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R. A. Everett, Jr., and W. T. Matthews
U.S. Army Research Laboratory
Vehicle Technology Directorate
Langley Research Center, Hampton,Virginia

R. Prabhakaran
Old Dominion University, Norfolk, Virginia

J. C. Newman, Jr.
Langley Research Center, Hampton,Virginia

M. J. Dubberly
M. J. Dubberly, Inc., Woodbridge, Virginia

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M. J. Dubberly, Inc., Woodbridge, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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THE EFFECTS OF SHOT AND LASER PEENING ON CRACK GROWTH AND FATIGUE LIFE IN 2024 ALUMINUM ALLOY AND 4340 STEEL

[(1)]R.A. Everett, Jr., [(1)]W.T. Matthews, [(2)]R. Prabhakaran, [(3)]J.C. Newman, Jr., and [(4)]M.J. Dubberly

ABSTRACT

Fatigue and crack growth tests have been conducted on 4340 steel and 2024-T3 aluminum alloy, respectively, to assess the effects of shot peening on fatigue life and the effects of shot and laser peening on crack growth. This work is of current interest to the U.S. Air Force as well as the rotorcraft community. Two current programs in the aerospace community involving fixed and rotary-wing aircraft will not be using shot peened structures. The reason for not shot peening these aircraft comes from arguments based on the premise that the shot peening compressive residual stress depth is less than the 0.05-inch initial damage tolerance crack size. Therefore, shot peening should have no beneficial effects toward retarding crack growth. In this study cracks were initiated from an electronic-discharged machining flaw which was cycled to produce a fatigue crack of approximately 0.05-inches in length and then the specimens were peened. Test results showed that after peening the crack growth rates were noticeably slower when the cracks were fairly short for both the shot and laser peened specimens resulting in a crack growth life that was a factor of 2 to 4 times greater than the results of the average unpeened test. Once the cracks reached a length of approximately 0.1-inches the growth rates were about the same for the peened and unpeened specimens. Fatigue tests on 4340 steel showed that the endurance limit of a test specimen with a 0.002-inch-deep machining-like scratch was reduced by approximately 40 percent. However, if the "scratched" specimen was shot peened after inserting the scratch, the fatigue life returned to almost 100 percent of the unflawed specimens original fatigue life.

INTRODUCTION

It has been recognized for a long time (Ref. 1) that the introduction of residual compressive stresses in metallic components leads to enhanced fatigue strength. Many engineering components have been surface-treated with the fatigue strength enhancement as the primary objective or as a by-product of a surface hardening treatment. Examples of the former type of treatment are shot-peening, laser shock peening (LSP), and cold working; examples of the latter type of treatment are nitriding and physical vapor deposition.

In shot peening, a high velocity stream of hard particles is directed at a materials surface often resulting in compressive residual stresses being produced at and below the surface of the material with a peak value being reached at some depth below the surface (Ref. 2,3,4). This peak value can reach a value as high as 60 % of the materials ultimate strength. Because of the direct impact of the particles on the metallic surface, significant surface roughness can result with a thin layer at the surface being work hardened. The net result of shot peening is often a noticeable improvement in fatigue properties (Ref. 5). Shot peening under a prestress can produce an even higher level of compressive stresses (Ref. 3).

Laser-shock peening (LSP) was first used by Battelle Columbus Laboratories in 1974 (Ref. 6). In this process, the surface of the material is covered with a thin layer of opaque material (such as black paint) and over this layer a thick layer of transparent material (such as water) is placed. The laser beam passes through the transparent material and causes a thin layer of the opaque material to vaporize. The rapidly expanding gas is confined by the transparent overlay and creates very high pressures. The surface pressure propagates into the metallic substrate as a shock wave, causing plastic deformation and subsurface residual compressive stresses. LSP is reported not to cause surface roughness. While the residual stress across the treated laser beam spot is mostly uniform and compressive, it changes to tension towards the periphery of the spot and beyond. But, when large areas are treated by overlapping laser beam spots, there is no indication of tensile residual stresses in the overlap regions; the distribution of residual stress is said to be relatively uniform on the surface, while the distribution below the surface is similar to that of shot-peening.

1) Senior Aerospace Engineer and Aerospace Engineer, Army Vehicle Technology Directorate, ARL; 2) Professor, Old Dominion University; 3) Senior Scientist, NASA Langley Research Center; 4) Consultant.

Most of the publications dealing with shot-peening or LSP cite increases in fatigue strength as shown by higher values of the materials endurance limit. A few publications (Ref. 7,8) show crack-length-versus-fatigue-load-cycle curves which show enhanced crack initiation lives for peened specimens; the crack propagation rates appear to be the same for the peened and unpeened specimens. In a paper by Lincoln and Yeh (Ref. 5), they showed an increase in the crack-growth life of a factor of ten for peened compared to unpeened. This was for an analytical study. In the open literature, there appear to be few papers that show da/dN versus ΔK results for shot peened and unpeened specimens. This paper has two objectives. One objective was to investigate the effect of shot and laser peening on crack growth in the 2024 aluminum alloy. The second objective was to show the effect of shot peening on the fatigue life of 4340 steel with and without a machine-like flaw.

TEST PROGRAM

To assess the affect of peening on crack growth and fatigue life, constant amplitude fatigue tests were conducted on small laboratory test specimens fabricated from 2024-T3 aluminum alloy and 4340 steel, respectively. The 2024 aluminum alloy is typical of the material found in the wing structure of fixed-wing aircraft and 4340 steel is typical of the material found in the landing gear of fixed-wing aircraft and in the dynamic components of rotary-wing aircraft. This section describes the material, test specimen configuration, constant-amplitude tests, shot and laser peening, and the machine-like flaws machined on the surface of the 4340 steel fatigue test specimens.

Material and Test Specimen Configuration

The material used for the fatigue life study was 4340 steel heat treated to an ultimate strength of 210 ksi. The fatigue endurance limit for this heat of material was determined to be about 68 ksi at a stress ratio, R=-1. This agreed with the value given in the Military Handbook 5B (Ref. 9.) Specimens were machined to have a surface finish of 32 rms which is a similar finish used on helicopter dynamic components. The nominal thickness of the test specimens was 0.35 inches. Specimens were machined to an hour glass shape (see Fig. 1(a) and 1(b)) producing an elastic stress concentration factor, K_T, of 1.03 as determined by the boundary force method (Ref. 10.) The test specimen was 7 inches in length and 1.5 inches in width at the mid-length.

The material used for the crack growth portion of this study was 2024-T3 aluminum alloy machined to a test specimen thickness of 0.25 inches. Specimens were machined with two semi-circular holes on both edges of the specimen as shown in Figure 1c. This resulted in an elastic stress concentration factor, K_T, based on gross stress of 3.20. To initiate fatigue cracks , there was a 45-degree crack starter slot at the root of each semi-circular hole, with slots at opposite corners of the cross section of the specimen as shown in Figure 1c. Before the specimens were peened, a fatigue crack was initiated by fatigue cycling the test specimen at the same constant amplitude loads as used in the crack growth tests until a length of approximately 0.05 inches was achieved. It should be noted that the U.S. Air Force damage tolerance rogue flaw length is 0.05 inches.

Constant Amplitude Tests

For the crack growth and fatigue studies, constant amplitude tests were conducted in servohydraulic, electronically controlled test stands at a cyclic frequency of 3 to10 hertz with loads controlled to within 1 percent. For the crack growth tests the stress ratio, R, was 0.1 and for the fatigue tests R was minus one. All fatigue test lives reported herein on the 4340 steel were to specimen failure.

Shot Peening and Scratch Dimensions

For the crack-growth tests, after precracking to approximately 0.05 inches, six specimens were shot peened and four specimens were laser peened. The shot peened specimens were shot peened over all surfaces, including the notch radius, except for the grip regions. The shot peening intensity was .010 to .012 Almen A, with 100% coverage.

The laser peened specimens were shocked using a laser input of 100 J/cm^2 . In the laser peening process a pulse of laser light is absorbed and rapidly forms a high pressure plasma of approximately 10^5 psi. A tamping layer confines the plasma and drives the pressure pulse into the material being peened. This pressure pulse induces the compressive residual stresses into the metallic material.

To show the effect of shot peening on the fatigue life of 4340 steel with and without a machine-like flaw, fatigue tests were conducted on test specimens with and without a machine-like flaw (see Figures 1(a) and 1(b).) The flaw for this study was a simulated machining scratch. Tests were also conducted on specimens that were shot peened after being scratched. The machine-like scratch was machined into the specimen surface using an end mill. The scratch was machined across the entire width of the specimen, but only on one side of the specimen (see Fig. 1(b).) Each specimen scratch was measured to insure uniformity in geometry of the scratches for the test specimens tested in this study. Measurements of the scratch depth of the test specimens showed a range in scratch depth of 0.0014 to 0.0029 inches with a mean value of 0.0020 inches and a standard deviation of 0.00036 inches. The width of the scratches was approximately twice the depth. The shot peening process on these specimens was done by a major U.S. helicopter manufacturer. X-ray diffraction measurements of the compressive residual stresses produced by the shot peening ranged from 60 to 90 ksi. The compressive residual stresses reached a zero stress level at about 0.006 inches below the specimen surface.

