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AD No. 102 534

WADC TECHNICAL REPORT 55-56  
PART II

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**PROTECTIVE SHOT PEENING OF PROPELLERS**

**Part II. Fatigue Tests**

*RONALD F. BRODRICK*

*LESSELLS AND ASSOCIATES, INC.*

*AUGUST 1955*

**WRIGHT AIR DEVELOPMENT CENTER**

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## **PROTECTIVE SHOT PEENING OF PROPELLERS**

**Part II. Fatigue Tests**

*RONALD F. BRODRICK*

*LESSELLS AND ASSOCIATES, INC.*

*AUGUST 1955*

PROPELLER LABORATORY  
CONTRACT No. AF 33(616)-2324  
PROJECT No. 3346  
TASK No. 33048

WRIGHT AIR DEVELOPMENT CENTER  
AIR RESEARCH AND DEVELOPMENT COMMAND  
UNITED STATES AIR FORCE  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.  
300 - June 1956

## FOREWORD

This report was prepared by Lessells and Associates, Inc., Boston Massachusetts, under U. S. Air Force Contract No. AF 33(616)-2324, Task No. 33048, Project No. 3346, "Propeller Blades." The contract was administered under the direction of the Propeller Laboratory, Directorate of Laboratories, Wright Air Development Center, by Mr. John S. Keeler and Mr. Marshall W. Baldwin. The author wishes to acknowledge the assistance of Mr. L. E. Babcock who designed the fatigue machine used for these tests.

## ABSTRACT

This report is the second of two reports covering work performed under Contract No. AF33(616)-2324 during the period from 1 February 1954 to 31 August 1955. The object of the investigation was to determine any benefits of shot peening as a means of protecting aircraft propeller blades against the reduction of fatigue strength arising from surface damage. The first report covered the investigation of the residual stresses induced by each of a variety of shot peening conditions on several materials. The second report covers Prot fatigue tests on SAE 4340 steel specimens which had been shot peened and subjected to simulated propeller blade damage.

The results indicate that shot peening acts as a barrier to the detrimental effects of surface damage. SAE 4340 specimens of hardness  $R_C 51$  which were peened before damage showed an average endurance limit 110% higher than those which were not peened prior to damage. Under similar conditions, specimens of hardness  $R_C 31$  and  $R_C 41$  showed increases in endurance limit of 30% and 87%, respectively.

## PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

*John O. Schulze*  
JOHN O. SCHULZE  
Chief, Structures Branch  
Propeller Laboratory  
Directorate of Development

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## I. INTRODUCTION

Aircraft propeller blades, like many aircraft parts, are subjected to large numbers of alternating loads during operation. Their design strength, therefore, must be based upon fatigue strength rather than on other criteria of failure. Propeller blade design is further complicated by the fact that the blades are commonly subjected to surface damage by the impingement of foreign objects such as bits of macadam runway, etc. The sites of this damage act as stress raisers which encourage fatigue failure. Other effects, such as cold work, are present and are difficult to analyze, but the general result of this damage is a reduction in the fatigue properties of the propeller blades. In order to ensure safety, either the propeller must be designed at low stress levels, with consequent inefficient utilization of material, or the blades must be subjected to frequent inspection and rework. These procedures are expensive in time or in aircraft efficiency if safety is to be maintained.

Considerable thought has been given to methods of armoring the propeller blades against damage caused by these foreign objects. Among the ideas presented is the possibility of introducing compressive residual stresses into the blade surfaces. This procedure has received common acceptance as a means for increasing the fatigue strength of many materials (1, 2). \* It has been suggested that this procedure might be capable of masking the detrimental effects of surface damage. It was postulated that the damage would not have detrimental effects on surfaces containing residual compressive stresses of sufficient depth and magnitude as to be partially retained even after surface damage.

Of the several available methods for introducing compressive surface stresses, shot peening is probably the most common and most easily applied to propeller blades. It was, therefore, selected for the present investigation.

The first phase of this investigation consisted of a detailed study in which the residual stresses resulting from each of a wide variety of shot-peening treatments were measured. This information was necessary for application to propellers and could be useful in a wide variety of other applications. The details and results of this study are given in Reference (3).

The second phase of the investigation was directed toward the evaluation of shot peening in connection with surface damage. Fatigue tests were performed on specimens which had been subjected to various shot-peening treatments and subsequently damaged. Details of the procedure are given in succeeding paragraphs.

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\* Numbers in Parenthesis Refer to Bibliography

## II. PROCEDURE

### SPECIMENS

Fatigue test specimens were of SAE 4340 aircraft quality alloy steel. The material was forged into rough bars 2 1/2 in. wide by 3/8 in. thick by 6 ft long. Test specimens cut from these bars were 1 in. wide by 0.250 in. thick by 15 in. long. The 0.250 in. thickness was rough ground about .010 in. oversize, the bars heat-treated, then finish ground and polished to final dimensions. A 45° by 1/16 in. chamfer was provided at the corners.

As delivered, the bars had been normalized and annealed. After rough machining, they were oil quenched from 1475°F and drawn to three levels of tensile strength of about 130,000 psi, 190,000 psi and 260,000 psi. Tensile test results are given in Table 1. Composition, as certified by the supplier, is given in Table 2.

TABLE 1

#### TENSILE TEST RESULTS

Note: Each number represents the average of 5 specimens

| <u>Material</u>        | <u>Hardness</u>  | <u>Yield Pt.</u><br><u>(psi)</u> | <u>Ultimate</u><br><u>Strength (psi)</u> |
|------------------------|------------------|----------------------------------|------------------------------------------|
| SAE 4340 (Heat E69643) | 52R <sub>C</sub> | 226,000                          | 257,000                                  |
| SAE 4340 (Heat E69643) | 41R <sub>C</sub> | 174,000                          | 187,000                                  |
| SAE 4340 (Heat E69643) | 30R <sub>C</sub> | 107,000                          | 131,000                                  |

TABLE 2

#### ANALYSIS OF TEST MATERIAL

##### SAE 4340    Heat No. E69643

| C   | Mn  | P    | S    | Si  | Ni   | Cr  | Mo  |
|-----|-----|------|------|-----|------|-----|-----|
| .40 | .76 | .010 | .016 | .24 | 1.75 | .85 | .24 |

Most of the tests were performed on the 190,000 psi steel, using several different peening treatments. The plan here was to study a variety of peening treatments on a single hardness of material, determining any benefits of the treatment and establishing values of peening variables which resulted in the greatest benefit. The results on the single hardness were then used to predict optimum peening treatments for the harder and softer specimen. A single peening treatment was used on each of the latter hardnesses.

Table 3 lists the specimens and their peening depths. Failure stresses are also included here for convenience. Depth of compression refers to the depth of residual compressive stress existing prior to surface damage. This is further explained in the section on shot peening. The shot peening treatments used to obtain these depths are given in Table 4. Residual stress patterns resulting from these treatments can be obtained from Reference (3).

## SHOT PEENING

The various peening conditions were set up on the basis of depth of residual stress as it seemed reasonable that the relation between depth of residual stress and depth of surface damage would be a significant parameter. The depth of the layer of compressive stress was chosen as the measure of depth of residual stress. This is defined as the distance from the metal surface to the plane at which the residual stress changes from compression to tension. This distance showed a high degree of consistency in the residual stress studies (Reference 3). Scatter in this parameter was less than the scatter in value of surface stress and in maximum stress.

All peening was done at high coverage, defined here as four times the duration of peening required to cover 98% of the surface of the specimen. Details of peening procedure and equipment are given in Reference (3) but can be briefly described as follows: An air blast cabinet was modified so that the rate of shot flow could be controlled. A reciprocating table was provided for transport of the specimen through the shot stream. Control of peening intensity was obtained through variations in nozzle size, air pressure, shot size, shot flow rate, and number of passes through the shot stream at a constant velocity of 10 in. per minute.

Actual peening conditions for each specimen were determined by selecting a desired depth, then obtaining the necessary conditions from Reference (3). The central 6-in. length of each bar was peened on both sides, except in the case of the highest strength bars. In the latter, it was necessary to peen the entire length in order to avoid fracture outside the peened section.

## SIMULATED BLADE DAMAGE

Surface damage was introduced into the specimens (except those tested in the parent condition) in order to simulate service aircraft conditions. This process was performed on a special machine at the Propeller Laboratory, Wright Air Development Center. Figure 1 is a schematic of this device. A steel club propeller about 5 ft long and averaging about 3 in. wide is rotated by a large electric motor. Attached to one end of the club is a piece of glass about 3 in. by 1 in. by 1/4 in. With the motor running at speed, about 2400 rpm, a solenoid places an obstruction in the path of the glass. This causes pieces of broken glass to take up paths tangential to the arc of rotation where they strike fatigue test specimens on a nearby stand. Each specimen was subjected to 10 cycles of this treatment on either side. Tenspecimens were placed on the stand simultaneously, their relative positions being rotated between runs, such that the damage was identical insofar as possible.

## FATIGUE TESTING MACHINE

The machine used for these tests was specially constructed to enable testing of the specimens by the Prot (4, 5) accelerated method. The specimens were magnetically excited in the fundamental free-free bending mode. For these bars this mode was at a frequency of about 230 cycles per second. Electronic controls were provided to maintain the required stress. In order to provide the control circuits with information of the stress level, a small accelerometer was attached near one end of the specimen. The accelerometer output was calibrated with respect to the optically-determined deflection

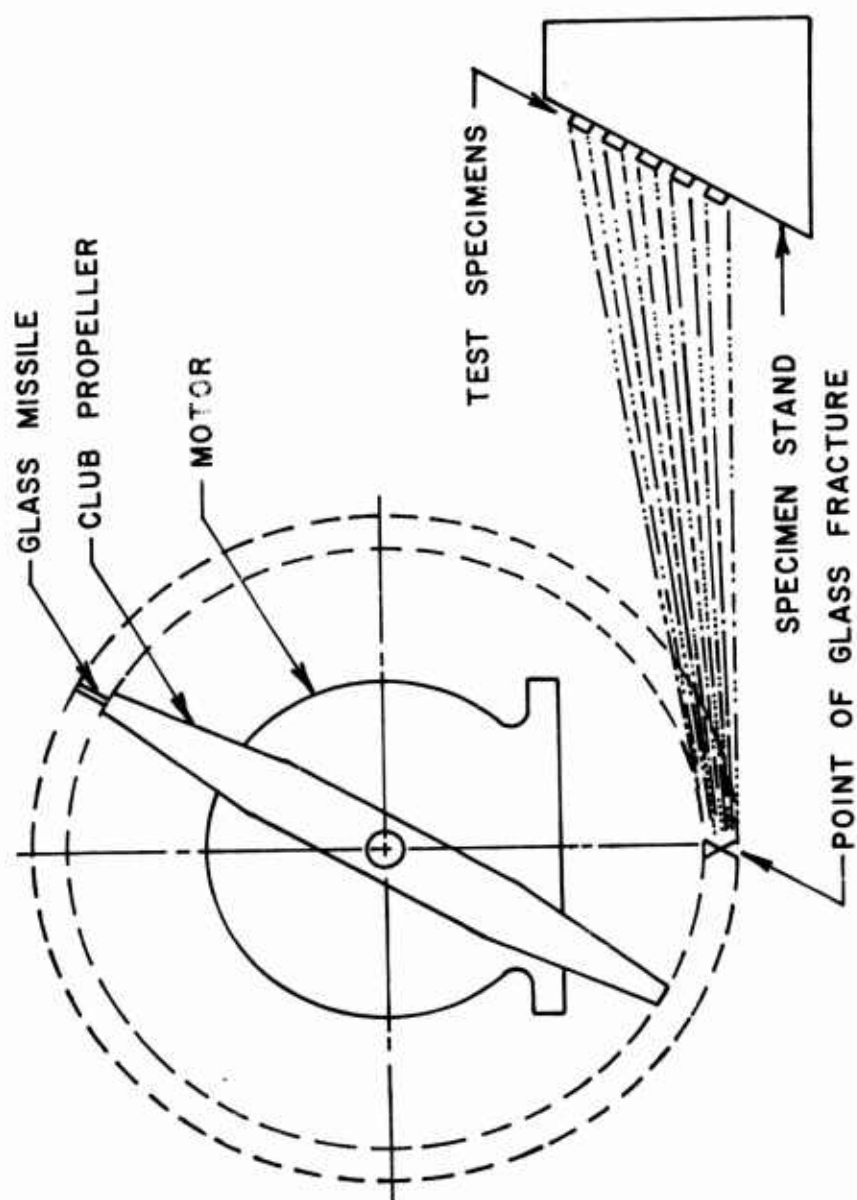


FIGURE 1. SCHEMATIC OF DAMAGING APPARATUS

amplitude of the specimen at its midpoint. An alternative arrangement consisted of a linear deflection-sensitive transducer placed adjacent to the midpoint of the specimen. This eliminated the necessity for making attachments directly to the specimen. Both arrangements worked satisfactorily.

Controls of the machine could be set so as to provide a continuously increasing amplitude of vibration at any desired rate. Specimen failure was detected by reduction in natural frequency. This phenomenon was used to control the automatic shutoff. In this regard, it might be mentioned that the earliest indication of failure was an audible ring of about 6000 cycles per second. This was presumed to be a longitudinal acoustical wave excited in the bar by the impact of the sides of a crack against each other.

Figure 2 is a photograph of the fatigue machine. At the right a test specimen is shown in position for testing. It is supported at its nodal points. Electromagnets supplying the power for deflection are just below each end of the specimen. At the left in Figure 2 is the cabinet containing the excitation power supply and controls.

#### METHOD OF TEST

Because of the comparative nature of the tests and the number of specimens involved, the fairly high value of 0.04 psi per cycle was used as the rate of stress increase in most instances. It was not possible to run enough tests to establish the Prot slope (5) of failure stress vs.  $\sqrt{a}$  ( $a$  = rate of stress increase in psi per cycle). Therefore, other sources of data on SAE 4340 were applied in estimating endurance limits from the failure stresses obtained.

The shape of the vibrating bar was assumed to be as follows:

$$y = a(1.153 \cos 4.73 \frac{X}{L} - 0.153 \cosh 4.73 \frac{X}{L}) \cos wt$$

where:  $y$  = displacement from quiescent condition (inches)

$a$  = displacement at midpoint of specimen (inches)

$X$  = distance from midpoint (inches)

$L$  = total length (inches)

$w$  = frequency (radians per second)

$t$  = time (seconds)

This assumption, together with assumption of Hooke's Law leads to the following relation between midpoint amplitude and stress.

$$S = 14.61 \frac{EaT}{L^2}$$

where:  $S$  = Stress at midpoint (psi)

$E$  = Young's Modulus

$T$  = Thickness of flat bar specimen

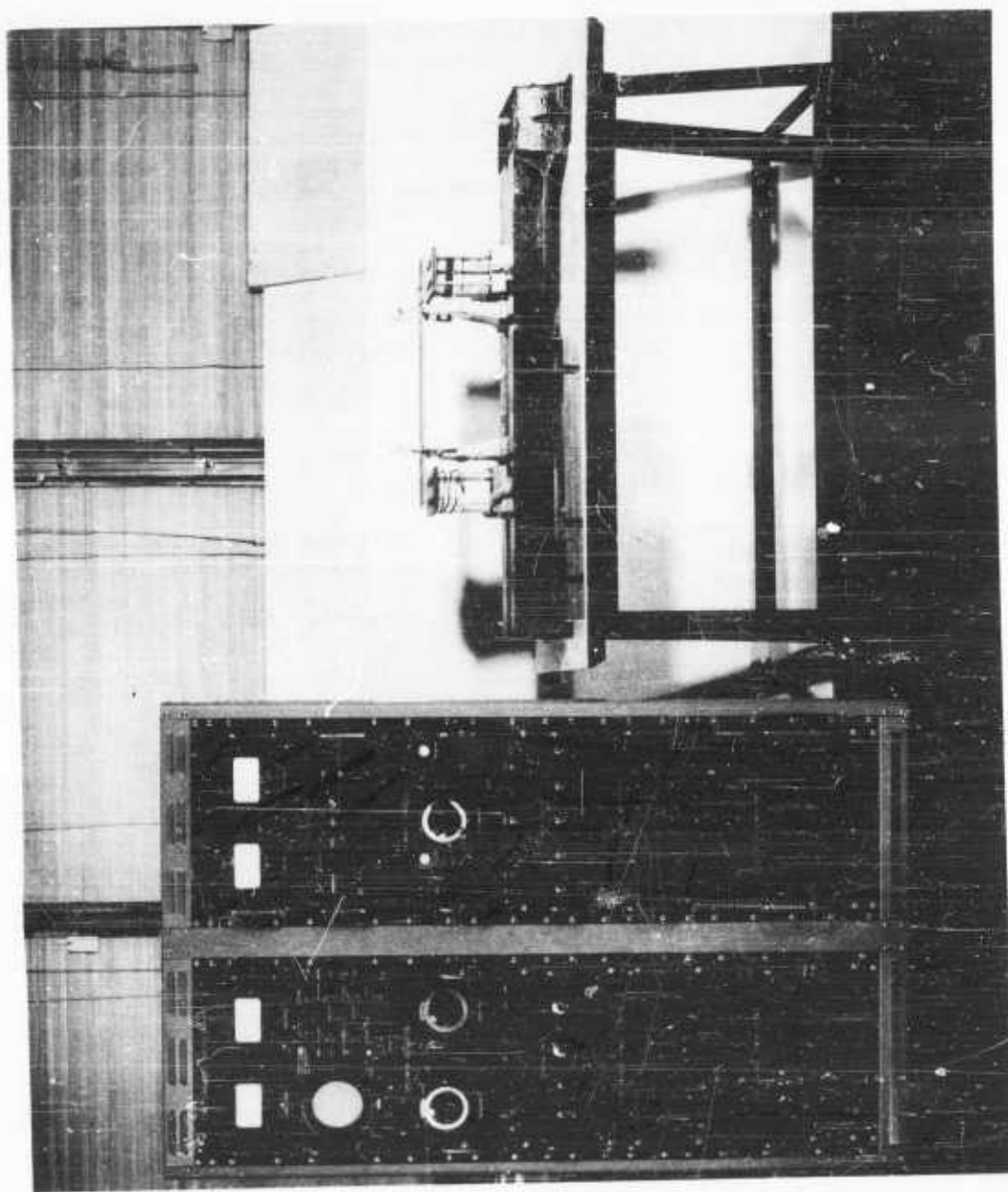


FIGURE 2. RESONANT BENDING FATIGUE MACHINE

Strain gage measurements at the midpoint of the bar were in good agreement with the above relation.

