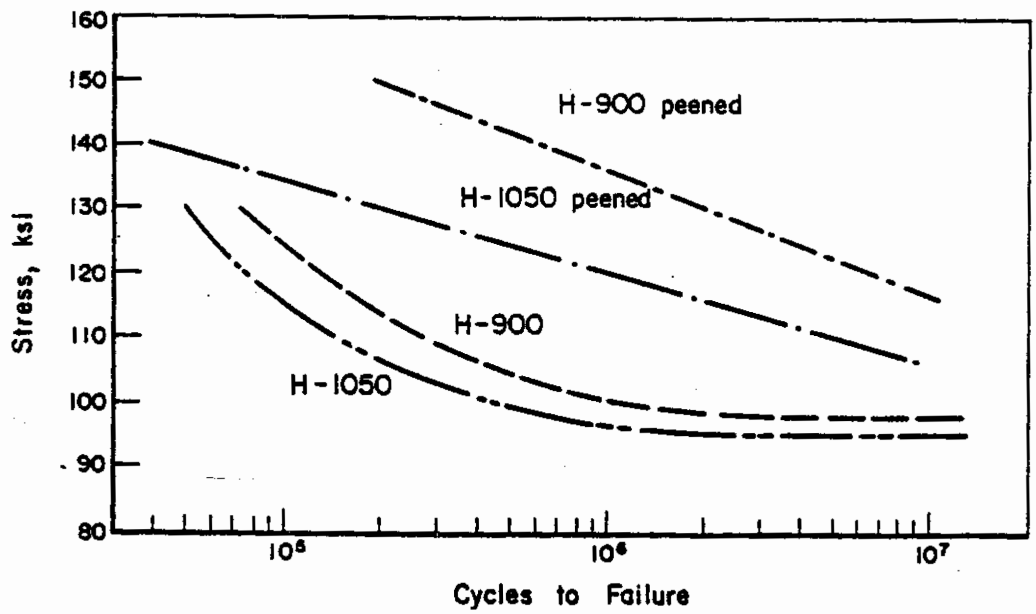


FIGURE 24. S-N CURVES FOR ROTATING-BEAM FATIGUE TESTS ON SPECIMENS OF 15-5 PH STAINLESS STEEL IN THE H-900 AND H-1050 CONDITIONS[22]

improvement in fatigue life by peening. Note that the fatigue data to 10^7 cycles for the peened specimens do not show a "knee" in either of the curves, indicating that an endurance limit has not been reached.

Shot Peening Aluminum Alloys

Peening of aluminum alloys for improved fatigue resistance is usually limited to the high-strength alloys that are used most often in aerospace applications. Weight must be kept to a minimum in these applications and the service stresses are relatively high. Furthermore, anodizing or some other coating technique often is required to minimize corrosion. Anodized coatings tend to reduce the fatigue life, for example, as shown in the solid-line curves in Figure 25.[23] The upper solid-line curve is for tension-tension tests with no coating and no peening for specimens of 7075-T6 aluminum alloy sheet. The lower solid curve is for similar specimens with an anodized coating. At 10^6 cycles, anodizing reduced the failure stress by about 14 percent.

The open circles in Figure 25 are for data obtained on peened and anodized specimens. The data points indicate that anodizing after peening results in fatigue properties almost equal to those of the unpeened specimens that had not been anodized. The data points for peened specimens not anodized (+) and peened specimens with a proprietary nonelectrochemical coating (solid circles) did not indicate a significant improvement in fatigue life over that of the unpeened and uncoated specimens. Fatigue cracks apparently initiated at the edges of the specimens, which were not peened.

The data points in Figure 26 also are for sheet specimens of the 7075-T6 aluminum alloy with the edges rounded to allow for peening in these regions. The open-circle data points indicate that under these conditions, peening can compensate for the effect of anodizing on the fatigue properties. Furthermore, the combined effect of peening along with with a proprietary nonelectrochemical coating (solid circles) can yield a 15 percent increase in the fatigue failure stress at 10^6 cycles over that for untreated specimens.

The residual stress pattern near the surfaces of these specimens is shown in Figure 27 for the curve marked 0.008A. Compressive residual stresses occur from the surface to a depth of about 0.009 inch. Longer peening to an intensity of 0.014 produces compressive stresses to a greater depth, about 0.013 inch, as shown in the figure. Beyond this depth, the residual stresses are in tension to compensate for the

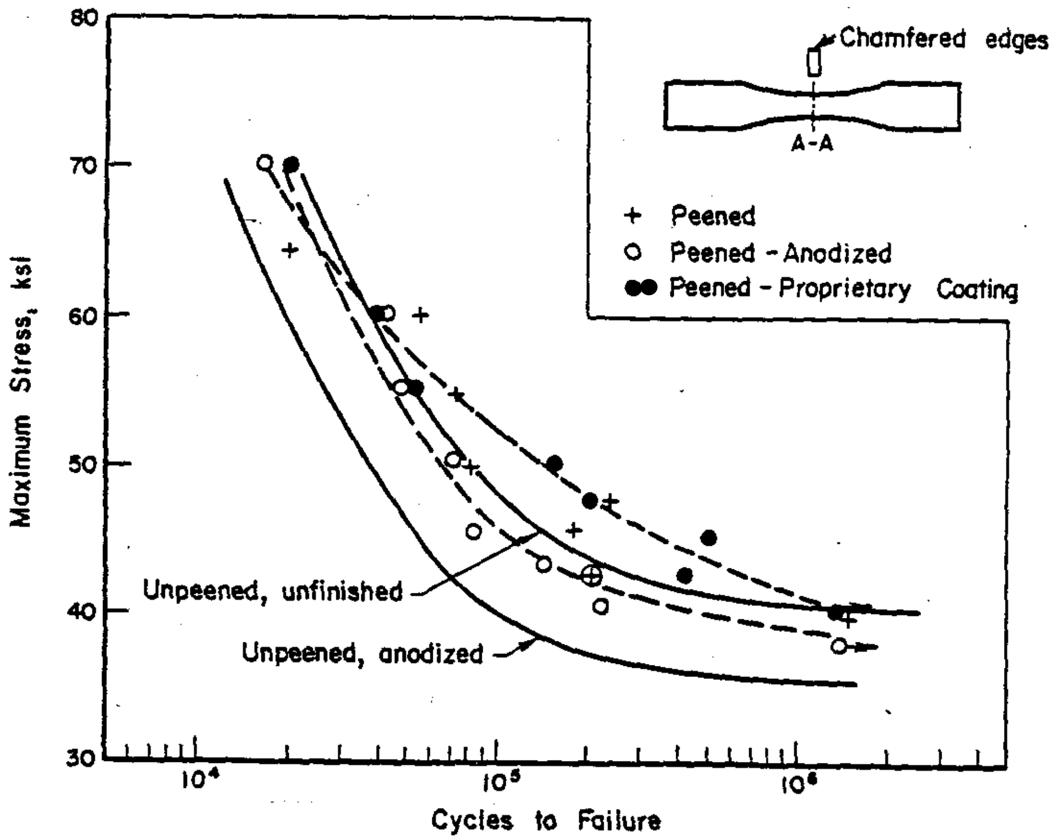


FIGURE 25. TENSION-TENSION FATIGUE CURVES FOR 7075-T6 ALUMINUM ALLOY SHEET 0.090 INCH THICK (R = + 0.2)[23]

P28 shot used for peening to intensity of 0.008A to 0.010A.

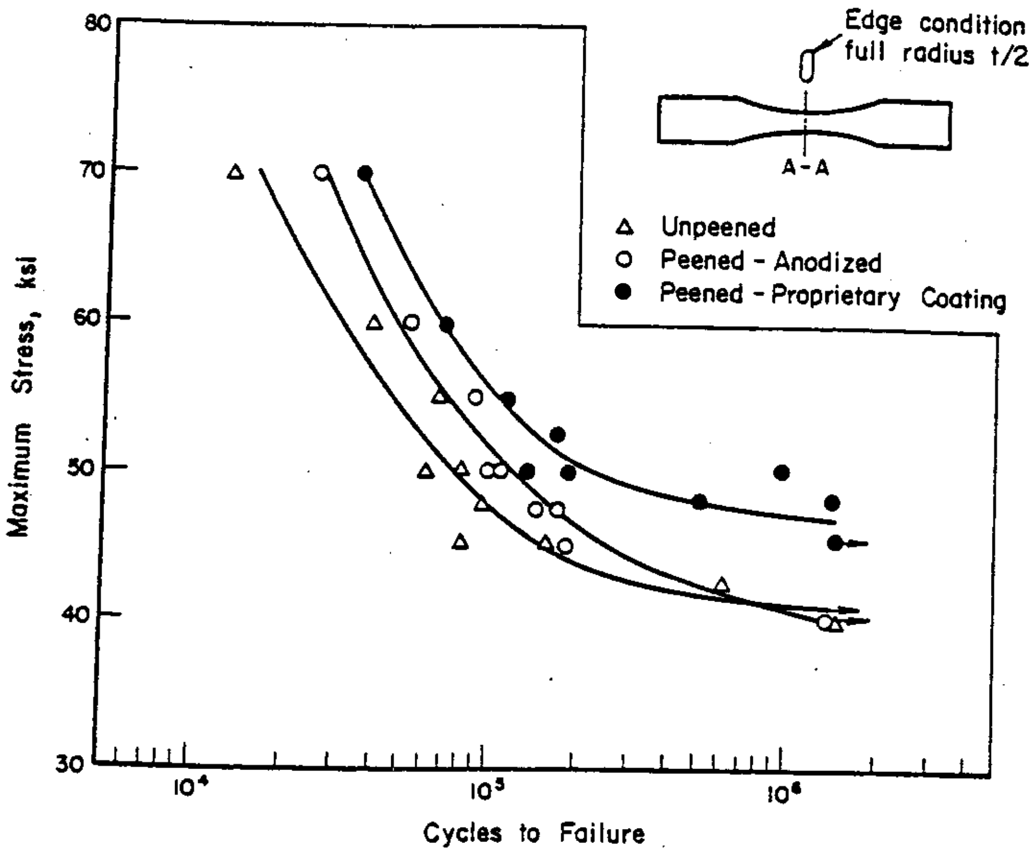


FIGURE 26. TENSION-TENSION FATIGUE CURVES FOR 7075-T6 ALUMINUM ALLOY SHEET 0.090 INCH THICK (R = +0.2) [23]

P28 shot used for peening to intensity 0.006A to 0.010A

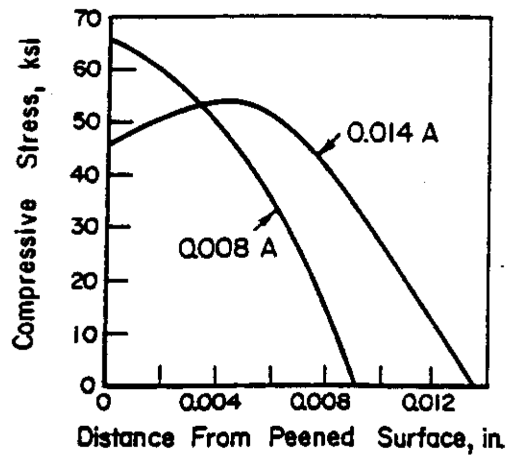


FIGURE 27. COMPRESSIVE RESIDUAL STRESSES NEAR SURFACES OF PEENED SPECIMENS OF 7075-T6 ALUMINUM ALLOY [23]

The 0.008A-intensity curve is typical for specimens shown in Figures 26 and 27. P28 shot was used.

the residual stresses are in tension to compensate for the residual compressive stresses near the surface. To avoid distortion of peened components, and particularly for components of sheet metal, the peening intensity must be the same on opposite surfaces. If the edges are not peened, the surface residual stresses there will be in tension. Fatigue cracks will then start at the edges, if the service stresses are uniform across the stressed are of the component.