Fatigue Tests Specimen Types

Four different specimen types were used in the 4340 steel test program. For the baseline data, specimens were machined as pristinely as possible to provide fatigue life test data of specimens with no machining flaws. A second set of specimens were machined to the proper specimen geometry, then a machine-like scratch was machined on the specimen surface with the dimensions and procedures stated previously. A third set of specimens were shot peened after being machined. Finally, a fourth set was machined to the hour-glass geometry, then the machine-like scratch was machined on the specimen surface followed by shot peening.

TEST RESULTS

Corner cracks were formed in all 2024-T3 aluminum alloy specimens at the starter slots by fatigue cycling until a fatigue crack of approximately 0.05 inches was reached under constant amplitude loading with a maximum loading of either 10 or 13.3 ksi, gross stress, with an R-value of 0.1. The minimum load was then increased to obtain an R-value of 0.7 or 0.8 and the crack advanced approximately 0.005 inches in order to mark the shape of the corner crack for examination after failure.

Crack growth life

The effect of shot peening on crack growth lives is shown in Figures 2 and 3. Crack growth life being the number of load cycles it takes for the crack to grow from the initial crack size, approximately 0.05 inches, to failure. In general shot peening had a noticeable affect on crack growth life by increasing the time to failure between a factor of 2 to 4 for the lower applied stress level tests, Figure 2 at 10 ksi, or from 1.2 to 2.7 for the higher stress level, Figure 3 at 13.3 ksi. Because of the limited number of test specimens used in this study, it was not possible to determine what caused this scatter in the crack growth lives.

The primary influence of shot peening appears to occur during the very early extension of the crack even though the entire specimen was shot peened. These results suggest that the impact of the shot peening process at the precrack position is critical in affecting the crack growth lives.

The effect of laser peening on crack growth lives is shown in Figures 4 and 5. The crack growth lives for the laser peening tests showed less scatter than the shot peened tests. At the lower stress level of 10 ksi, Figure 4, the crack growth life was increased by approximately 1.8, while at the higher stress level of 13.3 ksi, Figure 5, the increase was between 2.1 and 2.6.

Crack Growth Rate

To assess the effect of shot and laser peening on crack growth, baseline tests were conducted on specimens that were not peened to compare with the peened test results. The test results from the unpeened specimens are shown in Figure 6. The solid curve is the ΔK versus rate curve for R = 0.1. The current results show good agreement with previous results on 2024-T3 aluminum alloy (solid line.) The dashed curve is the ΔK_{eff} versus rate curve for the thin-sheet aluminum alloy and the α -values denote a constraint-loss regime (plane-strain to plane-stress behavior.) Below a rate of 4 x 10^{-6} inches/cycle, the crack is under high constraint (α=2) and above 1 x 10^{-4} inches/cycle, the crack is under plane-stress (α=1) conditions. The departure from the da/dN versus ΔK at R=0.1 as shown in Figure 6 at the higher ΔK values may be due to the effects of width on fracture. The current tests were conducted on specimens of 1.5 inches in width whereas the solid curve was on specimens that were 12 inches in width. Smaller width specimens have lower stress-intensity factors at failure than larger width specimens. The procedure to calculate the stress intensity for this specimen configuration with a corner and through crack is given in Appendix I.

As shown in Figures 7 and 8 , the test results from the shot and laser peening tests show that in general when the cracks are small (ΔK less than 10 ksi-in$^{1/2}$) peening does noticeably reduce the crack growth rates. This probably accounts for the longer crack growth lives shown in figures 2 through 5. Figure 7, which shows the shot peening test results, shows that the crack growth rate behavior at the higher ΔK values exhibited the same width effect as shown for the nonpeened test data.

The laser peening crack growth comparisons shown in Figure 8 show a tendency for higher crack growth rates when ΔK is approximately between 10 and 20 ksi-in$^{1/2}$ This is probably because the laser peening done on these test specimens seemed to be very severe thus possibly producing significant tensile stresses which are needed to equilibrate the residual compressive stresses that result near the surface because of the peening. The specimen surface on the laser peened specimens had a noticeable crater-like appearance. Comments in the literature indicate that laser peening should not cause a noticeable change in surface appearance (i.e., surface roughness).

Fatigue life

To assess the effect of shot peening on the fatigue life of 4340 steel with and without a machine-like flaw, constant amplitude fatigue tests were conducted on unnotched specimens with and without a machine-like scratch with a series of tests also conducted on specimens that were shot peened after the scratch was machined onto the specimen surface. The scratch was machined onto one side of the specimen to a nominal depth of 0.002 inches.

Figure 9 shows the results of the fatigue tests on the pristine specimens as well as the specimens that had been shot peened with no surface scratch (symbols with arrows indicate a runout, test stopped before failure.) The results of these data showed a definite increase in the fatigue life of the baseline material as a result of shot peening. Based on the limited amount of tests, the endurance limit of the baseline material appears to be about 10 percent higher with a shot- peened surface. It is also noted that the baseline material endurance limit of about 68 ksi agrees very well with that found in Military Handbook 5B (Ref. 9.) A general increase in fatigue life at all the stress levels tested is noted from the data shown in Figure 9. The shape of the two S/N curves seems to be similar, but with the limited amount of tests run this similarity can only be assumed.

Figure 10 shows the results of the fatigue tests on the specimens with machine-like scratches compared to the pristine specimens. As seen in this figure the endurance limit was reduced from 68 ksi for the pristine specimen to about 40 ksi for the specimen with a 0.002 inch deep scratch. This is a decrease of about 40 percent. A scratch of this size could easily be missed by an optical inspection of an aircraft component. With this magnitude of reduction in the endurance limit resulting from a fairly small machine-like scratch, it can be seen that some fabrication procedure is needed to protect against this possible loss in fatigue strength.

As somewhat of a standard practice, most helicopter manufacturers shot peen their life limited dynamic components after machining. Figure 11 shows the effect on the fatigue life of specimens that have been shot peened after a scratch was machined onto the specimen surface. As shown by the test data, the fatigue life of the specimens containing a scratch with shot peening is almost the same as that of the pristine specimen. Hence, shot peening is potentially a successful method in keeping the fatigue strength of a material at its pristine value when a fabrication flaw may be present in of the structure.

Fatigue life analysis

Since about the mid-1980's, a trend has been developing to predict total fatigue life (from the first load cycle to failure) using only fatigue crack growth considerations (Ref. 11.) In order for this to be accomplished, a very small initial crack size (0.00004 to 0.002 inches) had to be assumed to exist in the material. Furthermore, as shown by numerous investigations (Ref. 12-14), these very small cracks have crack growth characteristics that are considerably different than large cracks (cracks longer than 0.08 inches). In fact, these small cracks are considered to exhibit a "small-crack effect" which as described by linear-elastic fracture mechanics (LEFM), are small cracks that grow faster than long cracks at the same stress intensity factor range and grow at stress intensity factors below the long-crack threshold (ΔK_{th}). A review of the concepts involved in "small-crack" theory is given by Newman in reference (Ref. 15).

After conducting the fatigue life experimental portion of this study, it was decided to investigate the ability of the small-crack crack theory to predict the fatigue life of the test specimens that contained the machine-like scratch. Since several studies by Newman and his colleagues (Ref. 16-18) had shown a crack growth analysis using small-crack considerations could predict total fatigue life using only a crack growth analysis, it was logical to try to employ these concepts to predict the fatigue life of the test specimens with the machine-like scratches. In Newman's studies he used a crack-closure based model (Ref. 19) to predict total fatigue life (Ref. 11). While the work in reference 11 illustrates analysis only on aluminum alloys, this method has also been shown to work on high aircraft quality steels (Ref. 16).

As a first step in the analysis of the machine-like scratch, it was decided to use the small-crack analysis to predict the life of the as-manufactured test specimens in order to check the basic material data input into the crack-growth computer code. As stated previously, perhaps the most important input to this analysis is the initial crack size. The long and small crack characteristics of the 4340 steel used in this study were thoroughly investigated as part of an AGARD study done during the 1980's (Ref. 16). In the study, conducted by Swain et al, examination of 35 crack initiation sites described the distribution of initiation sites as shown in Figure 12. The dominate initiation site was a spherical (calcium-aluminate) particle as shown in Figure 13. The mean defect size was determined to be a radius of about 0.0005 inches. From Figure 12 it is seen that defects found in this study ranged from a radius of about 0.0002 to 0.0016 inches.