Testing was carried either to the point where the audible indication of cracking was apparent or until the machine shut down because of a drop in bar frequency. Cracks were well developed under the latter condition. These two conditions occurred within a few thousand cycles, indicating rapid crack growth. Growth was more rapid at the higher failure stresses and was extremely rapid in the high strength steel where only about one thousand cycles elapsed between the first audible indication of cracking and complete fracture of the specimen.

After testing, the failures were examined. In the cases where failure originated at a simulated gouge, the gouge depth was measured optically by means of a microscope with a dial gage mounted between the barrel and the stage. This arrangement is shown in Figure 3. In the case of shallow gouges a metallurgical microscope with a 6 mm objective and micrometer screw was used for increased accuracy. Accuracy of gouge depth measurement decreased with increasing peening intensity because of the rough surface. It was impossible to observe gouges on many of the heavily peened specimens, much less measure their depths. Photographs of the cracks were taken in many cases. Where necessary, specimens were bent to a small permanent set in order to delineate the cracks.

Nominal failure stresses were corrected for location along the bar and for the depth of the gouge at which failure occurred. An attempt was made to correlate failure with the type of damage. This was only partially successful, as discussed in succeeding paragraphs.



Figure 3. Apparatus for Gouge Depth Measurement

### III. RESULTS

Failure stresses of all specimens are given in Table 3. Individual test points for each group of specimens are plotted in Figures 4 through 14. Endurance limits are obtained by extrapolation to zero rate of stress increase.

As noted, the slope of the extrapolation is assumed to be that reported in Reference (6). The 95% confidence limits are extrapolated at the same slope, although it should be realized that they may be in error near the zero ordinate.

Figure 15 is a summary of results for the 190,000 psi steel. From this plot it can be seen that nearly a 50% improvement over the unpeened damaged condition arises from the shot peening. Under the conditions of damage attained in these tests there appears to be an optimum depth of compression of about 0.015 in., beyond which the strength is slightly reduced from maximum. This reduction is probably a result of surface roughness caused by extremely heavy shot peening. Even at the lightest peening treatment, an improvement of about 30% was obtained. This light treatment had the appearance of a burnished surface, with only very slight surface roughness.

In order to indicate the benefits of peening on a dimensionless basis, Figure 16 is included. In this figure the parameter of depth of compression over depth of damage is used. It appears that a value of five for this ratio represents the maximum attainable improvement over the unpeened case. However, even a ratio of two represents a considerable improvement.

Figures 17 and 18 show the degree of improvement for the 130,000 psi and 260,000 psi steel, respectively. In selecting the single depth of compression to be used in the 130,000 psi steel, and similarly in the 260,000 psi steel, an attempt was made to establish a ratio of five for depth of compression over depth of damage. Although the depth of compression could be controlled quite accurately, it was necessary to extrapolate depth of damage from data on the 190,000 psi specimens. This depth was estimated on the basis of the relative depths of a spherical hardness indenter in the different materials. Actual measurement of damage depth was somewhat inaccurate in the case of the very hard specimens, since the depths were very small. Measurement was also inaccurate in the cases of very heavy peening of the medium strength steel, since the rough peened surface offered a poor reference plane for the fairly shallow depths of damage. Figure 19 shows the relation of endurance limit to depth ratio for the 190,000 psi steel. Although the number of test points is limited, it appears that a depth ratio of about five represents the maximum improvement.

It was not possible to analyze the depth ratio for the 260,000 psi steel as the damage depths were extremely small and only ten peened and damaged specimens were tested. Nevertheless, this material, in the peened and damaged condition, showed about a 50% increase in endurance limit over the parent material and about a 110% increase over the unpeened damaged condition, as depicted in Figure 18.

In this regard it may be observed that endurance limits for the parent materials in the polished condition appear somewhat low. This may be a result of inclusions (which were observed in some failures) or of the polishing procedure. Polishing was done by hand, using decreasing sizes of grit and finishing with 600 grit abrasive paper. Although the polishing was performed with considerable care, differences in average endurance limit can be noted between groups of specimens of the same treatment but prepared at different times. These groups can be distinguished in Table 3 by discontinuity in numbering for specimens of the same treatment. Low values of

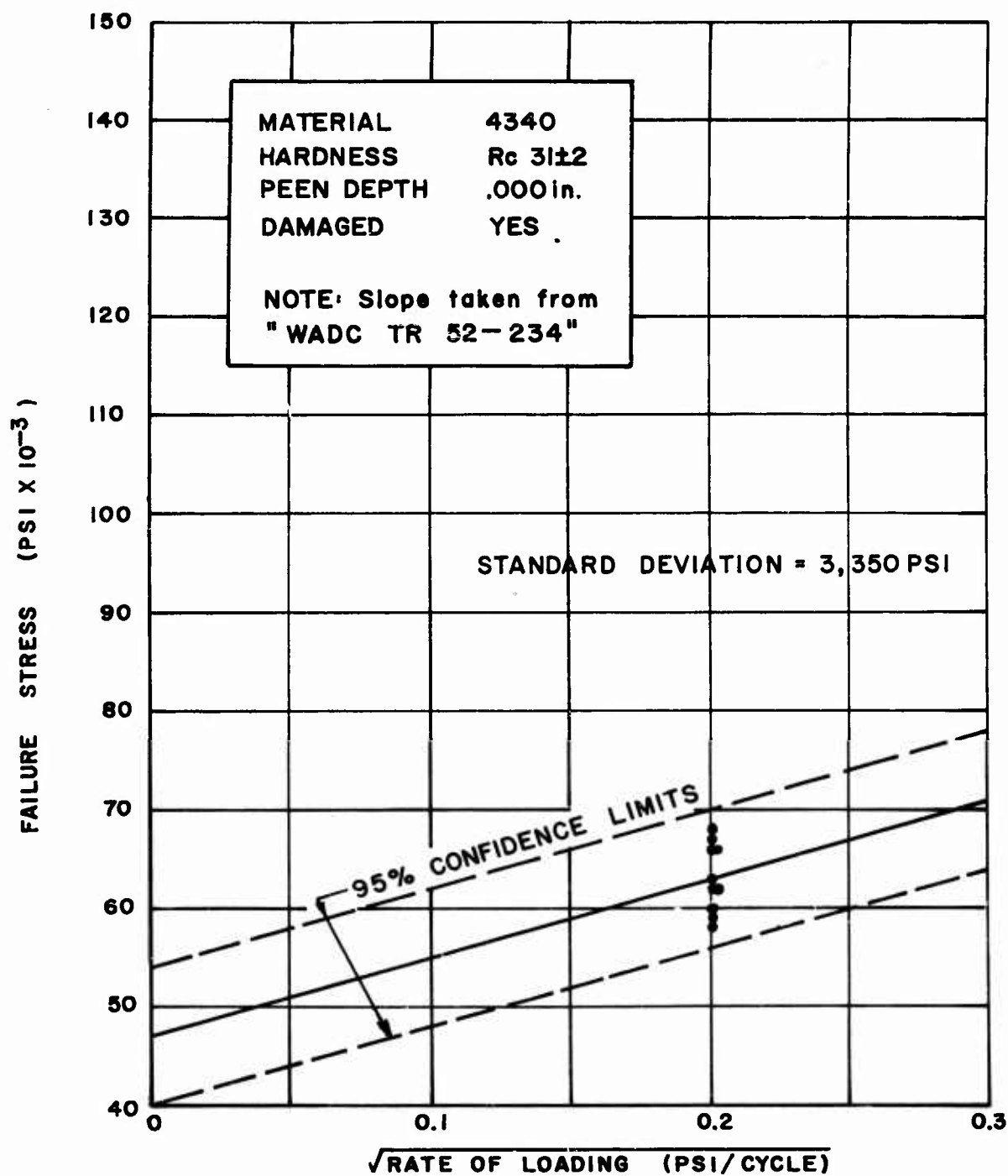
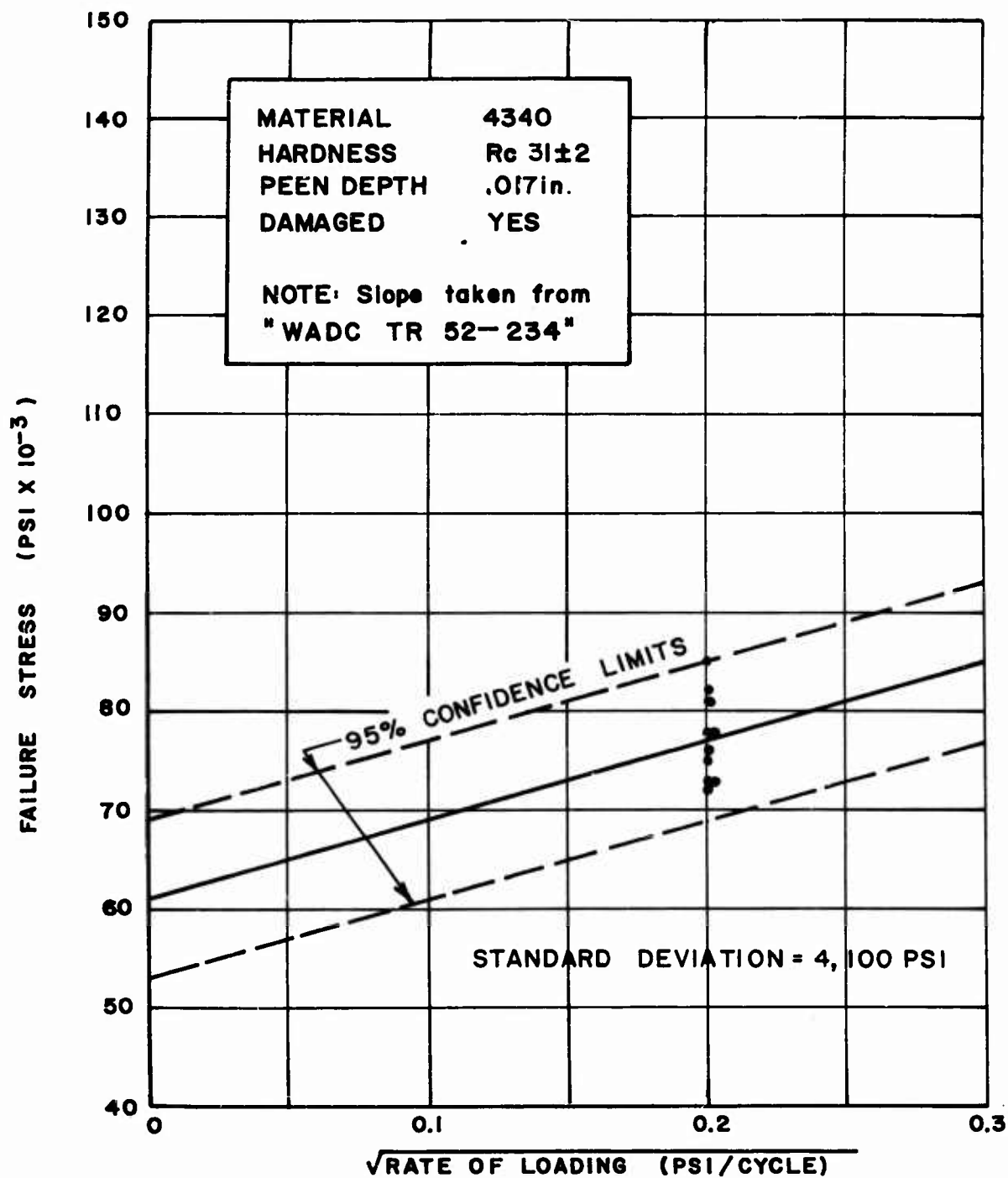


FIGURE 4. FATIGUE TEST RESULTS, Rc 31, .000 in.  
PEEN DEPTH, DAMAGED.



**FIGURE 5. FATIGUE TEST RESULTS, Rc 31, .017 in. PEEN DEPTH, DAMAGED.**

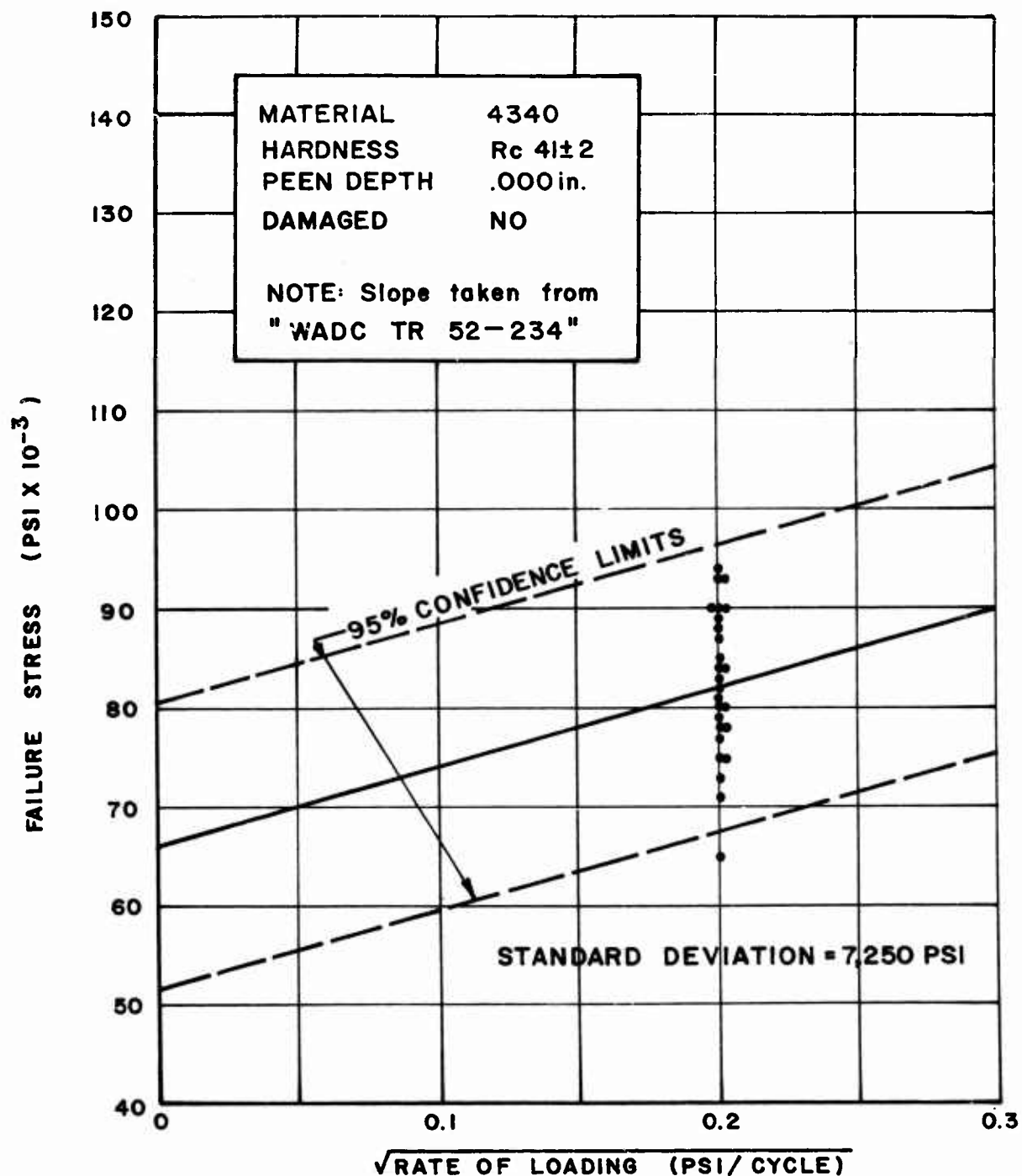


FIGURE 6. FATIGUE TEST RESULTS, Rc 41, .000 in. PEEN DEPTH, NO DAMAGE.

