## ABSTRACT

Smooth axial crack initiation fatigue tests were conducted to determine the difference in fatigue strength between large forging and small diameter barstock materials for steel currently employed in fatigue applications at Sikorsky. A~~n~~ [redacted] Shaft (forged E4340 heat treated to $R_c$ 44-48 after rough machining) and one-inch diameter barstock (E4340 heat treated to $R_c$ 43-46, min. 200 ksi $F_{tu}$) were compared. These materials were electric furnace air melted steels as are currently used at Sikorsky for fatigue applications. In addition, the effects of polished and shot peened surface finishes were evaluated on both forging and barstock materials.

This testing was conducted employing a specimen design, steady stress level and shot peening to be comparable with previous tests of titanium Ti-6Al-4V alloy forgings and barstock. END

It was determined that:

- The forging material had a mean fatigue strength 17% lower than the barstock material tested (for the polished surface finish at + 45 ksi steady stress and $10^8$ cycles).
- Shot Peening (#110 shot, .008-.012A intensity) significantly increased the fatigue strength (12% improvement in mean value at $10^8$ cycles) of this forging material but had only a slight beneficial effect on the barstock material.
- The forging material tested herein exhibited a banded microstructure associated with segregation of alloying elements traceable to the starting ingot. This segregation would primarily effect the hardenability of the steel. An average equivalent hardness difference of 7.4 $R_c$ was determined between adjacent regions in the banded structure of forging test specimen material. Four of six failed fatigue specimens examined were determined to have origin locations in the "light" microstructural (mixed martensitic-ferritic) region.
- A fatigue strength comparison, corrected for density differences, was made to Ti-6Al-4V annealed forgings. It was determined that E4340 material is superior to annealed conventionally forged Ti-6Al-4V in large forged components, such as the [redacted]. However, large Ti-6Al-4V forgings produced in a combination "forged-extrusion" process by [redacted] exhibits a fatigue strength which is superior to E4340 within the normal range of working steady stresses.

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## DATE AND PLACE

The testing reported herein was conducted in the Materials and Process Test Engineering and Operations Laboratory from March to October, 1968.

## PURPOSE

A. To compare the crack initiation fatigue strength of E4340 steel from forgings and barstock, (for the min. 200 ksi U.T.S. heat treat condition).

B. To determine the effect of shot peening on the crack initiation fatigue strength of E4340 as compared to a polished surface finish.

C. To compare results of these tests to those known for the Ti-6Al-4V titanium alloy.

## INTRODUCTION

Sikorsky results on axial fatigue tests of material specimens of Ti-6Al-4V titanium alloy have shown a decrease of approximately 50% in the mean crack initiation fatigue strength of conventionally forged annealed material as compared to small diameter barstock. This comparison is at +45 ksi steady stress and $10^8$ cycles. Shot peened and polished surface finishes on Ti-6Al-4V have been shown to result in equal fatigue lives at about $10^7$ cycles or higher.

Since Ti-6Al-4V has been substituted for E4340 steel in many applications, it is of interest to determine what decrease, if any, occurs in E4340 (at the min. 200 ksi U.T.S. heat treat level) between forgings and barstock. Use of the Ti-6Al-4V alloy as a substitute for E4340 was initially based on the test results for small diameter barstock. Using values based on the testing of forged material may reveal the E4340 to be a better material.

The tests performed herein determined the fatigue strength of E4340 forging and barstock material and compared these values to published small diameter barstock fatigue properties. Polished and shot peened surfaces were evaluated for their effect on the fatigue characteristics of these materials.

To provide data comparisons, the specimen design, steady stress level and shot peening employed for the steel specimens were identical to that of the Ti-6Al-4V materials tested previously.

## APPARATUS

1. Sonntag SF-1-U Fatigue Test Machines with 5:1 Load Amplifiers
2. Baldwin IV-12 Fatigue Test Machine
3. Ellis BA-12 Bridge Amplifier and Oscilloscope Console
4. Riehle PS-60 Universal Testing Machine
5. Wiediman, 1-inch Extensometer, T2M-87
6. American Optical Company Metallograph, Model 2400
7. Fatigue Test Fixtures, Flat Threaded End Plate Type, as shown in Figure 4.
8. Wilson Tukon Hardness Tester
9. Wilson Rockwell Hardness Tester, Model 5-JR-BB

# METHODS AND PROCEDURES

## A. Fatigue Tests:

### 1. Material Preparation and Processing:

All materials evaluated herein were electric furnace air melted E4340 steel to comply with Reference (a), which is the condition currently employed for fatigue applications of this alloy at Sikorsky.

#### (a) Forging Material:

An [redacted] Shaft, Reference (b) was obtained in the finish machined condition. This part was rejected for machining defects. However, the material condition was in accordance with drawing requirements. The processing history from cast billet to finished part is presented in Table I. The as-forged and the rough machined size at the time of final heat treatment as reported by the Dayton Forging and Heat Treating Co. are presented in Figure 1. The part drawing specifies heat treatment to $R_C$ 44-48 per Reference (c). This shaft was normalized prior to the heat treat operation as designated by its part number. The rough machined and heat treated part was then shipped to the Beuhler Corp. (Indiana Gear Works), for finish machining.

#### (b) Barstock Material:

One-inch diameter annealed E4340 bar, to comply with Reference (a) was obtained and tested. Specimens were rough machined to the dimensions of Figure 2, and then quenched and tempered at Sikorsky to $R_c$ 43-46 (min. 200 ksi Ftu) in accordance with Reference (c).

### 2. Test Specimens:

#### (a) Specimen Design:

Specimens were of the standard smooth axial crack initiation type, machined to the requirements of Reference (d), as shown in Figure 2. This specimen design has been used previously in all Sikorsky smooth axial titanium forging fatigue testing, including References (e) and (f).

## METHODS AND PROCEDURES (Cont'd)

### A. Fatigue Tests: (Cont'd)

### 2. Test Specimens: (Cont'd)

#### (b) Specimen Location:

Specimen locations in the finish machined drive shaft were as shown in Figure 3. All specimens were located with their major axis in the longitudinal direction in the shaft and barstock materials.

#### (c) Final Surface Finish Preparation:

After finish machining the specimens to the dimensions of Figure 2, all specimens were hand polished with silicon carbide abrasive paper in the critical test section with the final operations as follows:

1) Polish circumferentially with 600 grit silicon carbide paper.

2) Final polishing longitudinally with 600 grit paper, all previous machining and polishing marks were removed.

After the final polishing operation, one-half of the forging material specimens and one-half of the barstock material specimens were randomly selected for shot peening in the critical test section with #110 steel shot, to an .008-.012 A intensity per Reference (g). This shot peening operation is identical to that employed on most of Sikorsky's titanium fatigue specimens, including those of References (e) and (f).

### 3. Test Setup:

Testing was axial and was performed on Sonntag SF-1-U fatigue test machines with 5 to 1 load amplifiers and on an IV-12 fatigue test machine. The grip end setup was the same on both machines and employed threaded end plates, shown schematically in Figure 4. This setup permitted tension tension or tension/compression loadings to be applied to the specimens.

A Sikorsky load cell was placed in series with the test specimen and loads were determined with an Ellis BA-12 Bridge Amplifier and Oscilloscope Console. The load cells were recalibrated every two months during the test program duration on the Riehle PS-60 Universal Testing Machine using a digital strain indicator. The resistance calibration ($R_{cal}$) equivalent load value was determined during the static calibration and utilized to correct for instrument sensitivity when using the Ellis console.

## METHODS AND PROCEDURES (Cont'd)

## A. Fatigue Tests: (Cont'd)

### 4. Test Conditions:

#### (a) Stress Levels:

All testing was conducted at a constant steady stress level of +45 ksi. This steady stress level was employed in the titanium testing of References (e) and (f).

Specimens of all material conditions were tested at ±70 and ±60 ksi with various other vibratory stress levels employed for each specimen condition to obtain failures in the range of $4 \times 10^4$ to $2 \times 10^7$ cycles.

Specimen tests at the ±90 ksi stress level were conducted only on the IV-12-2 machine, since this loading exceeded the capacity of the Sonntags for the specimen design employed. Testing at stress levels of ±80 ksi or lower was conducted on both machines. The Sonntags operate at 1800 rpm while the IV-12 machines operate at 1200 rpm. This difference in test frequency is small and is known not to influence test results. The machine on which each specimen was tested is tabulated in Table II.

#### (b) Environment:

No special environments were employed, only the usual laboratory variation in temperature and humidity were encountered. Temperature and relative humidity readings were taken twice daily during the test program duration using a Bendix Model #566 Psychrometer. Temperature was found to vary from 70 to 83°F and humidity exhibited a range of 12 to 71% during the test program duration.

#### (c) Randomization:

The testing sequence and stress level assigned to the specimens were arrived at by use of a random selection for the forging and barstock, polished or shot peened surface specimen conditions.

## METHODS AND PROCEDURES (Cont'd)

### B. Tensile Tests:

Standard smooth (type R-3, one-inch gage length) tensile test specimens were prepared to the dimensions specified in Reference (h). Specimens were located at sections A and D in the shaft as shown in Figure 3. Some additional tensile specimens were obtained in sections B and C by remachining runout fatigue test specimens. Tensile specimens from the barstock were machined from the rough machined and heat treated specimen blanks shown in Figure 2. Tensile testing was performed in accordance with the procedures of Reference (h).

### C. Metallurgical Study:

#### 1. Macrostructural and Microstructural Appearance:

The macrostructural and microstructural appearances were obtained in the longitudinal and transverse directions for both forging and barstock materials.

#### 2. Hardness Values:

Tukon and Rockwell hardness values were obtained on a number of failed barstock and forging fatigue test specimens to insure conformity of the test specimens to proper heat treatment. An $R_C$ range of 43-46 is normally specified for the min. 200 ksi U.T.S. heat treat condition. An $R_C$ range of 44-48 was specified on the forging drawing, Reference (b).

#### 3. Failure Analysis:

All failed fatigue specimens were visually examined (< 50X) to determine the mode of failure, origin location and the extent of fatigue crack propagation. Some failed forging fatigue test specimens were further examined metallographically to determine the failure origin site.

#### 4. Chemical Composition Check:

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The chemical composition of the forging and barstock material was determined and compared to the requirements of Reference (a). Sulfur and Phosphorus contents were determined at the Bridgeport Testing Laboratory. Carbon content was determined at the Sikorsky Bridgeport Quality Control Laboratory. The remaining analyses were conducted in the Stratford M & P Laboratory using the wet chemistry method.

METHODS AND PROCEDURES (Cont'd)

C. Metallurgical Study: (Cont'd)

4. Chemical Composition Check: (Cont'd)

Several failed fatigue specimens were examined at the U.A.C. Research Laboratory with an electron probe microanalyzer to determine the chemistry of the "light" and "dark" regions which were exhibited in the microstructure of the forging material.

# ANALYSIS AND RESULTS

## A. Fatigue Tests:

### 1. Method of Fatigue Data Analysis:

The mean S/N curve through the fatigue test data points was determined according to the general procedures of Reference (i). Two S/N curve shapes were employed, the constants established are tabulated in Table III. The same S/N curve shape was employed in the analysis of the forging and barstock specimens tested with the polished surface finish. Similarly, another S/N curve shape was employed in the analysis of the forging and barstock specimens tested with the shot peened surface.

### 2. Summary of Fatigue Test Results:

Tabulated results for the fifty-five (55) fatigue tests performed are presented in Table II. Figures 5 to 8 present S/N graphs of the data and the mean S/N curve determined for each specimen condition. Figure 9 presents a comparison of the S/N curves determined for the specimen conditions. Table III summarizes the mean fatigue strengths, sample coefficients of variation and curve shape constants employed.

### 3. Statistical Analysis of Fatigue Test Results:

Statistical tests for the significance of the difference between the mean fatigue strengths at $10^8$ cycles were performed in accordance with Reference (j). Forging and barstock, polished and shot peened surfaces, and machine setups were tested for significant differences in fatigue strength, results are presented in Table IV.

### 4. Comparisons to the Ti-6Al-4V Alloy and to Published E4340 Data:

Pertinent results for which valid comparisons could be drawn for Ti-6Al-4V forgings and barstock, polished and shot peened surfaces were presented in Reference (f), as shown in Figure 10.

The E4340 materials tested herein are compared in Figure 11 to Mil-Hdbk-5A values for barstock. The barstock fatigue strength determined herein was closely comparable to the published data considering the slightly different tensile strength.

Figure 12 presents a comparison of E4340 and Ti-6Al-4V forging materials corrected to the density of steel.

## ANALYSIS AND RESULTS (Cont'd)

### B. Tensile Tests:

The results of tensile tests of forging and barstock material are presented in Table V. Also presented are minimum design values for tensile properties from Reference (k). The material evaluated herein meets the minimum properties expected. The tensile properties at sections A and D of the forging were slightly higher than those at sections B and C. The section thickness at B and C at the time of heat treatment was greater than that of sections A and D, refer to Figure 1.

### C. Metallurgical Study:

#### 1. Macrostructural and Microstructural Appearance:

The macrostructural appearance typical of the forging material is shown in Figure 14 for sections of the forging where tensile and fatigue specimens were located. Also shown in Figure 14 is the appearance of the barstock.

The microstructural appearance of the forging material exhibited "light" and "dark" banded regions.

The "dark" region consisted of a uniform tempered martensitic structure while the "light" region consisted of a mixed structure of tempered martensite and "blocky ferrite" as shown in Figure 15. The barstock exhibited the uniform tempered martensitic structure which is desired for optimum mechanical properties. The martensitic appearance of the forging material was slightly coarser than that of the barstock.

Figure 16 presents the appearance of the inclusions, which were typically of the oxide or silicate shape, as they appeared in the forging and barstock materials. The photographs shown illustrate about the most severe cases of inclusions observed in these materials. Occasional cases of larger single inclusions were observed in the forging material. As previously mentioned, these materials were electric furnace air melted. The slightly elongated inclusions observed in the forging material followed the banded structure (transverse section) and were observed in both "light" and "dark" microstructural regions. In this forging, the inclusion direction was observed to deviate by up to about 45° from the longitudinal direction in the axial fatigue specimen material. The barstock inclusions were usually highly strung out in the longitudinal direction of the bar.

The results of an inclusion rating, conducted in accordance with Referenc (1), Method C, showed a rating of 6-0, 3-S for the forging and 1-0, 4-S, for the barstock material. There are no specified limits for microexamin

## ANALYSIS AND RESULTS (Cont'd)

### C. Metallurgical Study: (Cont'd)

### 1.. Macrostructural and Microstructural Appearance: (Cont'd)

tion of inclusions in E4340 material procured to the requirements of Reference (c). The inclusion ratings obtained for this material are considered typical of large forgings and small diameter barstock of E4340.

### 2. Hardness Values:

Rockwell hardness values obtained on ten (10) forging material fatigue specimens exhibited an average value of 43.4 $R_C$. Hardness values obtained on ten (10) barstock material fatigue specimens exhibited an average value of 45.4 $R_C$.

Tukon microhardness readings were obtained on six (6) failed forging fatigue specimens, resulting in an average equivalent value of 40.9 $R_C$ in the "light" region of the microstructure. An average equivalent value of 48.3 $R_C$ was obtained in the "dark" region of the forging microstructure. The resultant difference in hardness between "light" and "dark" regions of the forging microstructure was, therefore, equivalent to 7.4 $R_C$. The microhardness average readings as obtained on the individual forging fatigue specimens are presented in Table VI.

Microhardness values were also obtained on shot peened barstock and forging material in an effort to determine whether the surface cold working would measurably increase the hardness. Tukon readings were obtained at 0.002-inch increments to a depth of 0.020 inch below the shot peened surface. The barstock material showed no measurable microhardness increase in the surface layers affected by shot peening. Similarly, microhardness readings in both "light" and "dark" regions of the forging microstructure obtained in a similar manner could show no measurable increase in hardness due to shot peening for either type microstructure. The microhardness values were more difficult to evaluate in the "light" region of the forging microstructure due to a considerable scatter in readings.