Most of the analysis done previously using FASTRAN has been done on specimen configurations that contained a hole with an elastic stress concentration, K_T, of about three (Ref. 16-18). As stated previously, the test specimen used in these tests had a nominal K_T of one. In a $K_T = 1$ stress distribution a much larger volume of material is available for the crack to initiate. In this larger volume of material, it is probable that a larger defect would exist that could initiate the crack. Newman, in his analysis of $K_T = 1$ specimens made of the aluminum alloy 2024-T3, required a 0.00079 inch radius crack to fit the constant amplitude test data for stress ratios, R = 0 and -1. But in a $K_T = 3$ specimen, a 0.00024 inch radius crack was needed to predict total fatigue life (Ref. 11). For the analysis conducted on the $K_T = 1$ geometry used in this study the mean defect size, 0.0005 inches, as shown in Figure 12 was used as the initial fatigue crack to predict the solid curves as shown in Figure 14. The FASTRAN analyses compared well with the test data, even predicting the endurance limit.

In order to predict the total fatigue life of the machine-like scratch test specimen, the geometry of the initial crack must be chosen in order to define the stress intensity factor to use in the crack growth analysis. For this study, it was decided to model the scratch as a single-edge crack under a tensile loading. As stated previously, measurements of the scratch depth of the test specimens showed a range in scratch depth of 0.0014 to 0.0029 inches with a mean value of 0.002 inches and a standard deviation of 0.00036 inches. Using the average scratch depth as the initial crack length, the crack geometry of a single-edge crack, and using the applied stress as the applied load divided by the cross-sectional area of the test specimen, the resulting predictions from FASTRAN are shown as the dashed curve in Figure 14. As shown, the agreement between the FASTRAN analysis and the test data is very good.

CONCLUDING REMARKS

The test results obtained in this study have shown similar effects of shot and laser peening on crack growth lives and fatigue life that have been previously reported in the literature. In general, both crack growth life and fatigue life are improved as a result of shot and laser peening. This study also indicates that when cracks are small, peening also has a noticeable affect on the crack growth rate producing a reduction in the crack growth rate. As previously postulated by others the peening depth being relative small would only affect the crack growth rates of fairly small cracks. There is some evidence that the compressive residual stresses from laser peening may approach a depth of 0.05 inches (Ref. 7).

The data from these tests as well as other data in the literature (Ref. 3) show the beneficial effects on fatigue life. Some data in the literature(Ref. 3) show an increase in fatigue life by as much as a factor of 10 at a given stress level. The fatigue life improvement of the 4340 steel tests in this study did not show that much benefit. It did show, however, that the endurance level of a flawed part can almost be returned to that of a pristine part if the part is peened after the flaw is induced.

The effect of laser peening on crack-growth life was not as beneficial in this study as has been shown by Clauer (Ref. 22). Clauer's study showed an increase in crack growth life even greater than a factor of 10. He also showed similar benefits in fatigue life.

The following conclusions are drawn from the work described herein.

1. The shot and laser peening processes used in this study had a noticeable affect on the crack growth rate of the 2024-T3 aluminum alloy in reducing the rates when the cracks are fairly small with ΔK being approximately less than 10 ksi-in$^{1/2}$.

2. In general shot peening had a noticeable affect on crack growth life by increasing the time to failure from a factor of 2 to 4 for the lower applied stress level tests, 10 ksi, or from 1.2 to 2.7 for the higher stress level, 13.3 ksi.

3. For laser peening the crack growth life at the lower applied stress level of 10 ksi was increased by approximately 1.8, while at the higher stress level of 13.3 ksi, the increase was between 2.1 and 2.6.

4. Shot peening of high strength 4340 steel produced a higher endurance limit by about 10 percent.

5. A machine-like scratch in high strength 4340 steel reduced the endurance limit by about 40 percent.

6. Shot peening a material that contains a machine-like scratch restored the endurance limit of the material to within about 10 percent of its original value.

7. A crack-growth closure based analysis using small-crack theory predicted the total fatigue life of pristine test specimens and specimens with a machine-like crack with very good accuracy.

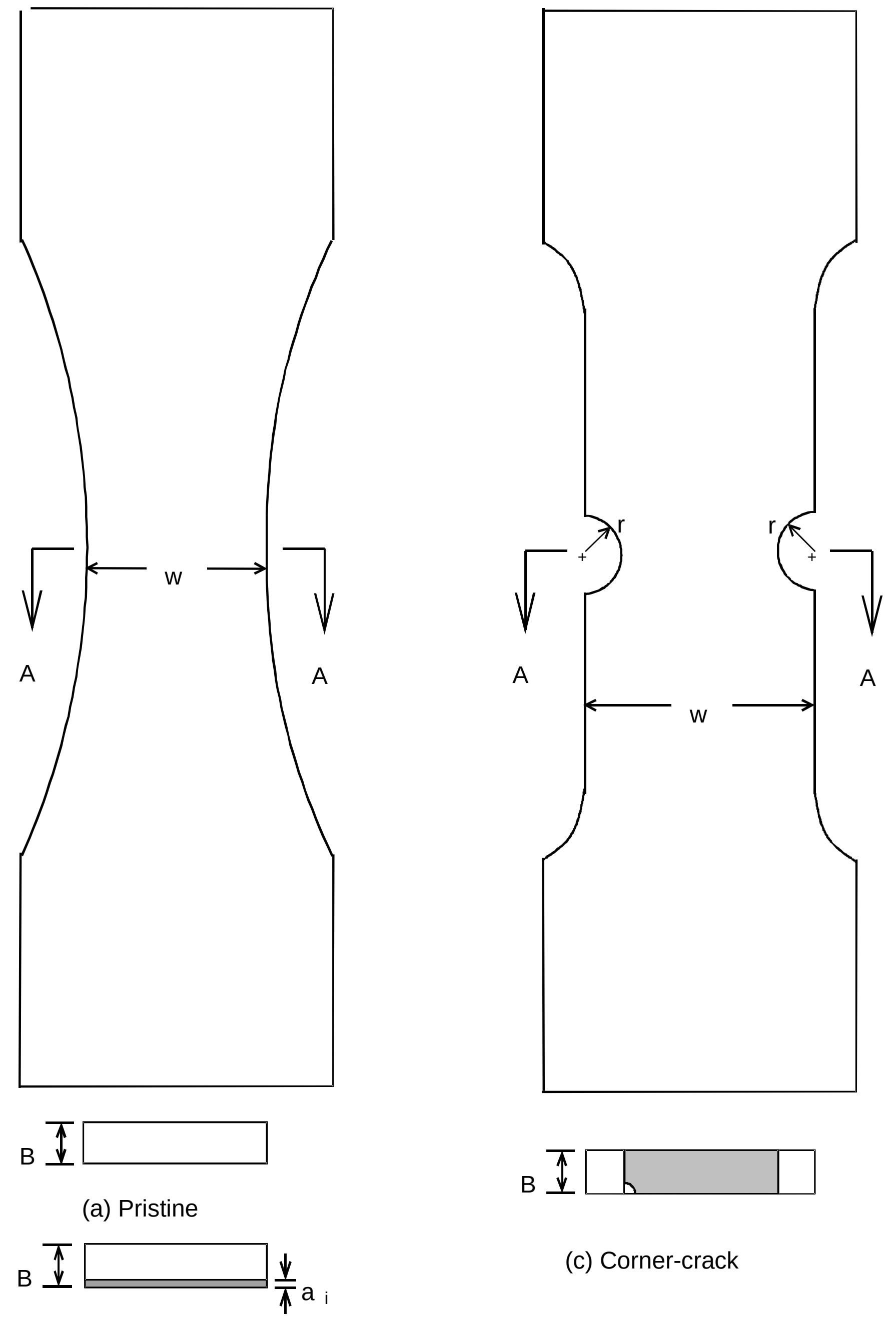

Figure 1. Fatigue (4340 steel) and crack-growth (2024-T3) specimens.

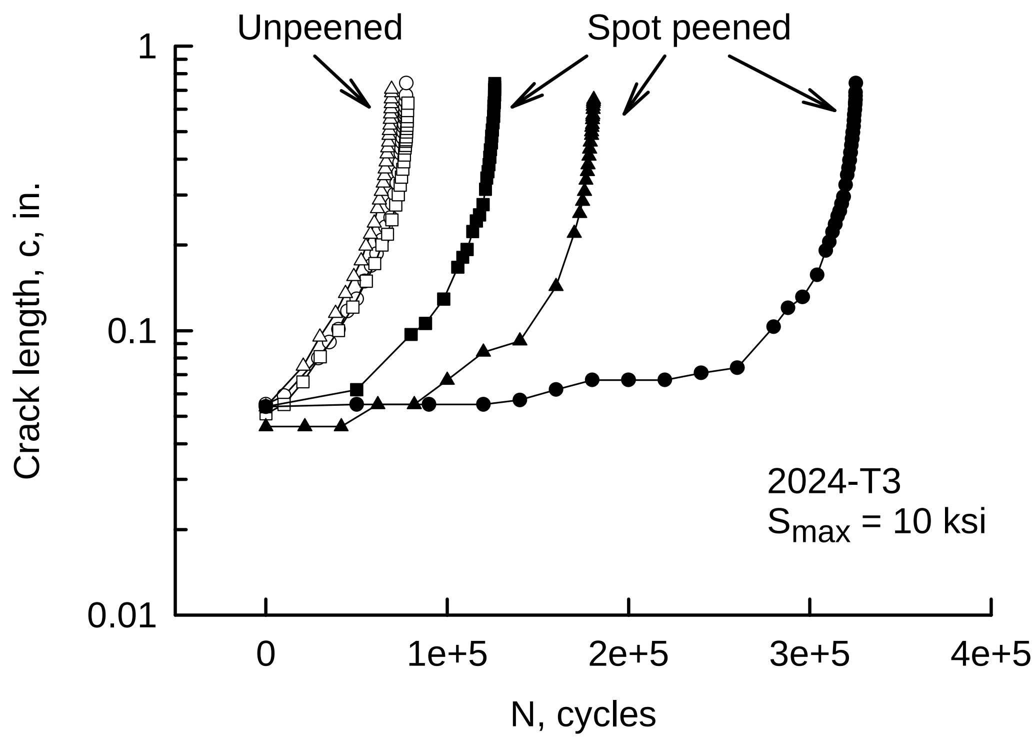

Figure 2. Crack length against cycles for unpeened and shot-peened specimens at an applied gross stess of 10 ksi.