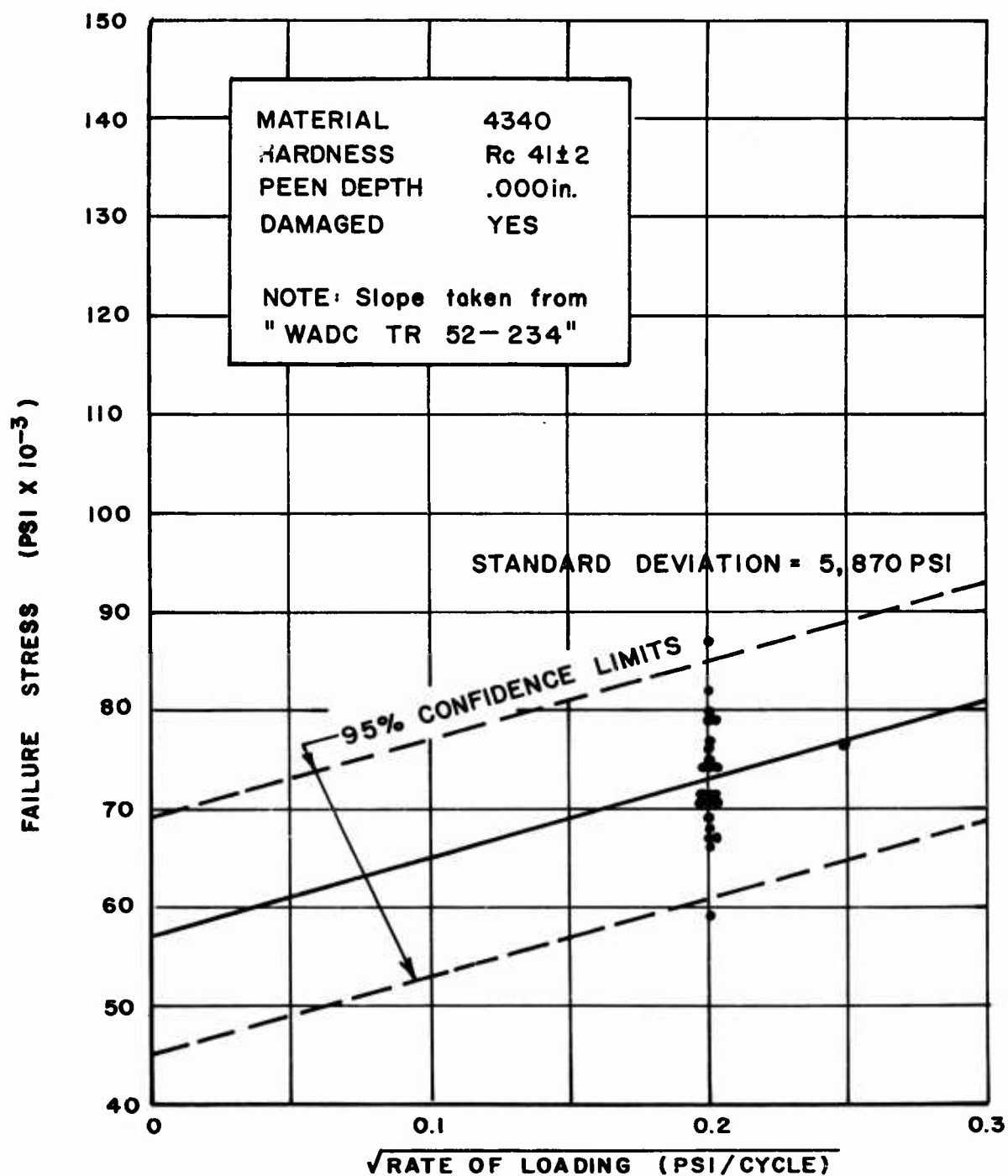
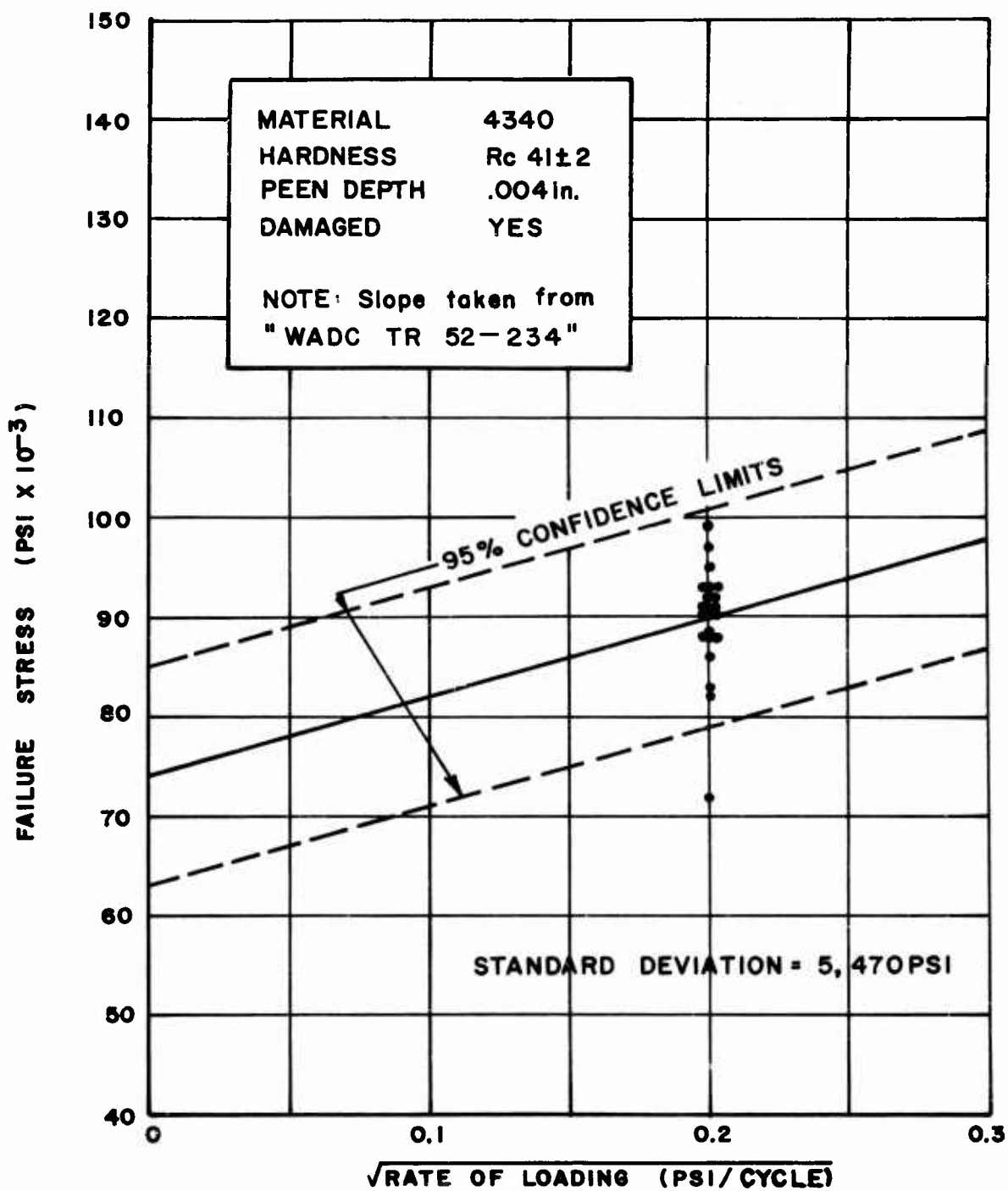


FIGURE 7. FATIGUE TEST RESULTS, Rc 41, .000 in. PEEN DEPTH, DAMAGED.



**FIGURE 8. FATIGUE TEST RESULTS, Rc 41, .004 in.  
PEEN DEPTH, DAMAGED.**

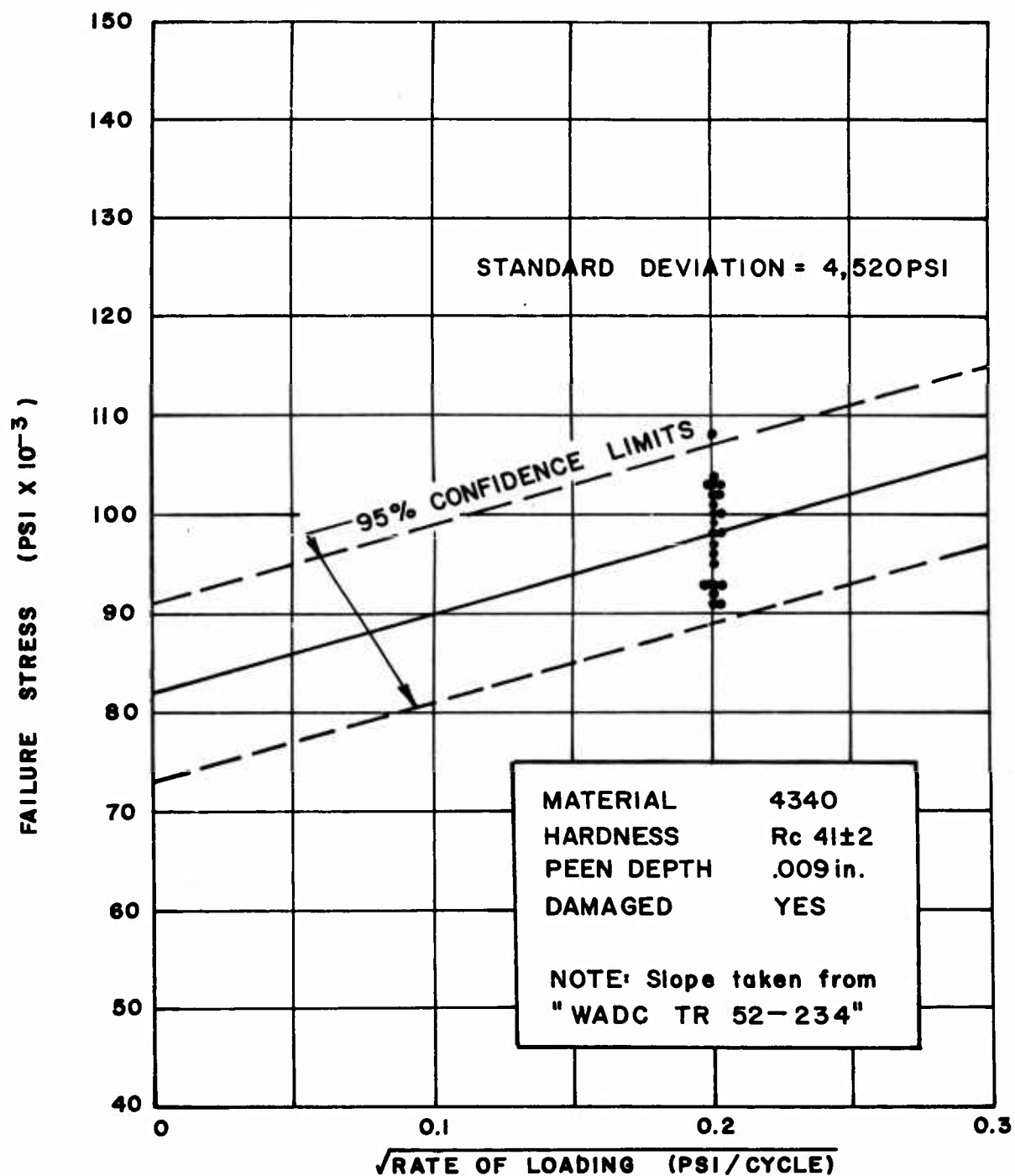


FIGURE 9 . FATIGUE TEST RESULTS, Rc 41, .009 in.  
PEEN DEPTH, DAMAGED.

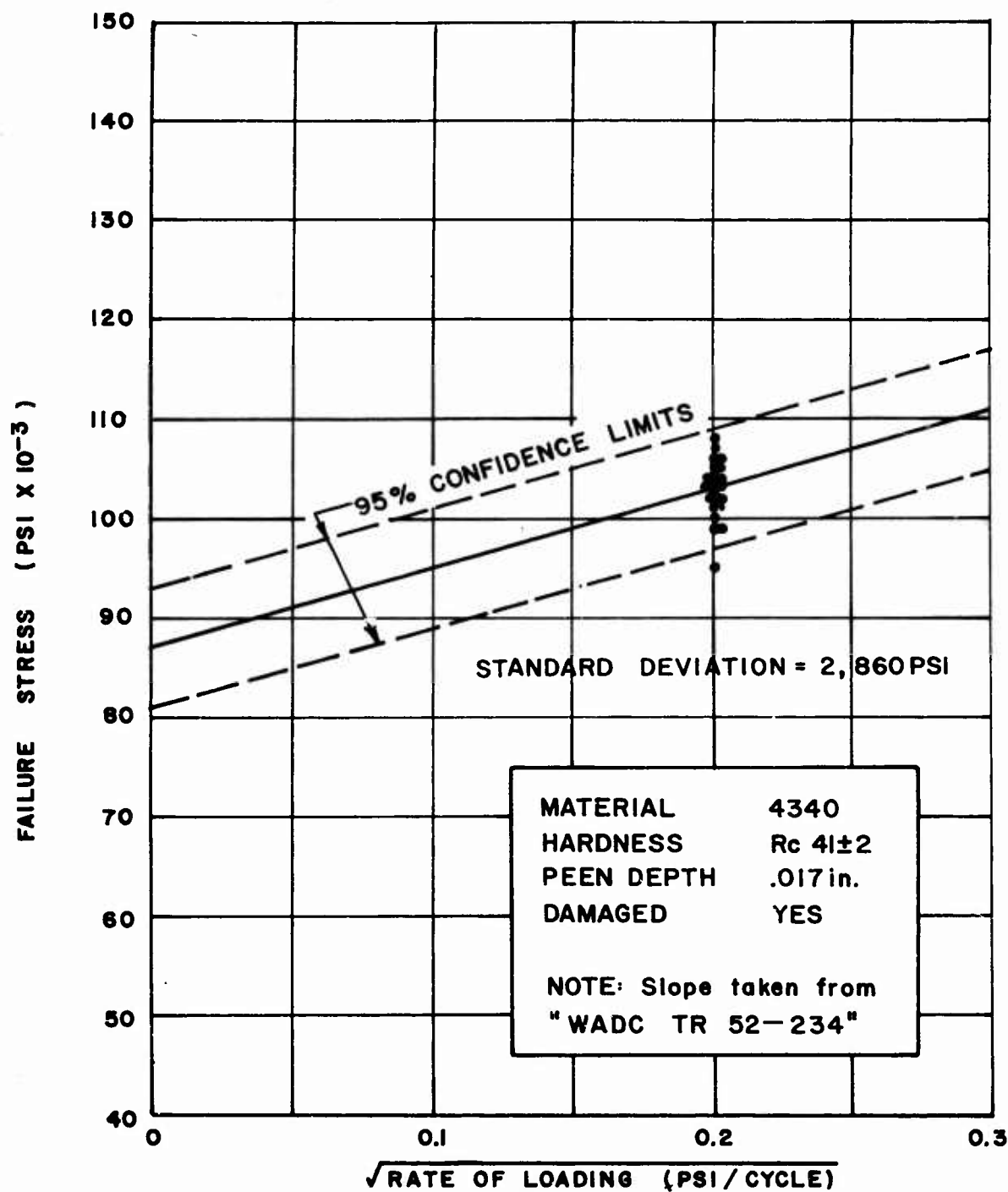


FIGURE 10. FATIGUE TEST RESULTS, Rc 41, .017 in.  
PEEN DEPTH, DAMAGED.

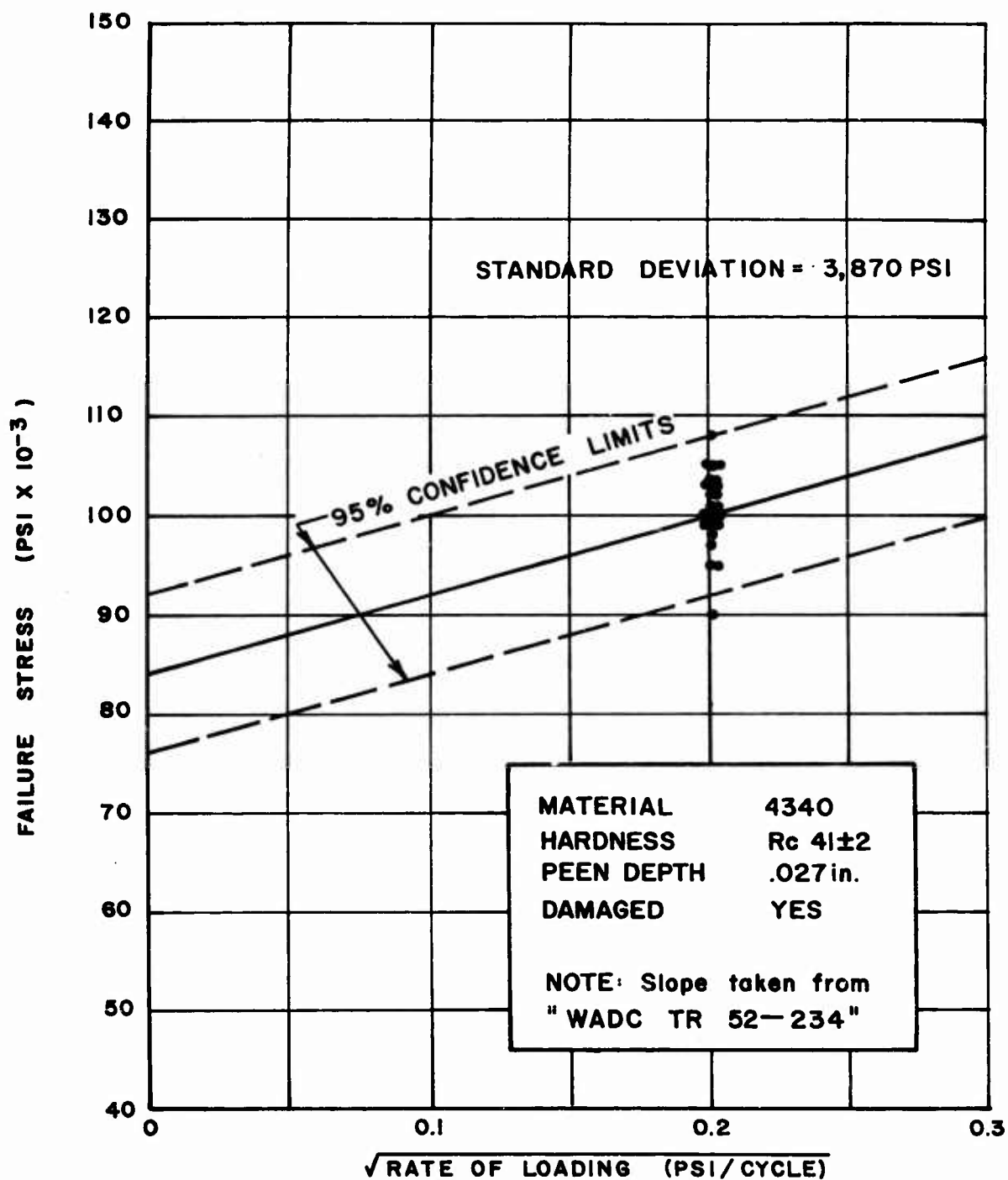


FIGURE 11. FATIGUE TEST RESULTS, Rc 41, .027 in. PEEN DEPTH, DAMAGED.