Specimens similar to those shown in Figure 25 were tested with 0.125-inch diameter drilled holes in the test sections. For specimens that were peened, anodized, and then drilled, the fatigue stress to cause failure at 10^6 cycles was 25 percent lower than for corresponding specimens that were anodized and drilled but not peened. The tensile residual stresses at the edges of the holes caused early failure even though the specimens had been peened. Therefore, to obtain the expected benefits from shot peening, all surfaces and edges should be uniformly peened. Any drilled holes, cutouts, or deep scratches made after peening can reduce fatigue properties.

Fatigue specimens were obtained from an extruded 7075-T6 aluminum alloy tube, 4-1/4-inch O.D. with a 7/8-inch wall, in a program at Menasco to determine optimum peening conditions. [24] The test sections of the specimens were hand polished in the longitudinal direction with 180-grit emery paper, shot peened and subjected to axial fatigue loading. Peening intensities were established using both Almen A test strips and 7075-T6 aluminum alloy test strips 0.125-inch thick and 0.750-inch wide. Shot sizes and peening intensities were as follows:

Chilled Iron Shot Sizes	Intensity Based on Tests with Steel Almen Strips	Intensity Based on Tests with 7075-T6 Al Strips
P23 (0.023 in. diam.)	0.0085A, 0.012A	0.0035, 0.0050
P55 (0.055 in. diam.)	0.009A, 0.015A, 0.019A	0.0035, 0.0055, 0.0070
P93 (0.093 in. diam.)	0.005A, 0.0085A, 0.009A	0.0035, 0.0055, 0.0070

Glass shot of 0.018-inch diameter also were used in peening additional specimens to intensities equivalent to 0.0035 and 0.0040 inch on the aluminum strips. An Almen gage was used in measuring curvature of the aluminum strips. Residual stress measurements were made on aluminum strips representing each peening condition. The fatigue specimens were subjected to axial tensile loading at R = 0.1. Tests were made at maximum stress levels of both 55,000 and 70,000 psi. Cycling rate was 1800 cycles per minute. Average fatigue data for quadruplicate specimens peened with steel shot are shown in Table 6.

Data in the table show comparisons between intensity values for peened aluminum strips and the standard Almen Type A values. The data also show that the compressive surface stress and the maximum compressive stress in the peened layers near the surface increase as the peening intensity increases within the limits of these experiments. Results of the short-cycle fatigue tests indicate that the preferred shot size is P23 for 7075-T6 aluminum alloy at an intensity of 0.012A. However, other combinations of shot size and intensity develop nearly the same results for the fatigue tests.

The data for glass-bead peening in Table 6 indicate that equivalent peening intensity with glass beads does not develop the same fatigue life as does peening with chilled iron shot. No data were given for unpeened specimens.

Specimens from a British aluminum alloy extrusion were tested in tension-tension fatigue at the Royal Armanent Research and Development Establishment to determine effects of shot peening on parent metal and welded specimens. [21] Specimens were obtained from the longitudinal direction of a 9-1/2 x 1/4 inch extrusion. The material was a weldable British alloy somewhat similar to 7039 aluminum alloy, with composition 5.0 percent Zn, 1.2 percent Mg., 0.3 percent Mn, and 0.2 percent Cr. The extrusion had been solution treated and artificially aged to develop the following tensile properties:

Yield strength -- 51.7 ksi
Tensile strength -- 60.3 ksi
Elongation in 2 in. -- 19 percent.

Butt welds were made using the MIG process and NG 6* filler wire. The butt joint was prepared with a single V groove, and a triangular-grooved backing bar was positioned under the weld joint prior to welding. After 12 weeks aging at room temperature, tensile properties of a butt weld measured on a 2-inch gage length were:

Yield strength -- 24.6 ksi
Tensile strength -- 42.1 ksi.

Specimens of the parent metal plate and the welded specimens were peened to a 0.012A intensity using 0.17-inch diameter steel shot. All specimens were tested by tension-tension loading (minimum stress of 0) at 33 cycles per second.

Average S-N curves and the specimen configurations for each series of fatigue tests are shown in Figure 28. Shot peening the parent-metal plate specimens improved the fatigue life only slightly in the high-stress range but not at all at stress levels where failure occurs in 10^7 cycles. However, shot peening improved the fatigue life of the butt welded specimens over the entire stress range so that these specimens

*Presumably a British designation; composition not available.

had fatigue properties nearly the same as those of the parent metal specimens. Peening the fillet-weld specimens improved the fatigue life only in the higher stress range and resulted in initiation of fracture at a different location than that in the unpeened specimens.

Shot Peening Titanium Alloys

An extensive program on peening of Ti-6Al-4V was conducted at Bendix to determine the preferred peening procedure and intensity for extended performance of titanium alloy flight control actuators.[25] Standard rotating-beam fatigue test specimens were machined from annealed 1/2 inch Ti-6Al-4V alloy rod. After machining, all specimens were stress relieved at 1000 F for 1 hour. Tensile properties of the annealed Ti-6Al-4V rod were: yield strength 149,000 psi, ultimate tensile strength 157,000 psi, elongation 16 percent in 1 inch, and reduction in area 50.5 percent.

Peening treatments for the fatigue specimens consisted of one, two, or three peening steps, as shown in Table 7. Details of shot size, blast pressures, and peening times are given in Table 8. The specimens were fatigue tested at a speed of 10,000 rpm. Fatigue data for unpeened specimens of the same Ti-6Al-4V alloy are shown at the end of Table 7. A comparison of the fatigue data for the peened specimens with the data for the unpeened specimens indicates the extent of the improvement in fatigue life that is possible as a result of the various peening treatments. The following shot peening steps were recommended for the Ti-6Al-4V alloy actuators (0.060 to 0.125-inch thick) at the conclusion of the program:

Step A - Shot peen with steel shot to an intensity of 0.008 to 0.012A with 200 percent or more coverage

Step B - Glass-bead peen to an intensity of 0.007 to 0.009N with 400 percent or more coverage.

For sections thinner than 0.060 inch, the first peening step could be to an intensity of 0.004A with steel shot and the second to an intensity of 0.005 to 0.007N with glass beads. For sections thicker than 0.125 inch, higher intensities might be considered for the first peening step but apparently are not necessary.

Two or three peening steps tend to increase the extent of coverage. The author of the cited report contends that for the conditions covered in this program at least 200 percent (defined in Table 7, Footnote (b)) or greater coverage during peening is necessary. Even greater coverage (from 5[illegible] to 800 percent) would be beneficial in preventing random early failures at relatively high stresses in titanium alloys.

Residual Stresses From Peening Titanium Alloys

Residual surface stresses from glass bead peening of two titanium alloys have been measured by X-ray diffraction

TABLE 6. RESIDUAL STRESS DATA AND AVERAGE FATIGUE LIFE FOR AXIALLY STRESSED SPECIMENS OF 7075-T6 ALUMINUM ALLOY[24]

Shot	Aluminum Strip Intensity	Almen A Strip Intensity	Residual Stresses From Peening: Surface Stress, ksi	Residual Stresses From Peening: Maximum Stress, ksi	Residual Stresses From Peening: Maximum Stress Depth, in.	Average Fatigue Life(a) When Maximum Stress is: 55,000 psi, 10^3 cycles	Average Fatigue Life(a) When Maximum Stress is: 70,000 psi, 10^3 cycles
P23	0.0035	0.0085	-48.4	-62.5	0.004	165	55
P23	0.005	0.012	-59.8	-73.0	0.004	185	64
P55	0.0035	0.009	-49.8	-59.3	0.0055	150	68
P55	0.0055	0.015	-52.5	-74.5	0.0080	170	48
P55	0.0070	0.019	-64.4	-81.0	0.0105	180	43
P93	0.0035	0.005	-36.5	-58.5	0.008	170	47
P93	0.0055	0.0085	-54.4	-62.8	0.010	175	44
P93	0.0070	0.009	-62.7	-82.9	0.0085	140	34
Glass 0.018(b)	0.0035	0.008	--	--	--	99	43
Glass 0.018(b)	0.0040	0.010	--	--	--	107	16
Glass 0.018(c)	0.0040	0.010	-44.5	-56.4	0.0115	143	39

(a) R = 0.1
(b) 0.018-inch diameter, dry
(c) 0.018-inch diameter, wet.

TABLE 7. RESULTS OF FATIGUE TESTS ON PEENED ROTATING-BEAM FATIGUE SPECIMENS OF ANNEALED Ti-6Al-4V ALLOY [25]

Peening Treatments				Rotating-Beam Fatigue Data		
Peening Steps	Shot Type	Almen Intensity	Coverage,[b] percent	Maximum Stress, ksi	Maximum Stress as Percent of UTS	Cycles to Failure
1	Glass	0.004N	200	105	66.8	223,000
1	Glass	0.004N	200	110	70.0	218,000
1	Steel	0.004A	200	110	70.0	90,000
1	Steel	0.008A	200	100	63.6	519,000*
1	Steel	0.008A	200	110	70.0	162,000
1	Steel	0.004A	200			
2	Glass	0.008N	100	110	70.0	149,000
1	Steel	0.004A	200			
2	Glass	0.008N	200	110	70.0	2,806,000*
1	Steel	0.004A	200			
2	Glass[a]	0.008N	200	110	70.0	113,000
1	Steel	0.008A	200			
2	Glass	0.008N	100	110	70.0	218,000
1	Steel	0.008A	200			
2	Glass[a]	0.008N	200	110	70.0	2,064,000*
1	Steel	0.012A	200			
2	Glass	0.008N	100	110	70.0	2,050,000*
1	Steel	0.012A	200			
2	Glass	0.008N	100	110	70.0	3,417,000
1	Steel	0.012A	200			
2	Glass	0.008N	100	115	73.2	94,000
1	Steel	0.012A	200			
2	Glass	0.008N	200	105	66.8	2,044,000*
				110	70.0	1,162,000*
				115	73.2	1,265,000*
				120	76.5	1,168,000*
				125	79.5	101,000[c]
1	Steel	0.012A	200			
2	Glass	0.008N	200	110	70.0	74,000
1	Steel	0.012A	200			
2	Glass[a]	0.008N	200	105	66.8	79,000
1	Steel	0.012A	200			
2	Glass[a]	0.008N	200	110	70.0	340,000
1	Steel	0.012A	200			
2	Steel	0.004A	200	100	63.6	2,506,000*
1	Steel	0.012A	200			
2	Steel	0.004A	200	105	66.8	174,000

(Continued)

TABLE 7. (Continued)

Peening Treatments				Rotating-Beam Fatigue Data		
Peening Steps	Shot Type	Almen Intensity	Coverage,(b) percent	Maximum Stress, ksi	Maximum Stress as Percent of UTS	Cycles to Failure
1	Steel	0.012A	200			
2	Steel	0.004A	200	105	66.8	1,036,000
1	Steel	0.012A	200			
2	Steel	0.004A	200	105	66.8	419,000
1	Steel	0.012A	200			
2	Steel	0.004A	200	110	70.0	114,000
1	Steel	0.012A	200			
2	Steel	0.004A	200			
3	Glass(a)	0.004N	200	110	70.0	101,000
1	Steel	0.012A	200			
2	Steel	0.004A	200			
3	Glass(a)	0.004N	200	115	73.2	57,000
1	Steel	0.012A	200			
2	Steel	0.004A	200			
3	Glass	0.008N	100	110	70.0	2,000,000*
1	Steel	0.012A	200			
2	Steel	0.004A	200			
3	Glass	0.008N	100	110	70.0	2,000,000*
1	Steel	0.012A	200			
2	Steel	0.004A	200			
3	Glass	0.008N	100	110	70.0	6,280,000*
1	Steel	0.012A	200			
2	Steel	0.004A	200			
3	Glass	0.008N	100	120	76.5	34,000
1	Steel	0.012A	200			
2	Steel	0.004A	200			
3	Glass(a)	0.008N	200	110	70.0	109,000
1	Steel	0.012A	400			
2	Steel	0.004A	200	105	66.8	2,527,000*
1	Steel	0.012A	400			
2	Steel	0.004A	200	110	70.0	460,000
1	Steel	0.012A	400			
2	Steel	0.012A	200			
3	Glass	0.008N	100	115	73.2	158,000

Data for unpeened specimens--100 ksi, 13,000 cycles; 90 ksi, 20,000 cycles; 80 ksi, 51,000 cycles; 70 ksi, 57,000 cycles; and 60 ksi, 2,013,000* cycles.