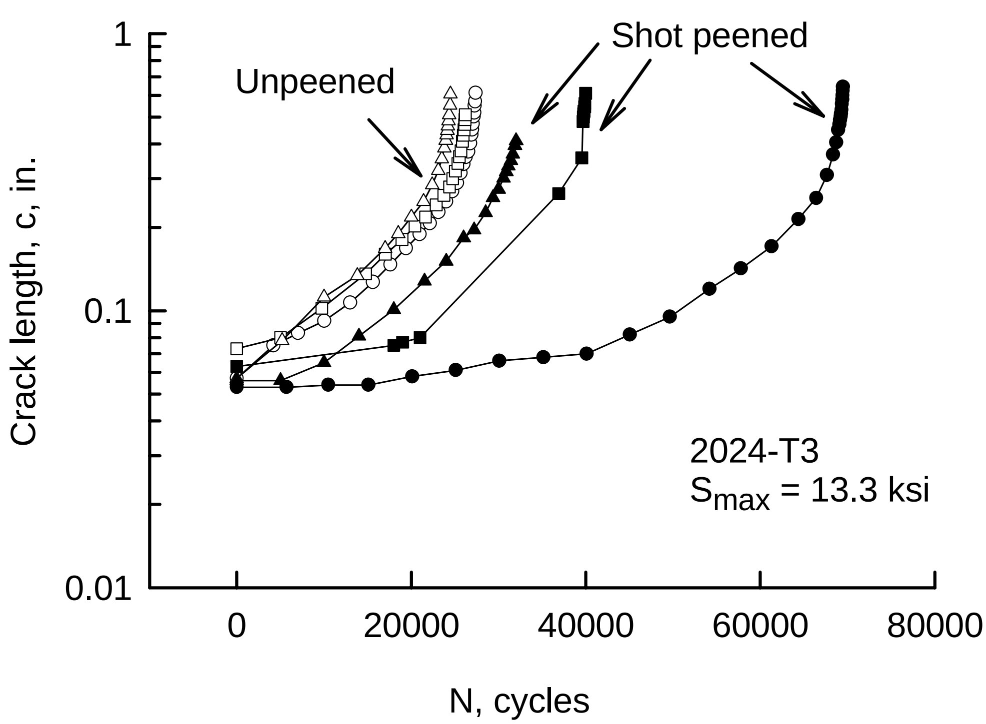

Figure 3. Crack length against load cycles for unpeened and shot-peened specimens at an applied gross stress of 13.3.ksi.

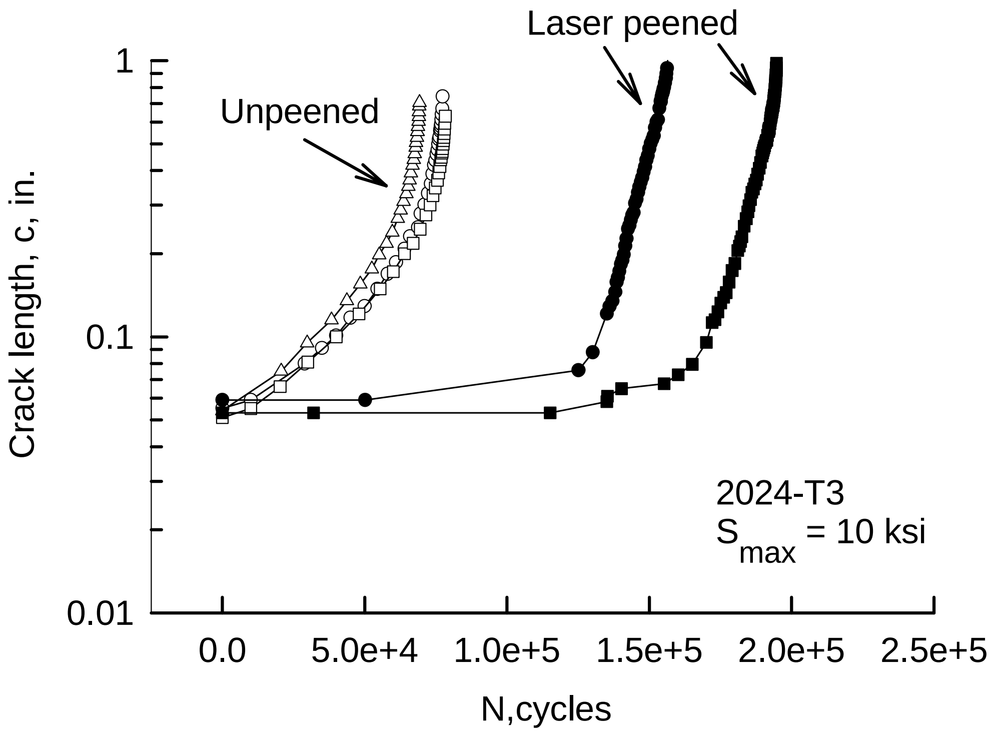

Figure 4. Crack length against load cycles for unpeened and laser-peened specimens at an applied gross stress of 10 ksi.

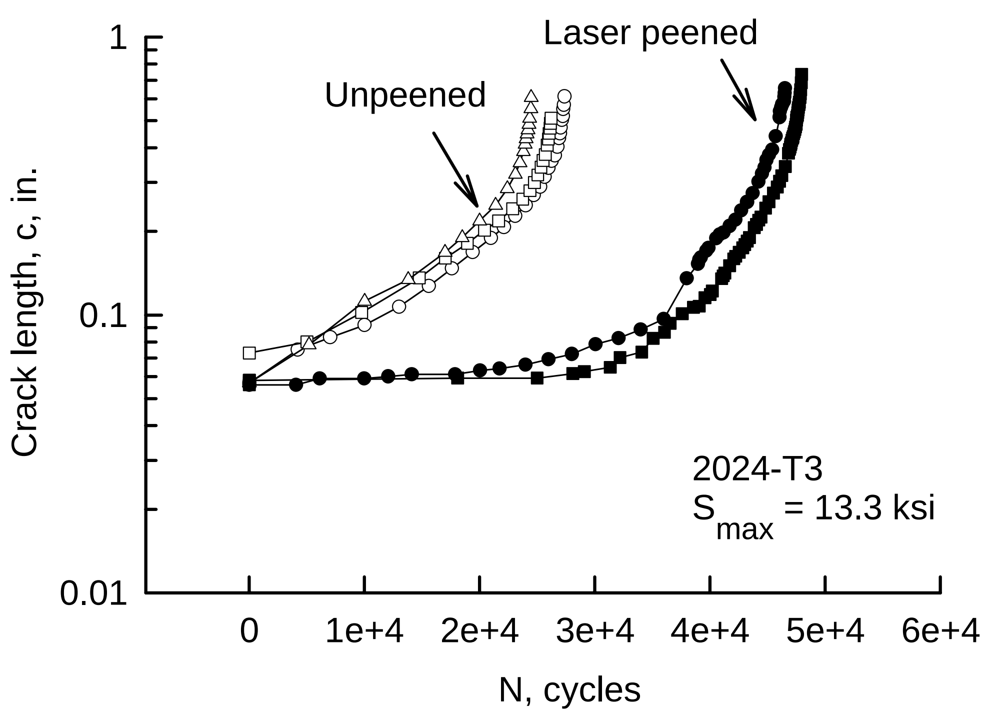

Figure 5. Crack length against load cycles for unpeened and laser-peened Specimens at an applied gross stress of 13.3 ksi.