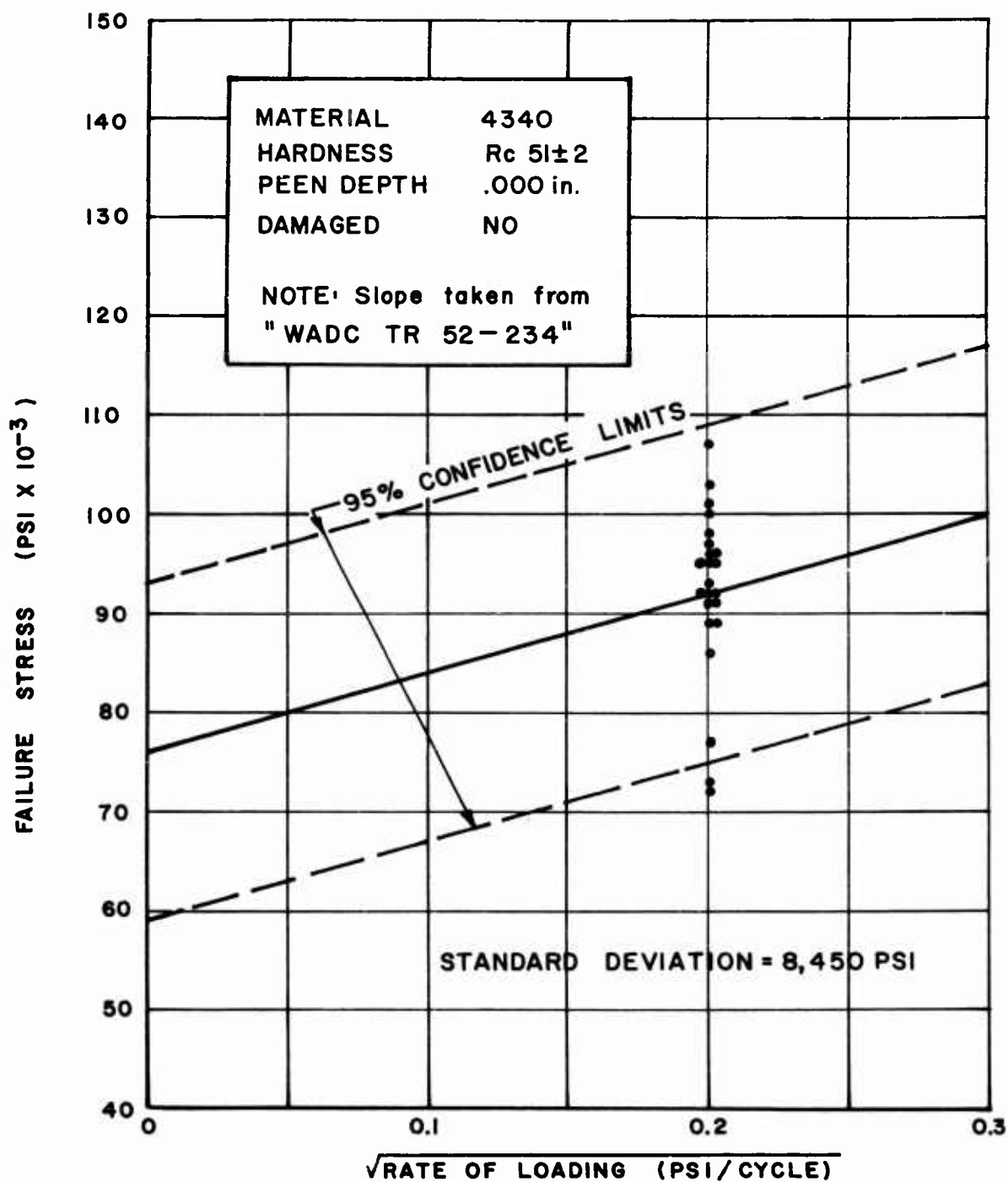


FIGURE 12. FATIGUE TEST RESULTS, Rc 51, .000 in. PEEN DEPTH, NO DAMAGE.

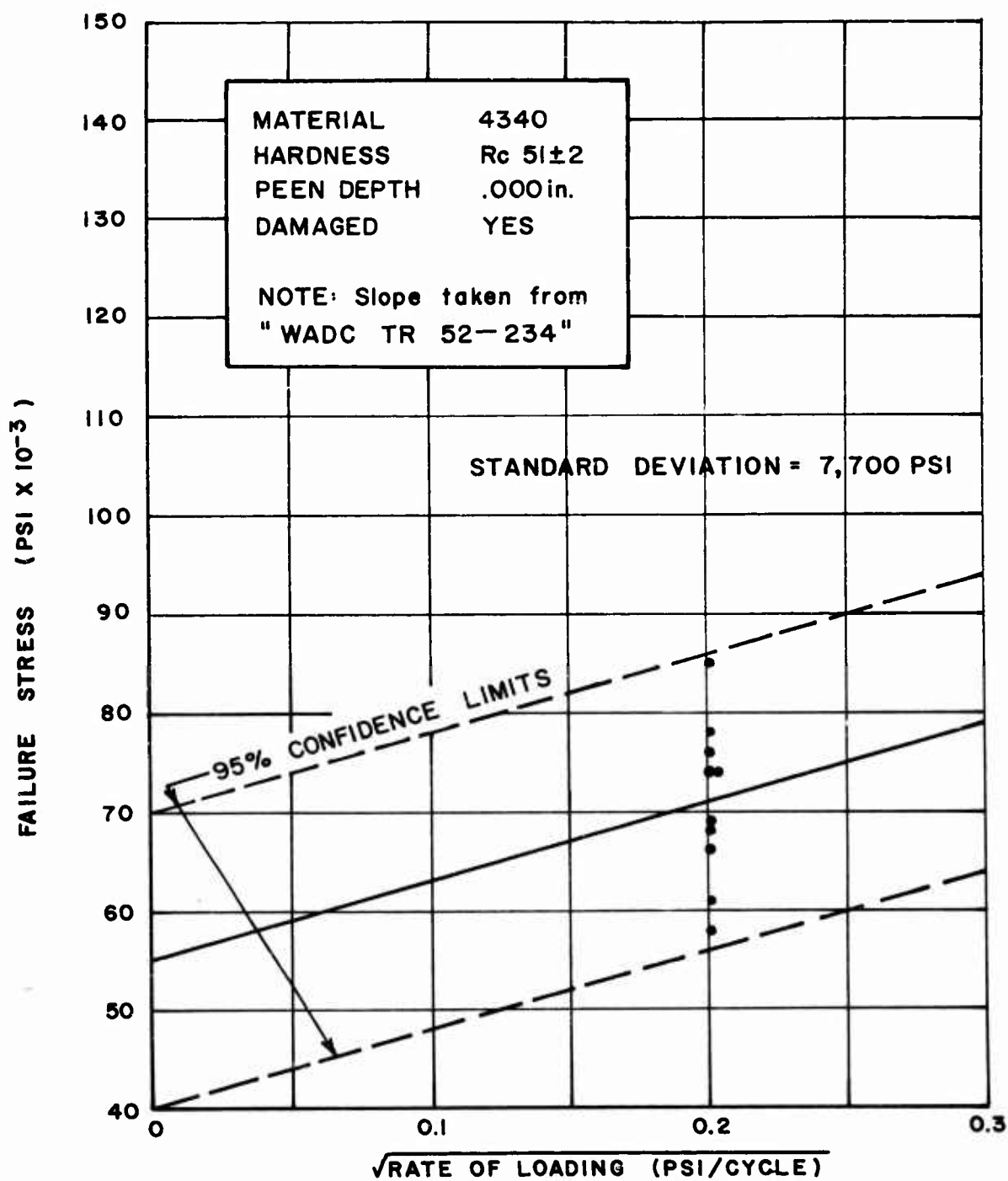


FIGURE 13. FATIGUE TEST RESULTS, Rc 51, .000 in.  
PEEN DEPTH, DAMAGED.

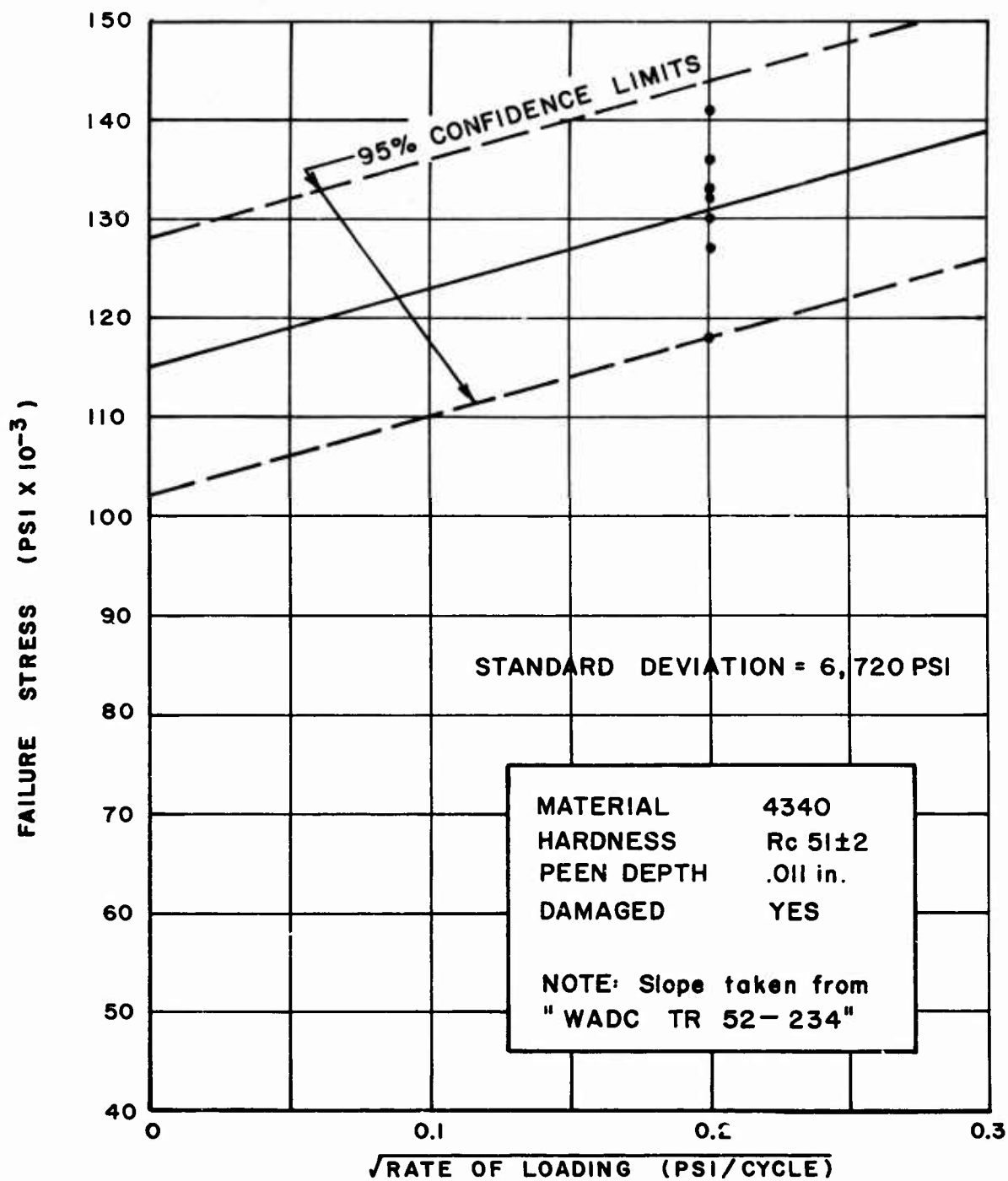


FIGURE 14. FATIGUE TEST RESULTS, Rc 51, .011 in. PEEN DEPTH, DAMAGED.