### 3. Failure Analysis:

All failed fatigue specimens were examined and determined to have fatigue failure modes. All fatigue origins were in material subject to 80% or higher of the maximum stress applied to a specimen. The region of fatigue crack propagation was typically 1/8 to 1/2 of the specimen fracture area.

ANALYSIS AND RESULTS (Cont'd)

C. Metallurgical Study: (Cont'd)

3. Failure Analysis: (Cont'd)

Many origin locations were unidentifiable (smeared) since the rigid grip end setup employed allowed the specimen fracture surfaces to impinge upon each other during machine shutdown. Almost all failed fatigue specimens exhibited single fatigue origins.

For the polished surface specimens, all origin locations which were identified were at the surface of the specimens.

For the shot peened surface specimens, most origin sites which could be identified were subsurface, typically .010 to .025 inch below the surface. Some specimens exhibited origin sites further below the surface than the range of values given above.

Typical examples of failed forging and barstock fatigue specimens are presented in Figures 17 and 18.

Six (6) failed forging fatigue specimens were further examined by sectioning techniques to determine if the fatigue origin site was in "light" or "dark" region of the microstructure. In four of the six specimens examined, the origin site was in the "light" region. The microstructural appearance near the fatigue origin sites for three (3) failed forging fatigue specimens are presented in Figures 19 to 21. These specimens (B2, B4, and B7) were further examined for segregation of alloying elements as discussed below.

4. Chemical Composition Check:

The forging and barstock chemical analyses (gross section) are tabulated in Table VII with comparison to the applicable chemistry requirements of Reference (c).

Failed forging fatigue specimens B2, B4, and B7 were sectioned through the fatigue origin sites and analyzed for the chemical segregation of alloying elements associated with the banded structure. The results of an electron microprobe analysis for alloying element segregation near the fatigue origin sites for these specimens is presented in Table VII.

Tukon microhardness values for these specimens near the fatigue origin locations are presented in Table VI. The microstructural appearance near the fatigue origin sites are presented in Figures 19 to 21.

## DISCUSSION

### A. Forging and Barstock Fatigue Properties:

The E4340 forged material (heat treated to $R_C$ 44-48) had a 17% lower mean fatigue strength than the one-inch diameter E4340 barstock evaluated herein for the same heat treat level (min. 200 ksi $F_{tu}$) (at +45 ksi steady stress and $10^6$ cycles for the polished surface finish). This difference was statistically significant as shown in Table IV. The tensile strength ($F_{tu}$) of the forging fatigue specimen material was approximately 7% lower than that of the barstock tested, as shown in Table V.

The forging material's fatigue strength was significantly improved by shot peening as shown in Table IV. The shot peened forging materials' fatigue strength was then closely comparable to the Mil-Hdbk-5A (barstock) value as shown in Figure 11.

The lower fatigue strength determined for the E4340 forging material is further substantiated by previous tests employing R. R. Moore Rotating Beam fatigue specimens as reported in Reference (m) and shown in Figure 13. Previous Sikorsky R. R. Moore data for small diameter E4340 barstock has shown properties near the middle of the published scatter band as shown in Figure 13. The rotating beam specimens of Reference (m) were located in Sections A and D of the same shaft tested herein as shown in Figure 3. Sections B and C of the shaft had slightly lower tensile properties (due to the thicker section at the time of heat treatment) refer to Table V and it was in these sections that the axial fatigue specimens were located.

Test results for Ti-6A1-4V conventionally forged and annealed small test forgings and small diameter barstock are presented in Figure 10 as previously reported in Reference (f). The Ti-6A1-4V small test forgings exhibit a fatigue strength which is lower than the barstock, the value is highly dependent on the steady stress level employed. The fatigue strength of large Ti-6A1-4V forgings is considerably lower than that of the small test forging material as shown in Figure 10.

Also shown are values for the Ti-6A1-4V [redacted] "forged-extrusion" materials which exhibit considerably improved fatigue strengths for large forgings. As discussed in Reference (u), this material exhibits a crystallographic preferred orientation and considerable microstructural grain flow with resultant anisotropy of fatigue properties. Other large forgings of Ti-6A1-4V exhibit little or no preferred orientation or discernable microstructural grain flow and exhibit low fatigue strength in all test directions.

DISCUSSION (Cont'd)

Figure 12 presents a comparison of E4340 and annealed Ti-6A1-4V large forging fatigue strength values on an equivalent density basis. E4340 large forged material (air melted material with a banded microstructure and polished surface finish) is superior to Ti-6A1-4V annealed conventionally forged material. The [redacted] "forged-extrusion" materials are superior to E4340 within the normal range of working steady stresses. It should be reiterated that air melted steel and vacuum melted titanium materials have been compared. Substantial increases in fatigue strength have been determined for vacuum melted steels. Large steel forgings of the vacuum melt variety may result in fatigue strengths equivalent to the [redacted] Ti-6A1-4V materials. Also, the good properties associated with the [redacted] type materials may only be exhibited in the longitudinal direction of the "forged-extrusion". The radial direction has shown an approximate 25% lower fatigue strength as discussed in Reference (u). The [redacted] processing may be advantageous only in components such as cylindrical shafts, rods and spars which have principal stresses lining up with the longitudinal axis of the component.

## A. Metallurgical Factors:

The macrostructure and microstructure of the forging material tested herein exhibited a banded appearance. Banding in steels has been a long term occurrence and the phenomenon has been investigated in Reference (o). Banding in E4340 steel is caused by chemical heterogeneity. This condition arises from dendritic segregation of alloying elements in the steel during solidification of the ingot. Alloying element segregation is difficult to remove without special procedures. The normal forging and heat treatment procedures are usually insufficient to completely homogenize the material. Figure 15 illustrates the "dendritic like" appearance exhibited more prominently in the transverse section of the forged material. The "light" or mixed microstructure region was determined to be lower in alloying element composition, and the "dark" (interdendritic) structure correspondingly richer in alloying composition, refer to Table VII.

Controlled remelting of the ingot to produce a finer dendrite size by control of the solidification rate, additional working of the billet during its fabrication or "homogenization annealing" (Reference (o) stated that 100 hours at 2200° F would be sufficient) of the forging billet or similar procedures might be feasible to remove the segregation.

The principal effect of the alloying element segregation would be to alter the hardenability of the steel. The manganese, molybdenum and chromium segregation would be more influential in determining hardenability whereas the nickel segregation would exert little influence in this case. The appearance of "light" and "dark" banded regions in the microstructure and the difference measured in microhardness was caused by the differences in hardenability. For the same

DISCUSSION (Cont'd)

location in a quenched part, the region richer in alloying elements would transform to a higher percent martensite upon quenching and would result in a higher hardness upon tempering than the region leaner in alloying elements. Four of six fatigue specimen origin locations were identified to be in the "light" microstructural region. Published literature, including References (p), (q) and (r) have shown that in steels, microstructures high in percent martensite as-quenched exhibit higher fatigue strengths (both smooth and notched) than mixed pearlitic-ferritic structures at the same tensile strength.

Shot Peening significantly improved the fatigue strength of the forging material, but no increase in microhardness for either "light" or "dark" region of the microstructure could be detected in the shot peened surface layer. Residual stresses may exist between the martensitic and non-martensitic structures present in the "light" region and may contribute to the lower fatigue strength of this material.

The inclusion sizes and distribution in the bar and forging materials evaluated herein are considered typical for E4340 material. As discussed in Reference (s) inclusions in air melt material did determine the occurrence of the first crack which would initiate and had a direct influence on the fatigue strength characteristics of the steel. There was an approx. 25% improvement reported in fatigue strength due to vacuum melting for 4340 steel (approx. 230 ksi $F_{tu}$; R. R. Moore Rotating Beam Specimens) in Reference (s). In the comparison presented in Figure 13 it is usually observed that vacuum melted material would result in values in the upper half of the scatter band while air melt material would result in values in the lower half of the band. Results of fatigue tests on cryogenic stretched 301 type stainless steel tested for Reference (t) revealed an approx. 20 to 25% improvement (measured at $R = +0.10$ where $R$ = min. stress/max. stress) obtained in part by use of vacuum melted material.

## CONCLUSIONS

It is concluded that:

1. The [redacted] Shaft material (forged E4340) had a mean crack initiation fatigue strength 17% lower than one-inch diameter barstock (E4340) at the same heat treat level (min. 200 ksi, Ftu, at +45 ksi steady stress and $10^8$ cycles).

2. Shot peening (#110 shot, .008 - .012A intensity) significantly improved the fatigue strength of the forging material. The improvement was a 12% increase in mean fatigue strength (at +45 ksi steady stress and $10^8$ cycles) as compared to the polished surface finish.

3. Shot peening as employed above increased the fatigue life of barstock material specimens in the range of approx. $5 \times 10^4$ to $10^7$ cycles. Above about $10^7$ cycles, shot peened and polished surface finishes resulted in equal fatigue lives for the barstock.

4. The forging material exhibited a banded microstructure caused by segregation of alloying elements traceable to the starting ingot. An average equivalent hardness difference of 7.4 $R_c$ was determined between "light" and "dark" microstructural regions in fatigue test specimen material.

5. The size and occurrence of inclusions in the air melted materials evaluated herein are considered typical of large forgings and small diameter barstock of E4340.

6. **The fatigue strength of E4340 forging material evaluated herein (corrected for density) is superior to annealed Ti-6Al-4V material, fabricated by conventional forging techniques in the large forging size.**

7. **Large annealed Ti-6Al-4V forgings produced in a combination "forged-extrusion" process by [redacted] exhibit a fatigue strength (corrected for density) which is superior to E4340 within the normal range of working steady stresses.**

## RECOMMENDATIONS

It is recommended that:

1. The axial notched crack initiation fatigue strength of banded E4340 forged material be determined.

2. Shot peening be continued as a method of improving the fatigue strength of E4340 forged parts.

3. Suitable methods be employed to remove the alloy segregation present in forging billets of E4340.

4. Vacuum melted 4340 with controls exercised over inclusion size and occurrence should be evaluated for fatigue critical aircraft applications as one substitute for annealed conventionally forged Ti-6Al-4V in the large forging size.

5. **Additional fatigue strength investigations be conducted on [redacted] Ti-6A1-4V forged-extrusions.**

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(c) Mil-H-6875D, "Heat Treatment of Steels," March 31, 1967

(d) SLGNM-1454, Rev. A, "Material Fatigue Specimen, Fatigue Lab"

(e) SER-50563, "Fatigue Evaluation of Beta Forged Ti-6Al-4V," May 13, 1969

(f) SER-50578, "Fatigue Evaluation of Titanium Forging Alloys, Effect of Forging Macrostructures and Heat Treatments"

(g) Mil-S-13165, "Shot Peening of Metal Parts," Dec. 31, 1966

(h) Federal Test Method Standard #151a, Method 211.1 "Tension Test"

(i) STM C-4, "Method of Establishing Standard Mean S/N Curves with Known Material Constant"

(j) STM C-1, "Statistical Tests for the Significance of the Difference Between the Means of Two Sets of Test Data"

(k) Mil-Hdbk-5A, "Metallic Materials and Elements for Aerospace Vehicle Structures"

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(s) "Relation of Inclusions to the Fatigue Properties of SAE 4340 Steel," H. N. Cummings, F. B. Stulen, and W. C. Schulte, Trans. A.S.M. 1957 P. 482

(t) Preliminary ETP #0000-1128A, "Fatigue Crack Initiation of Cryogenic Formed 301 Stainless Steel" May 2, 1969

(u) TRR-9313, 'Fatigue Strength of Ti-6A1-4V ABC Spar materials", (to be published).

(v) Aerospace Structural Metals Handbook, Vol. I, Ferrous Alloys.

## TABLE I

### Processing History

### [redacted] Shaft

The starting material, E4340 per Reference (b) was obtained from the Green River Steel Co. , as a cast ingot of approx. 30 inches by 30 inches in cross section. It was press upset to an approx. 40-inch diameter round, then rolled to an approx. 12-inch square stock which was furnished to the Dayton Forge and Heat Treating Co. At Dayton Forge, the 12-inch square stock was press upset to an approx. 13 1/2-inch square and then forged to the size shown in Figure 1. The forging was then rough machined as shown in Figure 1 and heat treated to $R_c$ 44-48 per Reference (c). The heat treated part was then finish machined at the Beuhler Co. (Indiana Gear).

## TABLE II

1-5110

## Fatigue Test Results

| Test No. | Machine | Specimen No. | Material | Surface Finish | Vibratory Stress (± ksi) @ +45 ksi Constant Steady Stress | Cycles to Fracture ( x $10^6$ ) | Comments |
|---|---|---|---|---|---|---|---|
| 1 | S-6 | C7 | Forging | Polished | 60.0 | 0.233 | |
| 2 | S-6 | 19 | Bar | Polished | 60.0 | 1.946 → | Grip End Fracture |
| 3 | S-6 | 25 | Bar | Polished | 75.0 | 0.307 | |
| 4 | S-6 | B4 | Forging | Polished | 60.0 | 0.644 | |
| 5 | S-6 | B8 | Forging | Polished | 70.0 | 0.080 | |
| 6 | S-6 | B6 | Forging | Shot Peened | 70.0 | 3.280 | |
| 7 | S-6 | C10 | Forging | Polished | 55.0 | 0.132 | |
| 8 | S-6 | 28 | Bar | Shot Peened | 75.0 | 0.585 | |
| 9 | S-6 | C8 | Forging | Shot Peened | 60.0 | 6.563 | |
| 10 | S-6 | 1 | Bar | Shot Peened | 75.0 | 5.655 | |
| 11 | S-6 | 7 | Bar | Shot Peened | 70.0 | 8.170 | |
| 12 | S-6 | B1 | Forging | Shot Peened | 50.0 | 25.652 → | No Fracture |
| 13 | S-6 | B3 | Forging | Shot Peened | 60.0 | 14.936 | |
| 14 | S-6 | C3 | Forging | Polished | 50.0 | 27.914 → | No Fracture |
| 15 | S-6 | 16 | Bar | Shot Peened | 70.0 | 10.379 | |
| 16 | S-6 | 10 | Bar | Shot Peened | 65.0 | 13.844 | |
| 17 | S-6 | 24 | Bar | Polished | 70.0 | 0.157 | |
| 18 | S-6 | B5 | Forging | Shot Peened | 70.0 | 3.149 | |
| 19 | S-6 | C5 | Forging | Shot Peened | 55.0 | 25.348 → | No Fracture |
| 20 | S-6 | 17 | Bar | Polished | 70.0 | 10.247 | |
| 21 | S-6 | C6 | Forging | Polished | 70.0 | 0.115 | |
| 22 | S-6 | 14 | Bar | Polished | 65.0 | 5.139 | |
| 23 | S-6 | C9 | Forging | Shot Peened | 70.0 | 0.846 | |
| 24 | S-6 | B10 | Forging | Polished | 60.0 | 1.194 | |
| 25 | S-6 | 4 | Bar | Shot Peened | 60.0 | 20.573 → | No Fracture |
| 26 | IVY12-2 | B11 | Forging | Shot Peened | 70.0 | 10.476 | |
| 27 | IVY12-2 | 20 | Bar | Polished | 80.0 | 0.063 | |