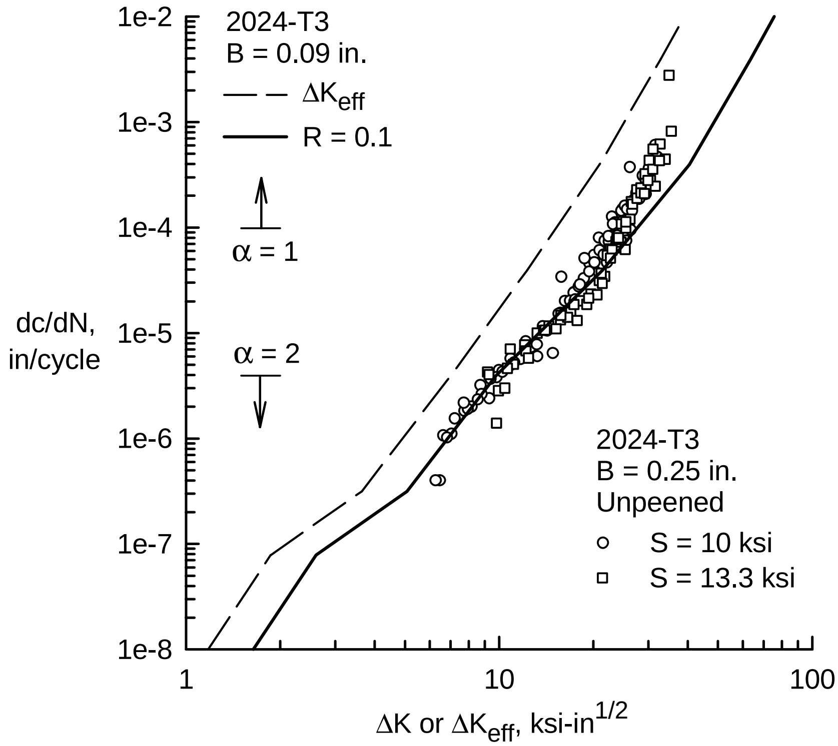

Figure 6. Comparison of crack growth rates for unpeened specimens with results from thin sheet 2024-T3.

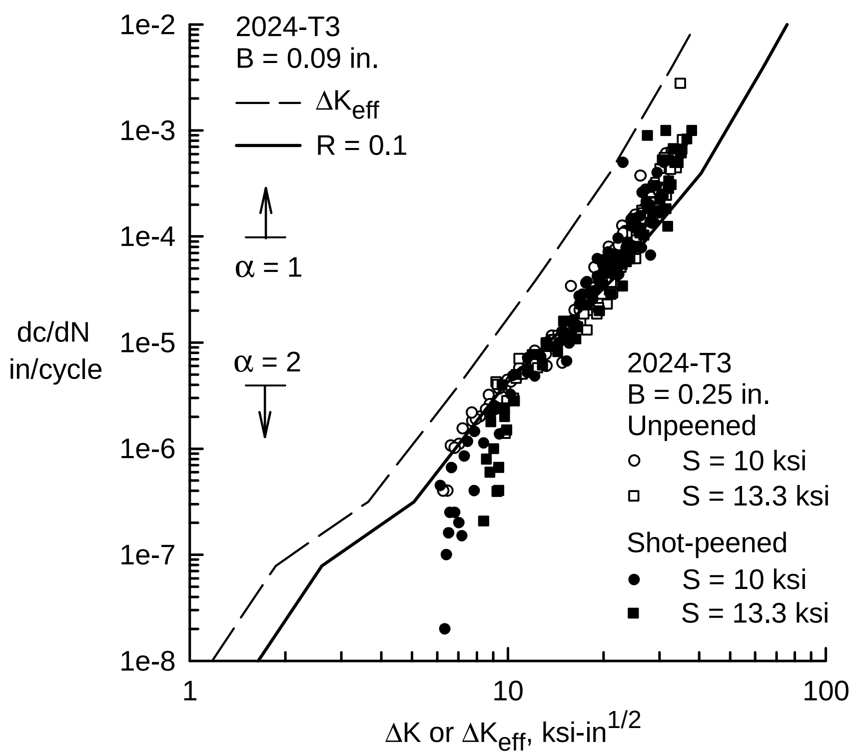

Figure 7. Crack growth rates for shot-peened specimens.

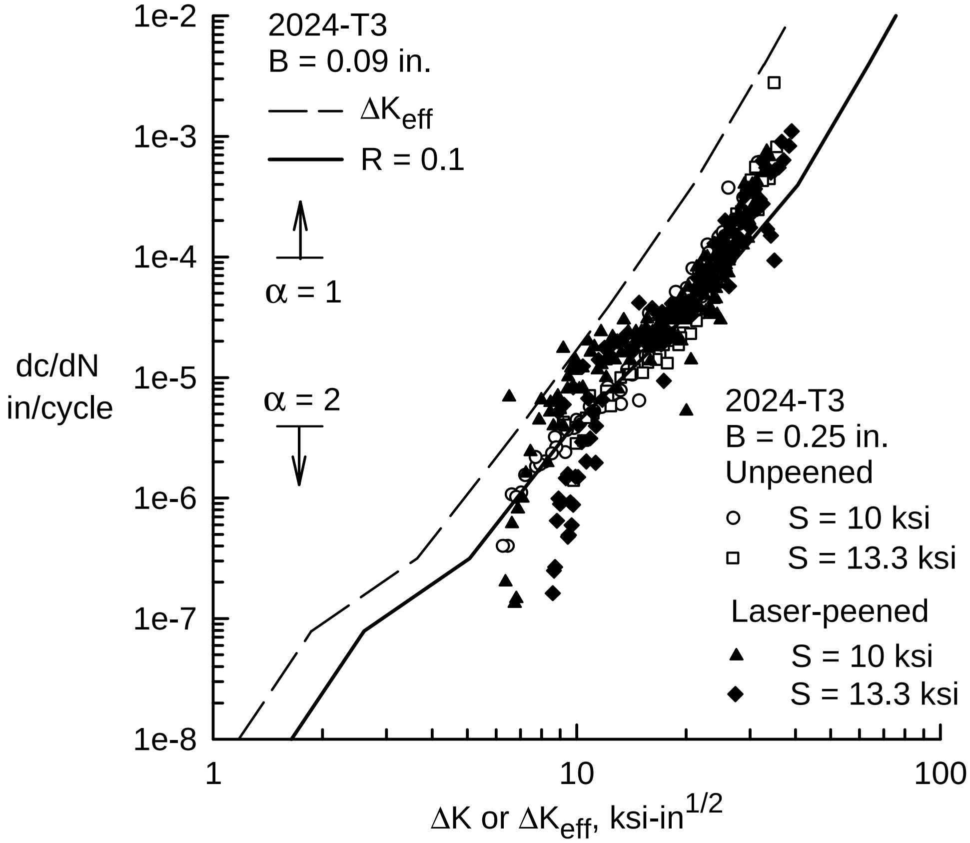

Figure 8. Crack growth rates for laser-peened specimens.

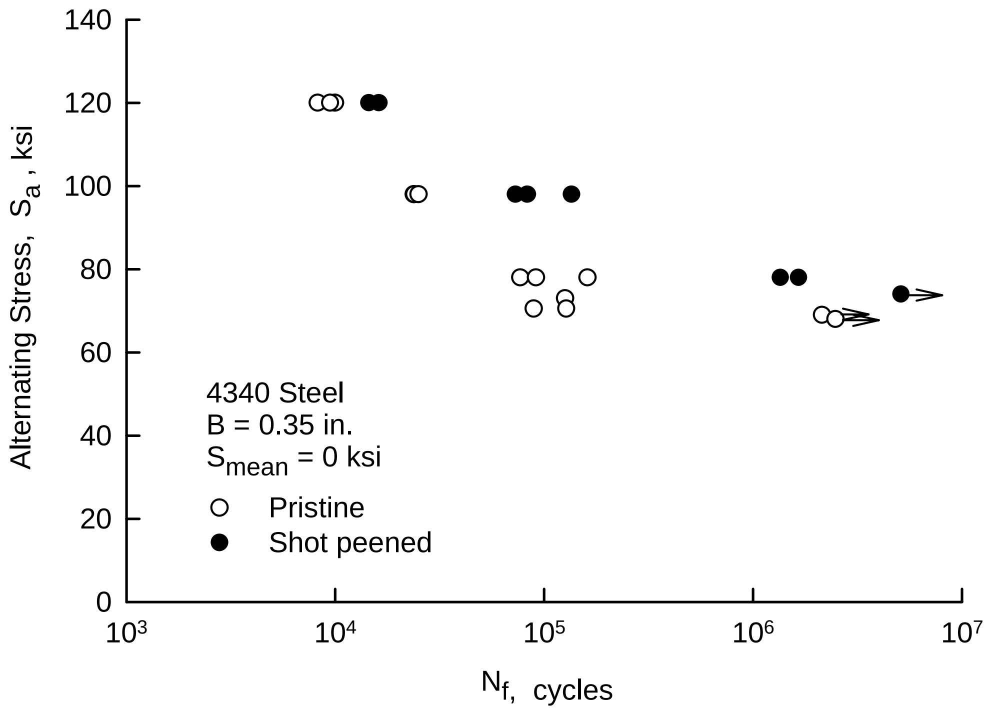

Figure 9. Fatigue life of pristine and shot-peened specimens for 4340 steel. (arrows indicate runout).