* Specimen did not fail.

(a) Glass bead slurry in water.
(b) X-hundred percent coverage = that achieved in a time period X times that required for 100% coverage.
(c) Specimen finally overheated and bent.

Additional data are given in Table 8.

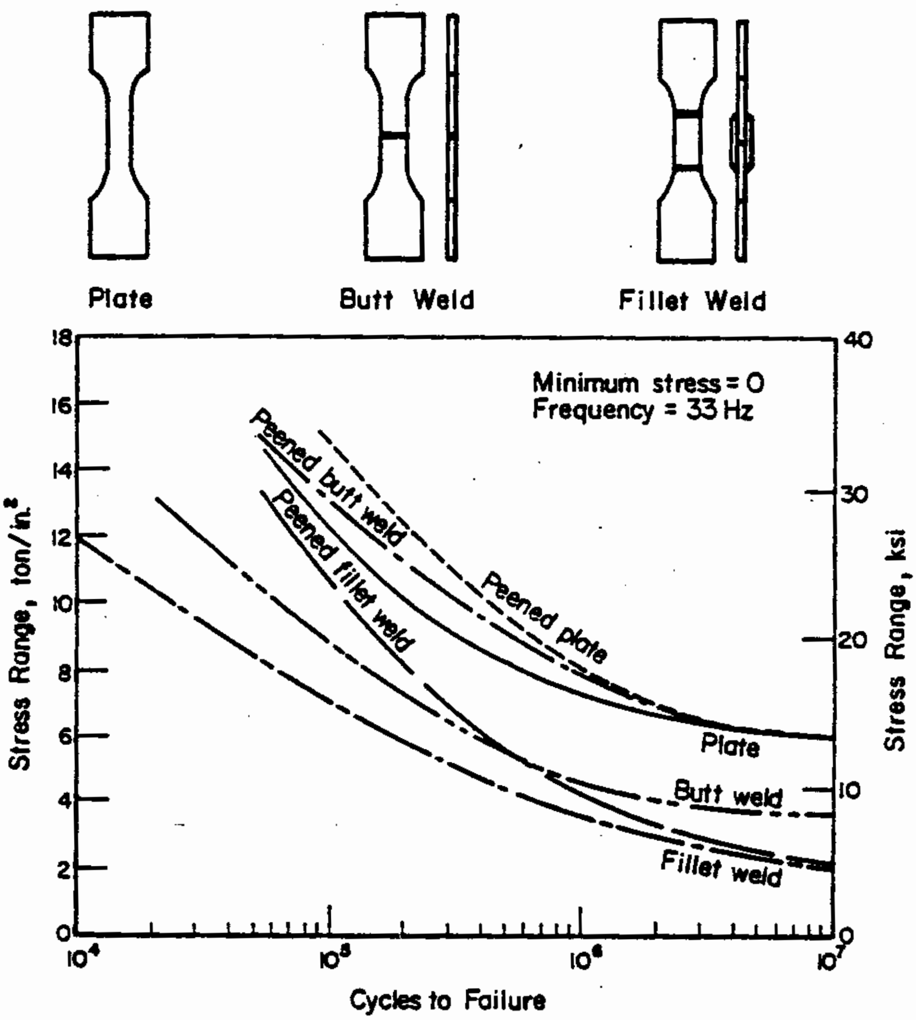


FIGURE 28. S-N CURVES FOR TENSION-TENSION FATIGUE TESTS ON PARENT METAL AND WELDED SPECIMENS OF Al-Zn-Mg ALLOY [21]

TABLE 8. SHOT PEENING DETAILS FOR INTENSITY LEVELS PRESENTED IN TABLE 7[25]

Shot Type	Average Shot Diam., in.	Blast Pressure, psi	Peening Time, min.	Resulting Intensity
Steel	0.011	40	1	0.001A
			2	0.004A(a)
			3	0.0045A
Steel	0.019	70	1	0.0055A
			3	0.0075A
			6	0.008A(a)
Steel	0.019	80	1	0.008A
			3	0.010A
			6	0.0115A
			8	0.012A(a)
Glass	0.002-0.004	30	2	0.004N(a)
Glass	0.002-0.004	50	1	0.008N(a)
			4	0.009N

(a) 100% coverage.

at NASA's Langley Research Center.[26] Specimens were 1.5-inch square from 0.046-inch thick sheet of annealed Ti-6Al-4V alloy and duplex-annealed Ti-8Al-1Mo-1V alloy 0.050-inch thick. Peening consisted of 2, 5, and 10 second exposure to beads delivered through a 3/16-inch nozzle at 60 psi air pressure. Bead diameter for specimens of both alloys was 0.0012 inch. In addition, some Ti-6Al-4V specimens were peened under the same conditions with beads of 0.0025 and 0.017 inch diameter. Specimens were peened on one side only, with a nozzle-to-specimen distance of about 6 inches. The unpeened surfaces were protected with a lacquer coating. X-ray diffraction measurements were made on the peened surfaces before and after removing layers of the surfaces by chemical milling thickness increments of 0.0001 inch until the residual stresses were zero. Because of the peening, the residual surface stresses were compressive, as shown in Figure 29. At depths beyond the zero residual stress level the residual stresses were tensile (in a plane parallel with the surface) to "balance" the surface compressive stresses. The chemical milling solution consisted of 55cc H_2O, 25cc HNO_3 (concentrated) and 8cc HF (45 percent).

The two-exposure X-ray diffraction technique was used in determining the residual stresses in the surface layers. The stresses were determined from measurements of elastic strains associated with a selected set of crystallographic planes. Details are given in Reference 26.

To determine the effects of glass-bead peening on the tensile properties, standard sheet-type tensile specimens of each alloy were peened on both faces and the edges in the reduced sections. The average tensile properties from duplicate tests for each condition are shown in Table 9. Specimens peened with the 0.017-inch beads had substantially lower yield strengths than the unpeened specimens or the specimens peened with the smaller beads, while the ultimate tensile strengths apparently were unaffected by peening. The lower yield strength is related to the residual stresses as discussed in the introductory paragraphs of the Shot Peening for Improved Fatigue Resistance section.

Additional studies were conducted on NASA's program, to determine the effect of prolonged heating to temperatures as high as 800 F on the residual compressive stress in peened specimens. The results are summarized in Figure 30. These relaxation data indicate that reduction in residual stresses occurs in the temperature range from 200 to 800 F and that it is a time-temperature effect. The initial residual compressive stresses at the surface would tend to be beneficial under fatigue loading conditions but reduction of the residual stresses by heating for prolonged periods at temperatures above 200 F would tend to reduce the residual stresses and also reduce the fatigue life of treated specimens.

Surface residual stresses resulting from glass-bead peening of Ti-6Al-4V alloy sheet specimens also have been evaluated at Pratt and Whitney.[27] Specimens for the program were 0.200-inch thick and 2.60-inches wide in the grip section. The test section of each specimen was reduced to a width of 0.90 inch by machining one 1.00-inch-radius arc 0.85 inch in from each edge. Both surfaces of each specimen were finished by grinding and then the specimens were annealed at 1250 F for 36 hours. Hardness after annealing was 30-32 RC. Peened specimens were wet blasted with 0.001-inch nominal diameter glass beads at 90 psi air pressure, resulting in a surface residual compressive stress of 108,000 psi. Residual stresses were determined on 2.60-inch-square specimens by measuring the curvature of one face of the specimen after removing layers from the other face by etching. The curvature was measured by an optical interferometer method. Increments removed during etching were determined by measuring the weight losses. Residual stress distribution near the surface is shown in Figure 31. Depth of the compressive residual stresses was 0.0027 inch.

Results of reversed bending fatigue tests on the peened specimens indicated an endurance limit at 10^6 cycles of 53,900 psi. The average endurance limit of specimens that were stress relieved after grinding was 41,500 psi. Glass-bead peening increased the endurance limit 30 percent.

Shot Peening Cast Magnesium

Early peening tests on cast magnesium alloys resulted in more damage than benefit because the conditions

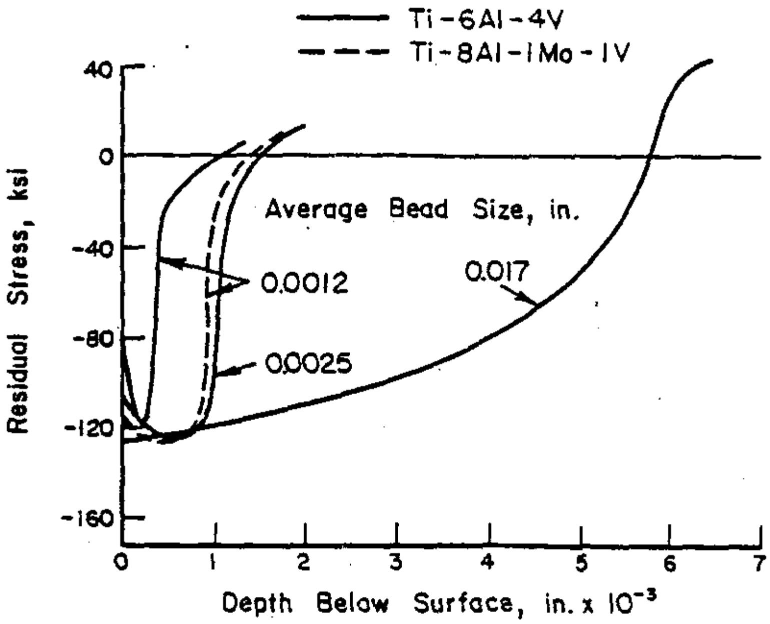


FIGURE 29. DISTRIBUTION OF RESIDUAL STRESSES NEAR SURFACES OF TITANIUM ALLOY SPECIMENS PEENED WITH GLASS BEADS FOR FIVE SECONDS[26]

TABLE 9. AVERAGE TENSILE PROPERTIES OF UNPEENED AND PEENED SPECIMENS OF TITANIUM ALLOY SHEET[26]

Alloy	Average Glass Bead Size, in.	Peening Time, sec	Yield Strength, ksi	Tensile Strength, ksi	Elongation in 2 in., percent
Ti-6Al-4V	--	None	151	163	10.5
	0.0012	15	151	167	9.2
	0.0012	30	154	168	9.0
	0.017	15	135	166	8.8
	0.017	30	135	166	8.2
Ti-8Al-1Mo-1V	--	None	135	150	13.0
	0.0012	15	134	151	12.2
	0.0012	30	134	151	12.2
	0.017	30	114	145	11.0

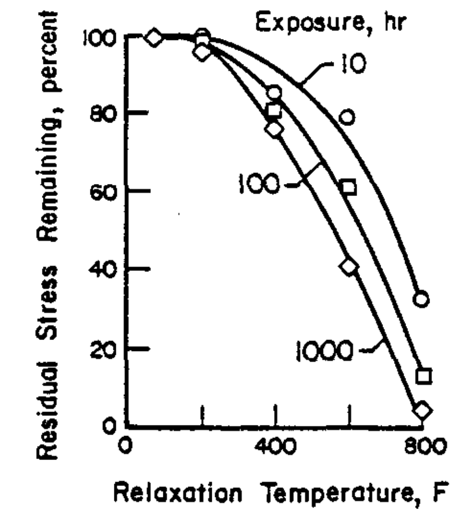


FIGURE 30. RELAXATION OF RESIDUAL STRESSES IN Ti-6Al-4V ALLOY SPECIMENS AFTER GLASS BEAD PEENING FOR FIVE SECONDS USING 0.017 INCH DIAMETER BEADS[26].