## TABLE II (Cont'd)

## Fatigue Test Results (Cont'd)

| Test No. | Machine | Specimen No. | Material | Surface Finish | Vibratory Stress (± ksi) @ +45 ksi Constant Steady Stress | Cycles to Fracture ( x $10^6$ ) | Comments |
|---|---|---|---|---|---|---|---|
| 28 | IVY12-2 | 27 | Bar | Polished | 80.0 | 0.143 | |
| 29 | IVY12-2 | C4 | Forging | Shot Peened | 90.0 | 0.062 | |
| 30 | IVY12-2 | 15 | Bar | Shot Peened | 90.0 | 0.089 | |
| 31 | IVY12-2 | 22 | Bar | Shot Peened | 90.0 | 0.099 | |
| 32 | IVY12-2 | 12 | Bar | Polished | 70.0 | 7.244 | |
| 33 | IVY12-2 | B9 | Forging | Shot Peened | 90.0 | 0.048 | |
| 34 | IVY12-2 | 9 | Bar | Polished | 70.0 | 26.330 → | No Fracture |
| 35 | IVY12-2 | C11 | Forging | Polished | 60.0 | 11.138 | |
| 36 | IVY12-2 | C1 | Forging | Polished | 55.0 | 8.724 → | No Fracture |
| 37 | S-7 | B2 | Forging | Polished | 55.0 | 8.074 | |
| 38 | S-7 | 13 | Bar | Shot Peened | 75.0 | 3.233 | |
| 39 | S-7 | 21 | Bar | Shot Peened | 70.0 | 13.336 | |
| 40 | S-7 | 26 | Bar | Polished | 70.0 | 5.872 | |
| 41 | S-7 | C12 | Forging | Polished | 80.0 | 0.132 | |
| 42 | S-7 | 18 | Bar | Shot Peened | 70.0 | 3.639 | |
| 43 | S-7 | 3 | Bar | Shot Peened | 75.0 | 3.651 | |
| 44 | S-7 | 2 | Bar | Shot Peened | 65.0 | 18.882 → | Grip End Fracture |
| 45 | S-7 | B13 | Forging | Shot Peened | 60.0 | 22.385 → | No Fracture |
| 46 | S-7 | 2-23 | Bar | Polished | 65.0 | 19.043 → | Grip End Fracture |
| 47 | IVY12-2 | 5 | Bar | Shot Peened | 65.0 | 1.166 → | Grip End Fracture |
| 48 | S-7 | 11 | Bar | Polished | 65.0 | 20.000 → | No Fracture |
| 49 | IVY12-2 | C2 | Forging | Shot Peened | 60.0 | 11.981 | |
| 50 | IVY12-2 | 8 | Bar | Polished | 90.0 | 0.038 | |
| 51 | IVY12-2 | 6 | Bar | Polished | 80.0 | 7.229 | |
| 52 | IVY12-2 | 23 | Bar | Shot Peened | 80.0 | 0.208 | |
| 53 | S-7 | B7 | Forging | Polished | 55.0 | 1.930 | |
| 54 | S-7 | B14 | Forging | Polished | 50.0 | 20.000 → | No Fracture |
| 55 | IVY12-2 | B12 | Forging | Shot Peened | 55.0 | 20.777 → | No Fracture |

## TABLE III

## Fatigue Test Summary

| Material Condition | $\overline{E_T}$ (ksi) | $\overline{X}$ (ksi) | S (ksi) | S/$\overline{X}$ (%) | $\gamma$ | $\beta$ | $n$ |
|---|---|---|---|---|---|---|---|
| E4340 1" Dia. Barstock polished surface finish | 65.6 | 65.9 | 6.2 | 9.4 | .610 | .070 | 11 |
| E4340 1" Dia. Barstock shot peened surface | 63.3 | 66.0 | 2.6 | 4.0 | .330 | .200 | 12 |
| E4340 [redacted] Shaft Forging, polished surface finish | 54.5 | 54.7 | 5.4 | 9.6 | .610 | .070 | 10 |
| E4340 [redacted] Shaft Forging, shot peened surface | 58.6 | 61.2 | 3.5 | 5.7 | .330 | .200 | 9 |

$\overline{E_T}$ = mean fatigue strength at an infinite number of cycles

$\overline{X}$ = mean fatigue strength at $10^8$ cycles

S = sample standard deviation at $10^8$ cycles

S/$\overline{X}$ = sample coefficient of variation

$\gamma, \beta$ = constants for a particular material curve shape

$n$ = number of test data points included in the mean curve

# TABLE IV

## Results of Statistical Tests

| Variable Compared | Description of Test Parameters | $\overline{X}_1$ (ksi) | $N_1$ | $\overline{X}_2$ (ksi) | $N_2$ | Result of Type I ① "Z" test at 90% confidence | Type II "$\beta$" error ② probability | Comments |
|---|---|---|---|---|---|---|---|---|
| E4340<br>Forging vs. Barstock | Specimen from the forging ($\overline{X}_2$) vs. the barstock ($\overline{X}_1$) material. (Polished Surface) | 65.9 | 11 | 54.7 | 10 | The fatigue strength of the forging material is lower than the barstock by at least 7.8 ksi |  | The mean fatigue strength of the forging material is lower than the barstock material by 17% (for the polished surface). |
|  | Specimens from the forging ($\overline{X}_2$ vs. the barstock ($\overline{X}_1$ material. (Shot Peened Surface) | 66.0 | 12 | 61.2 | 9 | The fatigue strength of the forging material is lower than the barstock by at least 1.2 ksi |  | The mean fatigue strength of the forging material is lower than the barstock material by 7% (for the shot peened surface). |
| E4340<br>Polished vs. Shot Peened Surface | Polished surface finish ($\overline{X}_2$) vs. Shot peened surface finish ($\overline{X}_1$) specimens. (Barstock Material) | 66.0 | 12 | 65.9 | 11 | Shot peening did not significantly improve the fatigue strength of the barstock material. | 13 |  |
|  | Polished surface finish ($\overline{X}_2$) vs. Shot peened surface finish ($\overline{X}_1$) specimens. (Forging Material) | 61.2 | 9 | 54.7 | 10 | Shot peening significantly raised the fatigue strength of the forging material by at least 3.0 ksi. |  | Shot Peening of Forging Material (Banded Microstructure) raised the mean fatigue strength at $10^8$ cycles by 12%. |

## TABLE IV (Cont'd)

### Results of Statistical Tests (Cont'd)

| Variable Compared | Description of Test Parameters | $\bar{X}_1$ (ksi) | $N_1$ | $\bar{X}_2$ (ksi) | $N_2$ | Result of Type I① "Z" test at 90% confidence | Type II "β" error② probability | Comments |
|---|---|---|---|---|---|---|---|---|
| Test Machine Setup | Specimens tested in Sonntags #6 and 7 ($\bar{X}_1$) vs. IVY12-2 ($\bar{X}_2$). (Barstock - Polished Surface) | 66.0 | 5 | 65.8 | 6 | No significant difference exists for fatigue strength between two testing machines employed. | 36 | The Sonntag SF-1-U machines operate at 1800 rpm while the IV-12 Machine operates at 1200 rpm. |

NOTES:

(1) The application of the "Z" test procedure requires prior knowledge of the population variance $\sigma$. A coefficient of variation ($\sigma/\mu$) for steel of 10% was employed. The larger of the two sample means is designated $\bar{X}_1$ and the smaller as $\bar{X}_2$ (values at $10^8$ cycles). A 90% confidence level ($\alpha$ = .10) was employed.

(2) The Type II or "β" error is the probability that there was in fact a difference between the population means. This difference, which was considered important to detect, was set at a value of 10% of the larger ($\bar{X}_1$) sample mean.

# TABLE V

## Tensile Test Results

| Material | Specimen Number | $F_{ty}$ (ksi) | $F_{tu}$ (ksi) | % el | % RA |
|---|---|---|---|---|---|
| One inch diameter Barstock | 1 | 202.0 | 223.5 | 12.0 | 48.0 |
| | 2 | 202.0 | 224.5 | 12.0 | 47.2 |
| | 3 | 204.0 | 224.0 | 12.0 | 43.8 |
| | Average | 202.7 | 224.0 | 12.0 | 46.3 |
| [redacted] Shaft Forging (sections A to D are shown in Figure 3) | A1 | 202.8 | 221.0 | 13.0 | 51.3 |
| | A2 | 205.5 | 222.0 | 11.0 | 41.7 |
| | A3 | 203.0 | 221.9 | 13.0 | 51.3 |
| | D1 | 214.0 | 226.5 | 12.0 | 47.7 |
| | D2 | 210.5 | 226.0 | 12.0 | 48.0 |
| | D3 | ---- | 228.0 | 11.0 | 44.2 |
| | ~~Avg. A&D~~ | ~~207.2~~ | ~~224.3~~ | ~~12.0~~ | ~~47.3~~ |
| (1) | B-14 | 183.1 | 207.5 | 13.0 | 40.0 |
| | C-5 (2) | 187.0 | 210.0 | 7.0 | 15.0 |
| | Avg. B&C | 185.5 | 208.8 | 13.0 | 40.0 |
| Mil Hdbk-5, Ref. (k) 4340 (at min. 200 ksi $F_{tu}$ heat treat level) | | 176 min. | 200 min. | 10 min. | 43 min. |

(1) These specimens were remachined from runout fatigue specimens of the same I.D. No. to establish tensile properties for the sections B and C refer to Figure 3, where the axial fatigue specimens were located.

(2) Punch break - elongation and reduction of area not averaged.

# TABLE VI

## Tukon Microhardness Values for Several Forging Fatigue Test Specimens

| Axial Fatigue Specimen: | "Light" Region Avg. Hardness KHN (300 gm) | "Light" Region Avg. Hardness approx. equivalent $R_C$ | "Dark" Region Avg. Hardness KHN (300 gm) | "Dark" Region Avg. Hardness approx. equivalent $R_C$ | $\Delta R_C$ approx. equivalent |
|---|---|---|---|---|---|
| B-8 | 392 | 38.7 | 493 | 46.9 | 8.2 |
| C-10 | 401 | 39.6 | 504 | 47.6 | 8.0 |
| B-6 | 422 | 41.6 | 494 | 47.0 | 5.4 |
| B2 | 431 | 42.3 | 527 | 49.1 | 6.8 |
| B4 | 427 | 42.0 | 524 | 49.0 | 7.0 |
| B7 | 417 | 41.2 | 541 | 50.0 | 8.8 |
| Avg. Values | --- | 40.9 | --- | 48.3 | 7.4 |

## TABLE VII

## Material
## Chemical Composition

Gross Chemical Analyses:

| | Mn<br>25<br>(weight%) | Ni<br>28<br>(weight%) | Cr<br>24<br>(weight%) | Mo<br>42<br>(weight%) | Si<br>14<br>(weight%) | S<br>16<br>(weight%) | P<br>15<br>(weight%) | C<br>06<br>(weight%) | Fe 26<br>(by diff.) |
|---|---|---|---|---|---|---|---|---|---|
| 04 one-inch diameter Barstock | 0.74 | 1.72 | 0.90 | 0.23 | 0.27 | 0.010 | 0.008 | 0.41 | 95.7 |
| 03 [redacted] Shaft Forging | 0.72 | 1.75 | 0.87 | 0.29 | 0.35 | 0.010 | 0.010 | 0.40 | 95.6 |
| Mil-S-500C, Ref. (a) requirements | 0.65 - 0.85 | 1.65 - 2.00 | 0.70 - 0.90 | 0.20 - 0.30 | 0.20 - 0.35 | 0.025 (max.) | 0.025 (max.) | 0.38 - 0.43 | Bal. |

Electron Microprobe Analyses of Forging Material:
(Using the gross analysis as an internal standard)

| | Mn ① (weight%) | Ni ① (weight%) | Cr ① (weight%) | Mo ① (weight%) | Fe ① (weight%) |
|---|---|---|---|---|---|
| Specimen B2 | | | | | |
| Dark② | 0.80 | 1.79 | 0.96 | 0.32 | 95.2 |
| Light | 0.61 | 1.69 | 0.78 | 0.25 | 96.2 |
| Specimen B4 | | | | | |
| Dark② | 0.79 | 1.82 | 0.94 | 0.33 | 95.3 |
| Light | 0.64 | 1.68 | 0.78 | 0.22 | 96.1 |
| Specimen B7 | | | | | |
| Dark② | 0.77 | 1.78 | 0.96 | 0.32 | 95.0 |
| Light | 0.65 | 1.72 | 0.78 | 0.26 | 96.2 |

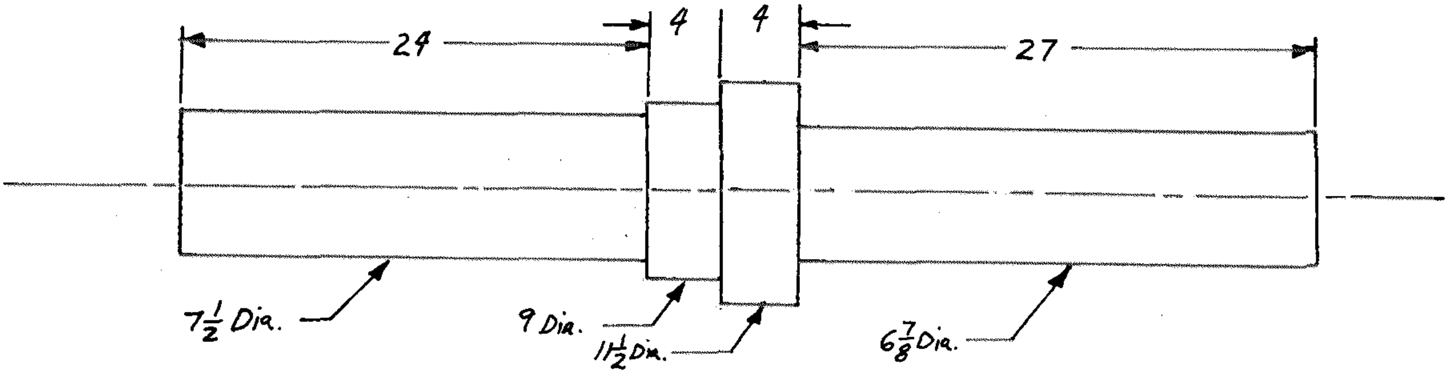
(1) Determined by an average of at least ten analyses employing the gross analysis as an internal standard.

(2) Refer to Figures 19 to 21, respectively for the appearance of light and dark regions.

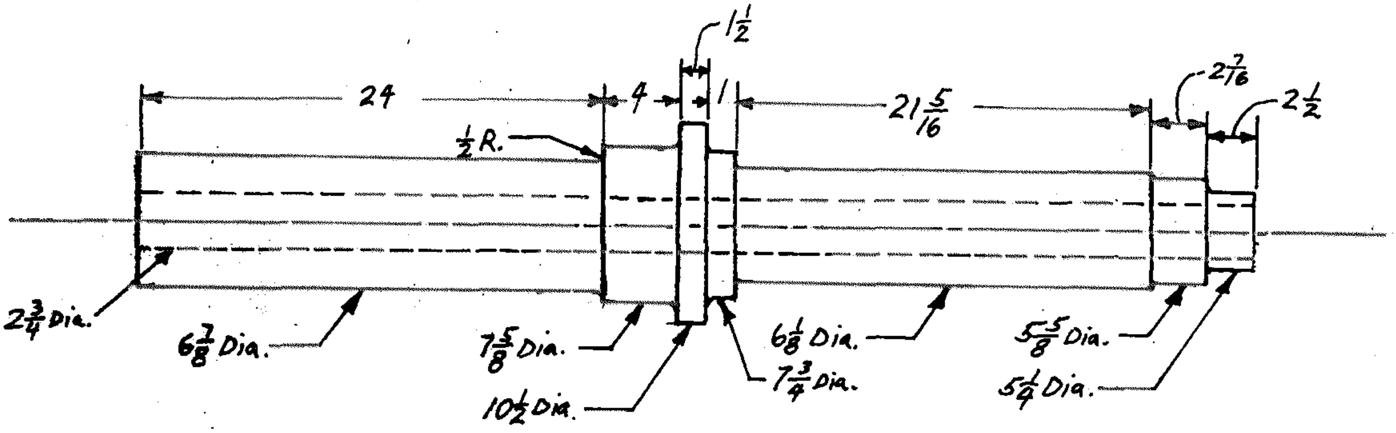
# Figure 1

## Forging Size and Rough Machined Size at Heat Treatment , [redacted]

Approximate Forge Size: S6135-20640 / S6137-23040 } identical forging



Approximate Rough Turn Size at time of Heat Treat:

