7

EFFECTS OF MULTIPLE SHOT PEENING/CADMIUM PLATING CYCLES ON HIGH STRENGTH STEEL

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ABSTRACT

A study was made of the effects of multiple shot peening and cadmium plating operations on high strength AISI 4340 steel used in aircraft landing gear applications. No detrimental effects were observed on surface microstructure and tensile properties nor on fatigue and unnotched stress corrosion resistance in high humidity air. An apparent degradation in stress corrosion life of fatigue precracked specimens was observed after four and five peening and plating operations.

Key Words

Shot peening, cadmium plating, fatigue, stress corrosion, tensile, high strength steel.

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INTRODUCTION

High strength steels are used widely for load bearing components in aircraft landing gear. Typically, such components are shot peened after machining, then are plated with cadmium and chromium followed by painting, all to enhance resistance to fatigue and corrosion. Overhaul rework procedures for such components includes stripping platings, inspecting for cracks, build-up and re-machining of worn areas, all followed by shot peening and plating as per the original finishing sequence. Landing gear components typically are subjected to several such overhaul procedures during their service life.

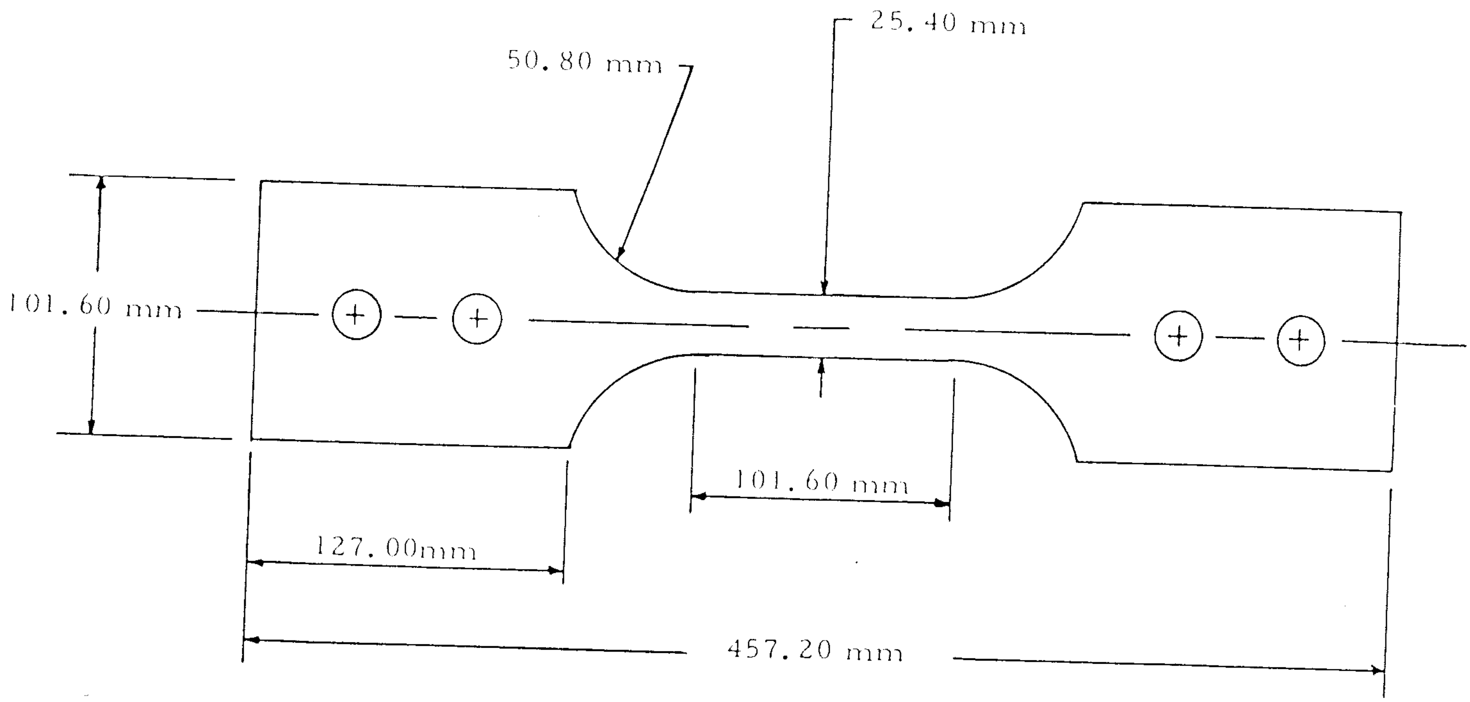
The objective of this program was to establish the effects of the original and overhaul rework peening and plating cycles on fatigue and stress corrosion resistance of high strength AISI 4340 steel which is commonly employed in aircraft landing gear components. Experimental evaluations involved metallography and tensile testing in addition to fatigue and stress corrosion testing in high humidity environments. The remaining sections of this paper are devoted to description of material and specimen preparation, test procedures, results obtained and interpretation thereof.