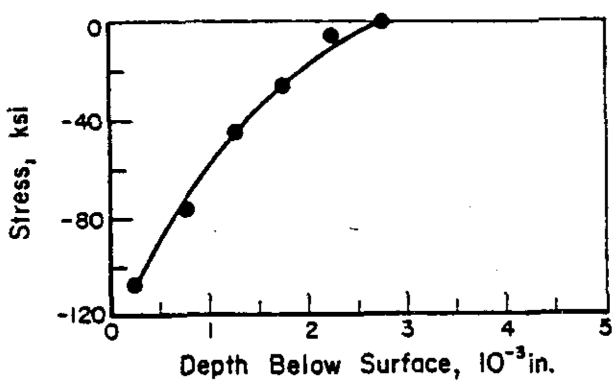


FIGURE 31. RESIDUAL STRESS DISTRIBUTION NEAR THE SURFACE OF GLASS BEAD PEENED SPECIMEN OF Ti-6Al-4V ALLOY[27]

Peening consisted of wet blast at 90 psi using 0.001-inch diameter beads.

were such that the peening produced considerable roughness and cracking of the surfaces. In later tests, at Dow Chemical Company, relatively large shot were used in peening fatigue specimens of cast H-T4 magnesium alloy.[28] The specimens were of the reversed-bending type and the shot was 3/16-inch-diameter hardened steel. Peening was accomplished by dropping the shot 24 to 48 feet onto the surfaces of the specimens. The treatment worked the specimen surfaces to a depth of about 0.003 inch and did not produce cracks. Results of fatigue tests on specimens peened by this method are shown in Figure 32. One series of specimens had as-cast surfaces and the other had machined surfaces. Improvement in fatigue properties resulting from the peening treatment is most effective in the short-cycle stress range. However, peening is rarely used for magnesium alloys because they are not generally selected for components that are subjected to critical fatigue loading conditions.

Glass-Bead Peening a Nickel-Base Superalloy

At Pratt and Whitney Aircraft, tests have been made on specimens of Udimet 700 nickel-base superalloy to determine effects of glass-bead peening and surface cold working on residual stresses and fatigue strengths.[29] Fatigue crack initiation and propagation were investigated in electropolished and glass-bead peened specimens at room temperature. Flat cantilever specimens, axial tension specimens, and rotating-beam specimens were subjected to fatigue loading. These specimens were machined from the solutionized or fully-heat-treated alloy. All of them were polished through 600 grit paper and electropolished. Some were peened subsequently with 0.007 to 0.011 inch diameter glass beads in a water slurry to an intensity of 0.015N to 0.022N. The residual stress distribution near the surface is shown in Figure 33.

Tests on electropolished specimens indicated that solutionizing or conventional solution treating and aging resulted in the same fatigue properties. Fatigue strength of these specimens was taken as the stress for initiating a propagating crack in about 2×10^6 cycles. For the flat reversed-bending specimens, the value was $\pm$ 30 to $\pm$ 35 ksi. For glass-bead peened specimens, fatigue strength was increased to a maximum of $\pm$ 75 ksi. Fatigue strength for the other peened specimens depended on the extent of blasting coverage. In order to achieve maximum benefit, Udimet 700 apparently must be glass-bead peened in excess of the usual saturation peening intensity. Half-crack fatigue propagation rates at various alternating stresses for electropolished and glass-bead peened specimens are shown in Figure 34.

One axially stressed electropolished specimen failed after 0.8×10^6 cycles at 35 $\pm$ 30 ksi stress range while an axial specimen that was glass-bead peened to 0.022N withstood 1.0×10^6 cycles at 50 $\pm$ 45 ksi without failure and failed only after 4.0×10^5 additional cycles at 52.5 $\pm$ 47.5 ksi.

In both electropolished and peened specimens, cracks first appeared along twin boundaries oriented for maximum in-plane shear stress. Initial propagation rates were much lower in the peened specimens, as shown in Figure 34, until the crack progressed out of the region affected by the peening.

Specimens machined from the cold swaged alloy showed no improvement in fatigue behavior over the unswaged specimens even though the yield strength was increased from 130 ksi to 160 ksi and the hardness was increased from 35 to 48 RC.

Results of these tests indicate that the major benefit from glass bead peening on fatigue properties of Udimet 700

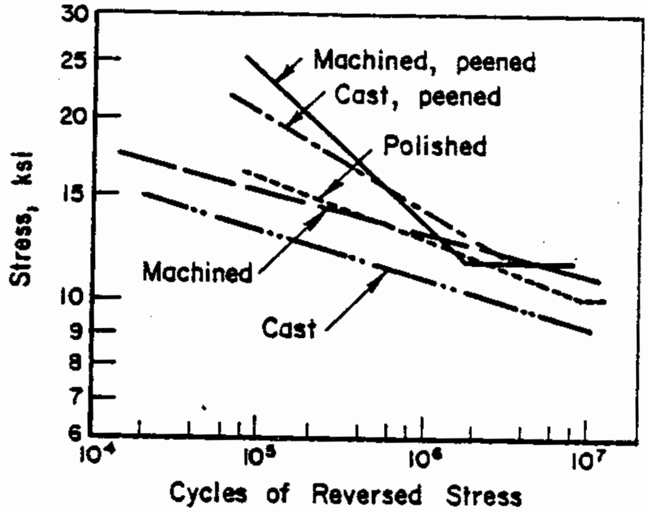


FIGURE 32. S-N CURVES FOR REVERSED-BENDING FATIGUE SPECIMENS OF AS-CAST H-T4 MAGNESIUM ALLOY[28]

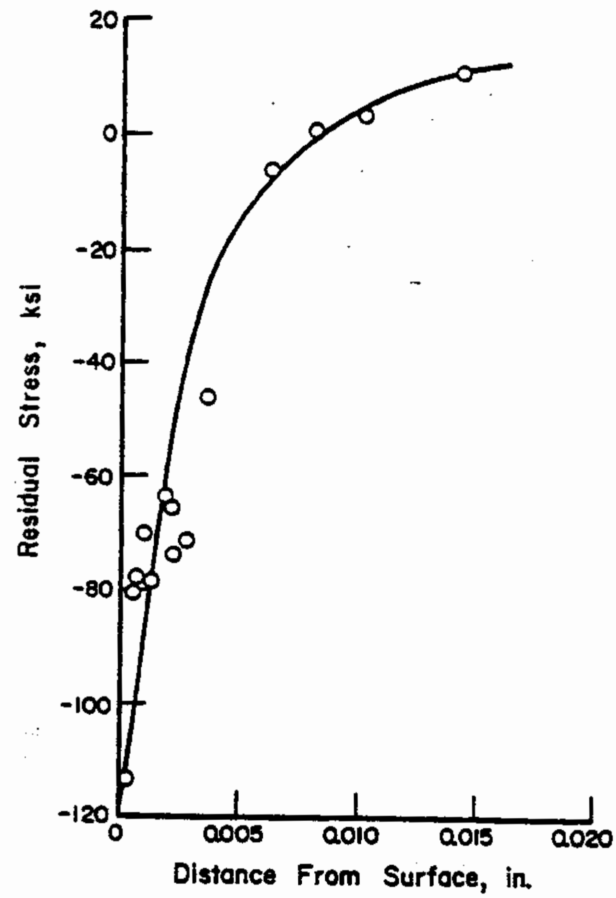


FIGURE 33. RESIDUAL STRESS DISTRIBUTION NEAR SURFACE OF SPECIMEN OF UDIMET 700 ALLOY GLASS BEAD PEENED TO 0.015 N INTENSITY[29]

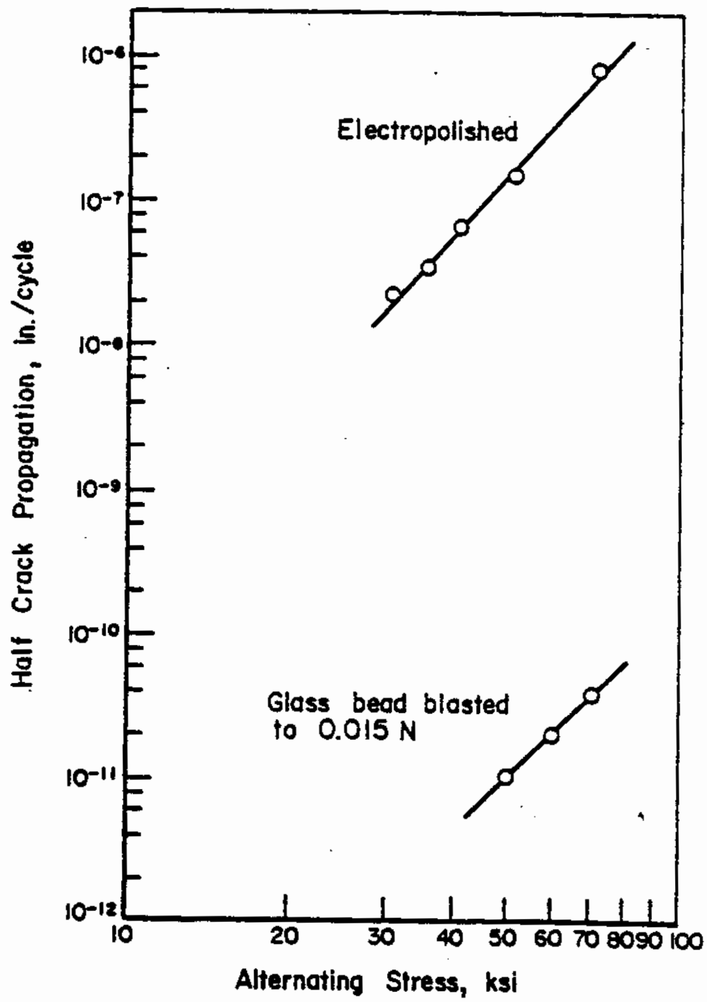


FIGURE 34. HALF-CRACK FATIGUE PROPAGATION RATES IN ELECTROPOLISHED AND GLASS-BEAD PEENED SPECIMENS OF UDIMET 700 ALLOY SUBJECTED TO ALTERNATING BENDING[29]

specimens may be attributed to the very low rate of crack propagation in the surface layers that are characterized by residual compressive stresses.