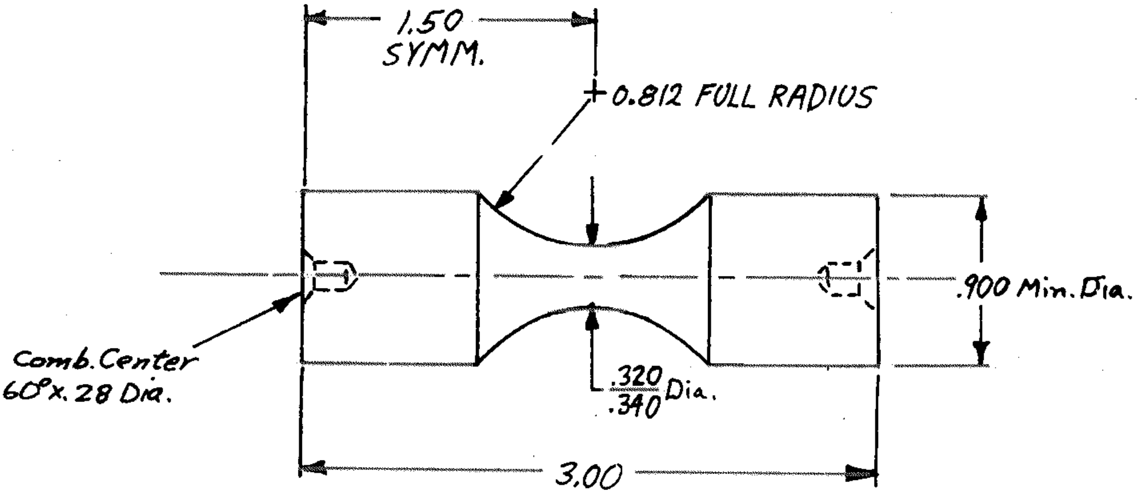


[redacted] has $3\frac{1}{4}$ Dia. thru bore } at time of Heat Treat.
has $2\frac{3}{4}$ Dia. thru bore }

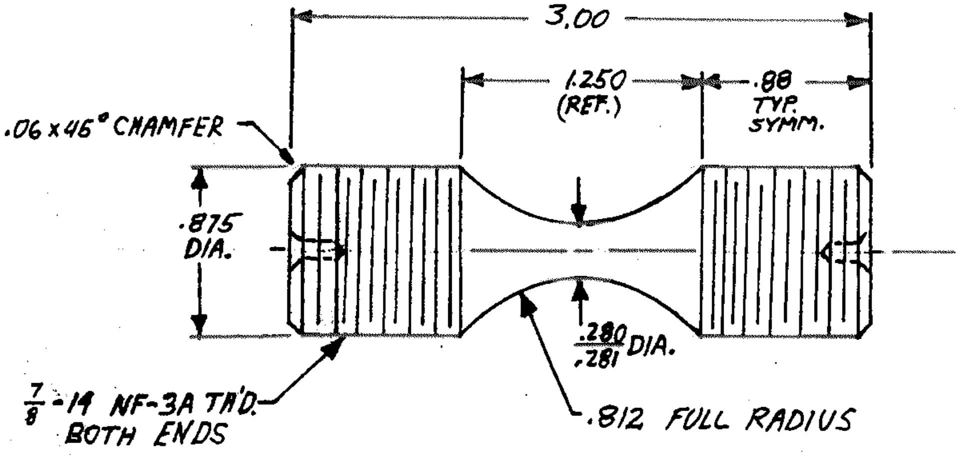
Note: All dimensions in inches.

## Figure 2

## Rough Machined Barstock Size and Finish Machined Axial Fatigue Specimen Design



SPECIMENS FROM THE BARSTOCK (BAR FORNISHED MILL ANNEALED) WERE ROUGH MACHINED TO THE SKETCH SHOWN ABOVE.

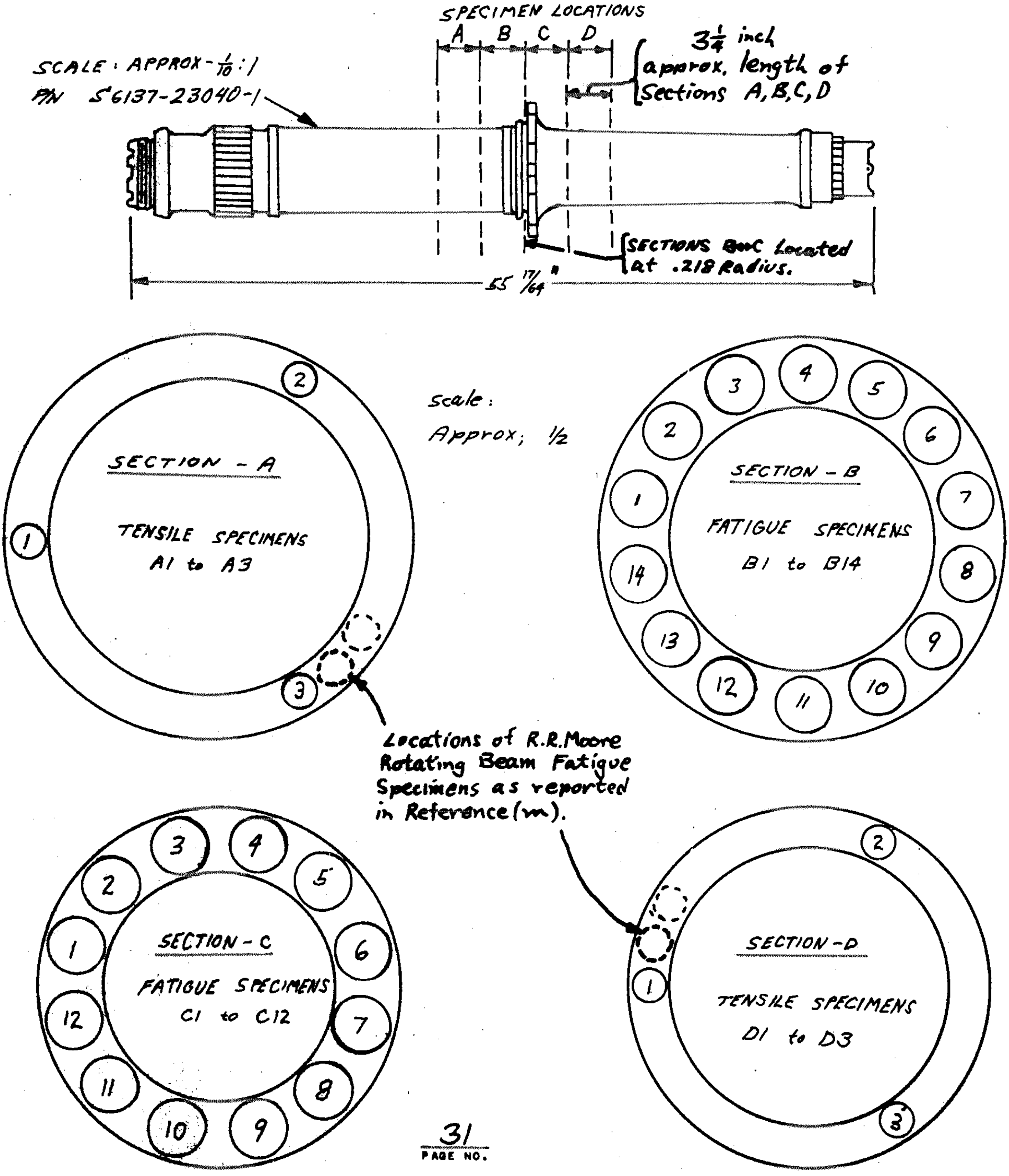


FINISH MACHINED AXIAL FATIGUE SPECIMEN

SLGNM - 1454 REV. A.

**Note: All dimensions in inches.**

**Figure 3** Specimen Location in Finish Machined [redacted]



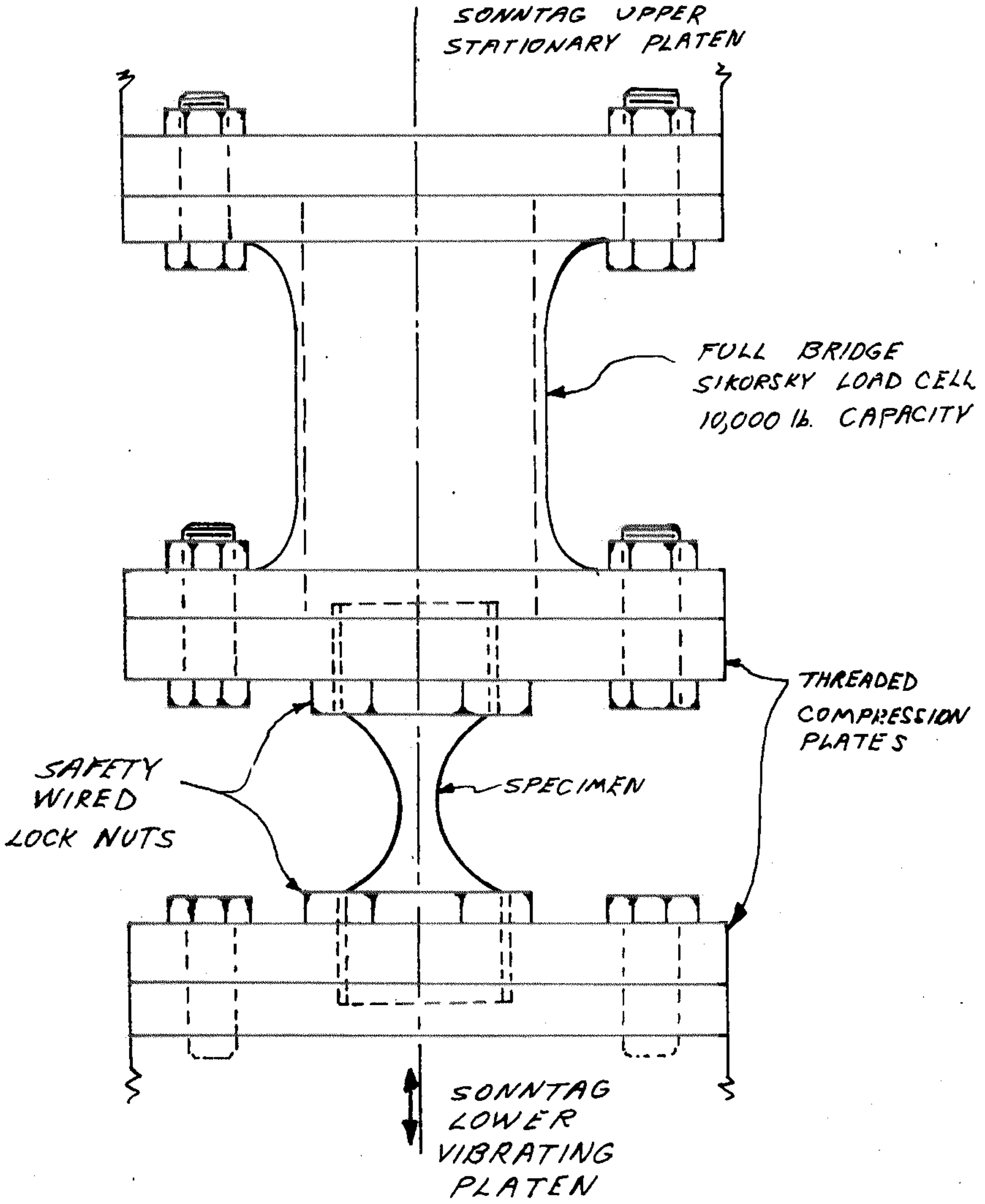
3 1/4 inch approx. length of Sections A, B, C, D

SECTIONS B & C Located at .218 Radius.

Locations of R.R. Moore Rotating Beam Fatigue Specimens as reported in Reference (m).

# Figure 4

# Axial Fatigue Test Tension-Compression Configuration



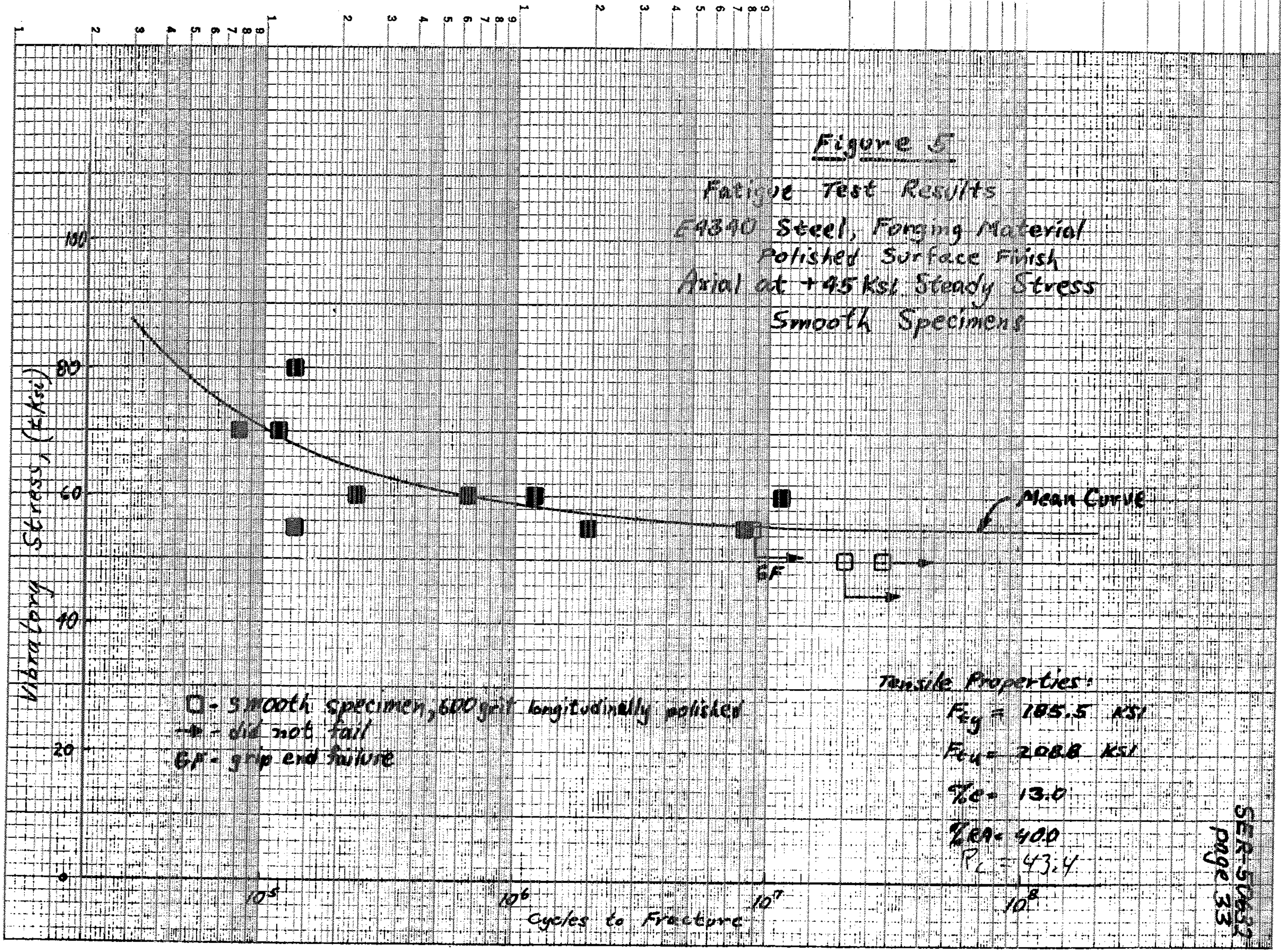


Figure 5

Fatigue Test Results
E4340 Steel, Forging Material
Polished Surface Finish
Axial at +45 ksi Steady Stress
Smooth Specimens