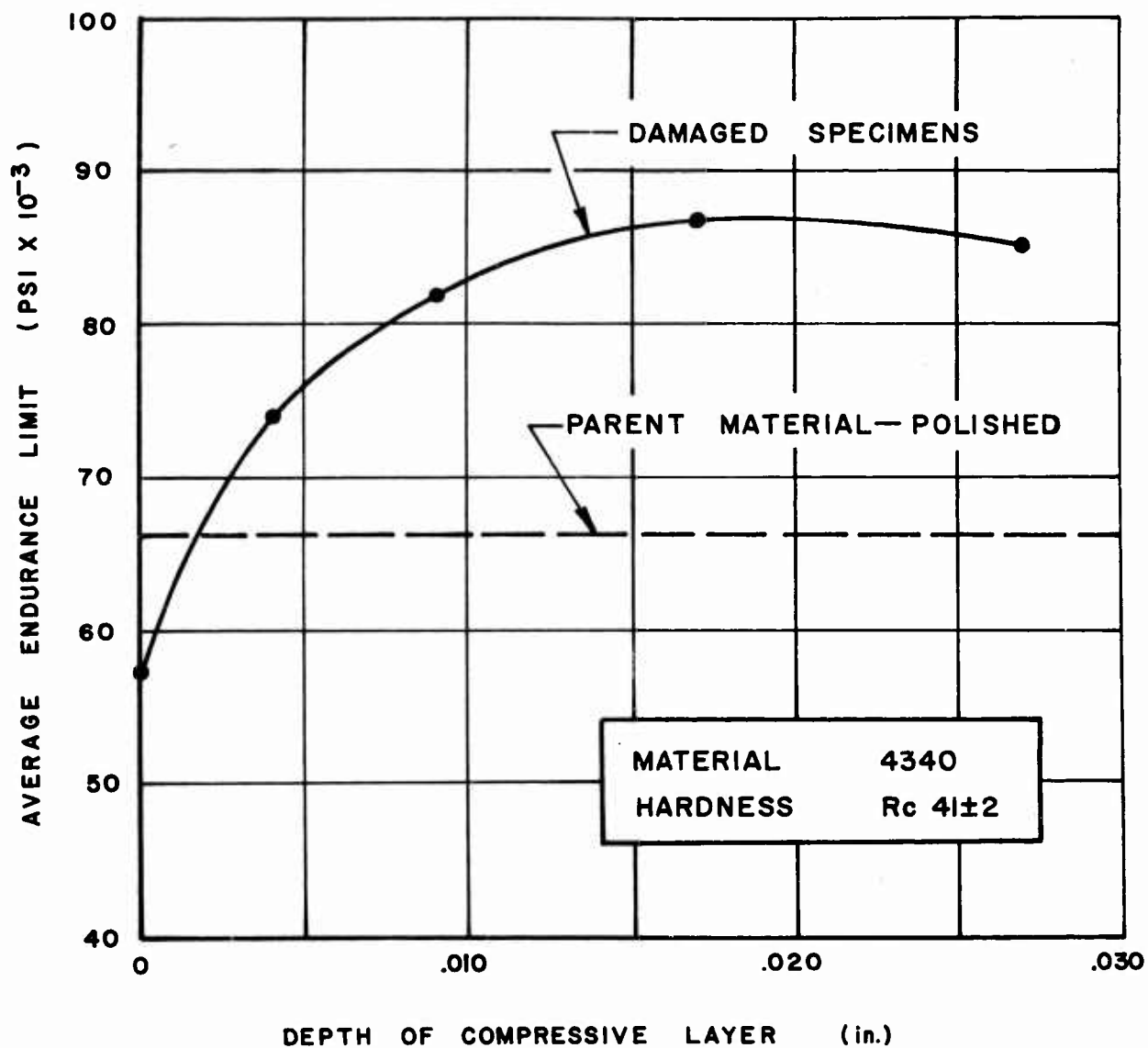


FIGURE 15. SUMMARY OF RESULTS — Rc 41

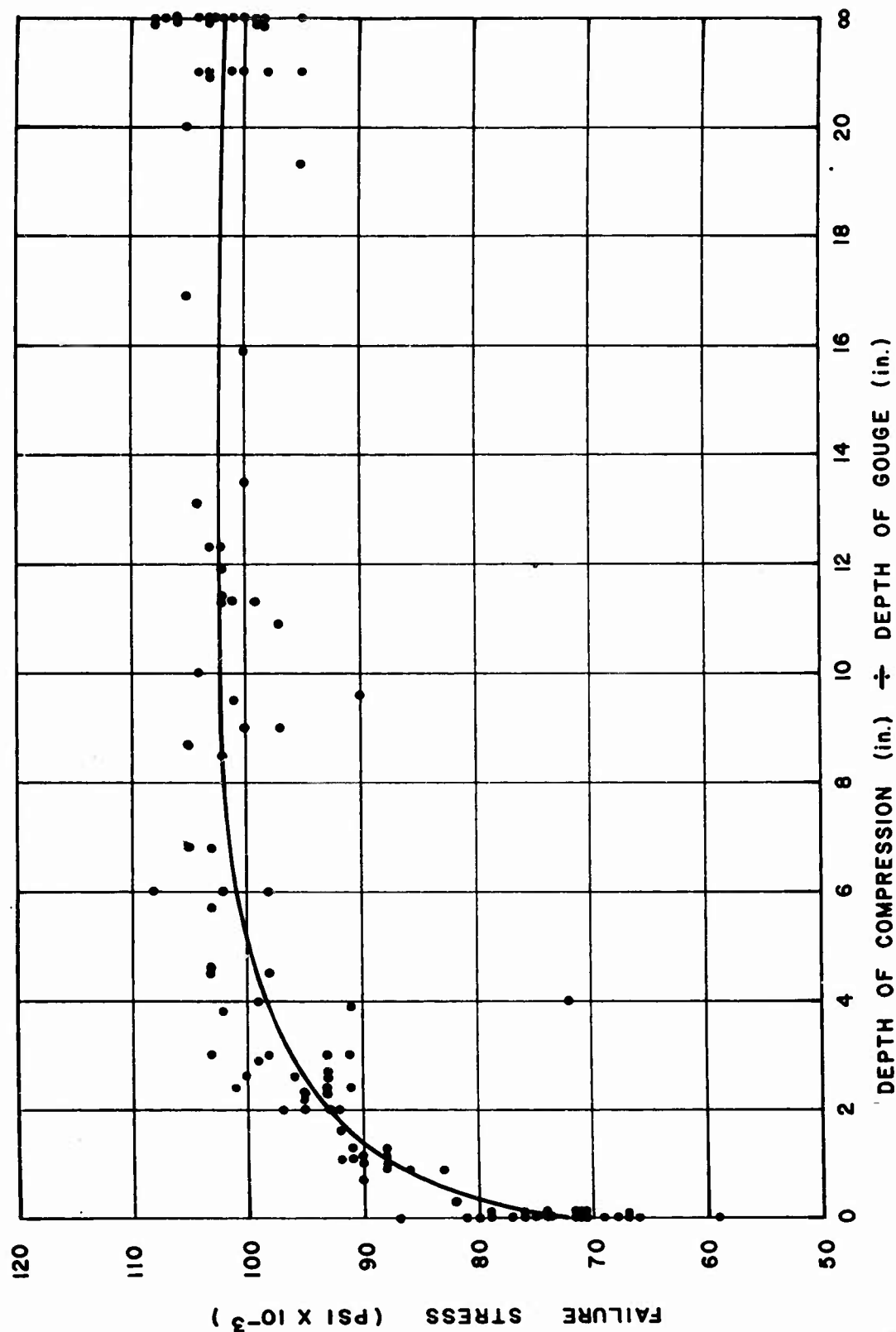


FIGURE 16. ENDURANCE LIMIT Vs. DEPTH RATIO OF Rc 41 DAMAGED SPECIMENS

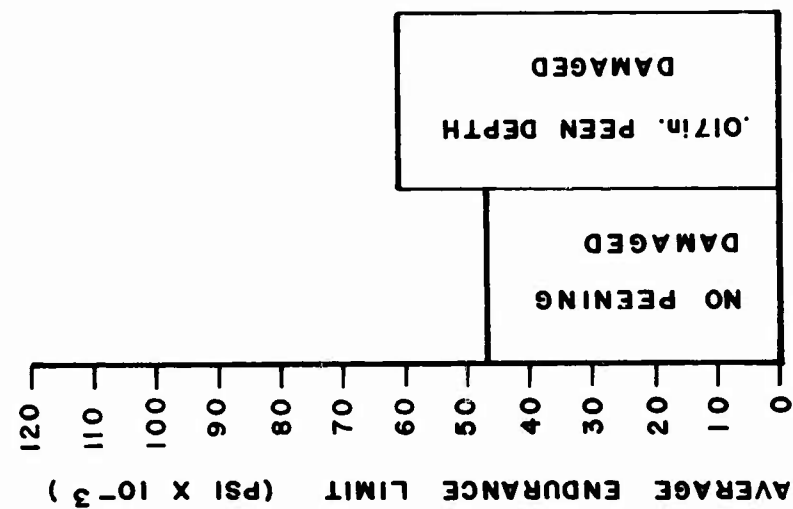


FIGURE 17. SUMMARY OF RESULTS—Rc 31

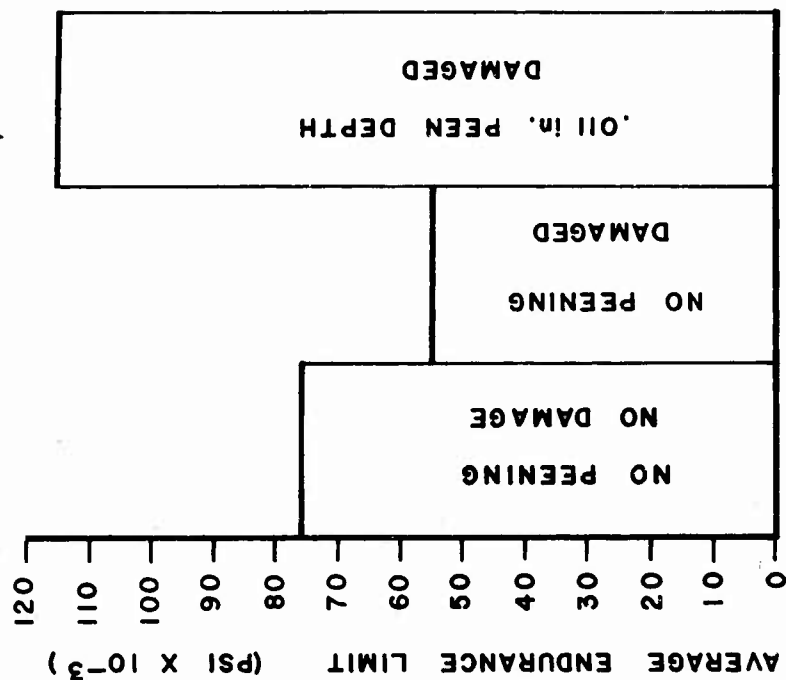


FIGURE 18. SUMMARY OF RESULTS—Rc 51

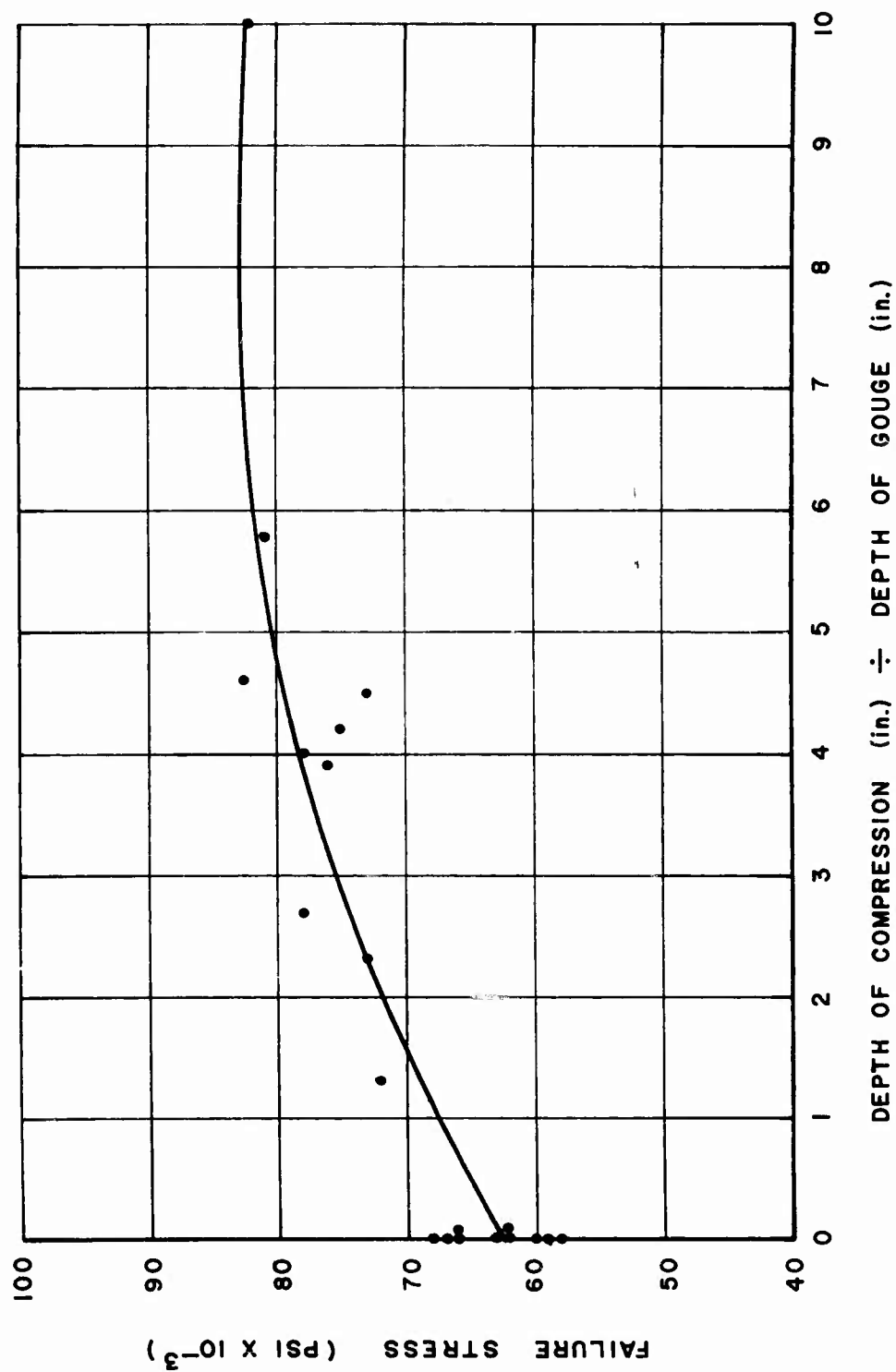


FIGURE 19. ENDURANCE LIMIT VS. DEPTH RATIO OF Rc 31 DAMAGED SPECIMENS

endurance limit for the parent material would, of course, tend to make the benefits of peening appear large. Nevertheless, there can be little doubt that these benefits are of considerable magnitude.

Figures 20 through 45 are photographs of failed test specimens, showing several typical failures. Many of the cracks run to at least one edge of the specimen. This is usually a result of crack growth from a nucleus nearer the midpoint of the specimen, although some cracks did start at the chamfered edge. The stress at this edge is calculated to be less than one percent greater (due to anticlastic curvature) than the stress along the center line of the bar. In cases where there was doubt as to the origin of failure, the bars were broken in two and examined for beach marks pointing to the origin. In a few cases, two or more cracks were formed.

An attempt to analyze the nature of the simulated damage and its relation to fatigue failure was unsuccessful, except for the factor of gouge depth. Shape and form of the individual damage loci were so widely variant (as they are in service propellers) as to make it impossible to group them into patterns for analysis. In general the deeper gouges resulted in lowest endurance limits (as can be seen in Figure 16), although there were many exceptions.

#### IV. CONCLUSIONS

In general, it can be concluded that previous shot peening, properly controlled, considerably improves fatigue strength of damaged surfaces. Maximum improvement appears to occur under conditions where the depth of compressive residual stress is about five times the depth of the gouges introduced for the type of damage used in these tests. For depth ratios of less than five the improvement is less, but is still appreciable.

Benefits were more marked with increasing hardness of steel. The peened and damaged steels of 130,000 psi, 190,000 psi and 260,000 psi ultimate strength showed maximum increases in endurance limit of about 30%, 87% and 110%, respectively, over the unpeened but damaged cases.

Scatter of results decreased with increasing endurance limit such that the peening treatments giving the greater benefits also gave decreased scatter.

No conclusions can be drawn at present regarding the nature of surface damage and its relation to failure.

Some limitations on the use of shot peening in minimizing the effects of damage can be anticipated. First, it will be necessary to produce residual stress patterns of sufficient depth and magnitude to provide the desired benefits. There is a minimum blade thickness below which this cannot be accomplished. Second, the dimensional changes resulting from peening must be kept within tolerances. Here again there is a blade thickness below which this condition cannot be satisfied.

These limitations become less severe with increasing hardness of material. In harder material the depth of damage, hence the required depth of peening, is less than in softer material. Since dimensional change due to peening is primarily a function of depth of peening, less dimensional change would be encountered in applying adequate protective peening to a hard material than to a soft one.

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## APPENDIX I

### LIST OF SPECIMEN TREATMENTS AND FAILURE STRESSES

Table 3 lists the fatigue test specimens in groups according to the treatments received. Specimen numbers are consecutive except where additional tests were added to a group during the conduct of the investigation. These latter specimens carry numbers over 200 but are otherwise identical to those carrying lower numbers in the same group.

Table 4 lists the shot peening conditions applied to each group of specimens, according to depth of compressive residual stress.

TABLE 3

## FATIGUE TEST SPECIMENS

| Specimen No. | (R <sub>c</sub> ) Hardness | Depth of Compression | Failure Stress (psi) | Failure Gouge Depth | Remarks          |
|--------------|----------------------------|----------------------|----------------------|---------------------|------------------|
| 1            | 41.0                       | None                 | 88,000               | None                | Polished Surface |
| 2            | 40.0                       | None                 | 93,000               | None                | Polished Surface |
| 2A           | 41.0                       | None                 | 93,000               | None                | Polished Surface |
| 3            | 42.5                       | None                 | 78,000               | None                | Polished Surface |
| 3A           | 41.5                       | None                 | 81,000               | None                | Polished Surface |
| 4            | 40.5                       | None                 | 90,000               | None                | Polished Surface |
| 5            | 41.5                       | None                 | 79,000               | None                | Polished Surface |
| 6            | 41.0                       | None                 | 89,000               | None                | Polished Surface |
| 7            | 42.0                       | None                 | 85,000               | None                | Polished Surface |
| 8            | 41.0                       | None                 | 90,000               | None                | Polished Surface |
| 9            | 41.0                       | None                 | 84,000               | None                | Polished Surface |
| 10           | 42.0                       | None                 | 94,000               | None                | Polished Surface |
| 211          | 44.0                       | None                 | 71,000               | None                | Polished Surface |
| 212          | 44.0                       | None                 | 75,000               | None                | Polished Surface |
| 213          | 45.0                       | None                 | 82,000               | None                | Polished Surface |
| 214          | 45.0                       | None                 | 75,000               | None                | Polished Surface |
| 215          | 45.0                       | None                 | 77,000               | None                | Polished Surface |
| 216          | 45.0                       | None                 | 82,000               | None                | Polished Surface |
| 217          | 44.0                       | None                 | 80,000               | None                | Polished Surface |
| 218          | 44.0                       | None                 | 65,000               | None                | Polished Surface |
| 219          | 44.0                       | None                 | 84,000               | None                | Polished Surface |
| 220          | 43.0                       | None                 | 80,000               | None                | Polished Surface |
| 221          | 45.0                       | None                 | 87,000               | None                | Polished Surface |
| 222          | 45.0                       | None                 | 90,000               | None                | Polished Surface |
| 223          | 44.0                       | None                 | 78,000               | None                | Polished Surface |
| 224          | 43.0                       | None                 | 73,000               | None                | Polished Surface |

TABLE 3 (CONTINUED)

## FATIGUE TEST SPECIMENS

| Specimen No. | (R <sub>c</sub> ) Hardness | Depth of Compression | Failure Stress (psi) | Failure Gouge Depth | Remarks |
|--------------|----------------------------|----------------------|----------------------|---------------------|---------|
| 11           | 43.0                       | None                 | 71,000               | .004                |         |
| 12           | 44.0                       | None                 | 80,000               | .002                |         |
| 13           | 44.0                       | None                 | 77,000               | **                  |         |
| 14           | 43.5                       | None                 | 67,000               | **                  |         |
| 15           | 43.5                       | None                 | 74,000               | .002                |         |
| 16           | 43.5                       | None                 | 71,000               | **                  |         |
| 17           | 44.0                       | None                 | 71,000               | .003                |         |
| 18           | 41.0                       | None                 | 76,000               | .002                |         |
| 19           | 44.5                       | None                 | 66,000               | .001                |         |
| 20           | 43.5                       | None                 | 74,000               | .002                |         |
| 21           | 44.0                       | None                 | 59,000               | **                  |         |
| 22           | 43.5                       | None                 | 69,000               | **                  |         |
| 23           | 45.0                       | None                 | 79,000               | .002                |         |
| 24           | 44.0                       | None                 | 75,000               | .002                |         |
| 25           | 43.5                       | None                 | 71,000               | .004                |         |
| 26           | 44.0                       | None                 | 77,000               | **                  |         |
| 27           | 44.0                       | None                 | 67,000               | **                  |         |
| 28           | 44.5                       | None                 | 68,000               | **                  |         |
| 29           | 44.5                       | None                 | 71,000               | .001                |         |
| 30           | 45.0                       | None                 | 71,000               | .004                |         |
| 31           | 40.0                       | None                 | 74,000               | .002                |         |
| 32           | 41.0                       | None                 | 79,000               | .006                |         |
| 33           | 41.0                       | None                 | 82,000               | **                  |         |
| 34           | 41.5                       | None                 | 87,000               | **                  |         |

\*\* Did not fail through a gouge.