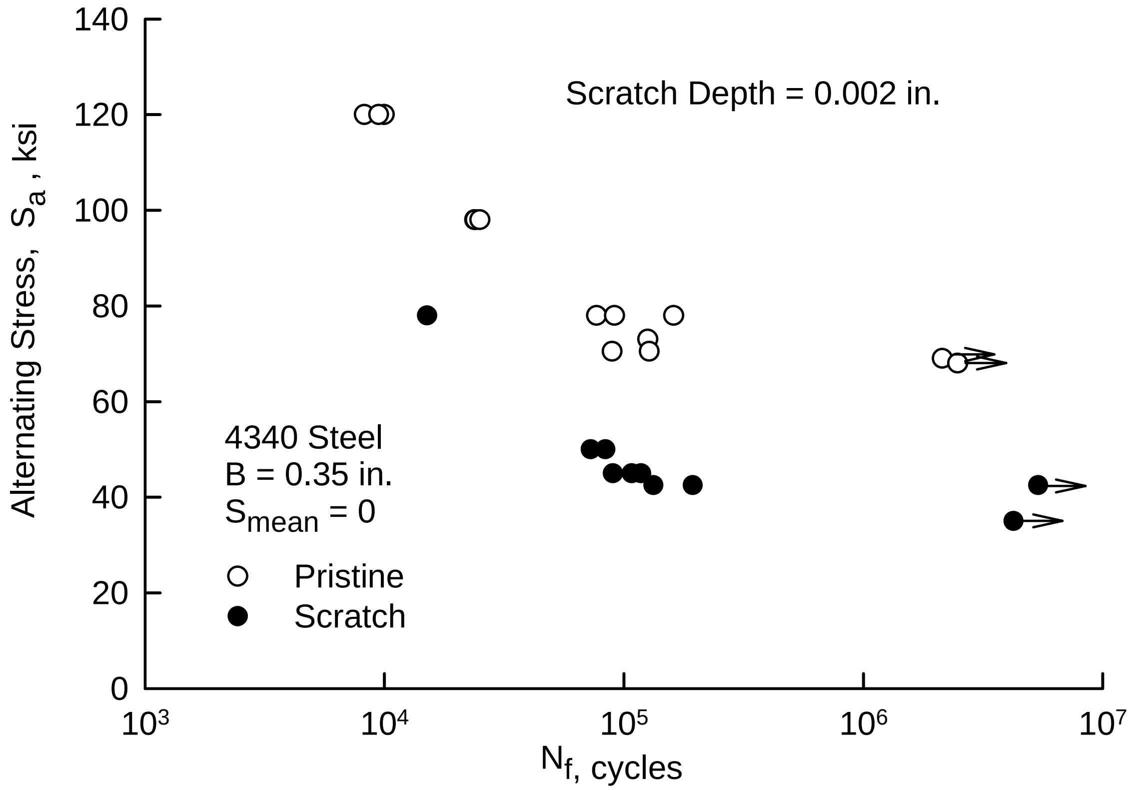

Figure 10. Fatigue life of pristine and scratch specimens (arrows indicate runout).

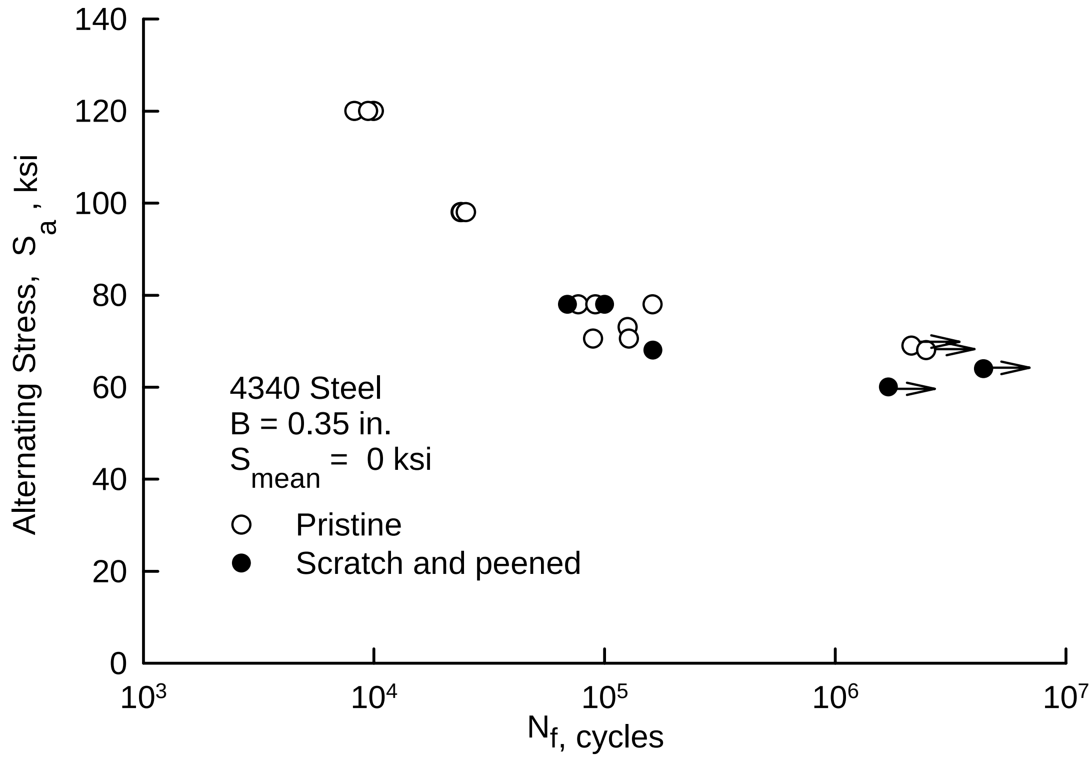

Figure 11. Fatigue and life of pristine and scratch-peened specimens (arrow indicates runout).

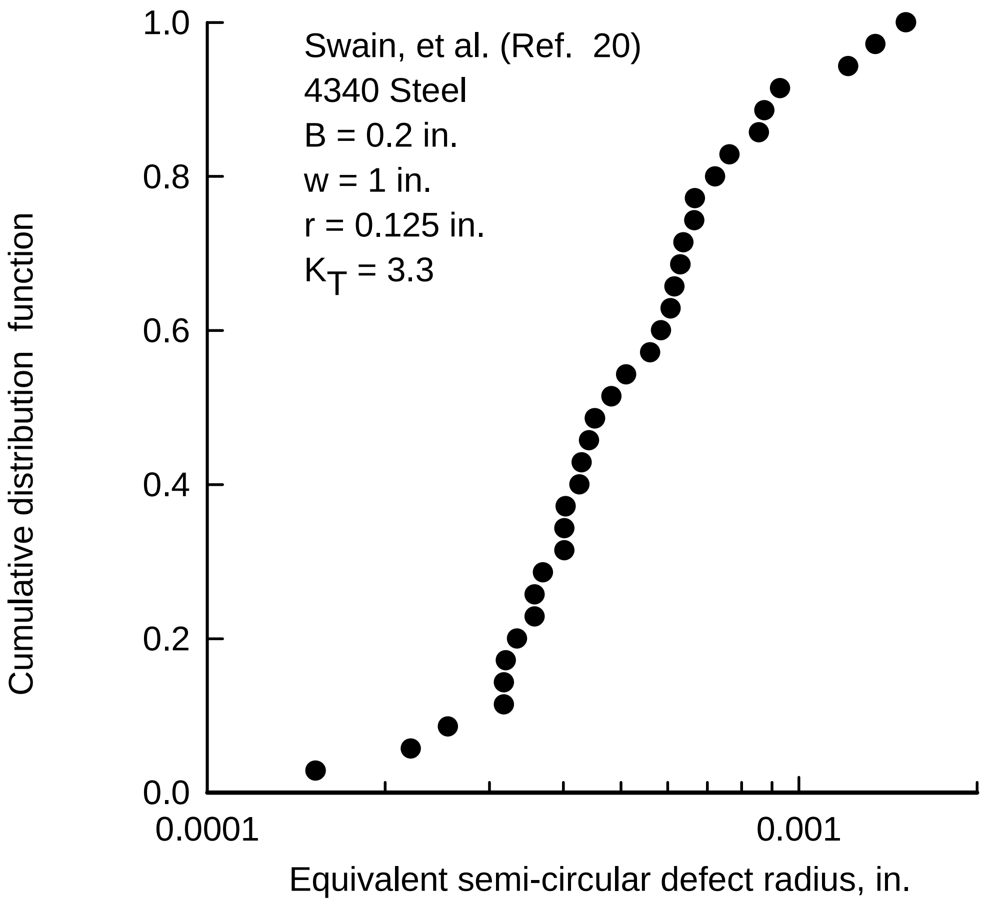

Figure 12. Cumulative distribution function for initiation sites in 4340 steel.