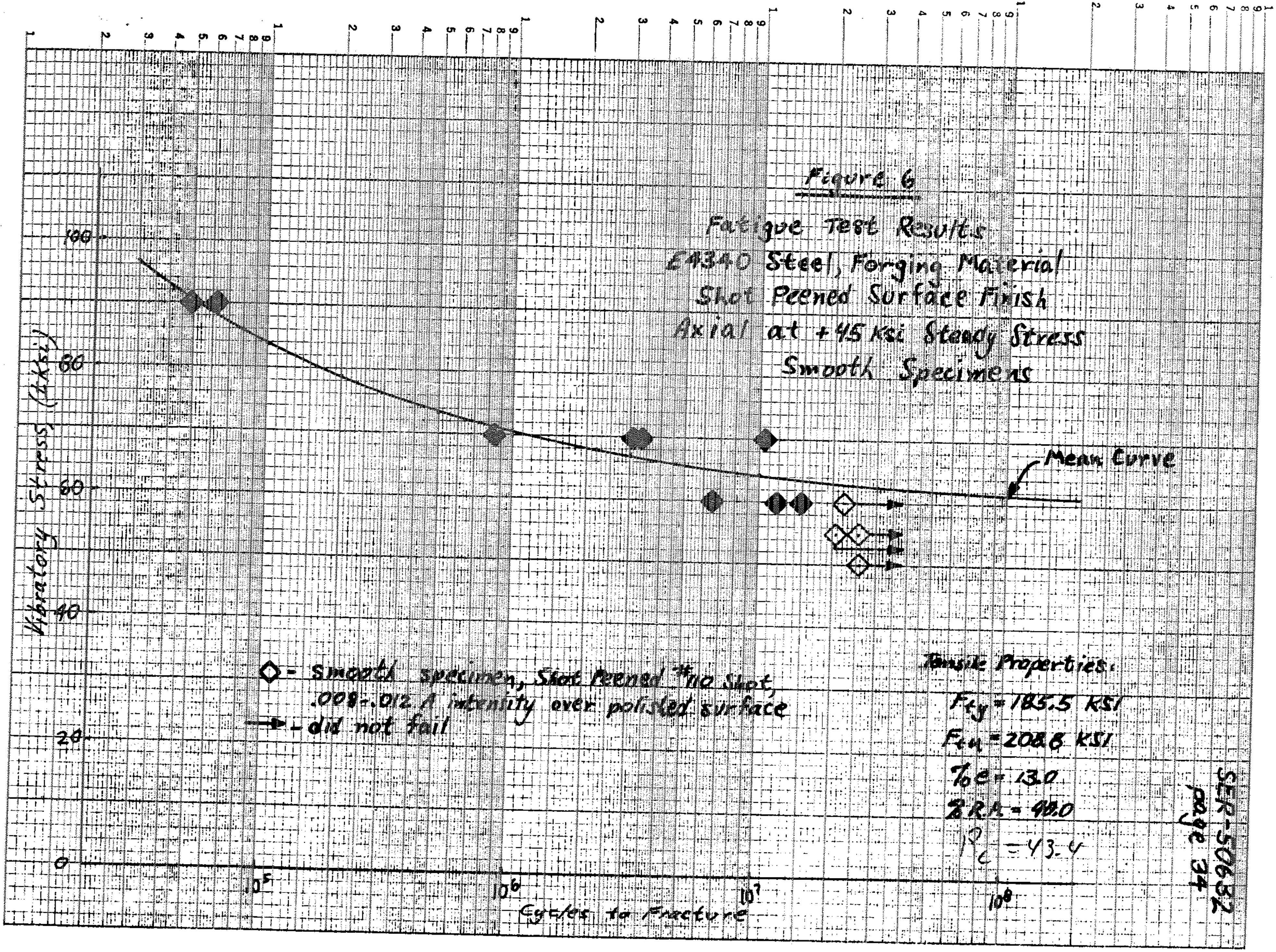


Figure 6

Fatigue Test Results
E4340 Steel, Forging Material
Shot Peened Surface Finish
Axial at +45 ksi Steady Stress
Smooth Specimens

◇ - Smooth specimen, Shot Peened #110 Shot, .008-.012 A intensity over polished surface
→ - did not fail

Tensile Properties:
$F_{ty}$ = 185.5 KSI
$F_{tu}$ = 208.8 KSI
%e = 13.0
%RA = 48.0
$R_c$ = 43.4

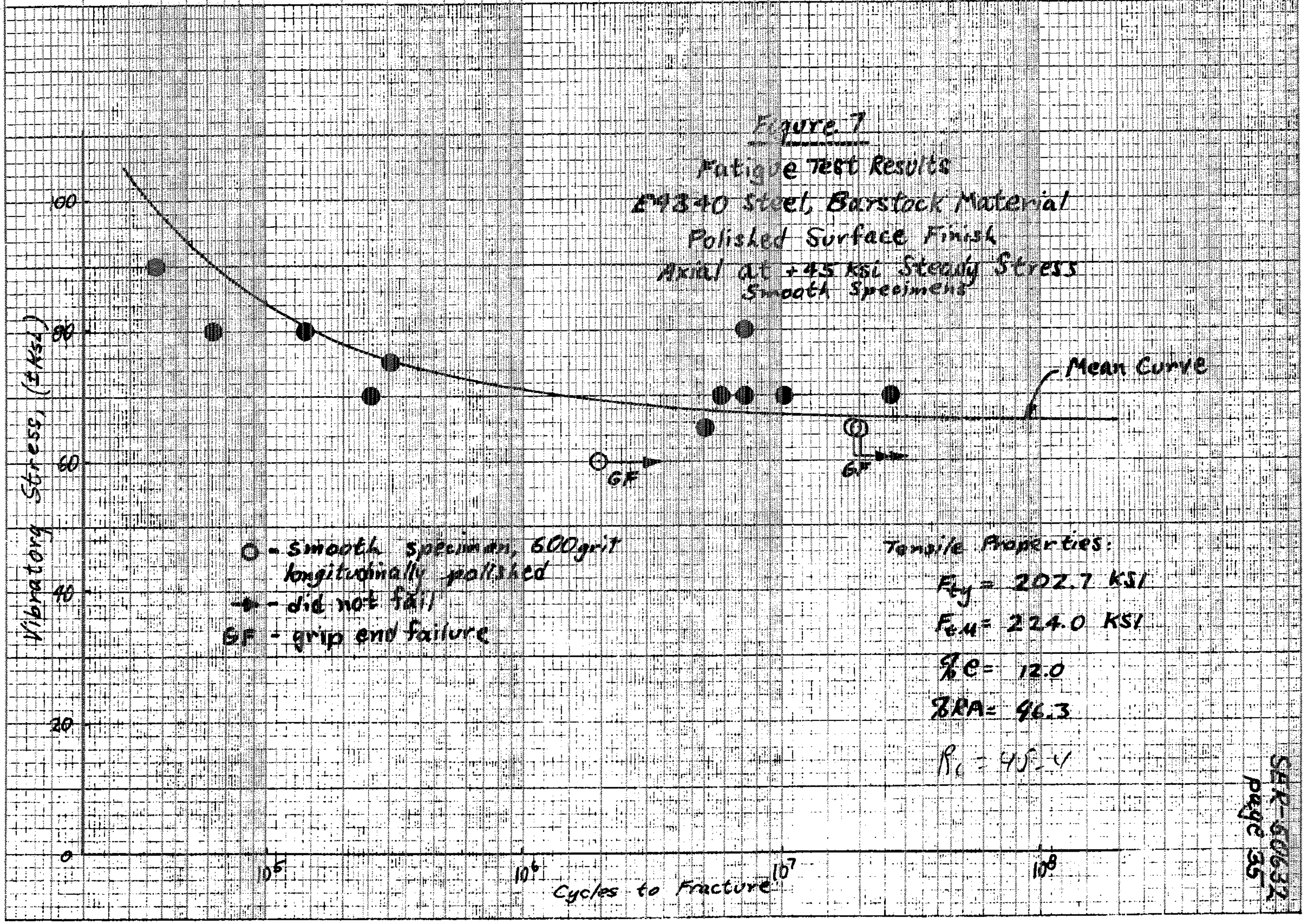


Figure 7

Fatigue Test Results

E4340 Steel, Barstock Material

Polished Surface Finish

Axial at +45 ksi Steady Stress

Smooth Specimens

Tensile Properties:

$F_{ty}$ = 202.7 KSI

$F_{tu}$ = 224.0 KSI

%e = 12.0

%RA = 46.3

$R_c$ = 45-4

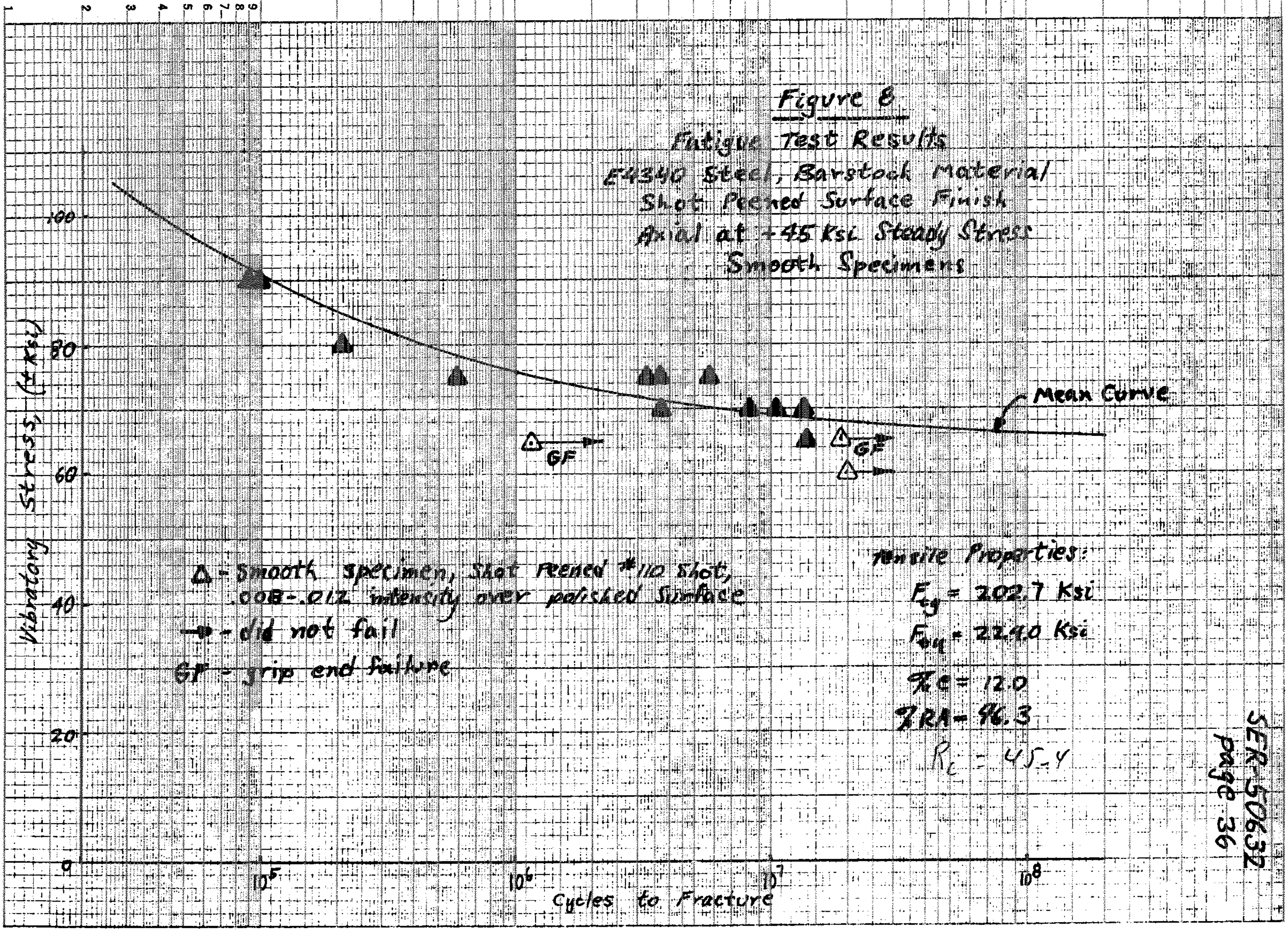


**Figure 8**

Fatigue Test Results
E4340 Steel, Barstock Material
Shot Peened Surface Finish
Axial at +45 Ksi Steady Stress
Smooth Specimens

Tensile Properties:
$F_{ty}$ = 202.7 Ksi
$F_{tu}$ = 224.0 Ksi
%e = 12.0
%RA = 46.3
$R_c$ = 45.4

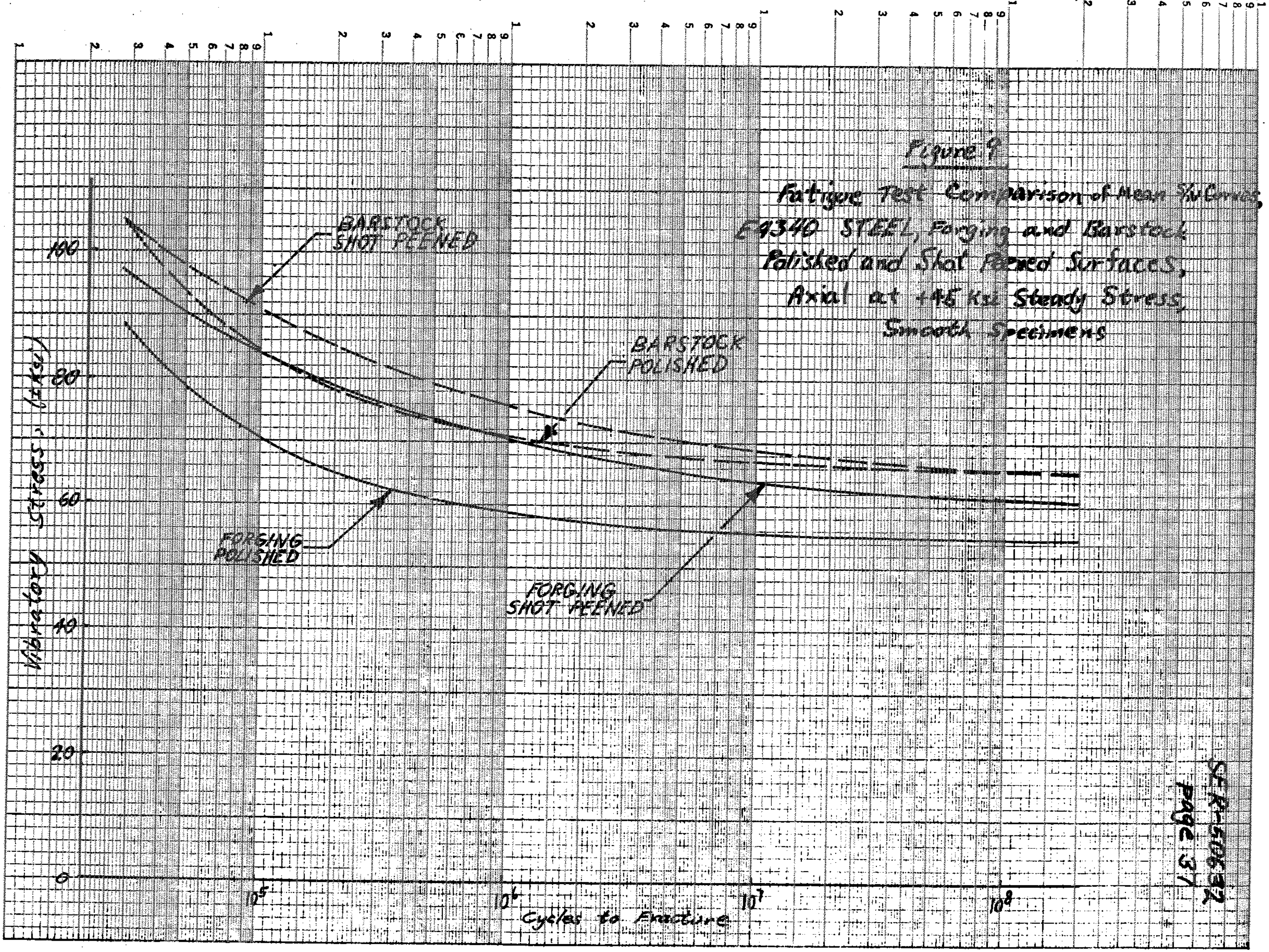


Figure 9

Fatigue Test Comparison of Mean S/N Curves, E4340 STEEL, Forging and Barstock Polished and Shot Peened Surfaces, Axial at +45 Ksi Steady Stress, Smooth Specimens