TABLE 3 (CONTINUED)

## FATIGUE TEST SPECIMENS

| Specimen No. | (R <sub>c</sub> ) Hardness | Depth of Compression | Failure Stress (psi) | Failure Gage Depth | Remarks                                  |
|--------------|----------------------------|----------------------|----------------------|--------------------|------------------------------------------|
| 35           | 43.5                       | .004                 | 93,000               | .002               |                                          |
| 36           | 44.0                       | .004                 | 88,000               | .004               |                                          |
| 37           | 43.5                       | .004                 | 83,000               | .004               |                                          |
| 38           | 44.0                       | .004                 | 90,000               | .006               |                                          |
| 39           | 43.0                       | .004                 | 92,000               | .002               |                                          |
| 40           | 44.5                       | .004                 | 90,000               | .004               |                                          |
| 41           | 43.5                       | .004                 | 88,000               | .004               |                                          |
| 42           | 44.5                       | .004                 | 88,000               | .004               |                                          |
| 43           | 44.0                       | .004                 | 91,000               | .004               |                                          |
| 44           | 43.0                       | .004                 | —                    | .002               | Bad Test                                 |
| 45           | 43.0                       | .004                 | 92,000               | .004               |                                          |
| 46           | 42.0                       | .004                 | 93,000               | .002               |                                          |
| 47           | 43.0                       | .004                 | 82,000               | .002               |                                          |
| 48           | 42.0                       | .004                 | 95,000               | .002               |                                          |
| 49           | 40.0                       | .004                 | 93,000               | .002               |                                          |
| 50           | 40.5                       | .004                 | 91,000               | .002               |                                          |
| 51           | 41.5                       | .004                 | 99,000               | .001               |                                          |
| 52           | 42.0                       | .004                 | 86,000               | .005               |                                          |
| 53           | 41.5                       | .004                 | 59,000               | **                 | { Failed Outside of Shot Peening Section |
| 54           | 44.0                       | .004                 | 91,000               | .003               |                                          |
| 55           | 42.5                       | .004                 | 90,000               | .004               |                                          |
| 56           | 42.5                       | .004                 | 97,000               | .002               |                                          |
| 57           | 42.0                       | .004                 | 72,000               | .001               | Large Inclusion                          |
| 58           | 42.5                       | .004                 | 88,000               | .003               |                                          |

\*\* Did not fail through a gouge.

TABLE 3 (CONTINUED)

## FATIGUE TEST SPECIMENS

| Specimen<br>No. | (R <sub>c</sub> )<br>Hardness | Depth of<br>Compression | Failure<br>Stress<br>(psi) | Failure<br>Gauge Depth | Remarks  |
|-----------------|-------------------------------|-------------------------|----------------------------|------------------------|----------|
| 59              | 44.0                          | .009                    | 101,000                    | .004                   |          |
| 60              | 43.5                          | .009                    | 95,000                     | .004                   |          |
| 61              | 42.0                          | .009                    | 103,000                    | .002                   |          |
| 62              | 42.5                          | .009                    | 93,000                     | .004                   |          |
| 63              | 44.0                          | .009                    | 93,000                     | .003                   |          |
| 64              | 43.0                          | .009                    | 100,000                    | .001                   |          |
| 65              | 42.0                          | .009                    | 96,000                     | .004                   |          |
| 66              | 41.5                          | .009                    | 97,000                     | .001                   |          |
| 67              | 42.5                          | .009                    | 98,000                     | .002                   |          |
| 68              | 41.5                          | .009                    | 91,000                     | .002                   |          |
| 69              | 41.0                          | .009                    | —                          | .005                   |          |
| 70              | 42.0                          | .009                    | —                          | .004                   | Bad Test |
| 71              | 41.0                          | .009                    | 108,000                    | .002                   | Bad Test |
| 72              | 43.0                          | .009                    | 98,000                     | .003                   |          |
| 73              | 42.5                          | .009                    | 93,000                     | .004                   |          |
| 74              | 42.5                          | .009                    | 103,000                    | .002                   |          |
| 75              | 43.0                          | .009                    | 100,000                    | .003                   |          |
| 76              | 43.5                          | .009                    | 102,000                    | .002                   |          |
| 77              | 41.5                          | .009                    | 92,000                     | .006                   |          |
| 78              | 41.0                          | .009                    | 99,000                     | .003                   |          |
| 79              | 41.0                          | .009                    | 102,000                    | .002                   |          |
| 80              | 42.0                          | .009                    | 103,000                    | .003                   |          |
| 81              | 42.0                          | .009                    | 91,000                     | .003                   |          |
| 82              | 43.0                          | .009                    | 98,000                     | .002                   |          |

TABLE 3 (CONTINUED)

## FATIGUE TEST SPECIMENS

| Specimen<br>No. | (R <sub>c</sub> )<br>Hardness | Depth of<br>Compression | Failure<br>Stress<br>(psi) | Failure<br>Gouge Depth | Remarks |
|-----------------|-------------------------------|-------------------------|----------------------------|------------------------|---------|
| 83              | 41.0                          | .017                    | 102,000                    | .002                   |         |
| 84              | 43.0                          | .017                    | 104,000                    | .001                   |         |
| 85              | 43.0                          | .017                    | 95,000                     | .008                   |         |
| 86              | 40.5                          | .017                    | 102,000                    | **                     |         |
| 87              | 41.0                          | .017                    | —                          | **                     |         |
| 88              | 41.0                          | .017                    | 99,000                     | .002                   |         |
| 89              | 42.0                          | .017                    | 102,000                    | .002                   |         |
| 90              | 42.0                          | .017                    | 99,000                     | **                     |         |
| 91              | 42.5                          | .017                    | 102,000                    | .002                   |         |
| 92              | 41.0                          | .017                    | 104,000                    | **                     |         |
| 93              | 42.0                          | .017                    | 107,000                    | **                     |         |
| 94              | 42.0                          | .017                    | 103,000                    | .003                   |         |
| 95              | 40.5                          | .017                    | 104,000                    | .002                   |         |
| 96              | 40.5                          | .017                    | 100,000                    | **                     |         |
| 97              | 40.0                          | .017                    | 108,000                    | **                     |         |
| 98              | 41.5                          | .017                    | 106,000                    | **                     |         |
| 99              | 42.5                          | .017                    | 101,000                    | .002                   |         |
| 100             | 42.0                          | .017                    | 103,000                    | .003                   |         |
| 101             | 40.0                          | .017                    | 103,000                    | **                     |         |
| 102             | 42.5                          | .017                    | 104,000                    | **                     |         |
| 103             | 41.0                          | .017                    | 105,000                    | .003                   |         |
| 104             | 42.0                          | .017                    | 106,000                    | **                     |         |
| 105             | 40.0                          | .017                    | 101,000                    | .002                   |         |
| 106             | 42.0                          | .017                    | 105,000                    | **                     |         |

Bad Test

\*\* Did not fail through a gouge.

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

| Specimen No. | (R <sub>c</sub> ) Hardness | Depth of Compression | Failure Stress (psi) | Failure Gouge Depth | Remarks |
|--------------|----------------------------|----------------------|----------------------|---------------------|---------|
| 107          | 43.0                       | .027                 | 100,000              | **                  |         |
| 108          | 41.0                       | .027                 | 105,000              | .002                |         |
| 109          | 43.0                       | .027                 | 108,000              | **                  |         |
| 110          | 42.0                       | .027                 | 101,000              | **                  |         |
| 111          | 42.0                       | .027                 | 99,000               | **                  |         |
| 112          | 41.0                       | .027                 | 97,000               | .003                |         |
| 113          | 42.5                       | .027                 | 103,000              | **                  |         |
| 114          | 43.0                       | .027                 | 102,000              | .002                |         |
| 115          | 42.5                       | .027                 | 105,000              | .001                |         |
| 116          | 43.0                       | .027                 | 99,000               | **                  |         |
| 117          | 39.5                       | .027                 | 95,000               | **                  |         |
| 118          | 41.0                       | .027                 | 102,000              | .002                |         |
| 119          | 43.0                       | .027                 | 103,000              | .001                |         |
| 120          | 40.5                       | .027                 | 103,000              | .002                |         |
| 121          | 41.0                       | .027                 | 103,000              | **                  |         |
| 122          | 43.5                       | .027                 | 90,000               | .028                |         |
| 123          | 43.5                       | .027                 | 100,000              | .002                |         |
| 124          | 44.0                       | .027                 | 95,000               | .001                |         |
| 125          | 43.5                       | .027                 | 103,000              | **                  |         |
| 126          | 43.5                       | .027                 | 99,000               | **                  |         |
| 127          | 43.0                       | .027                 | 100,000              | .002                |         |
| 128          | 43.5                       | .027                 | 95,000               | .001                |         |
| 129          | 43.0                       | .027                 | 101,000              | .001                |         |
| 130          | 43.0                       | .027                 | 98,000               | .001                |         |

Probable Inclusion

\*\* Did not fail through a gouge.

**TABLE 3 (CONTINUED)**

**FATIGUE TEST SPECIMENS**

| Specimen No. | (R <sub>c</sub> ) Hardness | Depth of Compression | Failure Stress (psi) | Failure Gouge Depth | Remarks |
|--------------|----------------------------|----------------------|----------------------|---------------------|---------|
| 131          | 30.5                       | None                 | 66,000               | .002                |         |
| 132          | 29.5                       | None                 | 58,000               | .004                |         |
| 133          | 30.0                       | None                 | 62,000               | **                  |         |
| 134          | 29.0                       | None                 | 63,000               | .002                |         |
| 135          | 30.0                       | None                 | 67,000               | .003                |         |
| 136          | 30.0                       | None                 | 60,000               | .010                |         |
| 137          | 30.5                       | None                 | 68,000               | .002                |         |
| 138          | 30.5                       | None                 | 66,000               | .002                |         |
| 139          | 29.0                       | None                 | 62,000               | **                  |         |
| 140          | 29.5                       | None                 | 59,000               | .005                |         |
| 141          | 30.5                       | .017                 | 85,000               | .004                |         |
| 142          | 29.0                       | .017                 | 72,000               | .013                |         |
| 143          | 30.5                       | .017                 | 73,000               | .004                |         |
| 144          | 29.5                       | .017                 | 73,000               | .007                |         |
| 145          | 29.0                       | .017                 | 78,000               | .006                |         |
| 146          | 30.5                       | .017                 | 75,000               | .004                |         |
| 147          | 30.0                       | .017                 | 76,000               | .004                |         |
| 148          | 30.0                       | .017                 | 78,000               | .004                |         |
| 149          | 29.5                       | .017                 | 81,000               | .003                |         |
| 150          | 30.0                       | .017                 | 82,000               | .002                |         |

\*\* Did not fail through a gouge.

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

| Specimen No. | (R <sub>c</sub> ) Hardness | Depth of Compression | Failure Stress (psi) | Failure Gouge Depth                     | Remarks |
|--------------|----------------------------|----------------------|----------------------|-----------------------------------------|---------|
| 151          | 51.0                       | None                 | 76,000               | **                                      |         |
| 152          | 50.5                       | None                 | 58,000               | **                                      |         |
| 153          | 51.0                       | None                 | 74,000               | .002                                    |         |
| 154          | 51.5                       | None                 | 78,000               | .001                                    |         |
| 155          | 52.0                       | None                 | 74,000               | **                                      |         |
| 156          | 50.0                       | None                 | 69,000               | **                                      |         |
| 157          | 51.0                       | None                 | 66,000               | **                                      |         |
| 158          | 52.0                       | None                 | 68,000               | **                                      |         |
| 159          | 52.0                       | None                 | 85,000               | .002                                    |         |
| 160          | 51.0                       | None                 | 61,000               | **                                      |         |
| 161          | 52.0                       | .011                 | 124,000              | } Failed Outside of Shot-Peened Section |         |
| 162          | 52.0                       | .011                 | 121,000              |                                         |         |
| 163          | 51.5                       | .011                 | 92,000               |                                         |         |
| 164          | 51.0                       | .011                 | 118,000              | **                                      |         |
| 165          | 52.0                       | .011                 | 133,000              | **                                      |         |
| 166          | 51.5                       | .011                 | 136,000              | **                                      |         |
| 167          | 52.5                       | .011                 | 130,000              | **                                      |         |
| 168          | 51.0                       | .011                 | 141,000              | **                                      |         |
| 169          | 52.0                       | .011                 | 127,000              | **                                      |         |
| 170          | 51.5                       | .011                 | 132,000              | .001                                    |         |

\*\* Did not fail through a gouge.

TABLE 3 (CONTINUED)

## FATIGUE TEST SPECIMENS

| Specimen No. | (R <sub>c</sub> ) Hardness | Depth of Compression | Failure Stress (psi) | Failure Gouge Depth | Remarks          |
|--------------|----------------------------|----------------------|----------------------|---------------------|------------------|
| 231          | 54.0                       | None                 | 100,000              | None                | Polished Surface |
| 232          | 54.0                       | None                 | 73,000               | None                | Polished Surface |
| 233          | 53.0                       | None                 | 92,000               | None                | Polished Surface |
| 234          | 54.0                       | None                 | 93,000               | None                | Polished Surface |
| 235          | 54.0                       | None                 | 72,000               | None                | Polished Surface |
| 236          | 54.0                       | None                 | 91,000               | None                | Polished Surface |
| 237          | 54.0                       | None                 | 89,000               | None                | Polished Surface |
| 238          | 53.0                       | None                 | 86,000               | None                | Polished Surface |
| 239          | 54.0                       | None                 | 98,000               | None                | Polished Surface |
| 240          | 54.0                       | None                 | 77,000               | None                | Polished Surface |
| 241          | 55.0                       | None                 | 91,000               | None                | Polished Surface |
| 242          | 54.0                       | None                 | 103,000              | None                | Polished Surface |
| 243          | 54.0                       | None                 | 96,000               | None                | Polished Surface |
| 244          | 54.0                       | None                 | 95,000               | None                | Polished Surface |
| 245          | 54.0                       | None                 | 97,000               | None                | Polished Surface |
| 246          | 54.0                       | None                 | 97,000               | None                | Polished Surface |
| 247          | 54.0                       | None                 | 101,000              | None                | Polished Surface |
| 248          | 54.0                       | None                 | 95,000               | None                | Polished Surface |
| 249          | 54.0                       | None                 | 107,000              | None                | Polished Surface |
| 250          | 54.0                       | None                 | 95,000               | None                | Polished Surface |
| 251          | 54.0                       | None                 | 92,000               | None                | Polished Surface |
| 252          | 54.0                       | None                 | 96,000               | None                | Polished Surface |
| 253          | 54.0                       | None                 | 89,000               | None                | Polished Surface |
| 254          | 54.0                       | None                 | 92,000               | None                | Polished Surface |

TABLE 4

SHOT PEENING CONDITIONS

SAE 4340 Steel

| Hardness ( $R_c$ ) | Depth of<br>Compression (in. ) | Shot<br>Diameter (in. ) | Air<br>Pressure (psig) |
|--------------------|--------------------------------|-------------------------|------------------------|
| 31                 | .017                           | .039                    | 50                     |
| 41                 | .004                           | .011                    | 30                     |
| 41                 | .009                           | .023                    | 50                     |
| 41                 | .017                           | .066                    | 50                     |
| 41                 | .027                           | .125                    | 90                     |
| 51                 | .011                           | .039                    | 50                     |

## APPENDIX II

### FAILED SPECIMENS

Figures 20 through 45 are included to show the general appearance of the shot peened surfaces, the artificial damage and the failures. The triangular pointer at the side of each photograph indicates the location of the failure. In case of multiple failures, multiple photographs are included. Photographs are approximately 4X magnification.