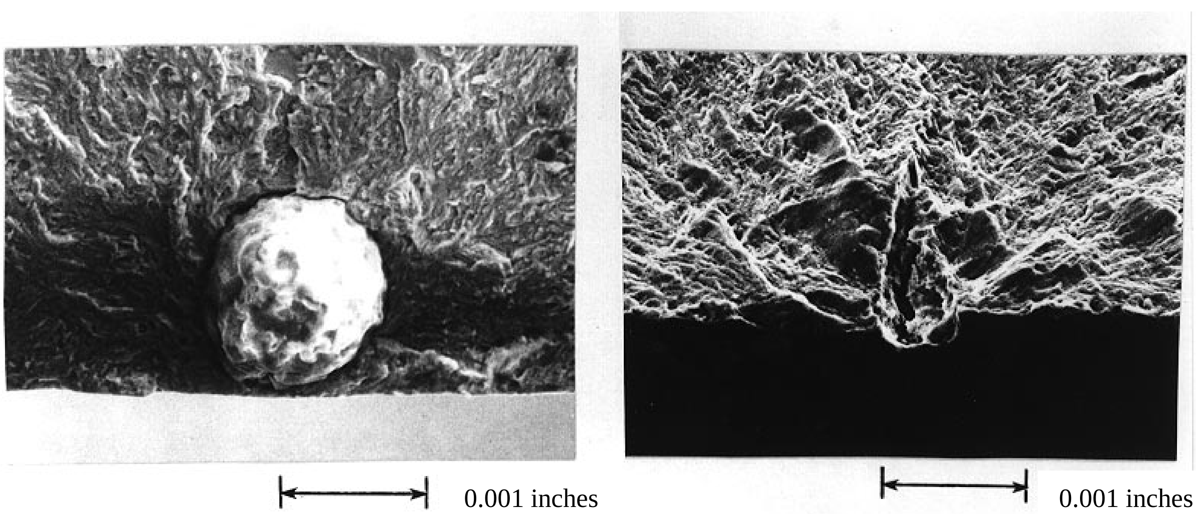

Figure 13. Crack initiation sites at spherical-inclusion particle and stringer in 4340 steel.

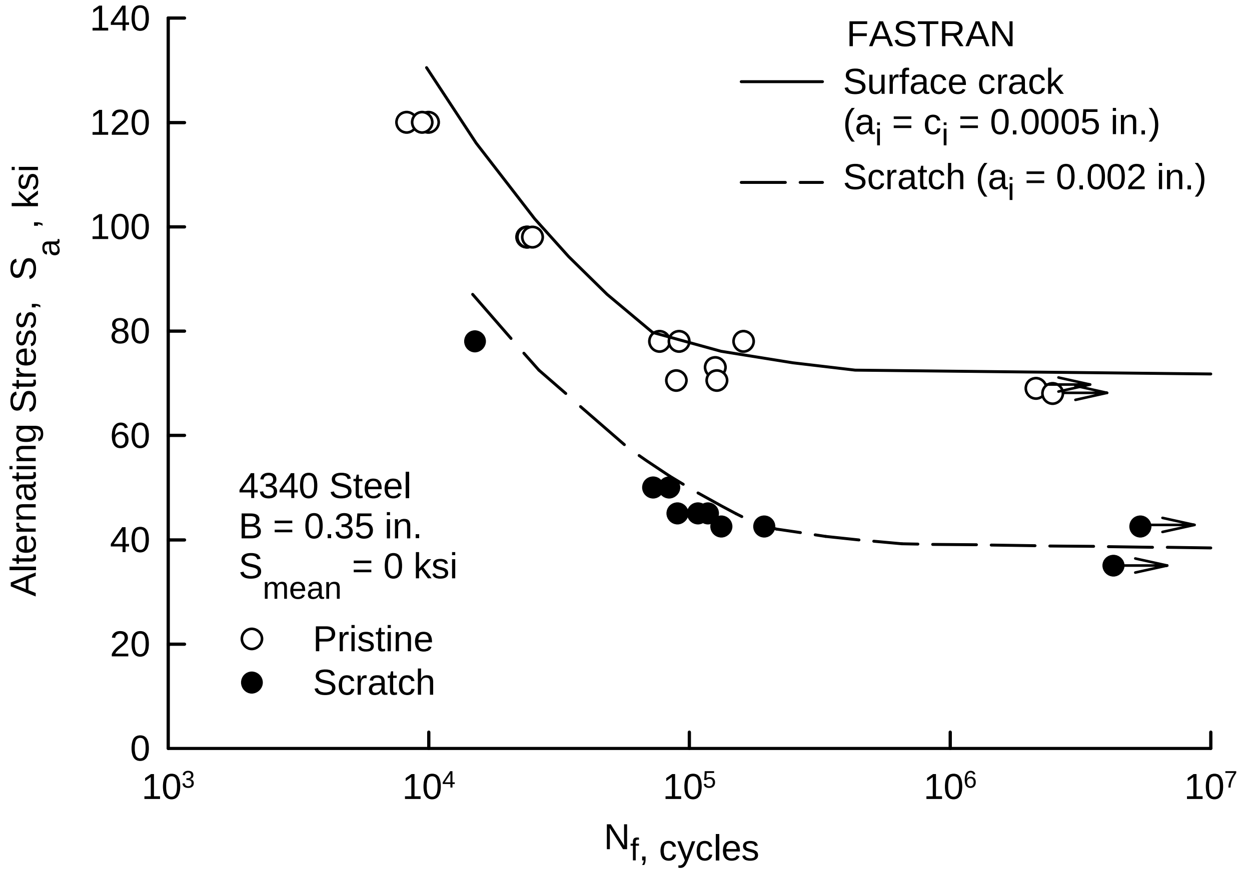

Figure 14. FASTRAN prediction of S-N behavior of pristine and scratch specimens (arrows indicate runout).

APPENDIX I

Stress-Intensity Factors

The stress-intensity factor (K) equations for a through crack and a corner crack emanating from a single notch in the double-edge-notch specimen, as shown in Figure A1, are developed herein. The FADD2D code (Ref. 23) was used to obtain the stress-intensity factors for a through crack and an engineering estimate (Ref. 24) was used to develop the stress-intensity factors for the corner crack. The FADD2D code is a boundary-element analysis. For the corner crack, the engineering estimate was based on previous finite-element analyses and equations for corner cracks at a hole in an infinite plate subjected to remote tensile stress (Ref. 25.)

Through crack at semi-circular edge notch:

The FADD2D code was used to analyze a single through crack emanating from one of the notches in the double-edge-notch specimen. The specimen was subjected to either remote uniform stress or uniform displacement. The normalized stress-intensity factor or boundary-correction factor (F) for these two cases are shown in Figure A2. Because the test specimens were loaded with hydraulic grips, a uniform displacement at the grip ends was suspected to be the most appropriate boundary conditions. An equation for the stress-intensity factor for a through crack was developed to fit the numerical calculations (circular symbols in Fig. A2). The equation is given by

$$K = S\,(\pi c)^{1/2}\,F \qquad (1)$$

where $F = f_1\, g_1\, f_w$ for $c/r \leq 3.5$. The function f_1 and g_1 account for the notch behavior and f_w accounts for the finite-width effect. Equations for the f_1, g_1, and f_w functions are:

$$f_1 = 1 + 0.358\,\lambda + 1.425\,\lambda^2 - 1.578\,\lambda^3 + 2.156\,\lambda^4 \quad \text{where } \lambda = 1 / (1 + c/r)$$

$$g_1 = K_T\,[0.36 - 0.032/(1 + c/r)^{1/2}] \quad \text{where } K_T = 3.05$$

$$f_w = 1 + 0.61\,\gamma + 3.46\,\gamma^2 - 7.55\,\gamma^3 + 5.82\,\gamma^4 \quad \text{where } \gamma = c / (w - 2r).$$

Equation (1) is shown as the solid curve in Figure A2 and is within about 1 percent of the numerical calculations from the FADD2D code.

Corner crack at semi-circular edge notch:

In lieu of conducting fully three-dimensional analyses for a corner crack emanating from the double-edge-notch specimen (Fig. A1(b)), an approximate method was used to estimate the K solutions. The approach was to take the ratio of the corner-crack (K_{cc}) solution to the through-crack (K_{tc}) solution for the same crack length, c, emanating from a hole in an infinite body subjected to remote applied stress. Then the stress-intensity factor for a corner crack at the edge notch can be estimated by multiplying the K_{cc}/K_{tc} ratio times the stress intensity factors for the through crack at the edge notch (Fig. A1(a)).

The stress-intensity factor for a corner crack at a hole was obtained from Newman and Raju (Ref. 25) and the through-crack solution from Newman (Ref. 26). Because the crack-growth analysis for the corner crack was treated as an average crack-growth process, the K values at the 10 and 80-degree locations were averaged to calculate Kcc. The K_{cc}/K_{tc} ratios for various corner-crack shapes (a/c ratios) are plotted in Figure A3 as symbols. An expression was chosen to fit these numerical values and the ratio is given by

$$K_{cc}/K_{tc} = 0.8 + 0.2\,a/B - 0.2\,(1 - a/B)\,(a/c) - 0.05\,(1 - a/B)^{15} \qquad (2)$$

Using equation (2), the K_{cc}/K_{tc} ratio approaches unity as the corner crack becomes a through crack (a/B = 1).