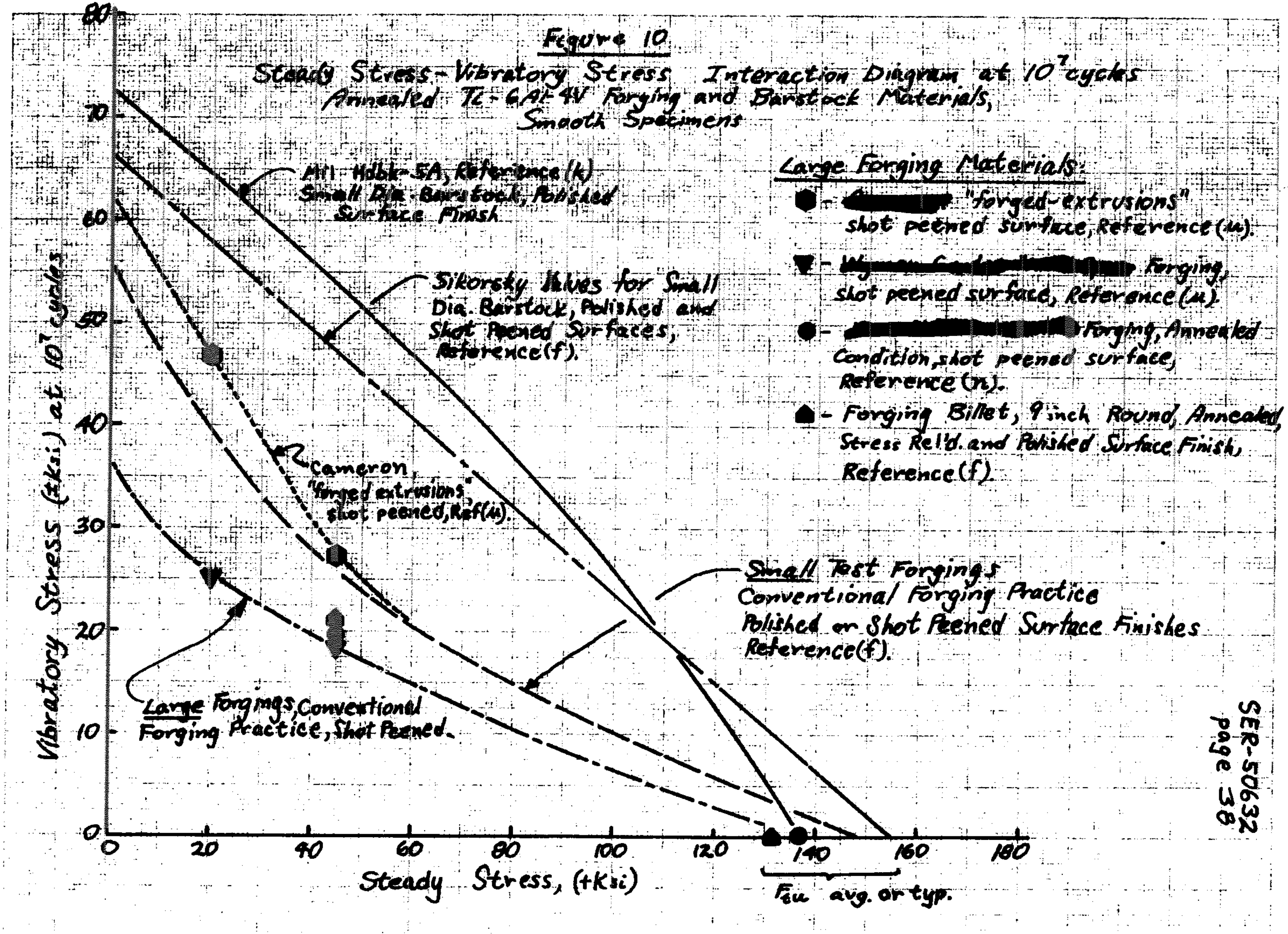


**Figure 10**

Steady Stress - Vibratory Stress Interaction Diagram at $10^7$ cycles
Annealed Ti-6Al-4V Forging and Barstock Materials,
Smooth Specimens

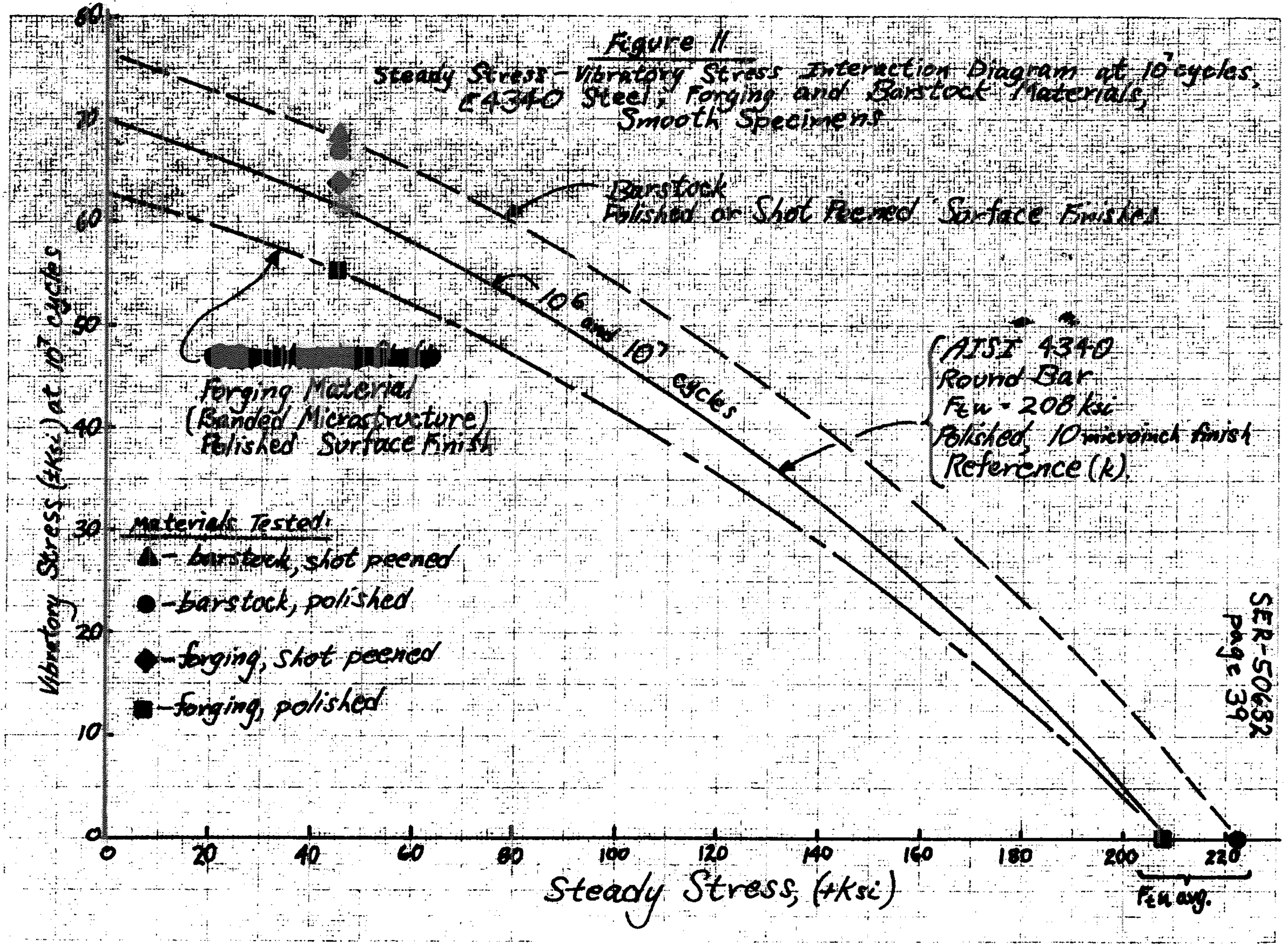
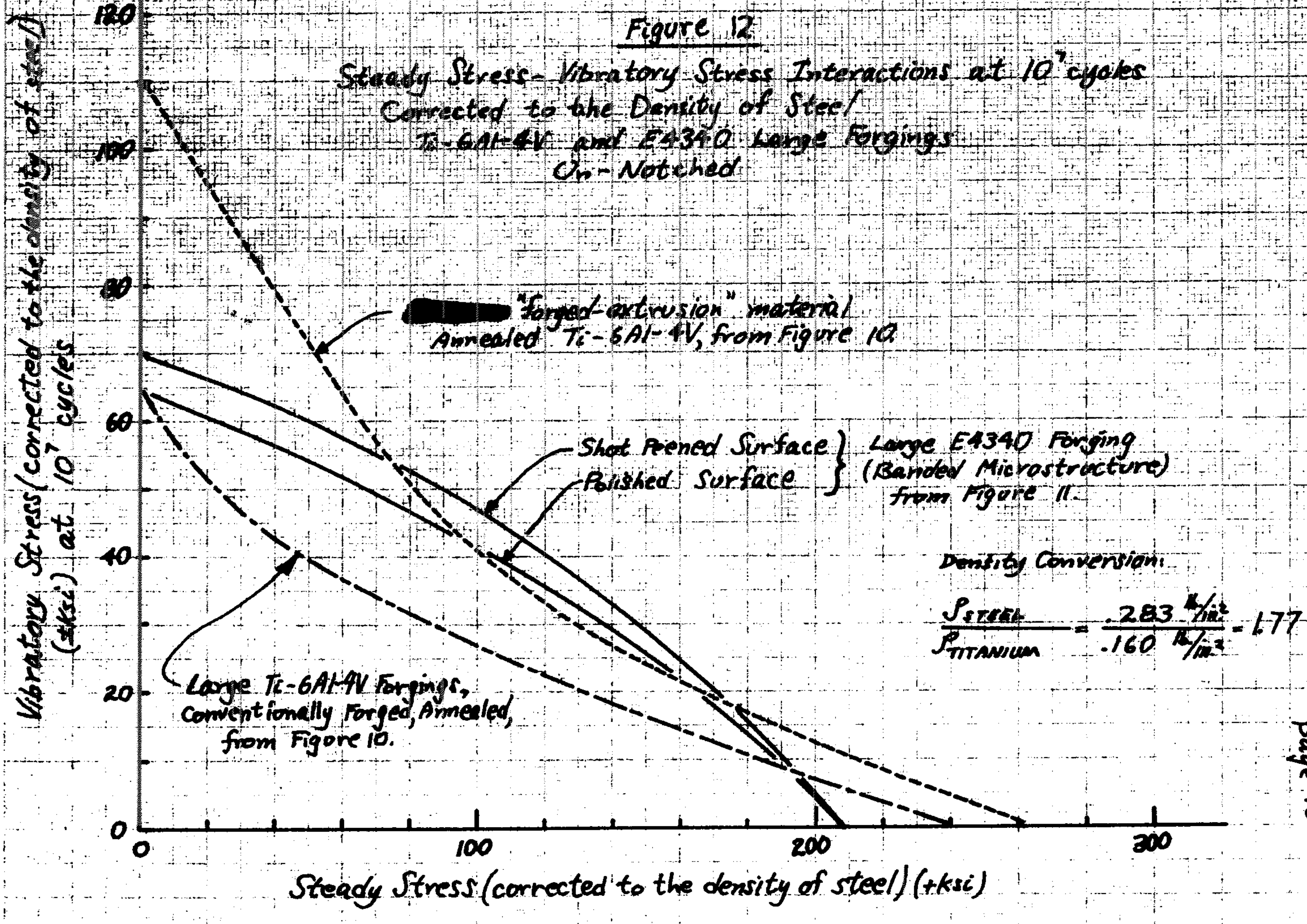


Figure 11

Steady Stress - Vibratory Stress Interaction Diagram at $10^7$ cycles, E4340 Steel; Forging and Barstock Materials, Smooth Specimens

## Figure 12

Steady Stress- Vibratory Stress Interactions at $10^7$ cycles
Corrected to the Density of Steel
Ti-6Al-4V and E4340 Large Forgings
Un-Notched



Density Conversion:

$$\frac{\rho_{STEEL}}{\rho_{TITANIUM}} = \frac{.283 \ lb/in^3}{.160 \ lb/in^3} = 1.77$$

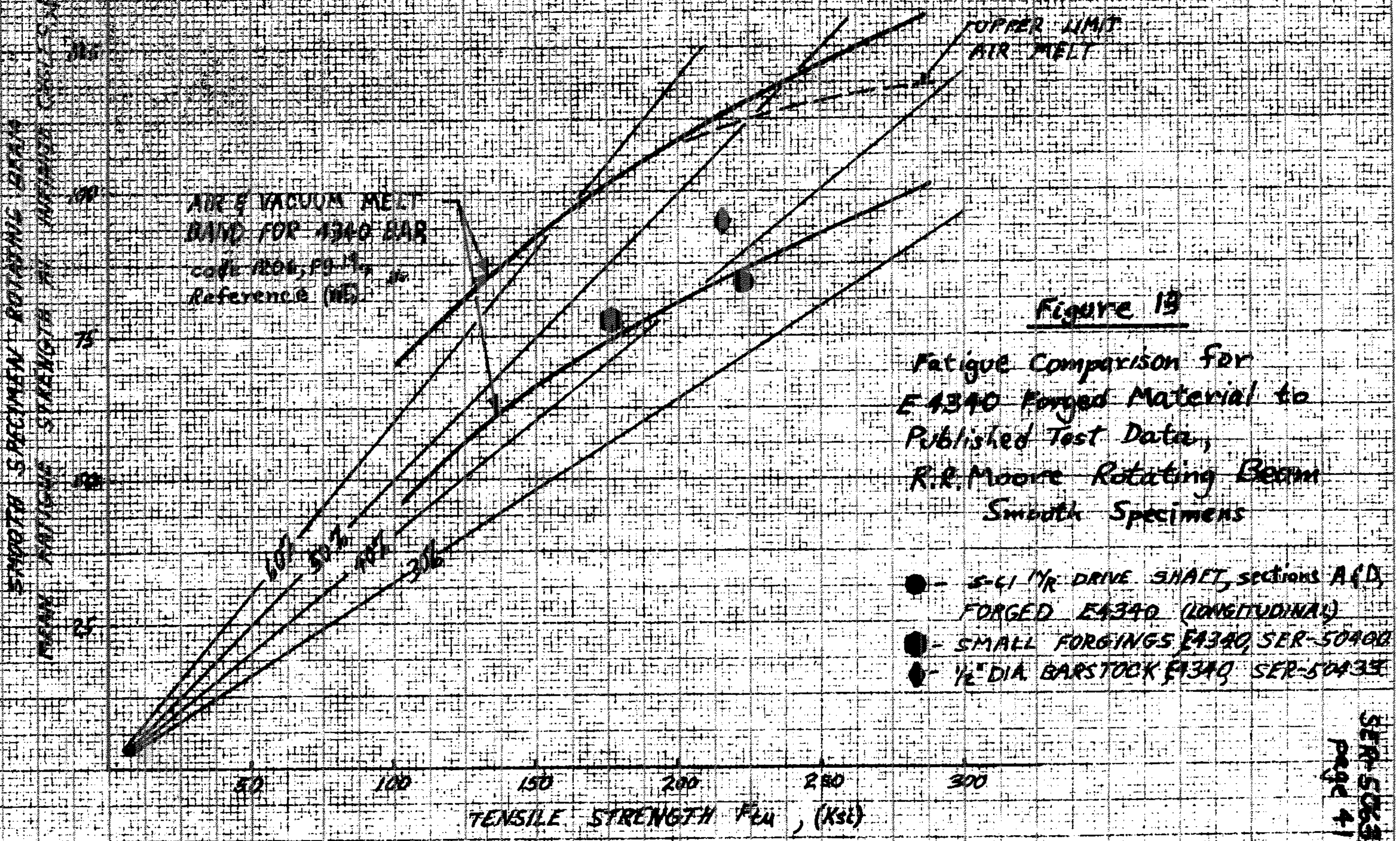
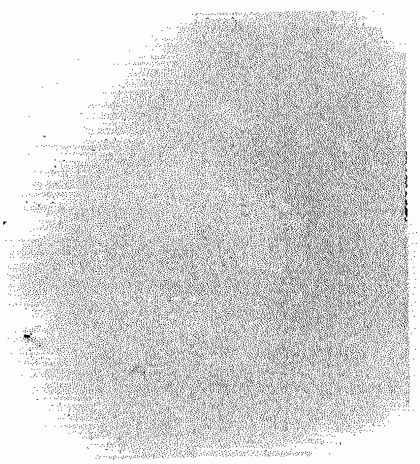


Figure 19

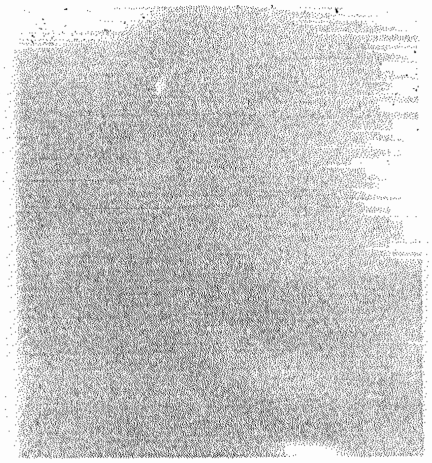
Fatigue Comparison for E4340 Forged Material to Published Test Data, R.R. Moore Rotating Beam Smooth Specimens

**FIGURE 14** Macrostructural Appearance, E4340 Forging and Bar Stock Material.

Bar Stock Material, Magnification 5X, 2% Nital Etchant.