PROCEDURE

Material and Specimen Preparation

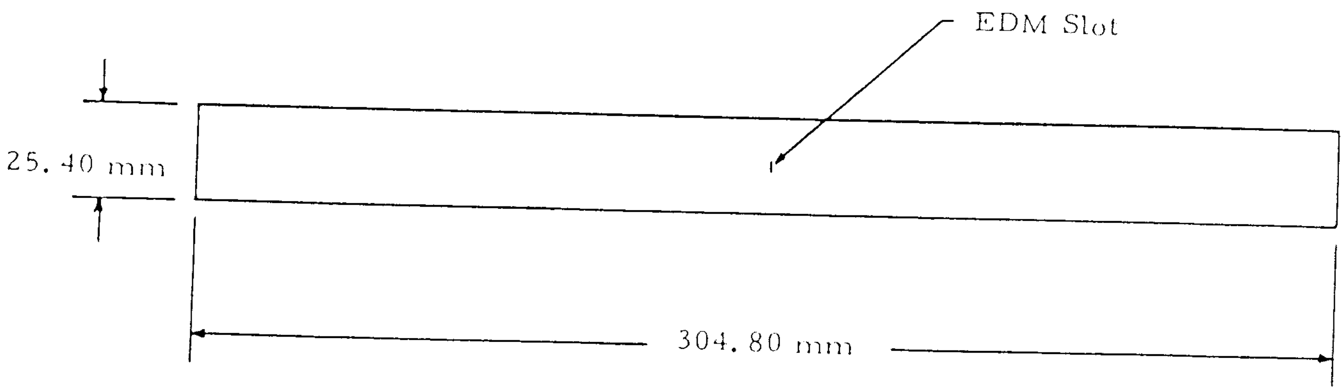
The material employed in this work was vacuum melted AISI 4340 steel per requirements of MIL-S-8844. This material, heat treated nominally to a 1790-~~1830~~ 1930 MPa ultimate strength level, was used in landing gear of many earlier aircraft. The material was procured in the form of forgings 25 x 108 x 1829 mm. Each forging was cut into eight specimen blanks approximately 12 x ~~25~~ 100 x 450 mm. Specimens were rough machined about 4 mm. oversize in all dimensions prior to heat treatment. The geometries of tensile, fatigue, and stress corrosion specimens are shown in Figure 1. Following rough machining, all specimens were heat treated.

The heat treatment consisted of oil quenching from 1085K and tempering at 480K. The resulting hardness was 52-54 R_C. The average results from tensile tests were 2070 MPa ultimate tensile strength, 1397 MPa 0.2% yield strength, 51% reduction of area and 12.4% elongation (25 mm gage length). After heat treatment, the specimens were finish machined. The final 0.5 mm. of material was removed from all surfaces by a controlled low stress grinding procedure [1] which introduces low level compressive stresses at the surface and within about 0.1 mm. beneath the surface. Further, this grinding procedure does not produce any overtempering or re-transformation



Thickness = 9.52 mm

(A) Fatigue and Tensile



Thickness = 9.52 mm

(B) Stress Corrosion

FIGURE 1 Specimen Geometries

of the martensitic surface microstructure. After finish grinding, the edges of the specimen gage sections were radiused to about 1 mm. and hand polished through 600 grit SiC paper to a surface roughness of about 0.2μ -m AA.

Shot Peening

Following heat treatment and machining, specimens other than those tested in the baseline condition (no shot peening or cadmium plating) were shot peened per MIL-S-13165B. Specimens were clamped in a vertical position and rotated at 10-15 RPM. Six nozzles were used to propel the shot simultaneously at the specimen. These nozzles oscillated during peening to ensure consistent overall coverage of the surface. After peening for three minutes, each specimen was flipped end for end and then peened for an additional three minutes. Peening was performed with hardened size 230 steel shot. Coverage was 200%. The resulting Almen strip intensity (or chordal elevation) was 0.2 to 0.3 mm.

Cadmium Plating

Cadmium plating was performed per MIL-C-8837, Type II. The procedure involves vacuum deposition of cadmium followed by a supplementary chromate treatment to form a protective oxide film. Specimens were cleaned in a solvent and were lightly dry blasted prior to insertion in the vacuum chamber to insure cleanliness of surfaces. The blasting did not roughen the surface beyond the finishes specified in Figure 1. The plating on specimens selected for multiple shot peening and plating cycles was stripped between each cycle.