FIGURE 20. FAILURE IN SPECIMEN NO. 7

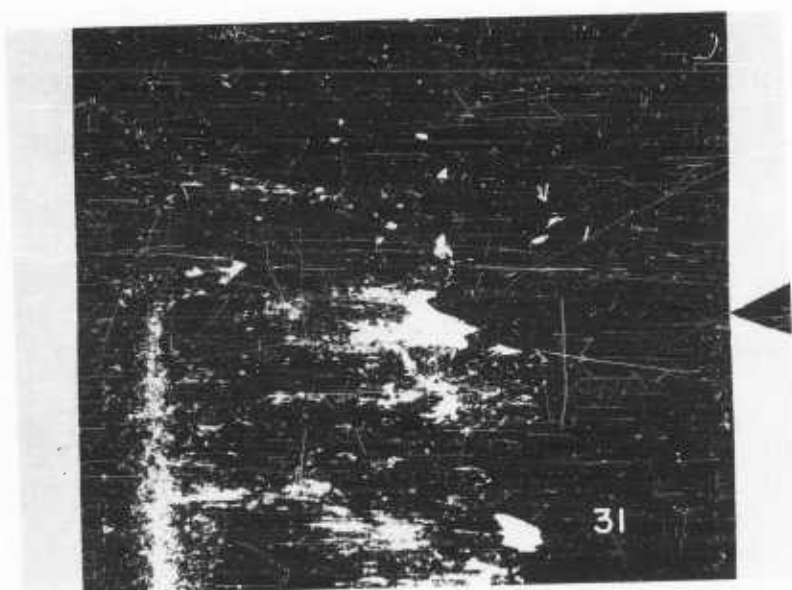


FIGURE 21. FAILURE IN SPECIMEN NO. 31

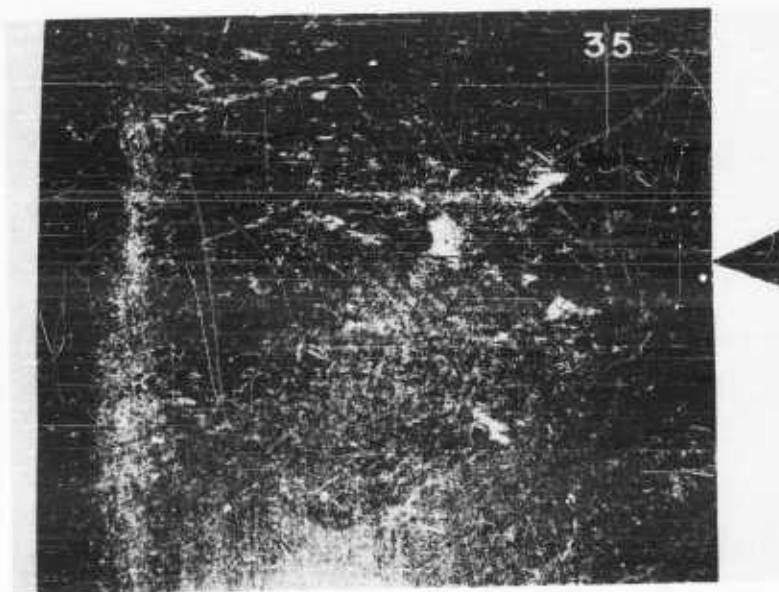


FIGURE 22. FAILURE IN SPECIMEN NO. 35

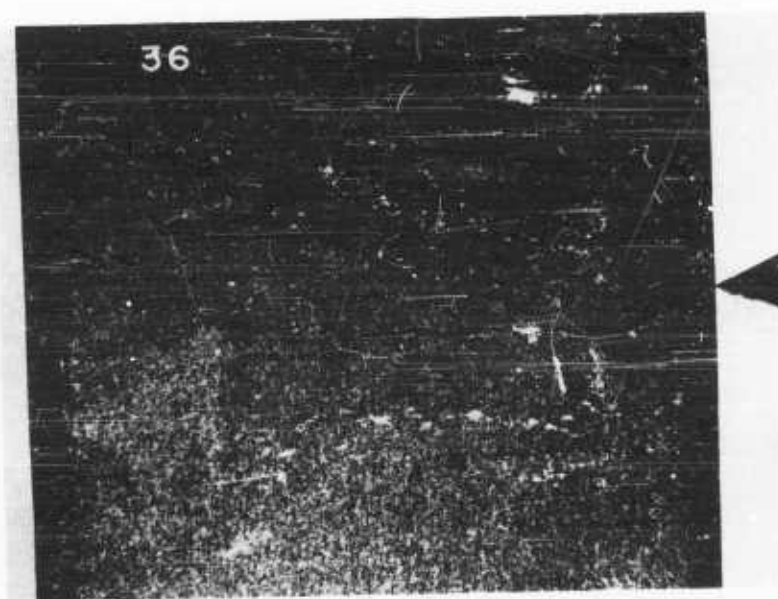


FIGURE 23. FAILURE IN SPECIMEN NO. 36

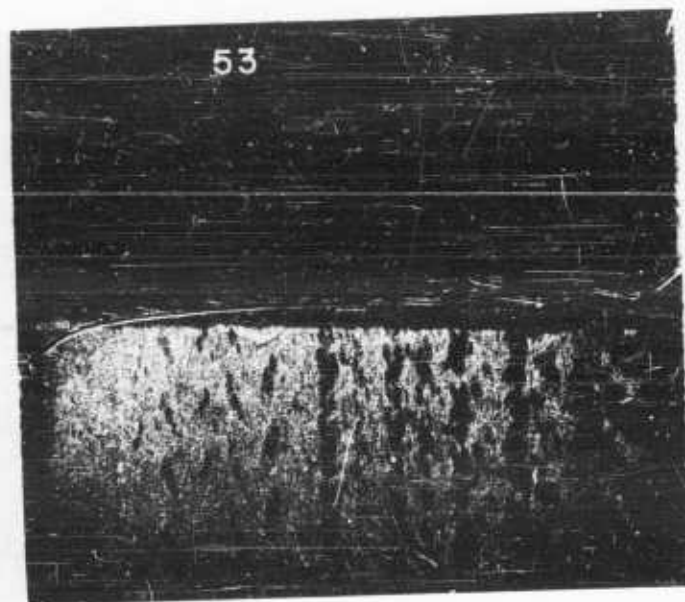


FIGURE 24. FAILURE IN SPECIMEN NO. 53



FIGURE 25. FAILURE IN SPECIMEN NO. 54

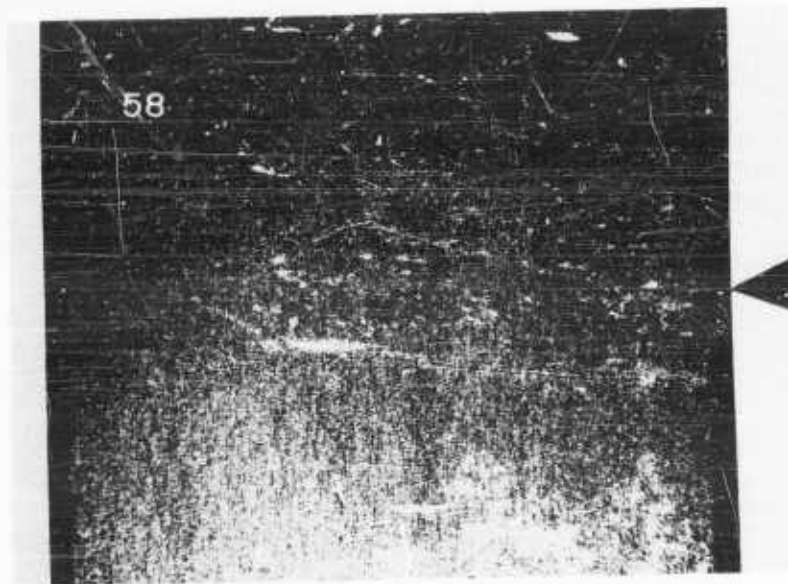


FIGURE 26. FAILURE IN SPECIMEN NO. 58

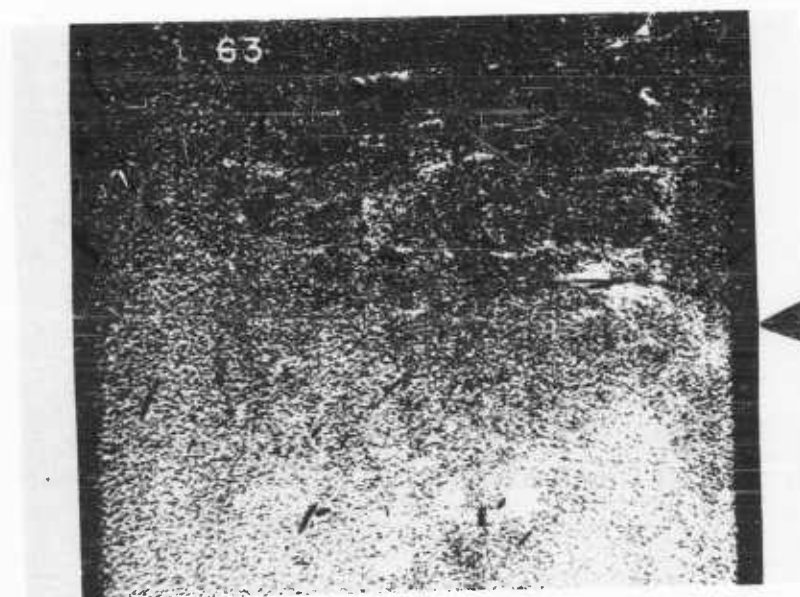


FIGURE 27. FAILURE IN SPECIMEN NO. 63.