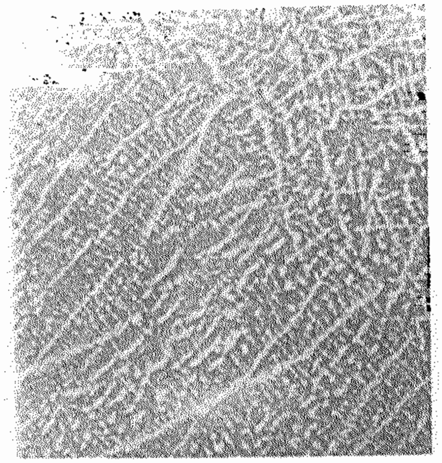


Transverse Section

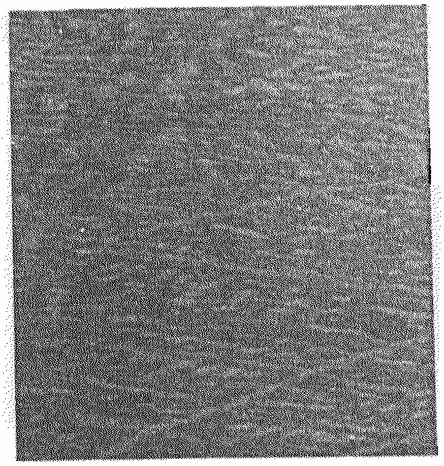


Longitudinal Section

Forging Material, Magnification 5X, 2% Nital Etchant.

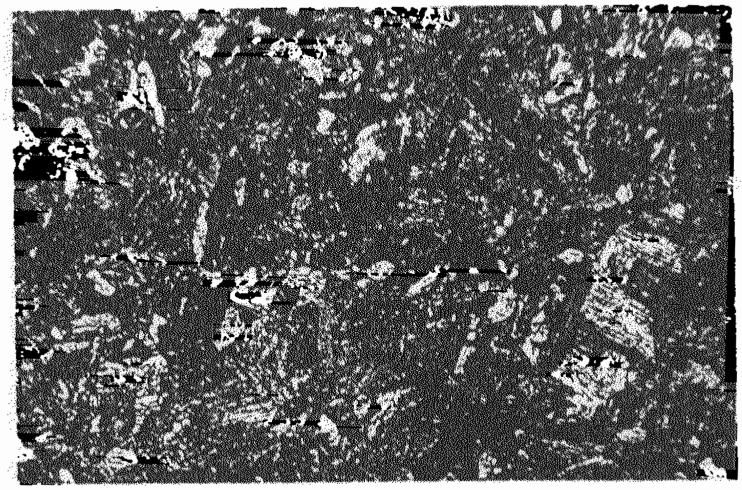


Transverse Section

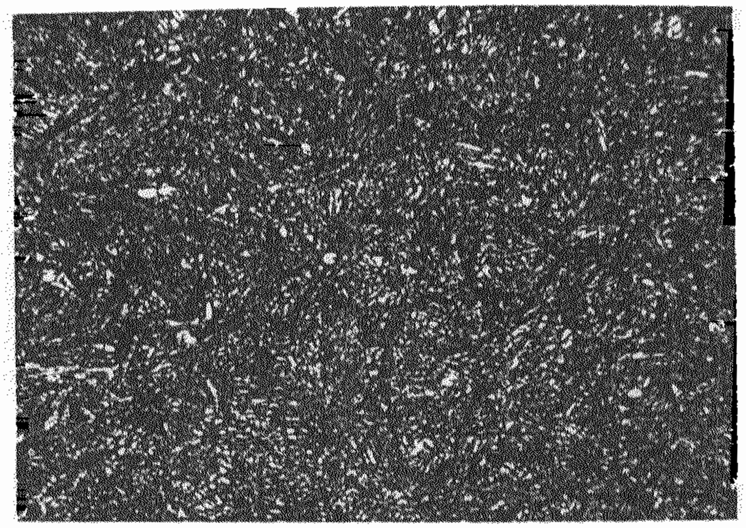


Longitudinal Section

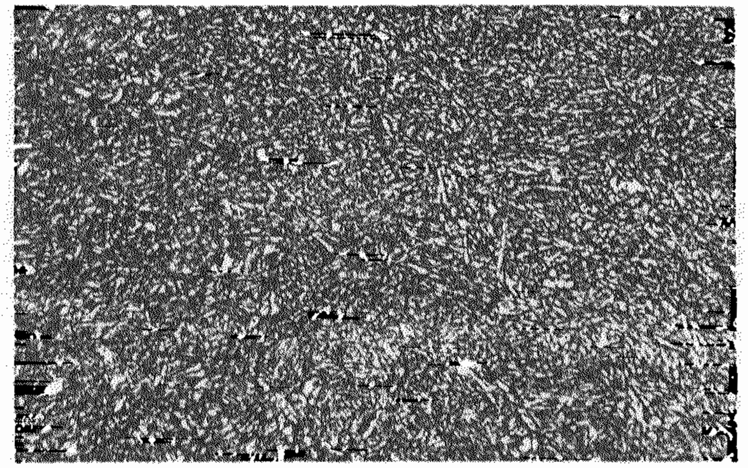
**FIGURE 15** Microstructural Appearance, E4340 Forging and Bar Stock Material.



Forging Material, "Light" Region
Magnification 500X, 2% Nital Etchant.



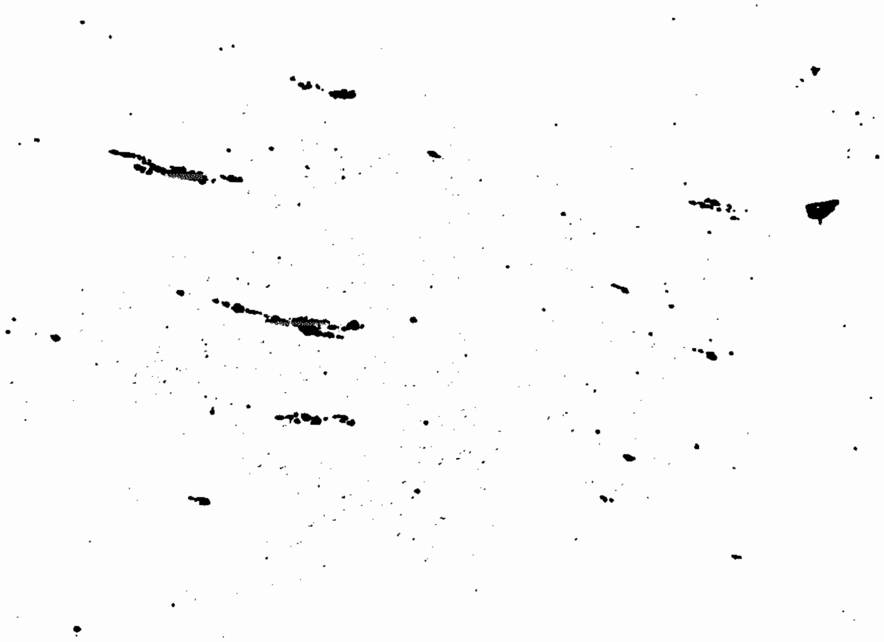
Forging Material, "Dark" Region,
Magnification 500X, 2% Nital Etchant.



Bar Stock Material, Magnification 500X,
2% Nital Etchant.

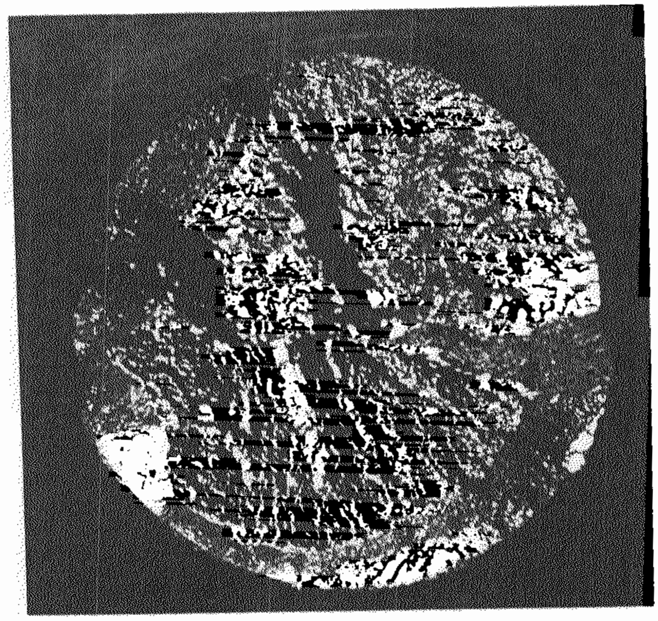
**FIGURE 16** **Inclusion Examination, E4340 Forging and Bar Stock Material.**

Bar Stock Material, Transverse Section, Magnification 100X, Unetched.

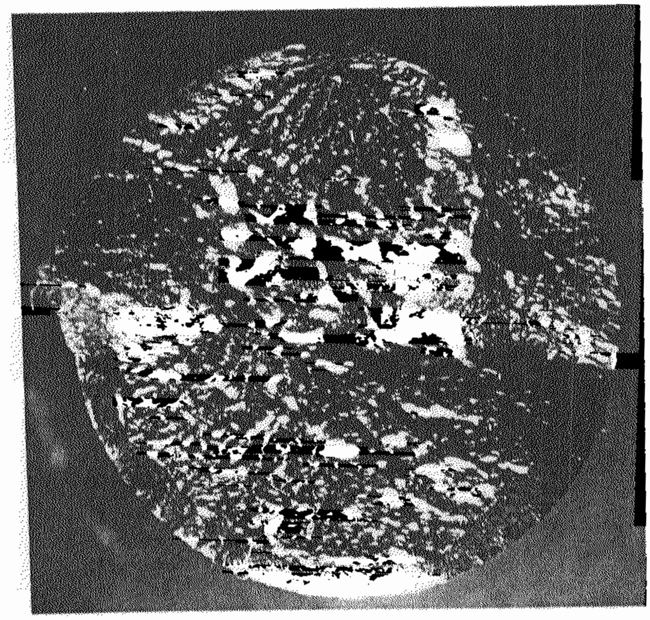


**Forging** Material, Transverse Section, **Magnification** 100X, Unetched.

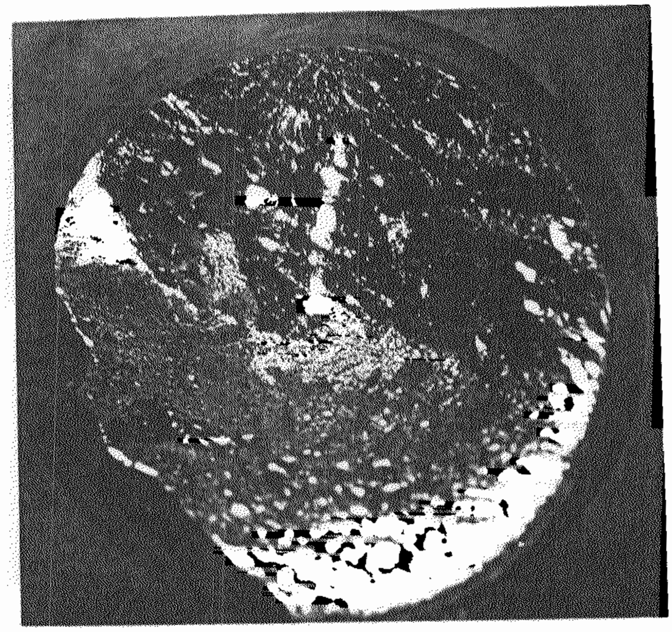
FIGURE 17 Typical Appearance of Failed Forging Fatigue Test Specimens.



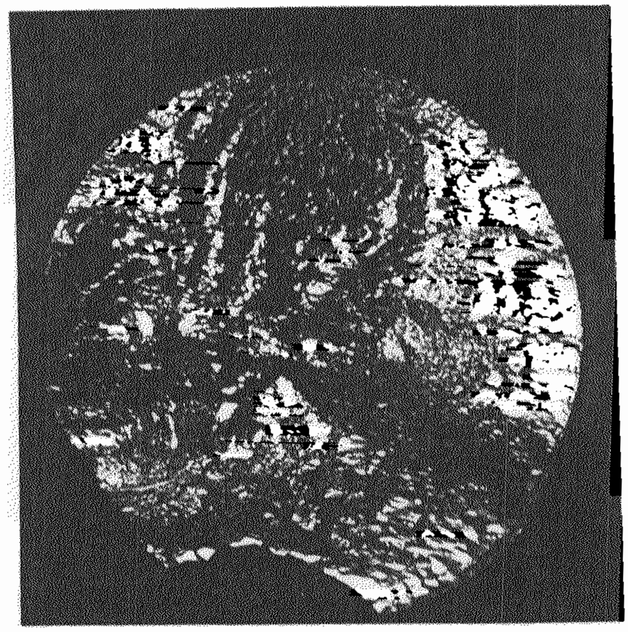
Specimen C12, Tested at + 45 ± 80 ksi, 132,000 Cycles to Fracture, Surface Origin Site. Polished Surface Finish.



Specimen B6, Tested at + 45 ± 70 ksi, 3,280,000 Cycles to Fracture, Subsurface Origin Site, Approx.: .010" Below Surface. Shot Peened Surface Finish.

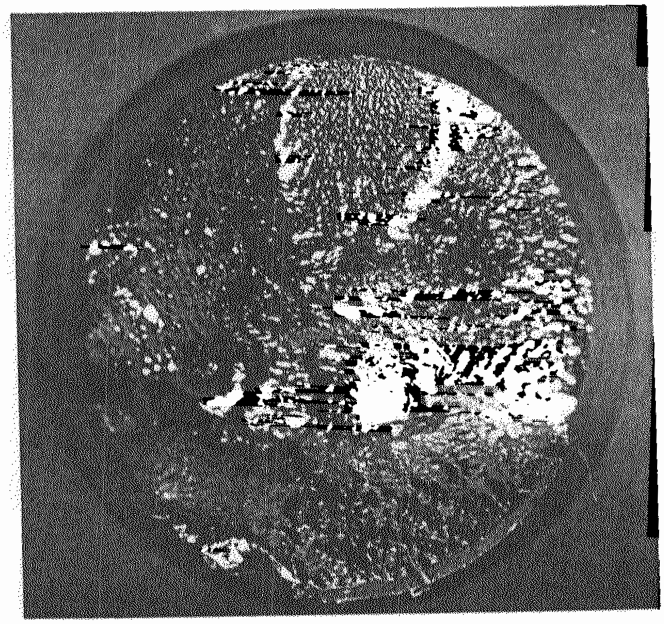


Specimen B8, Tested at + 45 ± 70 ksi, 80,000 Cycles to Fracture, Surface Origin Site. Polished Surface Finish.