SHOT PEENING FOR IMPROVED RESISTANCE TO STRESS CORROSION CRACKING

Failure by stress corrosion cracking implies that components of certain alloys develop cracks when subjected to constant tensile stresses above certain levels during exposure to specific corrosive environments. Since the corrosive action occurs only at the surface, any method of reducing the resultant surface tensile stresses should tend to increase the gross stress required to initiate stress corrosion damage. Shot peening is frequently used for this purpose.

There is less background information on the use of shot peening to reduce the effects of stress corrosion cracking than on its use to improve fatigue properties. However, as the number of applications for high-strength alloys increases, the problems with stress corrosion also will increase. Failure by stress corrosion occurs as intercrystalline cracking, but it is often difficult to identify the cause of failure because the fracture appearance is somewhat similar to that resulting from other causes of delayed failure. However, if shot peening is employed to minimize failure by fatigue, the peening also will decrease the tendency for stress-corrosion cracking if the environment is corrosive for the alloy.

Alloy Steels

Stress corrosion of several shot-peened high-strength steels was studied in a comprehensive research program at Boeing.[30] Modified U-bend specimens, 7.75 inches long, 1.000-inch wide and 0.250-inch thick were used for the stress-corrosion tests. Each of the specimens had a bolt hole through the thickness near each end (on 7.00-inch centers) for attachment to arms which were part of the U-bend configuration. Bending stress was provided by tightening a nut on a threaded bar that connected both of the arms in a way that tended to pull the ends of the "U" together. U-bend specimens and tensile specimens were obtained from billets of 4330M and AISI 4340 steel in the short-transverse direction. They were austenitized at 1550 F, oil quenched, and tempered twice at 400 F. The heat-treated tensile specimens of the 4330M steel had a yield strength of 217 ksi and a tensile strength of 253 ksi; those of the AISI 4340 steel had a yield strength of 217 ksi and a tensile strength of 280 ksi.

Among the surface preparations used for the specimens were (a) chemical milling, (b) face milling, and (c) face milling and shot peening. The face milling process, which produced a surface roughness of 32 RHR (Roughness Height Reading from profilometer), left a uniform layer of untempered martensite on the surfaces. In peening, the shot size was 0.023 inch average and the intensity was 0.008A. Residual surface stresses for the peened specimens of AISI 4340 steel were 59 to 120 ksi in compression as determined by X-ray diffraction.

For stress-corrosion testing, the specimens of 4330M steel were stressed to 90 percent of yield strength and those of AISI 4340 steel were stressed to 75 percent of yield strength on the outer tensile layers. The U-bend specimen assemblies were mounted on a ferris wheel apparatus that alternately immersed each specimen in a 3.5 percent NaCl solution for a total of 8 minutes each hour. The immersion treatment was continued for a given specimen until it fractured or until it had been cycled for 1000 hours. Results of the tests, shown graphically in Figure 35, indicate that peening has substantially retarded stress corrosion cracking.

Tests on 9Ni-4Co steels at Douglas showed that the 9Ni-4Co-0.45C type in the martensitic condition was more susceptible to failure by stress corrosion than the same alloy with a bainitic structure or than a similar alloy with a lower carbon content.[31] To show the effect of shot peening on resistance to stress-corrosion cracking, alternate immersion tests were conducted on prestressed sheet-type tension specimens of these steels. The specimens were 5.25 inches long with test sections 1.5 inches long, 0.500 inch wide, and 0.120 to 0.130 inch thick. They had pin holes in the grip sections for pin-type adapters. Blanks for these specimens were machined from the transverse direction in a 6-inch billet of HP-9-4-45 alloy that had been vacuum-arc remelted. The specimens were copper plated, austenitized at 1500 F in a protective atmosphere furnace, oil quenched, cooled to -100 F for 3 hours, and double tempered at 475 F for 2 hours each time. The copper plate was stripped from the specimens and they were baked at 395 F for 8 hours. Tensile properties in the transverse direction were: yield strength 235 ksi, tensile strength 275 ksi, elongation 8.5 percent, and reduction in area 31.5 percent (on round specimens). Hardness of these specimens was 52 RC.

Some of the specimens were peened with S280 cast steel shot to an intensity of 0.008A with 100 percent coverage in 5 minutes. The specimens were rotated at 15 to 20 rpm at a distance of 4 to 6 inches from a 3/8-inch nozzle supplied with 40 psi air pressure. Residual compressive stress at the surface of the peened specimens was 112 to 119 ksi.

Stress-corrosion tests were conducted in six-spring constant-load jigs of 12,000 pound capacity. The grip ends of the specimens and the jigs were coated with a masking material usually used in chemical milling. Only the test sections of the specimens were exposed during testing. Loads applied to the specimens were checked by loading the jigs on a universal testing machine. Loads also were indicated with a strain-gaged load-cell bolt in the drawbar of the jig. The 9Ni-4Co-0.45C steel specimens in the martensitic condition were stressed to 80 percent of their yield strength. Alternate immersion was in synthetic sea water (pH 7.8 to 8.2) with immersion for 1[illegible] minutes of each hour until the specimen failed or until it had been subjected to 1000 hours of testing.

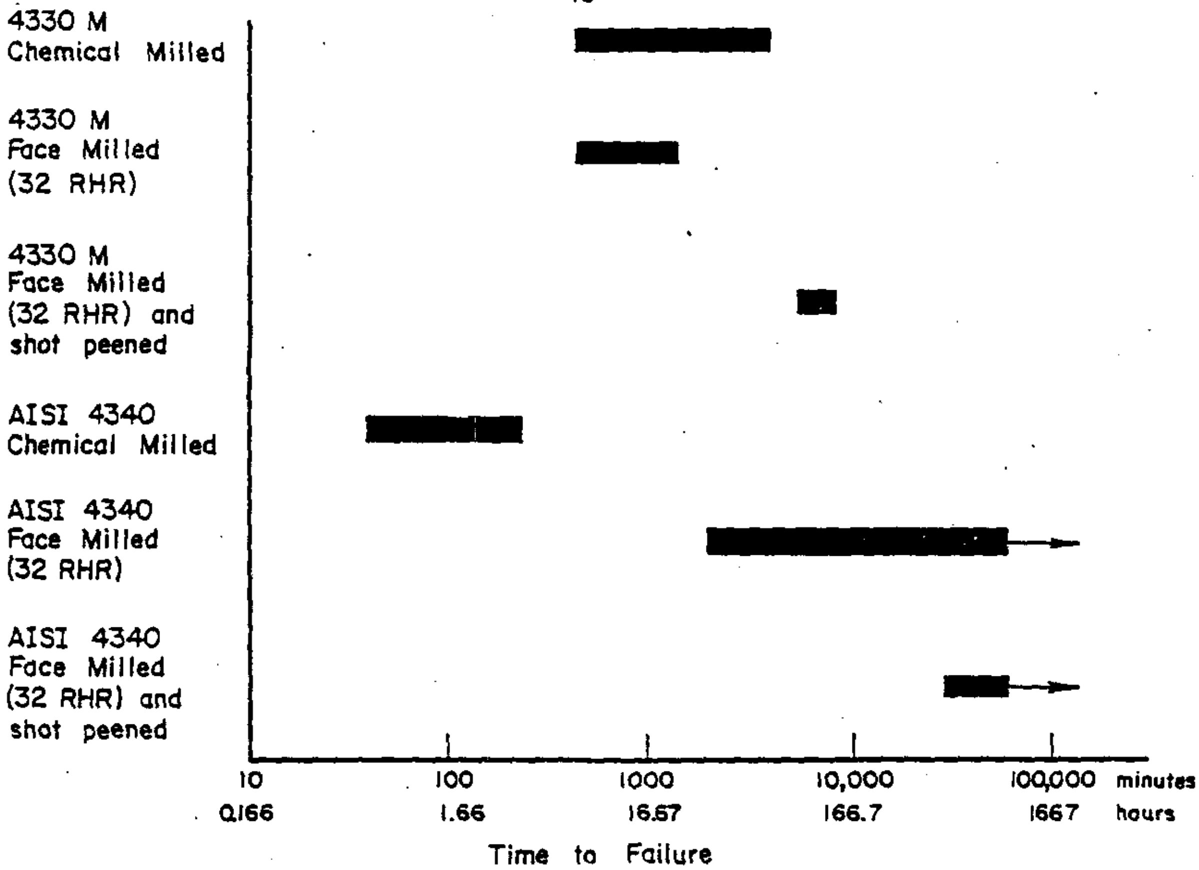


FIGURE 35. RANGE OF FAILURE TIMES FOR STRESS CORROSION TESTS ON U-BEND SPECIMENS OF 4330M AND AISI 4340 STEELS WITH VARIOUS SURFACE FINISHES[30]

Specimens obtained from short-transverse grain direction in billets.

Three unpeened specimens with a normal-grind finish failed in 43, 56, and 93 hours of alternate immersion testing while three peened specimens did not fail in 1000 hours of testing. Surface residual stresses in the normal-ground specimens were 36 to 57 ksi in compression. Of this series of tests on 9Ni-4Co-0.45C in the martensitic condition, cadmium-plated specimens were the most susceptible to stress-corrosion cracking while peened specimens were the most resistant.

Stainless Steels

Hardened and tempered AISI 410 stainless steel was selected at General Electric for components which would be exposed to high-purity water at 300 F.[32] However, this material is susceptible to stress-corrosion cracking when hardened to 36 to 42 RC and subjected to relatively high service stresses in hot high-purity water. To determine the advantages of shot peening for these components, heat-treated specimens of the alloy were shot peened to 0.007A and 0.017A intensities with 0.028 inch nominal diameter steel shot. These shot peened specimens and other, unpeened, specimens were subjected to a tensile stress of 60,000 psi and exposed to air-saturated water at 300 F in a static autoclave. The unpeened specimens failed in one week or less while none of the peened specimens failed during 8 weeks exposure.

Denhard, of Armco Steel, has recommended that shot peening of stainless steels be performed with stainless steel shot or glass beads to minimize stress corrosion problems.[33]

Aluminum Alloys

Stress corrosion tests have been conducted at Alcoa on specimens of two aluminum alloys to determine the effect of shot peening.[34] Ring-type specimens were obtained from 2.5-inch diameter bars of 2014-T651 and 7079-T651 alloys for these tests. The outside diameter of the rings was 2.250 inches, width was 0.500 inch, wall thickness 0.125 inch. The rings were shot peened for 3 minutes on the OD and for five minutes on the edges with S230 steel shot to an intensity of 0.011A to 0.012A at 70 psi air pressure. During peening, the rings were rotated at 10 rpm with the nozzle 12 inches away. After peening, iron contamination was removed by an Alcoa proprietary process (R164).* Both peened and unpeened rings were then pressed onto plugs of the required sizes (for interference fits) to produce tensile

*At Canadair, iron contamination is removed from peened aluminum alloy components by immersion in a 25 percent solution of nitric acid for about 25 minutes.[35] After they are rinsed, the peened surfaces are checked by means of a potassium ferrocyanide solution to insure that the iron contamination has been removed.

stresses in the rings of 75 percent of the yield strength. Sets of five rings each were subjected to (a) 3.5 percent NaCl alternate immersion tests (10 minutes submerged, 50 minutes drying), (b) Point Comfort, Texas, seacoast atmosphere, (c) Point Judith, Rhode Island seacoast atmosphere, and (d) New Kensington, Pennsylvania industrial atmosphere. Average lives of the specimens from each set of rings is shown in Figure 36 for three of the environments. Corresponding average lives of unpeened rings also are indicated in the figure.