Tensile and Fatigue Testing

Tensile and fatigue tests were performed on a servo-controlled closed loop hydraulic universal test machine. The load cell and all support equipment were calibrated immediately before and after this program using secondary standards whose calibrations were traceable to the National Bureau of Standards. The loading grips and associated fixtures were aligned using a strain gaged specimen of the same geometry as the test specimen.

Tensile tests were performed per ASTM E8 in ambient air at about 293K and 50% relative humidity. The strain rate for all tests was .005 $min.^{-1}$ to failure. Strain measurement was performed via an LVDT extensometer attached to the specimen gage section over a 25 mm. gage length.

Fatigue tests were conducted under constant load amplitude conditions at R = 0.1 and -0.3 in a high humidity air environment. The environment was maintained by bubbling compressed air slowly through a column of water and then passing the air into a plastic jacket surrounding the specimen gage section. All testing was performed at a frequency of 2-4 Hz using a sinusoidal load-time waveform. Tests were terminated after 10^6 cycles if fracture had not occurred beforehand.

Stress Corrosion Testing

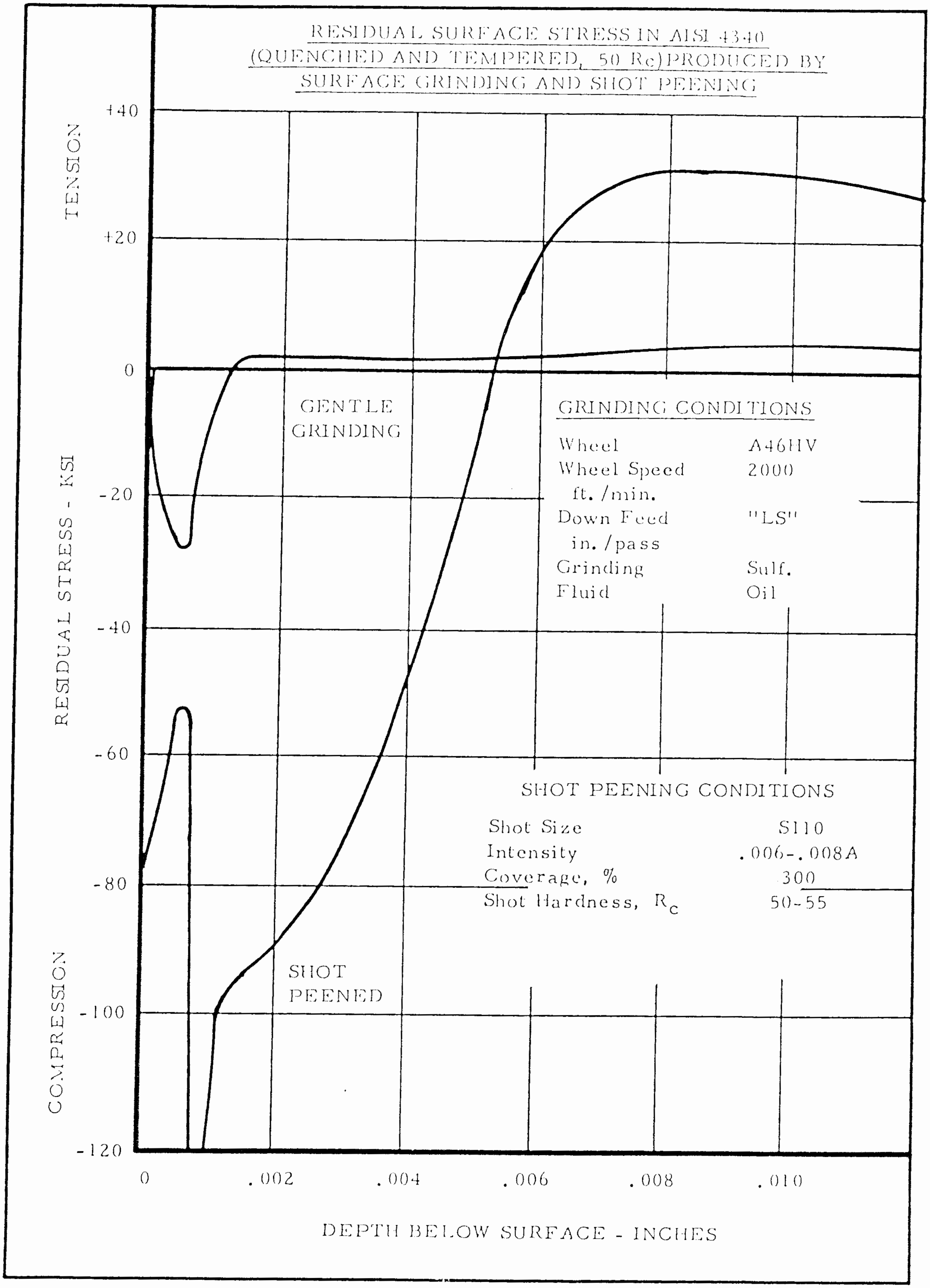
Stress corrosion testing was performed per ASTM B39 with the exception that tests were conducted under constant load rather than constant displacement in four point bending. Testing was conducted in dead weight loaded test frames, commonly used for creep and stress rupture testing. The frames were outfitted with four point bend fixturing specially designed for this program. The constant bending moment test section of each specimen was the central 75 mm. of its 300 mm. length.