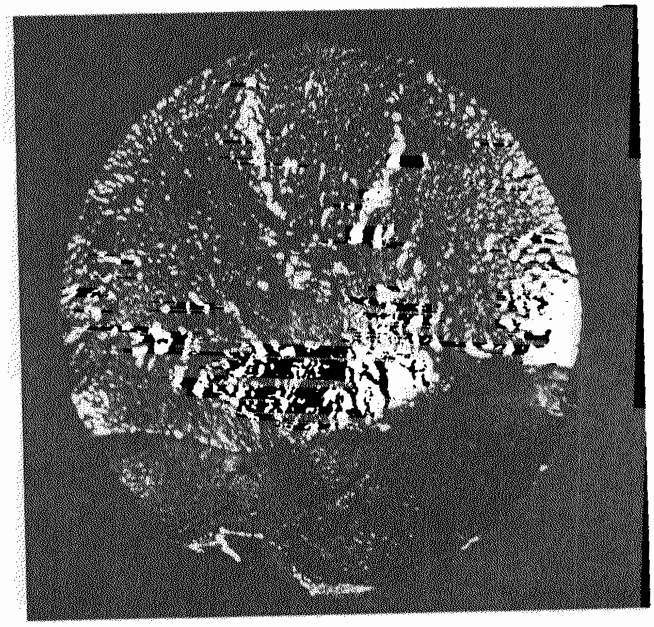


Specimen C10, Tested at + 45 ± 55 ksi, 132,000 Cycles to Fracture, Surface Origin Site. Polished Surface Finish.

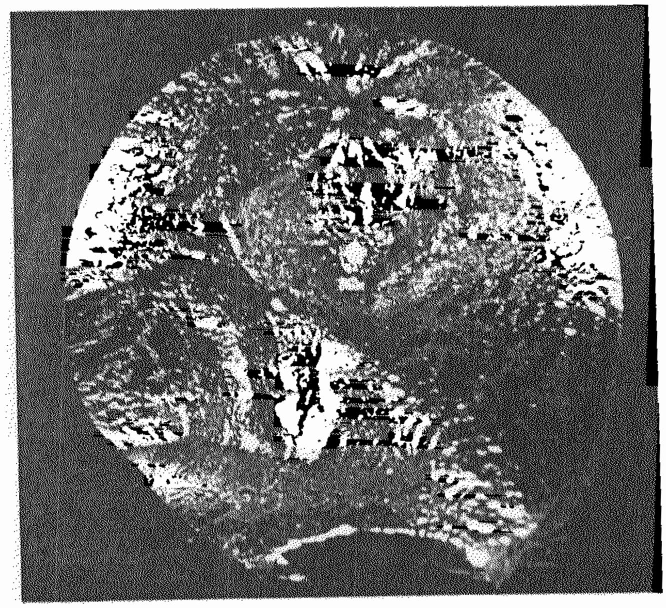
FIGURE 18 Typical Appearance of Failed Bar Stock Fatigue Test Specimens.



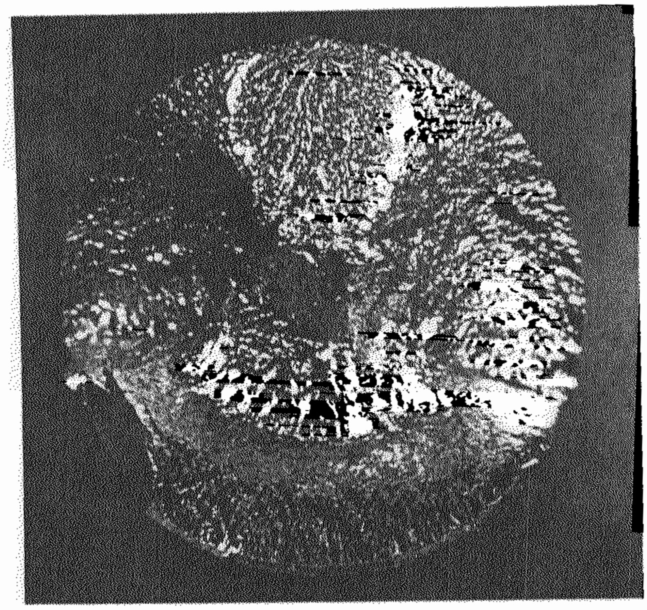
Specimen 24, Tested at + 45 ± 70 ksi, 157,000 Cycles to Fracture, Surface Origin Site. Polished Surface Finish.



Specimen 28, Tested at + 45 ± 75 ksi, 585,000 Cycles to Fracture, Subsurface Origin Site, Approx.: .010" Below Surface. Shot Peened Surface Finish.



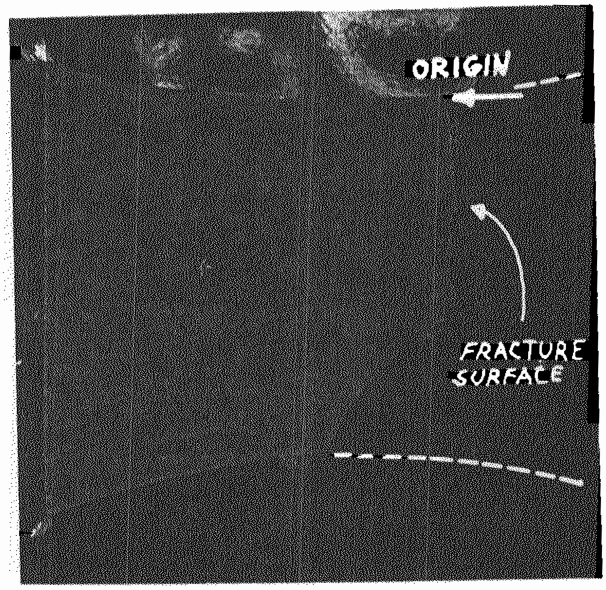
Specimen 1, Tested at + 45 ± 75 ksi, 5,655,000 Cycles to Fracture, Subsurface Origin Site, Approx.: .040" Below Surface. Shot Peened Surface Finish.



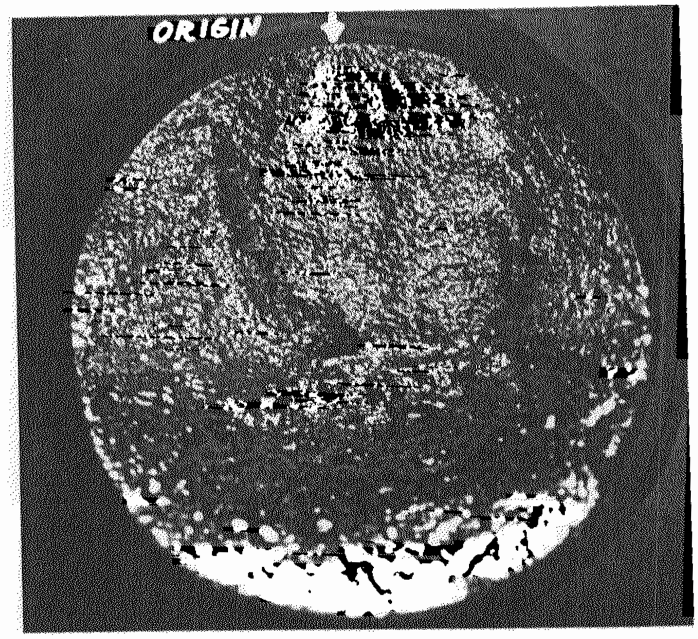
Specimen 10, Tested at + 45 ± 65 ksi, 13,844,000 Cycles to Fracture, Subsurface Origin Site, Approx.: .010" Below Surface. Shot Peened Surface Finish.

FIGURE 19

Failure Analysis of Forging Fatigue Specimen B2.



Section Through Origin Site,
Magnification 5X. 2% Nital Etchant.



Tested at + 45 ± 55 ksi, 8,074,000
Cycles to Fracture, Surface Origin
Location, Polished Surface Finish.

Origin Location, Magnification
50X, Nital Etchant.

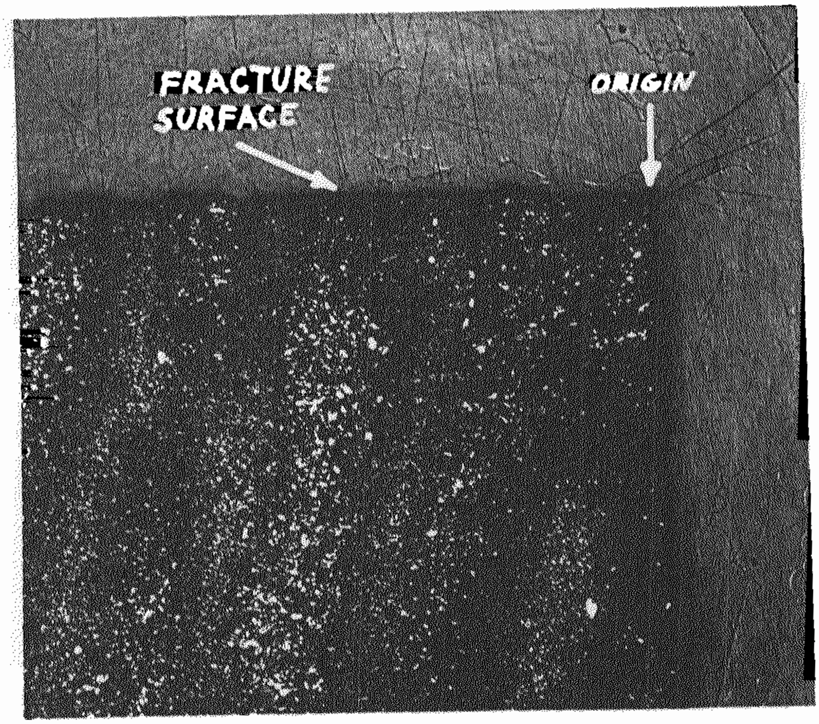
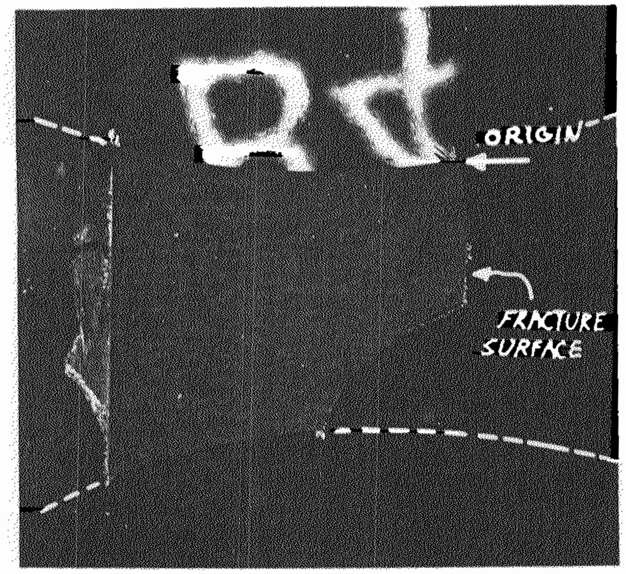
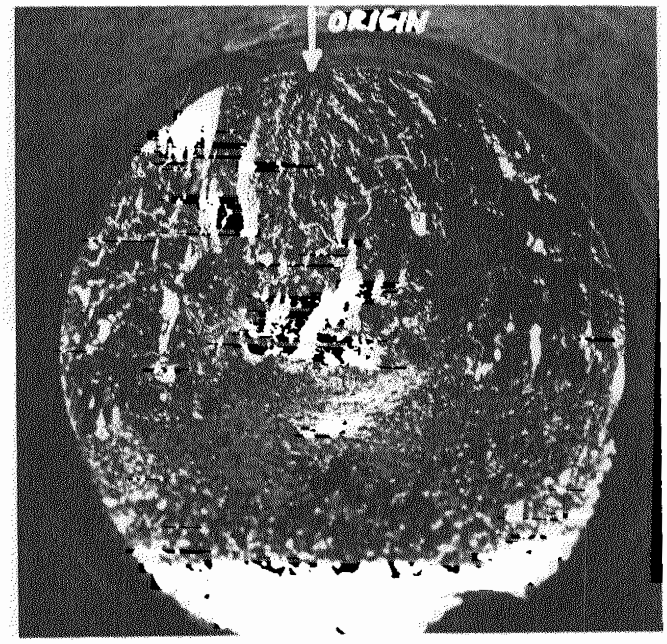


FIGURE 20

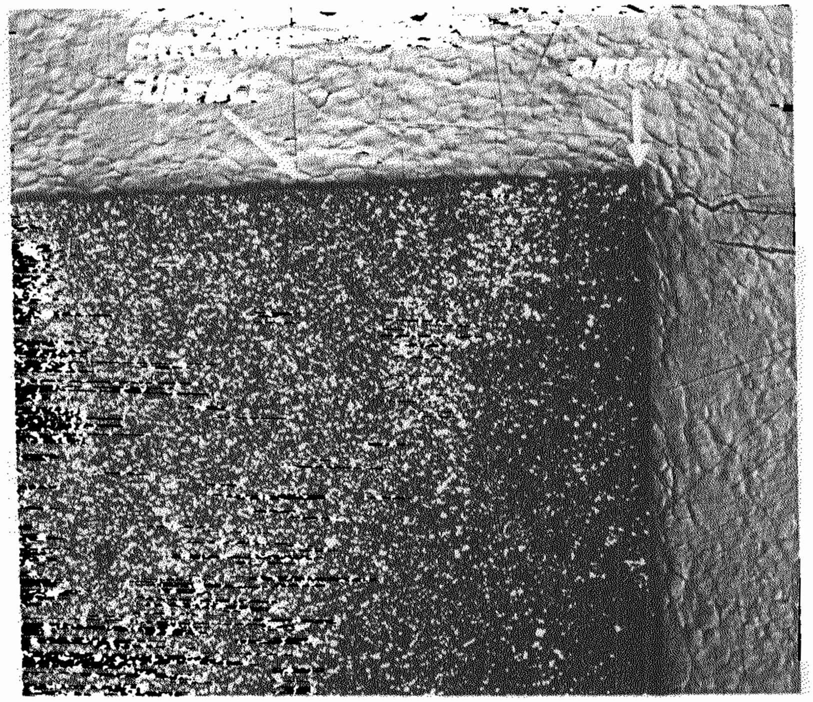
Failure Analysis of Forging Fatigue Specimen B4.



Section Through Origin Site,
Magnification 5X 2% Nital Etchant.

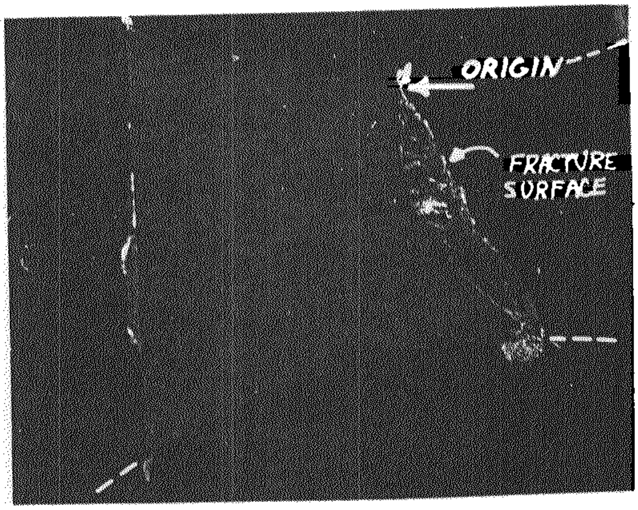


Tested at + 45 ± 60 ksi, 644,000 Cycles to Fracture, Surface Origin Location, Polished Surface Finish.



Origin Location, Magnification 50X, Nital Etchant.

**FIGURE 21** Failure Analysis of Forging Fatigue Specimen B7.



Section Through Origin Site,
Magnification 5X, 2% Nital Etchant.

Tested at + 45 ± 55 ksi, 1,930,000
Cycles to Fracture, Surface Origin
Location, Polished Surface Finish.

Origin Location, Magnification
50X, Nital Etchant.