Peening was of little benefit in protecting specimens of 2014-T651 alloy subjected to alternate immersion in NaCl solution because the alloy incurred severe surface attack. Although peening retarded fracture of the 7079-T651 alloy, it did not prevent failure at 75 percent of the yield strength. Peening had a greater effect in retarding or preventing fracture of specimens in less severe environments. Examination of failed specimens indicated that attack of the peened surface occurs by pitting. As soon as the peened layer is penetrated, intergranular attack can occur, causing cracks and final failure.

Peening can be effective in reducing initiation of stress corrosion cracking only if (1) all exposed surfaces subjected to tensile stresses are peened and (2) the peened surface layer remains intact so the corroding media do not come in contact with the layers that are under tensile stresses.

Various processing alternatives were considered at Northrop Norair to overcome the problem of stress corrosion cracking in aircraft structural forgings of 7079-T6 alloy.[36] Among these alternatives was shot peening of all 7079-T6 and also 7075-T6 structural components, including wing spars, landing gear cylinders, bulkheads, and fittings. Localized areas of residual tensile stress in the machined components are a major contributor to the tendency for stress corrosion cracking of these components. Residual tensile stresses occur as a result of removal by machining of the surface layers which may have been in compression after heat treating. Distortion may result if the stresses are of sufficient magnitude. Straightening after machining increases the localized residual tensile stresses. In addition, machining of the forgings may expose areas of short-transverse end grain, which are more susceptible to stress corrosion cracking than the other surface areas in a machined forging. Changing the design to avoid end grain exposure on machining is one alternative, but the cited references indicate that shot peening of these surfaces, and all other surfaces of the machined forgings, also will improve the stress corrosion resistance.

Experience gained with high-strength aluminum alloy forgings has indicated that shot peening without first establishing the most desirable peening conditions and without the required controls will not necessarily lead to improved stress-corrosion resistance. When peening aluminum forgings, use of the largest shot size and greatest intensity that will not produce warpage or distortion is usually recommended. Typical shot sizes and intensities are as follows: [36]

	Intensity	Shot Sizes
Sections 0.150 inch and over	0.010A-0.014A	230, 280 (0.023, 0.028 in.)
Sections under 0.150 inch	0.006A-0.0010A	170, 190 (0.017, 0.019 in.)
Holes	0.003A-0.005A	110, 130 (0.011, 0.013 in.)

Surface roughness tolerances also should be considered when selecting shot sizes. Minimum peening time should allow 100 percent saturation of the steel Almen test strip, which will be sufficient to assure more than 100 percent coverage for aluminum forgings, as discussed previously. The cited reference also indicates that all aluminum alloy components peened with metallic shot should be cleaned after peening by immersion in a nitric acid solution or by additional peening with glass beads. After cleaning, the forgings should be coated with a special oil supplied for this purpose until they are further protected by anodizing and painting.

At the Aeronautical Research Laboratories in Australia, studies were made of the effects of peening on stress corrosion in specimens obtained from the short-transverse direction in a 6 x 3-inch extrusion of the D.T.D. 5054 aluminum alloy, which is similar to aluminum alloys in the US 7000 series.[37] The alloy composition in weight percent is: Zn 6.0, Mg 2.4, Cu 0.74, Cr 0.10, Mn 0.28, balance aluminum. The extrusion was in the fully heat treated and stretched (2 percent) condition. The test specimens, measuring 0.3 x 0.2 inch in the test sections, were processed in three different ways prior to shot peening. Specimens of Type A were milled from the extrusion and not given any additional heat treatments. Residual surface stresses of these specimens were ± 690 psi before peening and 27,000 psi in compression after peening. Specimens of Type B were heated at 870 F for 1.5 hours, quenched in cold water, and aged at 275 F for 16 hours. Residual surface stresses were 11,000 to 17,000 psi in compression after heat treating and 31,000 psi in compression after peening. Specimens of Type C were cold formed into an arc of 8 inch radius and given the same heat treatment as Type B specimens. They were then straightened, producing tensile stresses on one side in the range of 13,500 to 21,000 psi. After peening, the surface residual stresses on the sides formerly in tension were about 29,000 psi in compression. Specimens were peened with 0.220 inch nominal diameter rust-free chilled steel shot to an intensity of 0.008A.

Residual surface stresses and depths of peened layers were measured by the X-ray technique. Successive layers were removed in steps of 0.001 inch prior to each determination by

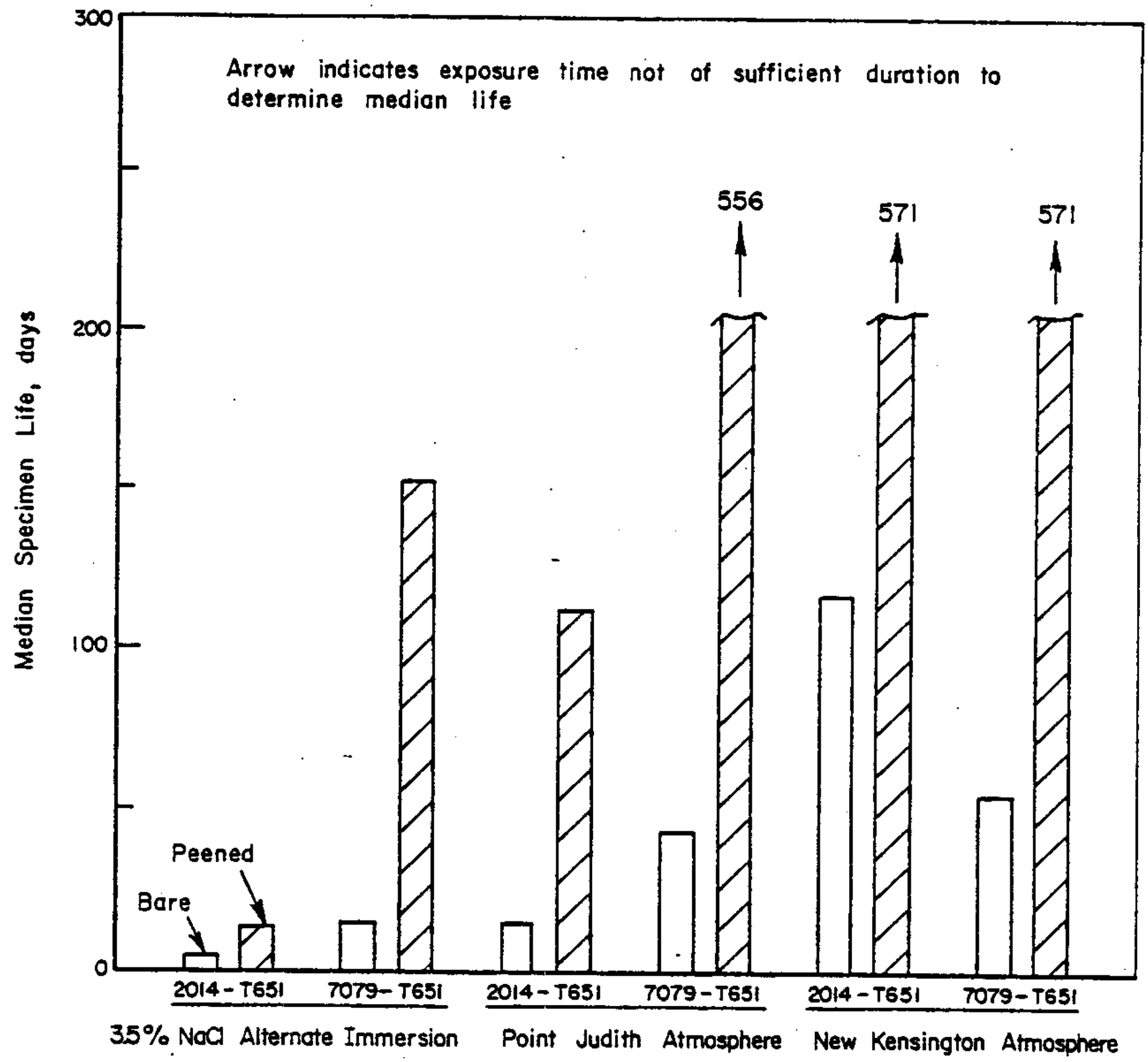


FIGURE 36. MEDIAN LIVES OF RING SPECIMENS OF 2014-T651 AND 7079-T651 ALUMINUM ALLOYS STRESSED TO 75 PERCENT OF YIELD STRENGTH AND EXPOSED TO THREE ENVIRONMENTS[34]

polishing and etching until the back reflection photographs indicated that the etched surface was no longer deformed plastically. Residual stress distribution near the surface was determined in a similar way but the specimens were bolted to 4 x 1 x 1 inch steel plates to hold them flat while the surface layers were removed from one side. Residual stress distribution in a specimen of Type A after shot peening is shown in Figure 37.

In the stress corrosion tests, each specimen was clamped at one end in a horizontal position and loaded on the other end as a cantilever beam. A salt solution of 0.5 normal NaCl and 0.005 normal $NaHCO_3$ in deionized water was dripped onto the specimens. Results of these tests for unpeened and peened specimens of Type A are shown in Figure 38. Even though there is noticeable scatter, data show that the peened specimens all had greater resistance to failure than the unpeened specimens. If the threshold stress for the peened specimens (Type A) in Figure 38 is 60,000 psi, the corresponding value for Type B specimens would be about 50,000 psi, and for Type C specimens 47,000 psi. For unpeened specimens, the threshold stresses are for Type A specimens 51,000 psi, for Type B specimens 34,000 psi, and for Type C specimens 29,000 psi. For each series, peening resulted in improved stress corrosion resistance. For an accelerated test such as this, it is only possible to indicate trends. Other environments and other conditions of stressing will give different results, but it is likely that the ratings will be in the same order, so long as the environment does not cause rapid attack on the alloy.

<u>Peening for Improved Resistance to Stress Corrosion Cracking at Fastener Holes in 7079-T61 Aluminum Alloy</u>

Stress corrosion cracks tend to start at fastener holes in certain aluminum alloy components, since the holes usually represent stress raisers. Furthermore, the corroding medium tends to be retained around the fasteners. The stress corrosion can be reduced by shot peening in the holes but it is not always convenient to do this, for example, when the holes must be drilled and reamed during aircraft assembly. A special tool was developed at Northrop Norair to duplicate the peening effect in drilled holes.[3] This tool contains several series of floating steel balls in races in an assembly that fits in the chuck of a drill press. As the tool is moved axially through the hole, the steel balls are forced against the hole surface by a revolving hammer.

To evaluate the effect of this process, called Norpeening, a series of tests was made on short transverse specimens of 7079-T61 aluminum alloy. The specimens were 8 inches long, 1.5 inches wide in the test section, and 0.250 inch thick. They were shot peened on all surfaces with 280 shot to an intensity of 0.010 to 0.012A. A 0.875-inch-diameter hole was drilled in the center of each specimen, which resulted in a stress concentration factor (K_t) of 2.0. The specimens were then masked except for the holes and either shot peened, glass bead peened, or Norpeened in the holes as designated in Table 10 and treated with Alodine 1200. They were then loaded in a testing fixture to a stress of 38,000 psi (65 percent

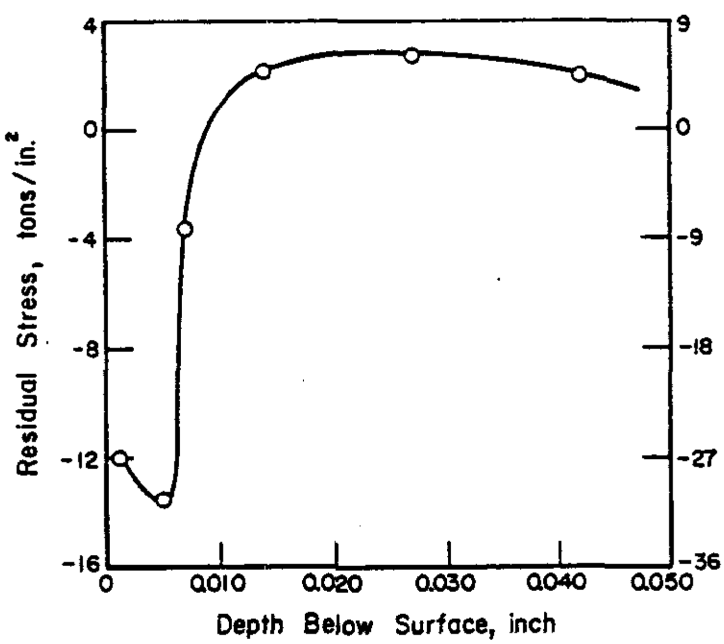


FIGURE 37. RESIDUAL STRESS DISTRIBUTION NEAR THE SURFACE OF A SPECIMEN (TYPE A) OF D.T.D. 5064 ALUMINUM ALLOY AFTER SHOT PEENING[37]

Specimen thickness 0.200 inch.