The test environment was 293K air at 80-100% relative humidity produced by slowly bubbling compressed air through a water reservoir and then passing it into a plastic bag surrounding the specimen test section. Both unnotched and fatigue precracked specimens were tested. The fatigue precracked specimen had been manufactured with 1.2 mm. wide by 0.6 mm. deep electrically discharge machined (EDM) notch in the geometric center of one surface. These specimens were fatigue precracked before any shot peening or plating cycles. Fatigue precracking was performed in ambient air under three-point bend loading at a frequency of 30 Hz and a stress ratio R of about 0.1. Fatigue cracks were initiated at a calculated maximum surface stress of 100 ksi and were permitted to grow until the total surface notch plus crack length reached 2.5 mm.

RESULTS AND DISCUSSION

Residual Stresses

No residual stress measurements were included in the scope of this work. In previous work, however, Metcut performed residual stress measurements on quenched and tempered AISI 4340 (50 Rc). (1) Residual stress results from that work, characterizing surface and subsurface residual stresses parallel to the grinding direction, are shown in Figure 2. As can be seen, the gentle grinding produced relatively low compressive stresses to a depth of less than 0.05 mm. while the shot peening produced relatively large compressive



RESIDUAL SURFACE STRESS IN AISI 4340 (QUENCHED AND TEMPERED, 50 Rc)PRODUCED BY SURFACE GRINDING AND SHOT PEENING
TENSION
RESIDUAL STRESS - KSI
COMPRESSION
+40
+20
0
-20
-40
-60
-80
-100
-120
GENTLE GRINDING
SHOT PEENED
GRINDING CONDITIONS
Wheel A46HV
Wheel Speed ft./min. 2000
Down Feed in./pass "LS"
Grinding Fluid Sulf. Oil
SHOT PEENING CONDITIONS
Shot Size S110
Intensity .006-.008A
Coverage, % 300
Shot Hardness, Rc 50-55
0
.002
.004
.006
.008
.010
DEPTH BELOW SURFACE - INCHES

stresses to a depth in excess of 0.1 mm. It is believed that the residual stress data shown in Figure 2 are representative of residual stresses created in the AISI 4340 steel employed in the current study since the same grinding and shot peening parameters were used.

Tensile Results

Tensile test results from baseline specimens (as heat treated and gently ground) and from specimens subjected to from one to five shot peening and plating cycles are summarized in Figure 3. As can be seen, no degradation of tensile strength, yield strength or percent elongation occurred as a result of shot peening and plating cycles.

Fatigue Results

Fatigue testing was performed axially at maximum stress levels of 1170 and 1380 MPa at stress ratios, R, of 0.1 and -0.3. Results representing each conbination of stress level and stress ratio are presented in Figure 4. It is evident that the average fatigue lives of specimens subjected to one to five shot peening plus plating cycles exceeded the average lives of all baseline specimens tested at the same stress level and stress ratio. This effect, however, was greater for specimens tested at the lower stress level (1170 MPa) than for specimens tested at the higher stress level (1380 MPa).