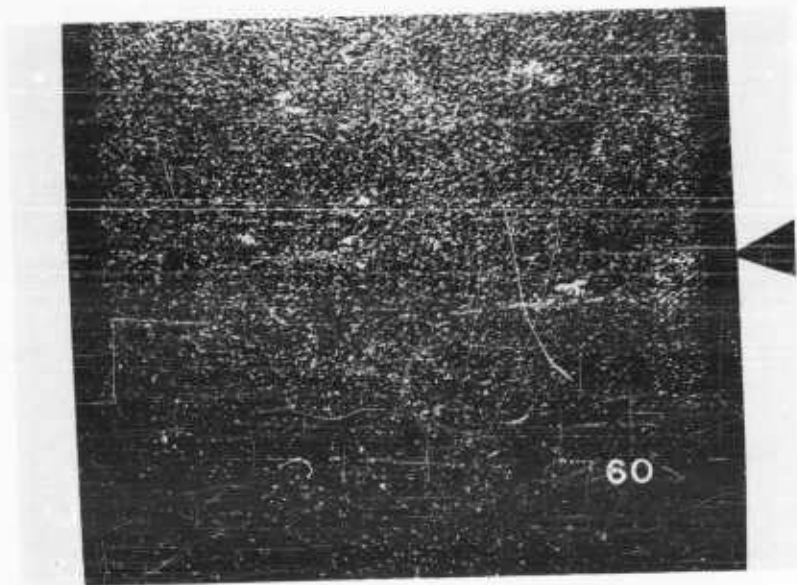


FIGURE 28. FAILURE IN SPECIMEN NO. 60

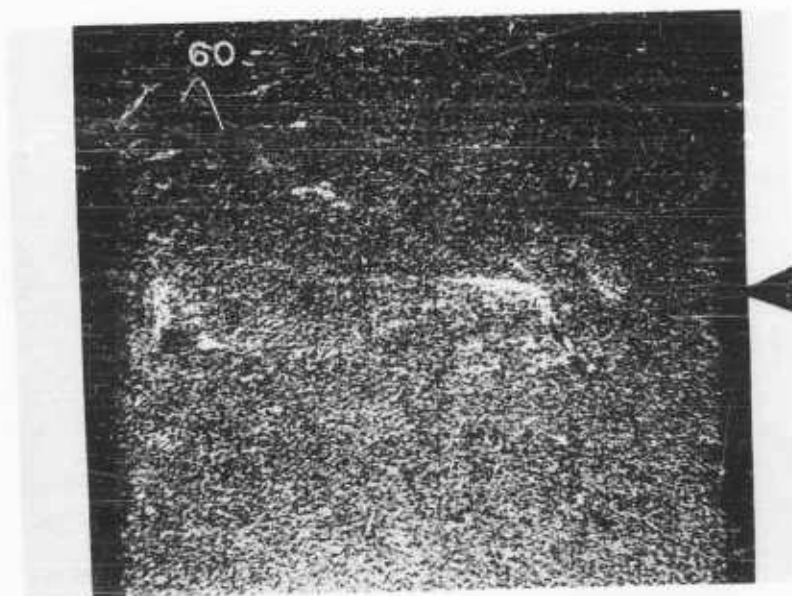


FIGURE 29. FAILURE IN SPECIMEN NO. 60

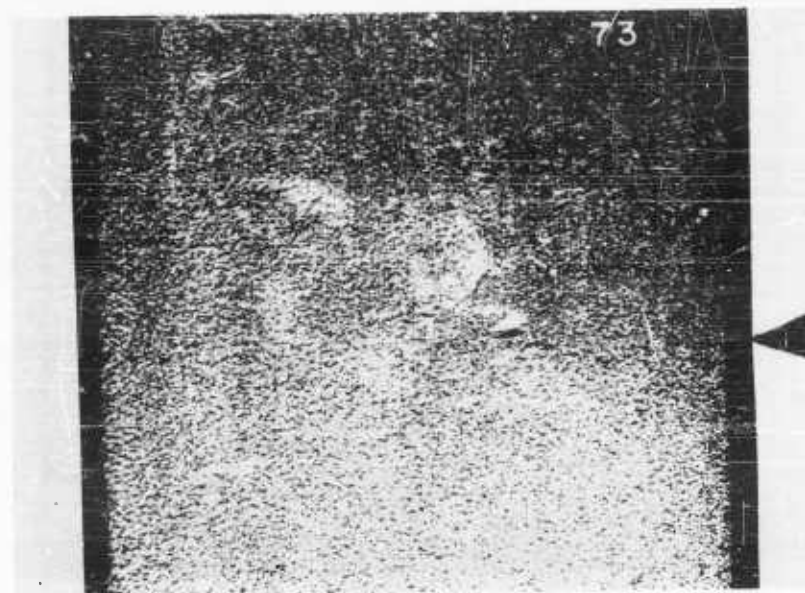


FIGURE 30. FAILURE IN SPECIMEN NO. 73

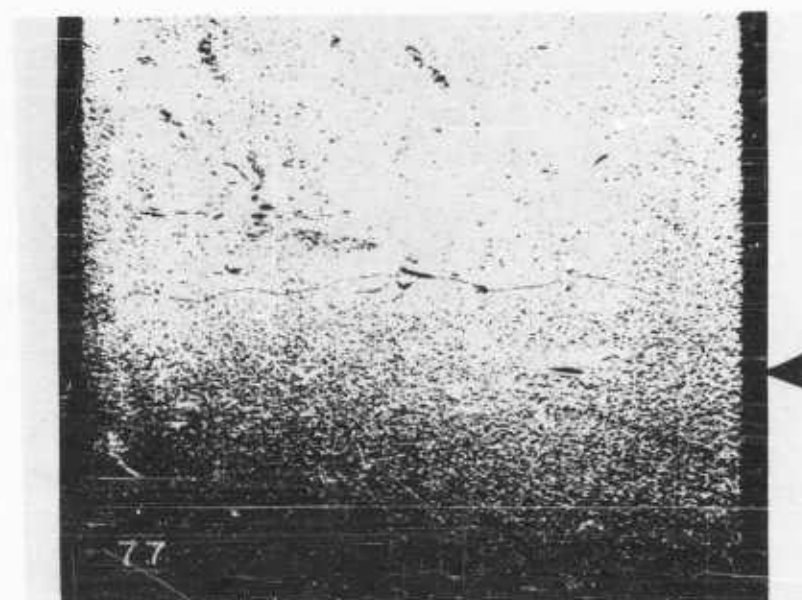


FIGURE 31. FAILURE IN SPECIMEN NO. 77

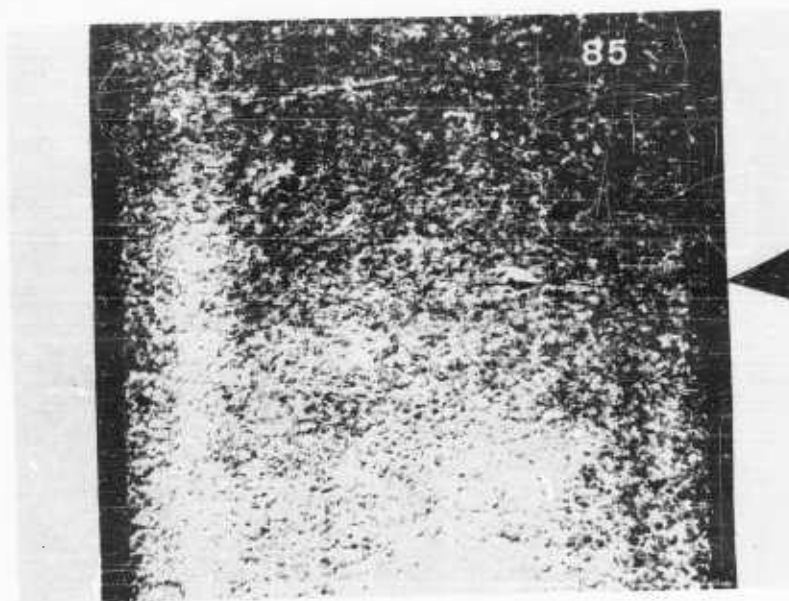


FIGURE 32. FAILURE IN SPECIMEN NO. 85

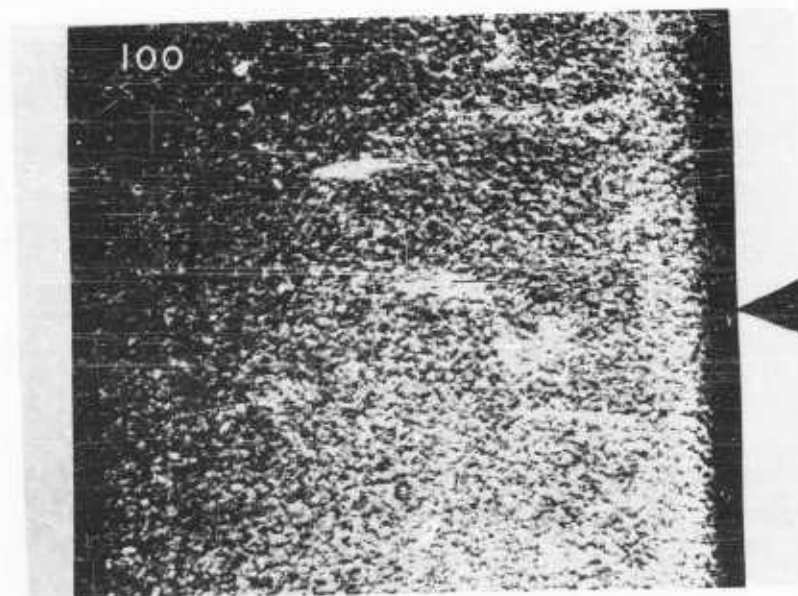


FIGURE 33. FAILURE IN SPECIMEN NO. 100

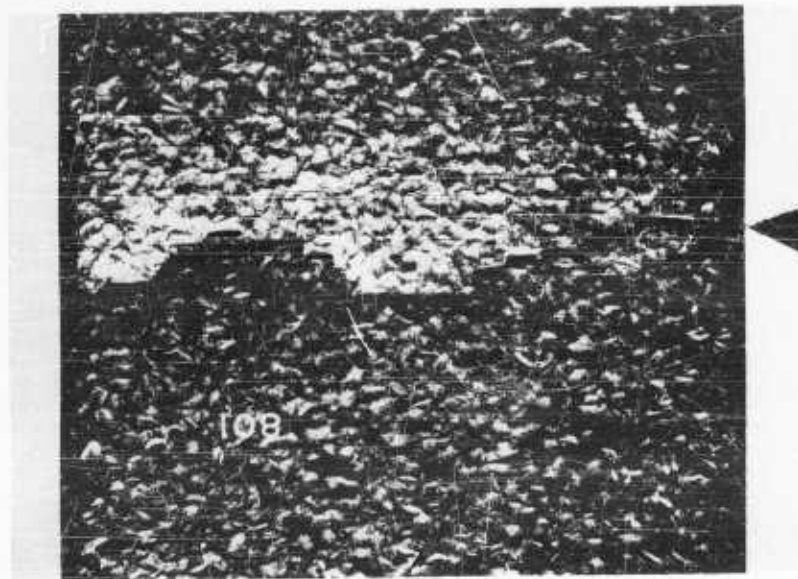


FIGURE 34. FAILURE IN SPECIMEN NO. 108

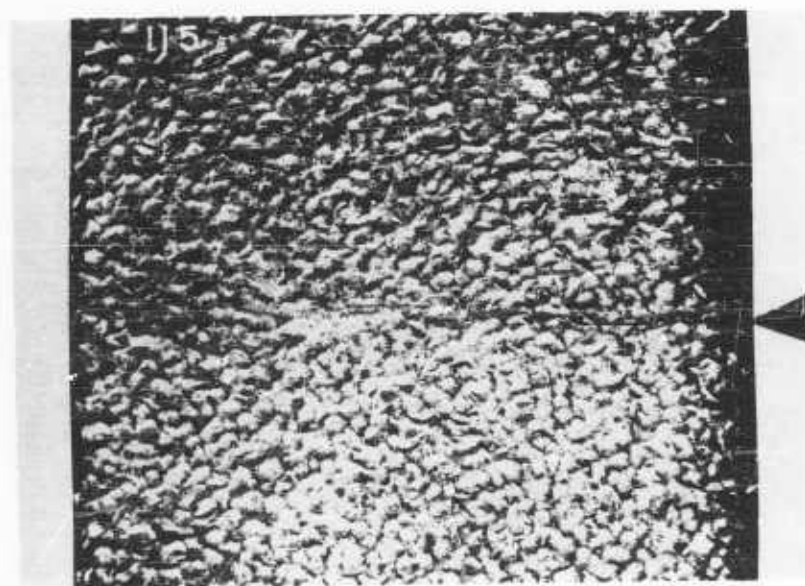


FIGURE 35. FAILURE IN SPECIMEN NO. 115

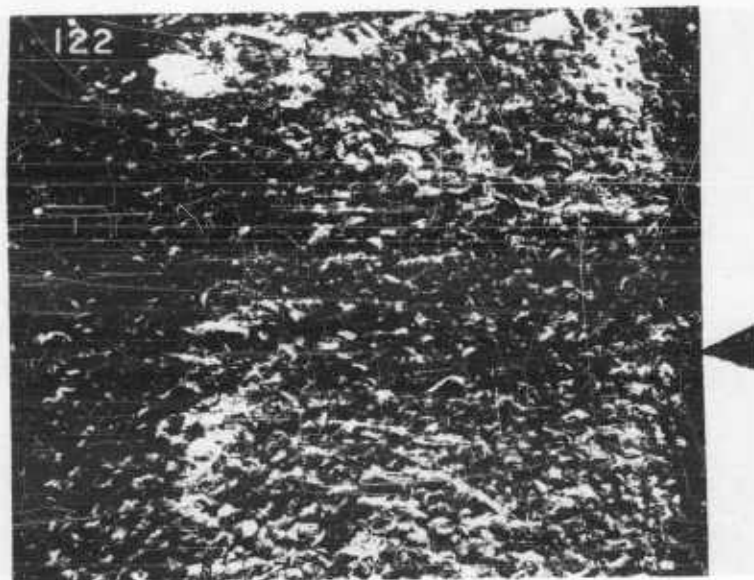


FIGURE 36. FAILURE IN SPECIMEN NO. 122



FIGURE 37. FAILURE IN SPECIMEN NO. 131

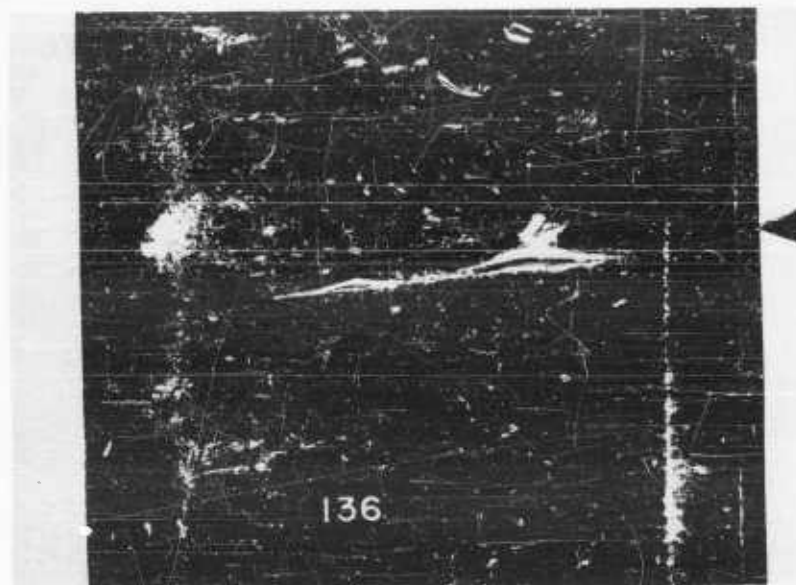


FIGURE 38. FAILURE IN SPECIMEN NO. 136

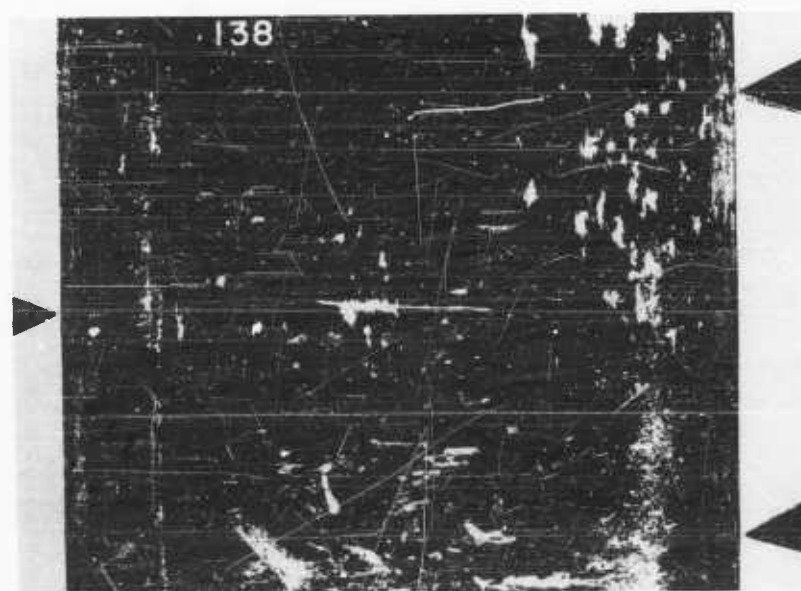


FIGURE 39. FAILURE IN SPECIMEN NO. 138

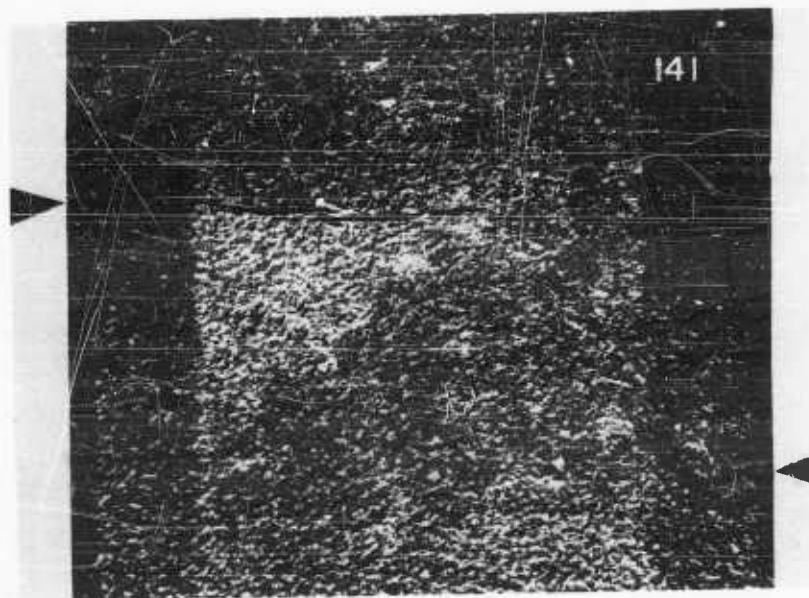


FIGURE 40. FAILURE IN SPECIMEN NO. 141



FIGURE 41. FAILURE IN SPECIMEN NO. 147

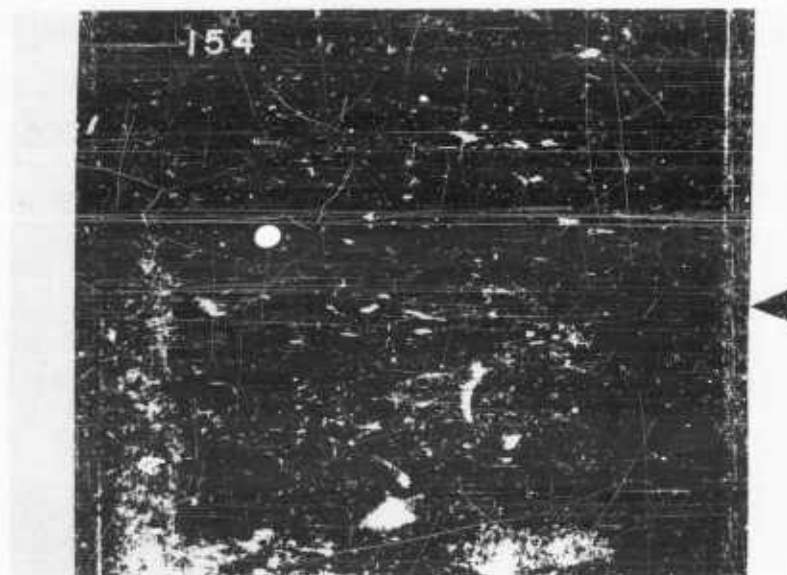


FIGURE 42. FAILURE IN SPECIMEN NO. 154

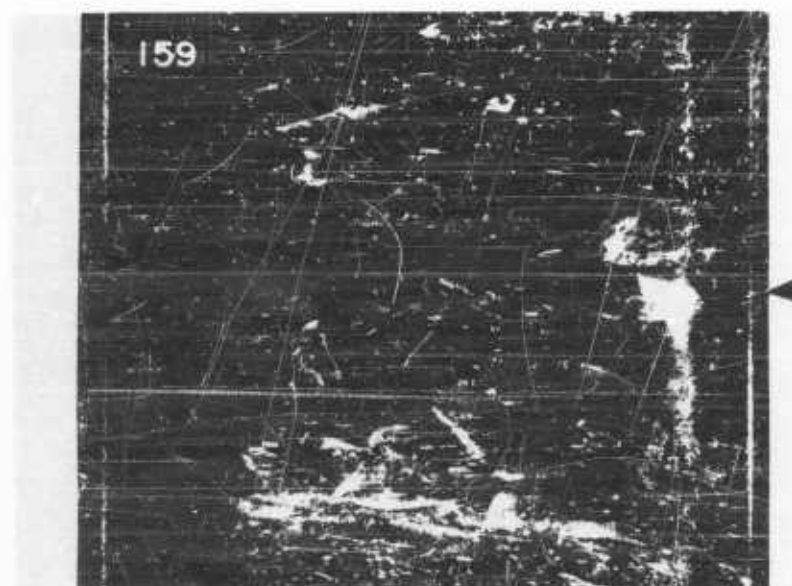


FIGURE 43. FAILURE IN SPECIMEN NO. 159

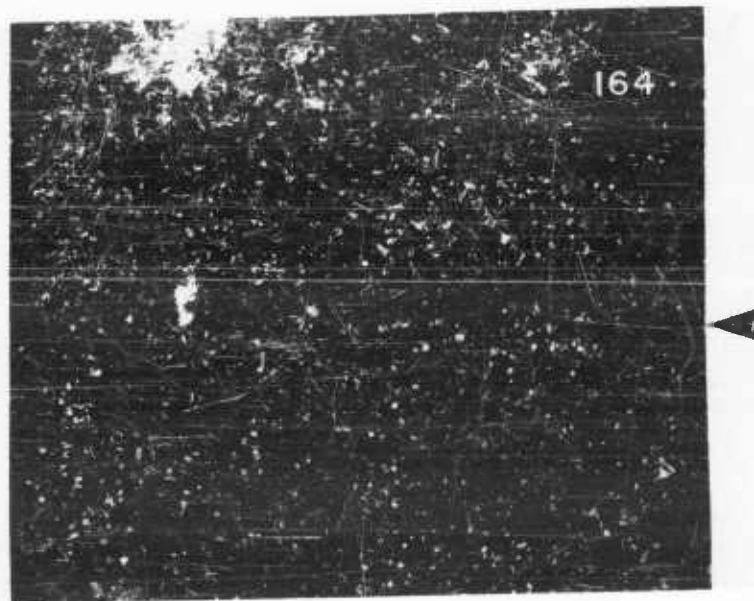


FIGURE 44. FAILURE IN SPECIMEN NO. 164

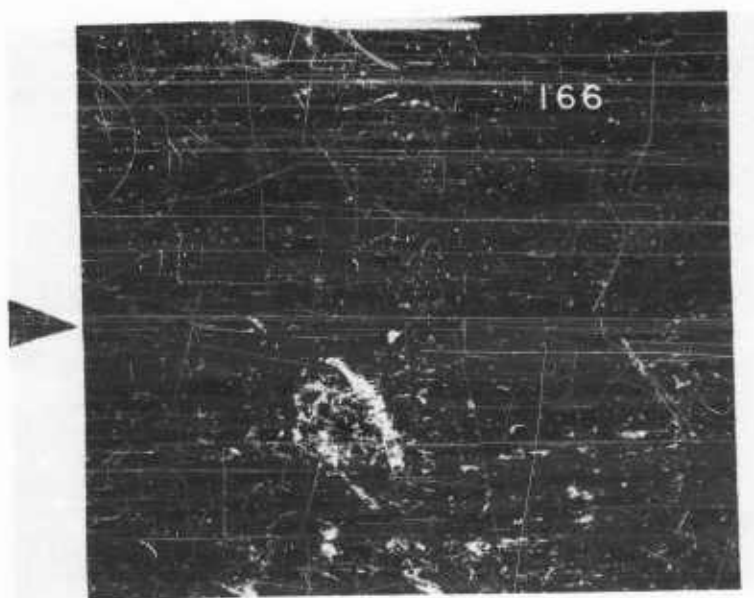


FIGURE 45. FAILURE IN SPECIMEN NO. 166

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