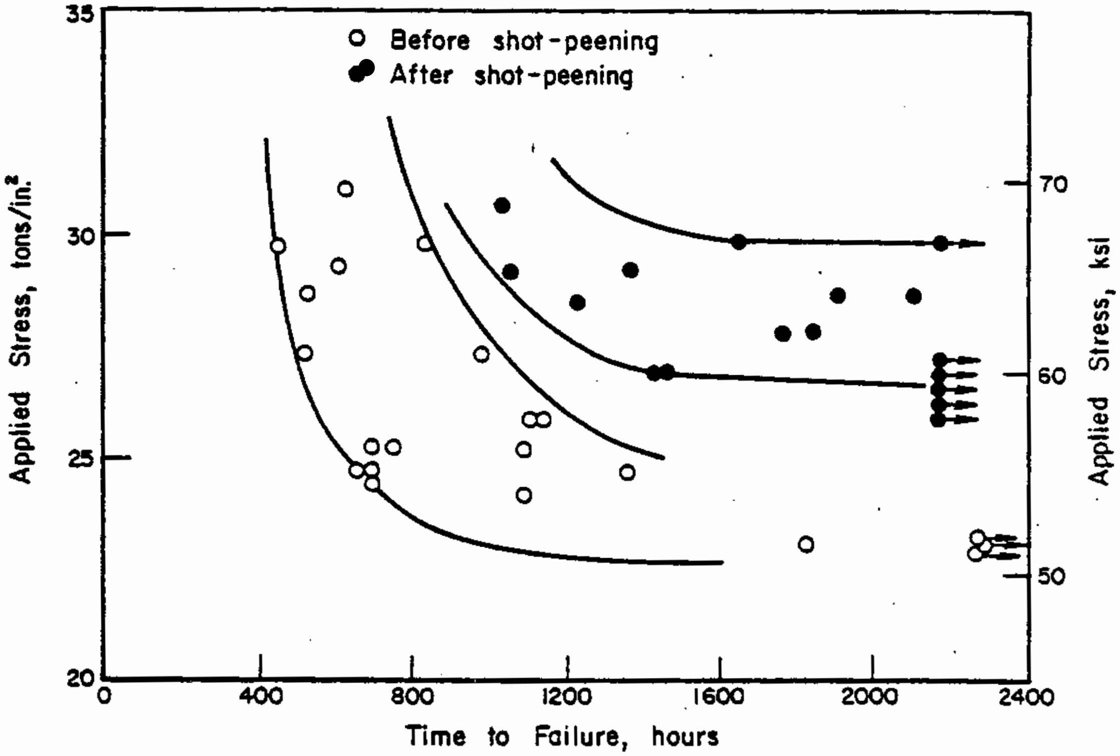


FIGURE 38. RESULTS OF STRESS CORROSION TESTS ON PEENED AND UNPEENED SPECIMENS (TYPE A) OF D.T.D. 5054 ALUMINUM ALLOY [37]

TABLE 10. RESULTS OF STRESS-CORROSION TESTS ON SPECIMENS OF 7079-T61 ALUMINUM ALLOY WITH PEENED HOLES[3]

Peening Method	Peening Variables: Intensity		Peening Variables: Shot or Bead Size	Hours to Failure
None (control)	As drilled and reamed			219.4 219.4
Shot Peening	0.003 to 0.005A		110	139.8 180.7 192.8
	0.003 to 0.005A plus glass bead cleaning		110	274.5 649.5 129.4
Glass Bead Peening	0.003 to 0.005A		0.013 Beads	195.1 223.2 224.3
	0.006 to 0.008N		0.002 to 0.004 Beads	197.8 245.2 275.3
	Hole Oversize[a]	Shaft Speed, RPM	Peening Time, minutes	
Norpeening	0.001	465	5	300.9 378.3 231.8
	0.001	825	2	106.0 366.8 219.1
	0.001	825	5	232.2 244.1 263.9
	0.003	825	5	432.3 347.6 347.5

(a) In relation to Norpeening tool size (0.875 inch diameter).

$$\text{Hole Oversize} = \frac{\text{hole diameter}}{\text{Norpeening tool size}} - 1$$

of yield strength) and subjected to alternate immersion in a 3.5 percent solution of sodium chloride (10 minutes in and 50 minutes out of the solution per cycle). Results of these stress corrosion tests are presented in the table. Examination of control specimens (as drilled and reamed) indicated that the reaming process also developed residual compressive stresses in the holes. This accounts for the fact that the control specimens survived longer than some of the peened specimens. However, results of these tests indicate that Norpeening may be used to cold work the surfaces of drilled holes to produce an effect equivalent to shot peening or glass-bead peening, thereby reducing stress-corrosion cracking. The surface residual compressive stresses resulting from peening the holes are shown in Figure 39.

Titanium Alloys

In 1965, a number of pressurized Ti-6Al-4V alloy tanks which contained nitrogen tetroxide (N_2O_4) failed by stress-corrosion cracking.[38] Earlier studies had indicated that Ti-6Al-4V alloy was not subject to stress-corrosion failure in N_2O_4. Since this oxidixer was being considered for several space propulsion systems, failures of the tanks represented a serious problem in the space program. Among many investigations that were initiated to overcome the problem was one in which the inner surfaces of Ti-6Al-4V tanks were peened with glass beads. When the tanks were pressurized and tested for 30 days at 105 F, the peened tanks containing "red" N_2O_4 did not fail. Unpeened tanks failed in 14 to 127 hours under the same conditions. All of the tanks were in the solution-treated-and-aged condition and were pressurized with red N_2O_4 at 250 psig, which was equivalent to producing a wall stress of 90,000 psi. Peening of Ti-6Al-4V is not required at the present time, because the "green" N_2O_4 that is now used contains a small amount of NO, which inhibits the stress-corrosion effect.

Since glass bead peening of titanium alloy components may help to overcome other stress-corrosion problems in the future, certain details of the peening procedure that were developed for the N_2O_4 tanks will be considered as presented in a NASA report.[39]

To peen the inside surfaces of the tanks, single-nozzle and multiple-nozzle lances were developed to carry the peening nozzles into each tank through an opening in one end. In the mechanized peening equipment, the lance was mounted on a motorized carriage which moved the nozzles into and out of the tank at a controlled rate. Controls also were provided to swing the nozzle head through an angle of 165 degrees in a horizontal plane. Each tank to be peened was positioned on a cradle furnished with a drive mechanism for rotating the tank at a controlled rate. A separate peening chamber containing lance-mounted nozzles also was provided for tests of specimens to establish peening parameters and to permit frequent checking of the peening procedure. Test specimens included Almen N test strips and strips of Ti-6Al-4V alloy 0.063 inch thick which were solution treated and aged the same as the tanks. Glass beads used in the program were 0.006 to 0.010 inch in diameter.

Almen N test strips were used to establish conditions for peening saturation. Individual test strips were peened for various time increments up to 40 seconds and at several different levels of air pressure. The point on the deflection-versus-time of peening curves for the Almen strips where the deflection did not increase by more than 15 percent when the peening time was increased 300 percent was defined as the saturation point. For the equipment used, saturation was obtained in about 8 seconds with 45 to 75 psi air pressure. At saturation, the surface coverage by the peening indentations approached 100 percent. The conditions established for obtaining saturation on the Almen N test strips were then used in peening the titanium alloy test strips. The residual surface stress on the peened titanium alloy strips as determined by X-ray diffraction was 120 ± 15 ksi in compression.

A dummy tank with Almen N test strips and titanium alloy test strips mounted at various locations on the inside diameter was peened by the programmed procedure to determine the uniformity of peening before processing the actual tanks. Tensile specimens also were mounted in the dummy tank. The peened tensile specimens had a yield strength 8 ksi lower than that of unpeened specimens, for reasons discussed in the introductory paragraphs of the Shot Peening for Improved Fatigue Resistance section. The tensile strength and elongation were the same for both peened and unpeened specimens.

Measurements made on titanium tanks before and after peening indicated that there was very little change in dimensions as a result of the peening process. A cylindrical titanium alloy tank 12.5 inches in diameter with a wall thickness of 0.025 inch was 0.0035 inch larger in diameter after peening. This same tank, which was 39 inches long, increased in length by 0.010 inch as a result of internal peening.

NASA's program demonstrated that mechanized glass-bead peening can be employed to uniformly peen the inside surfaces of titanium alloy tanks to improve their resistance to stress corrosion by N_2O_4.

Additional discussion of the effects of peening on properties of titanium alloys may be found in Reference 40.