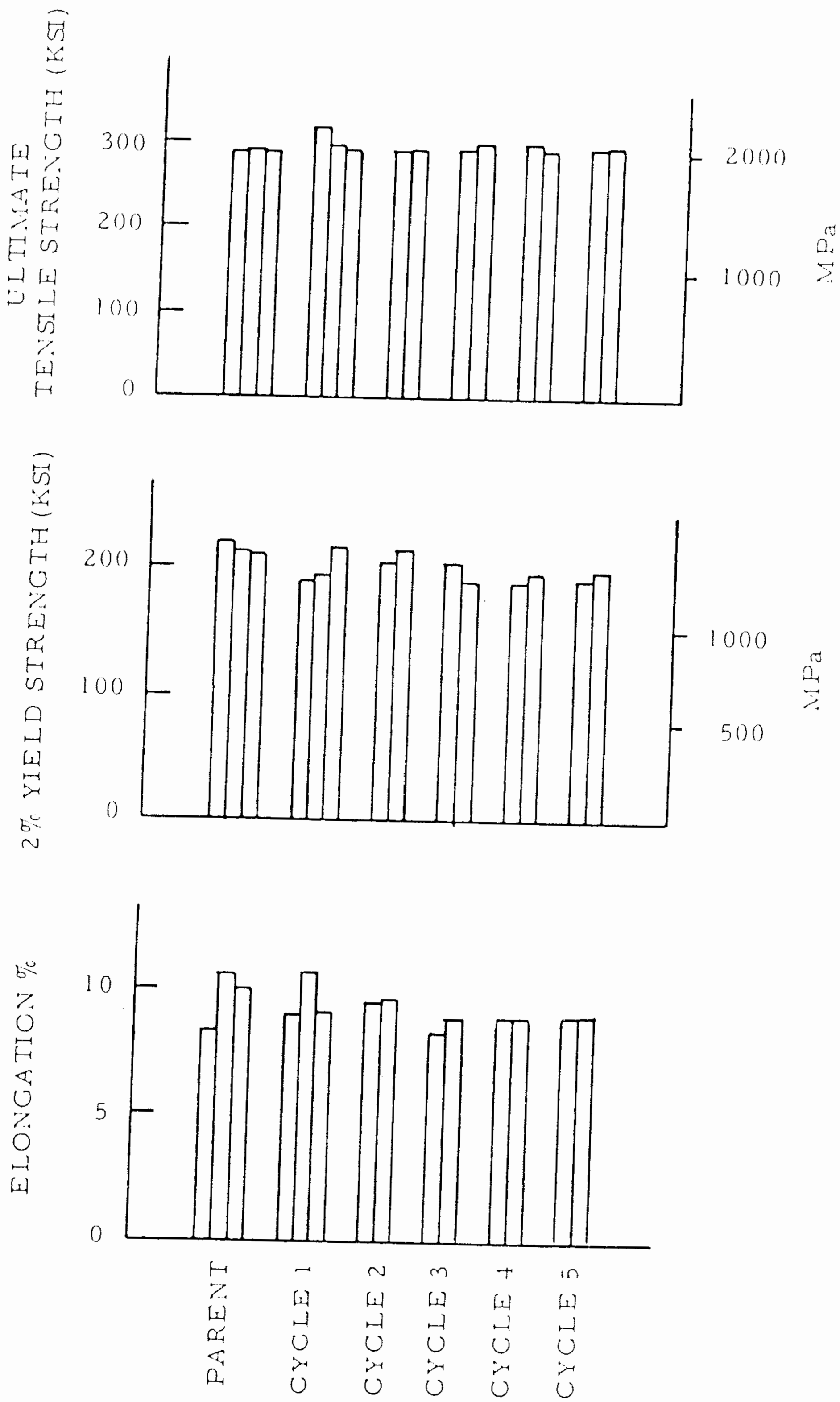


FIGURE 3 Tensile Results

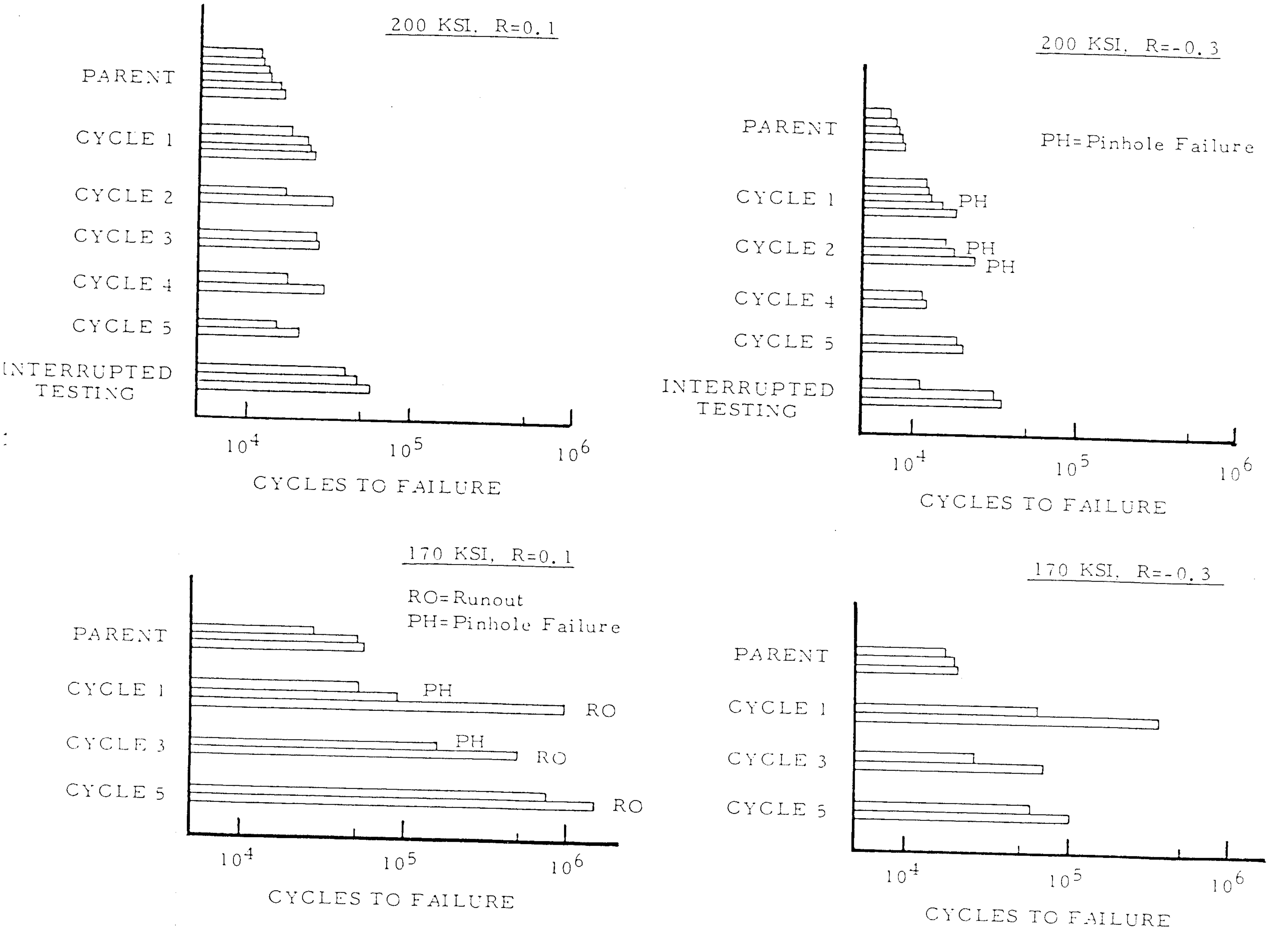


Figure 4 - Fatigue Results

The greater fatigue life after shot peening is consistent with the residual stress patterns presumed to be in the specimens since previous work by Metcut has shown a strong correlation between peak residual stress and fatigue strength in AISI 4340 steel.[2] It is believed further that the effect of shot peening is less pronounced for the higher testing stress level (1380 MPa) because this is close to the magnitude, though opposite in sense, to the peak magnitude of shot peening residual stresses presumed to be in the surface and subsurface layers.

It is also evident from the results in Figure 4 that fatigue lives of specimens subjected to from three to five shot peening and plating cycles were generally lower than lives of specimens subjected to one or two such cycles. No explanation can be offered for this. It is re-emphasized, however, that fatigue lives of shot peened and plated specimens generally exceeded those of baseline specimens regardless of the number of shot peening and plating cycles.

Also shown in Figure 4 are fatigue results from "interrupted testing" wherein specimens were cycled in fatigue between successive shot peening and plating cycles. The number of fatigue cycles applied after each shot peening and plating cycle was one-fourth the average fatigue life of specimens tested at the same stress level and stress ratio to failure after just one shot peening and plating treatment. After three such increments of fatigue cycling and four cycles of shot peening and plating, the specimens were tested to failure. It is evident that the lives of specimens thus treated exceeded those of all baseline specimens and generally exceeded those of specimens subjected to from one to five shot peening and plating cycles without intermittent fatigue cycling.

Stress Corrosion

A total of twenty-four stress corrosion tests were performed, fourteen on smooth specimens and ten on fatigue precracked specimens. All multiple shot peening and plating cycles were performed on individual specimens prior to stress corrosion testing. All precracking of notched specimens was performed prior to shot peening and plating cycles.

Initially, the maximum bending stress level for testing was chosen to be equal to the 0.2% offset yield stress (1415 MPa) for the material. This level subsequently was increased to 1655 MPa when no specimen failures were observed at the lower stress level. Therefore, the surface stress level, as reported herein is a pseudo-elastic stress level calculated per simple beam theory rather than an actual stress level. Specimens were held at load in the moist air environment for at least 200 hours or until fracture whichever occurred first.