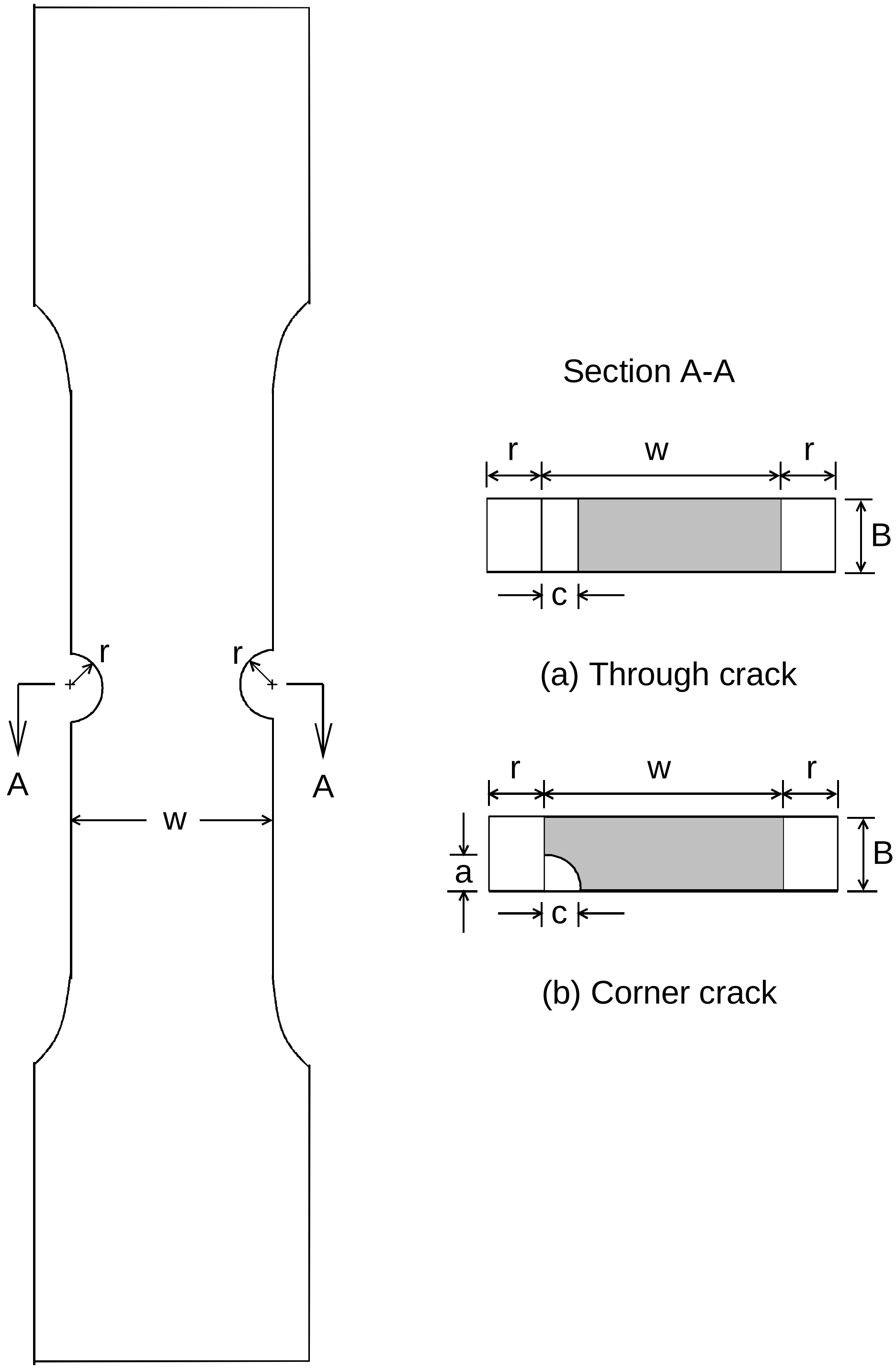

Figure A1. – Double-edge-notch tensile specimen.

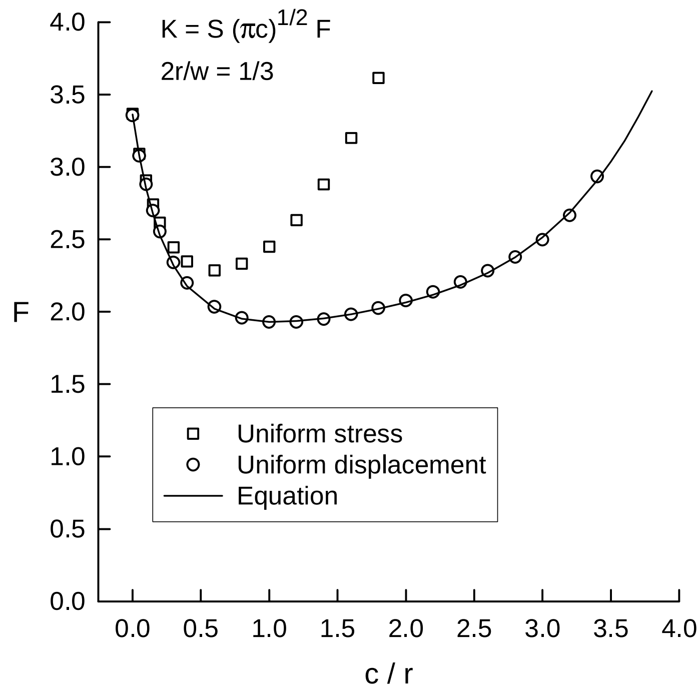

Figure A2. – Normalized stress-intensity factors for a through crack at an edge notch in the double-edge-notch tensile specimen.

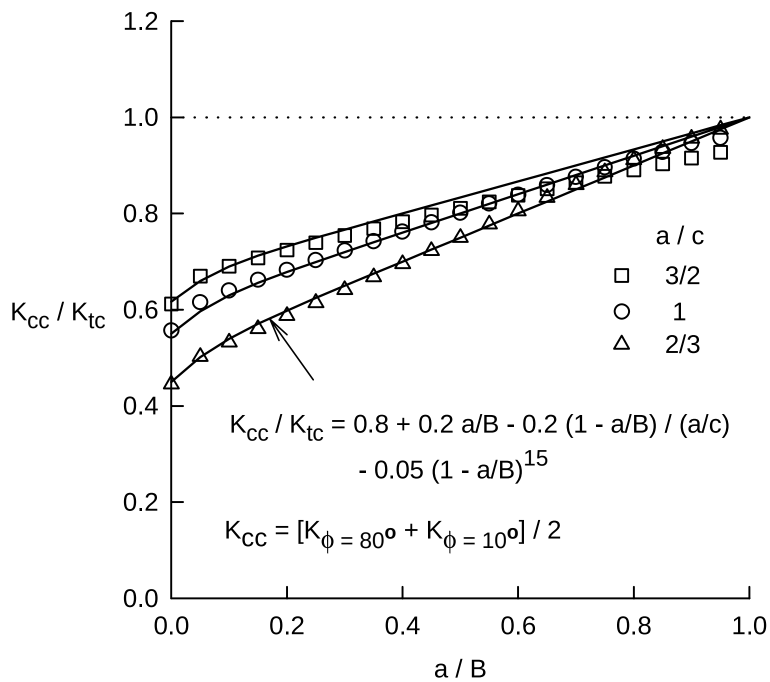

Figure A3. – Ratio of stress-intensity factors for corner crack and through crack at a hole in an infinite plate subjected to remote applied stress.

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R. A. Everett, Jr., W. T. Matthews, R. Prabhakaran, J. C. Newman, Jr., and M. J. Dubberly

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13. ABSTRACT *(Maximum 200 words)*
Fatigue and crack growth tests have been conducted on 4340 steel and 2024-T3 aluminum alloy, respectively, to assess the effects of shot peening on fatigue life and the effects of shot and laser peening on crack growth. Two current programs involving fixed and rotary-wing aircraft will not be using shot peened structures. Since the shot peening compressive residual stress depth is usually less than the 0.05-inch initial damage tolerance crack size, it is believed by some that shot peening should have no beneficial effects toward retarding crack growth. In this study cracks were initiated from an electronic-discharged machining flaw which was cycled to produce a fatigue crack of approximately 0.05-inches in length and then the specimens were peened. Test results showed that after peening the crack growth rates were noticeably slower when the cracks were fairly short for both the shot and laser peened specimens resulting in a crack growth life that was a factor of 2 to 4 times greater than the results of the average unpeened test. Once the cracks reached a length of approximately 0.1-inches the growth rates were about the same for the peened and unpeened specimens. Fatigue tests on 4340 steel showed that the endurance limit of a test specimen with a 0.002-inch-deep machining-like scratch was reduced by approximately 40 percent. However, if the "scratched" specimen was shot peened after inserting the scratch, the fatigue life returned to almost 100 percent of the unflawed specimens original fatigue life.

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