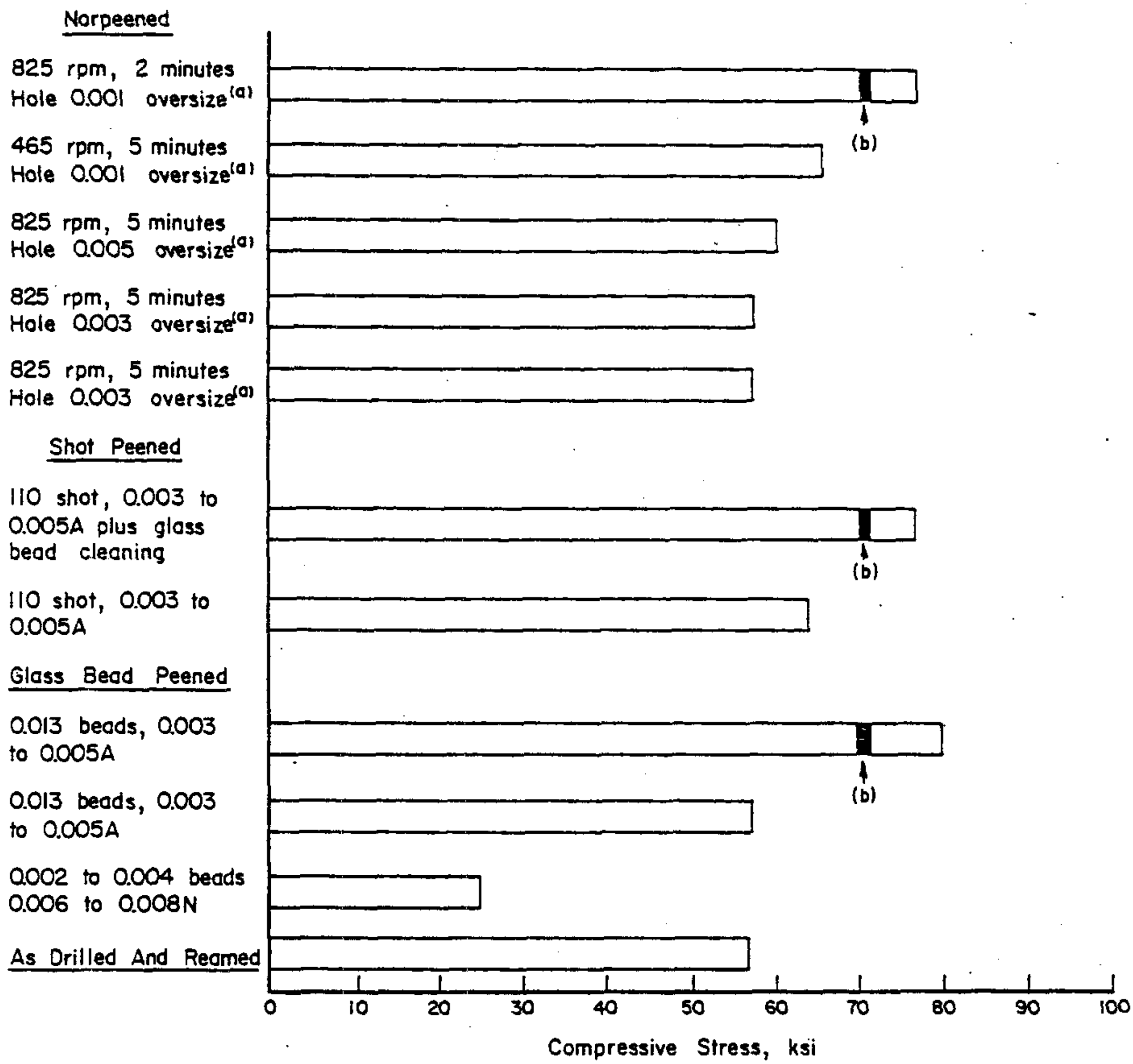


FIGURE 39. COMPRESSIVE RESIDUAL STRESSES AT PEENED AND UNPEENED HOLE SURFACES IN SPECIMENS OF 7079-T61 ALUMINUM ALLOY [3]

(a) In relation to Norpeening tool size (0.875 inch diameter).

$$\text{Hole Oversize} = \frac{\text{hole diameter}}{\text{Norpeening tool size}} - 1$$

(b) Compressive yield strength.

REFERENCES

(1) 1970 SAE Handbook, Society of Automotive Engineers, Two Pennsylvania Plaza, New York, New York 10001 (1970).

(2) "Bonding Shot to Rotating Flaps Makes Shot Peening Portable", Product Engineering, 41 (25) p. 44 (November 23, 1970).

(3) Smith, B. O., Lauchner, E. A., and Roda, D. A., "Evaluation of Norpeening", Report NOR-69-67, Northrop Corporation, Norair Division (May 1969).

(4) Fuchs, H. O., "Shotpeening Effects and Specifications", Metals, ASTM STP No. 196, American Society for Testing and Materials, Philadelphia, Penna. (1957).

(5) Esquivel, A. L., and Evans, K. R., "X-ray Diffraction Study of Residual Macrostresses in Shot Peened and Fatigued 4130 Steel", Experimental Mechanics, 8 (1) pp 496-503 (November 1968).

(6) Elsesser, T. M., "Influence of Repeated Bending Loads on Biaxial Residual Stresses in Shot Peened Plates", Transactions of the ASME, 79 (8) pp 1904-1910 (November 1957).

(7) Robertson, G. T., "The Effect of Shot Size on the Residual Stresses Resulting from Shot Peening", SAE Paper 710284, X-Ray Fatigue Division, SAE Fatigue Design and Evaluation Committee, Ann Arbor, Mich., September 24, 25, 1968.

(8) Zimmerli, F. P., "Shot Blasting and Its Effect on Fatigue Life", Preprint 51, American Society for Metals, (1940).

(9) Zimmerli, F. P., and Wood, W. P., "Effect of Temperature on Endurance Limit and Relaxation of Spring Materials", SAE Transactions, 62, pp 557-565 (1954).

(10) Mattson, R. L., and Coleman, W. S., Jr., "Effect of Shot Peening Variables and Residual Stresses on the Fatigue Life of Leaf-Spring Specimens", SAE Transactions, 62, pp 546-556 (1954).

(11) Mattson, R. L., and Roberts, J. G., "The Effect of Residual Stresses Induced by Strain Peening upon Fatigue Strength", Internal Stresses and Fatigue of Metals, (G. M. Rassweiler and W. L. Grube, editors), Elsevier, New York (1959).

(12) Evans, W. P., and Millan, J. F., "Effect of Microstrains and Particle Size on the Fatigue Properties of Steel", SAE Preprint 793B for paper presented at Automotive Engineering Congress, Society of Automotive Engineers, Detroit, Mich., January 13-17, 1964.

(13) Nelson, D. V., Ricklefs, R. E., and Evans, W. P., "The Role of Residual Stresses in Increasing Long-Life Fatigue Strength of Notched Machine Members", in Achievement of High Fatigue Resistance in Metals and Alloys, ASTM STP No. 467, pp 228-253, American Society for Testing and Materials, Philadelphia, Penna. (September 1970).

(14) Almen, J. O., "Fatigue, Loss and Gain by Electroplating", Product Engineering, pp 109-116 (June 1951).

(15) Cohen, B., "Effect of Shot-Peening Prior to Chromium Plating on the Fatigue Strength of High Strength Steel", WADC Technical Note 57-178, Wright-Patterson Air Force Base, Ohio (June 1957).

(16) Stareck, J., et al., "Development of a Substitute or Improvement of Chromium Electrodeposits", Technical Report 53-271, Wright Air Development Center (1953).

(17) Viglione, J., "The Effects of Shot Peening on the Fatigue Properties of Damaged Bare and Damaged Chromium Plated High Strength 4340 Steel", Report No. NAEC-AML-2187, Naval Air Engineering Center, Philadelphia, Penna. (July 30, 1965).

(18) Viglione, J., "Shot Peening Effects on the Fatigue Properties of Chromium Plated High Strength Steel for Use at Temperatures up to 1000 F", Report No. NAEC-AML-1760, Aeronautical Materials Laboratory, Naval Air Engineering Center, Philadelphia, Penna. (October 18, 1963).

(19) Communication from A. M. Federico, North American Aviation Corporation, Columbus Division, October 20, 1960.

(20) Tiffnell, J. W., Pasquine, D. L., and Olson, J. H., "An Investigation of the Fatigue Behavior of 18% Nickel Maraging Steel", ASM Transactions Quarterly, 59 (4), pp 769-783 (December 1966).

(21) Brine, F. E., Webber, D., and Baron, H. G., "Effect of Shot Peening on the Fatigue Properties of Maraging Steel and Al-Zn-Mg Alloy", British Welding Journal, 15 (11), pp 541-546 (November 1968).

(22) Raefsky, M., "Fatigue Properties of 17-4PH and 15-5PH Steel in the H-900 and H-1050 Condition", Report No. D8-1038, The Boeing Company, Vertol Division, Morton, Penna. (June 24, 1968).

(23) Phillips, A., "The Fatigue Strength of Shot Peened 7075-T6 Aluminum Alloy as Affected by Stress Concentration and Surface Finishes", Douglas Aircraft Company, Inc., Santa Monica Division (No date).

(24) Borehardt, T. J., "Effect of Shot Peening on the Fatigue Life of 7075-T6 Aluminum", Report R719-4, Menasco Manufacturing Company, Burbank, California (March 8, 1960).

(25) Barton, T. F., "Shot Peening of Titanium", Report MP 66-103, The Bendix Corporation, North Hollywood, California (December 20, 1966).

(26) Braski, D. N., and Royster, D. M., "X-Ray Measurement of Residual Stresses in Titanium Alloy Sheet", NASA Langley Research Center, Hampton, Va. paper presented at the 15th Annual Conference on Applications of X-Ray Analysis, Denver, Colorado, August 10-12, 1966 (also in Advances in X-Ray Analysis, 10, pp 295-310 (1967).

(27). Reed, E. C., and Viens, J. A., "The Influence of Surface Residual Stress on Fatigue Limit of Titanium", Journal of Engineering for Industry, Transactions of the ASME, Series B, 82 (1), pp 76-78 (February 1960).

(28) Found, G. H., "Increasing Endurance of Magnesium Castings by Surface Work", Metal Progress, 60 (2), pp 51-54 (August 1951).

(29) Burck, L. H., Sullivan, C. P., and Wells, C. H., "Fatigue of a Glass Bead Blasted Nickel-Base Superalloy", Metallurgical Transactions, 1, pp 1595-1600 (June 1970).

(30) Dreyer, G. A., "Investigation of Susceptibility of High Strength Martensitic Steel Alloys to Stress Corrosion", Report No. ASD-TDR-62-876, The Boeing Company, Renton, Wash., Contract No. AF33(616)-7839 (September 1962).

(31) Turley, R. V., et.al., "The Effect of Processing Variables on Stress Corrosion Cracking in 9Ni-4Co Steel Alloy", Report AFML-TR-66-388, Douglas Aircraft Company, Inc., Long Beach, Calif., Contract No. AF33(615)-2849 (December 1966).

(32) Suss, H., "Shot Peening of Metals for Protection Against Stress Corrosion Cracking", Corrosion, 18 (1), pp 17t to 20t (January 1962).

(33) Denhard, E. E., Jr., "Stress Corrosion Cracking of High Strength Stainless Steel", in Stress Corrosion Cracking in Aircraft Structural Materials, AGARD Conference Proceedings, Series No. 18, NATO Advisory Group for Aerospace Research and Development, Turin, Italy, April 18, 19, 1967, pp V-1 to V-35.

(34) Lifka, B. W., et al., "Investigation of the Stress-Corrosion Cracking of High Strength Aluminum Alloys", Summary Report, Alcoa Research Laboratories, New Kensington, Penna., Contract No. NAS8-5340 (August 1, 1965).

(35) Waller J. J., "Some Engineering Aspects of Stress Corrosion Cracking in High Strength Aluminum Alloys", in Stress Corrosion Cracking in Aircraft Structural Materials, AGARD Conference Proceedings, Series No. 18, NATO, Advisory Group for Aerospace Research and Development, Turin, Italy, April 18, 19, 1967, pp III-1 to III-14.

(36) Lauchner, E. A., "Design and Processing Requirements to Prevent Stress Corrosion in Aluminum Alloys", Paper W9-14.4 for presentation at the 1969 Western Metal and Tool Conference, Los Angeles, Calif., March 10-13, 1969.

(37) Hawkes, G. A., "The Effect of Shot Peening on the Stress Corrosion Properties of Aluminum Alloy D.T.D. 5054", ARL Metallurgy Note 52, Aeronautical Research Laboratories, Australian Defence Scientific Service, Melbourne, Australia (January 1968).

(38) Jackson, J. D., and Boyd, W. K., "Corrosion of Titanium", DMIC Memorandum 218, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (September 1, 1966).

39) Bales, T. T., Manning, Jr., C. R., and Lisagor, W. B., "Equipment and Procedures for Glass-Bead Peening Titanium-Alloy Tanks", NASA TN D-4288, Langley Research Center, Langley Station, Hampton, Virginia (January 1968).

(40) Williams, D. N., and Wood, R. A., "Effects of Surface Condition on the Mechanical Properties of Titanium and Its Alloys", MCIC-71-01, Metals and Ceramics Information Center, Columbus, Ohio (August 1971).