TABLE I

STRESS CORROSION RESULTS - SMOOTH SPECIMENS

Specimen Number	No. of Shot Peening and Plating Cycles	Nominal (Pseudo-elastic) Surface Stress MPa	Test Duration (hrs)	Result *
Smooth Surface				
11	None	1415	258	N
12	None	1415	257	N
13	None	1415	279	N
14	None	1415	279	N
16	1	1415	259	N
23	1	1415	259	N
18	2	1655	214	N
21	2	1655	209	N
19	3	1655	209	N
24	3	1655	213	N
17	4	1655	215	N
22	4	1655	215	N
15	5	1655	200	N
20	5	1655	200	N

* N = No cracking observed, test terminated

TABLE II

STRESS CORROSION RESULTS - FATIGUE PRECRACKED SPECIMENS

Specimen Number	No. of Shot Peening and Plating Cycles	Nominal (Pseudo-elastic) Surface Stress MPa	Nominal Surface ** Stress Intensity Factor MPa (in.) ½	Test Duration (hrs)	Result ***
Precracked Nominal Crack Length 0.10 in., 2.5 mm					
9	None	1415	46	266	N
10	None	1415	46	266	N
9 *	None	1550	50	216	N
10 *	None	1655	54	214	F
7	1	1655	54	362	N
8	1	1655	54	350	F
6	2	1655	54	213	N
3	3	1655	54	233	N
5	3	1655	54	204	F
1	4	1655	54	42	F
2	5	1655	54	97	F
4	5	1655	54	2.2	F

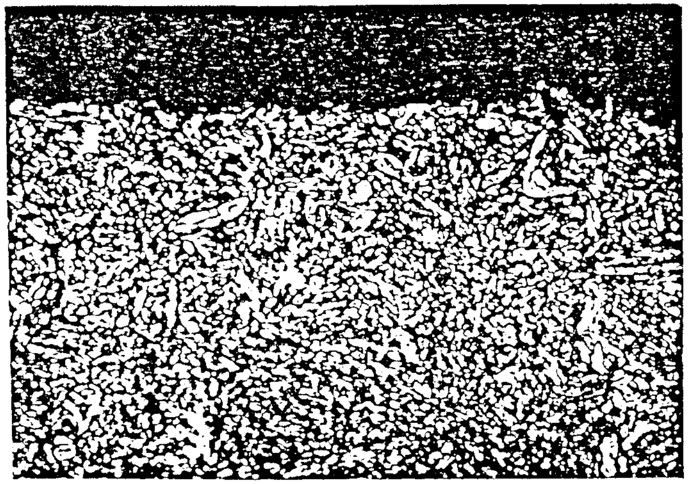
NOTES:
* Retest of a specimen from a terminated test at a lower stress.
** Calculated per Grandt & Sinclair, "Stress Intensity Factors for Surface Cracks In Bending", ASTM STP 513, Part 1, 1971, pp 37-58.
*** N = No crack extension observed (precracked specimens), test terminated.
F = Specimen fractured.

Stress corrosion results for smooth specimens are presented in Table I. These results are inconclusive with respect to the influence of shot peening and plating on stress corrosion resistance since no stress corrosion failures occurred. Visual examination of specimens after testing revealed neither any cracking nor any general corrosion on the specimens.

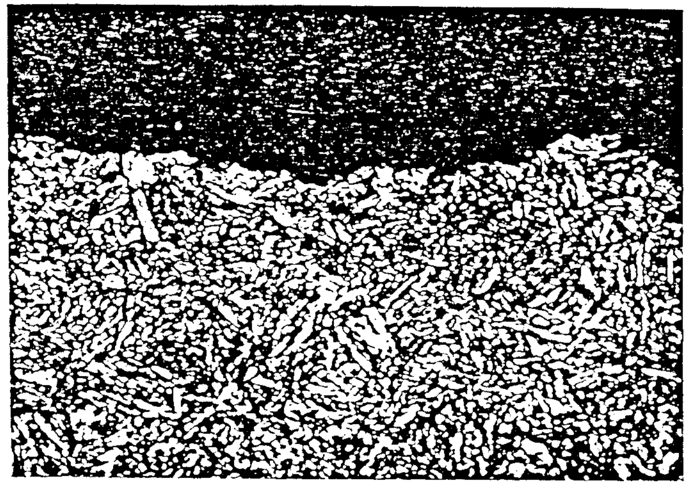
Stress corrosion results from notched and fatigue precracked specimens are presented in Table II. It is evident that lives of specimens subjected to four or five shot peening and plating cycles were lower than for baseline specimens or those subjected to a lesser number of such cycles. While no explanation can be given to explain or rationalize this observation, it can be speculated that it is the result of hydrogen accumulation from successive cadmium plating operations.

Metallography

The metallographic specimens prepared for this program were oriented parallel and perpendicular with respect to the machining lay. The specimens were mounted in epoxy material embedded with aluminum oxide pellets for optimum edge retention. They were polished by conventional means and examined in the unetched and etched conditions at magnifications of up to approximately 1000X. The etchant used was a 2% Nital solution.



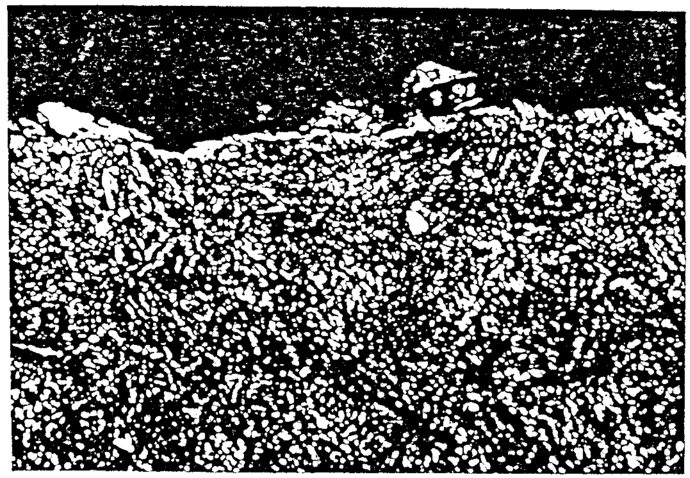
Baseline: As-Ground



After One Shot Peening/Plating Cycle

10 μ

After Three Shot Peening/Plating Cycles



After Five Shot Peening/Plating Cycles

Figure 5 - Metallographic Sections Through AISI 4340 Steel Specimen Surfaces; All Sections Parallel to Grinding Direction

Baseline 4340 samples and five groups of samples with varying number of shot peening and plating cycles were examined. Surface structural features are briefly described and characterized by photomicrographs shown in Figure 5. Traces of thin white layer were observed on the surface of the peened samples. These white or light etching layers and stringers may be attributable to a high degree of surface plastic deformation. The thin layers probably represent highly deformed "amorphous" material rather than untempered martensite which has a similar appearance.

In addition to the preceding general characterization of surface features, a metallographic study was performed on several failed test specimens in an attempt to ascertain whether or not the observed white layer influenced the failure process. The specimens selected for this study represented parent or baseline material and extremes in test life for various fatigue and stress corrosion test conditions.

Before proceeding with metallographic examination of the test specimens, a test blank and the two baseline specimens were macro-etched to investigate whether or not any significant grinding burn had occurred. This was done in order to resolve the issue of whether the presence of a white layer could be traceable to machining in the manufacture of the specimens. The three specimens were etched using a multi-step procedure widely used in industry which consisted of a dilute solution of 4% nitric acid in water and a solution of 2.5% hydrochloric acid in acetone. One of the parent specimens was also etched with a 2% nital solution. None of these etching techniques revealed presence of grinding burn on the specimens.

The test specimens were first examined on a binocular microscope at magnifications of up to approximately 40X in order to locate failure origins. Examination of the fatigue specimens revealed that failure origins were located at either one of the corners of the specimen or on the sides of the specimen. Failures in the stress corrosion specimens initiated from the pre-existing fatigue crack that was introduced at the bottom of the EDM notch.

Metallographic sections were made approximately through the center of each failure initiation site and examined in the unetched and etched conditions at magnifications up to approximately 1200X. Observations indicated that white layer was not associated exclusively with the initiative area of specimens exhibiting the lowest fatigue lives. Fatigue initiation was also influenced by apparently other forms of surface degradation, such as microcrack and slivers, and by specimen geometry (i.e., the corner areas).

CONCLUSIONS

Specific conclusions from experimental results were as follows:

1. Shot peening/cadmium plating cycles up to five in number had no influence on tensile properties relative to those from as-heat treated material.

2. Fatigue resistance in high humidity air at stress ratios, R of 0.1 and -0.3 was enhanced by shot peening/cadmium plating cycles up to five in number. The increase was most noticeable after one to three such cycles.

3. Stress corrosion results from unnotched specimens in high humidity air were inconclusive since both as-heat treated and shot peened/cadmium plated specimens survived 200 hours exposure at up to a 1650 MPa elastic surface stress level without cracking.

4. Fatigue pre-cracked stress corrosion specimens subjected to four and five shot peening/cadmium plating cycles exhibited shorter lives than as-heat treated specimens and specimens subjected to fewer shot peening/cadmium plating cycles. All specimens were fatigue precracked

to a surface crack length of about 2.5 mm. after heat treating, prior to any shot peening/plating cycles. Stress corrosion testing of precracked specimens was performed in 293K, 80-100% relative humidity air at a pseudo-elastic surface stress level of 1650 MPa.

5. No microstructural changes of significance relative to mechanical properties were observed to result from shot peening/cadmium plating cycles. White stringers observed metallographically at the surface tended to increase in prominence with increasing cycles. These stringers were believed to be an etching pnenomenon related to plastic deformation in the peened surface layers.

Acknowledgement

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W. J. Stross, Tensile and Fatigue Testing

L. R. Gatto, Metallography

T. E. Arnold, Stress Corrosion Testing

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