# NACA

# RESEARCH MEMORANDUM

## ELEVATED-TEMPERATURE COMBINED STRESS-RUPTURE PLUS FATIGUE STRENGTH OF WASPALOY HAVING DIFFERENT AGING TREATMENTS AND/OR MOLYBDENUM CONTENTS

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NATIONAL ADVISORY COMMITTEE
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# ELEVATED-TEMPERATURE COMBINED STRESS-RUPTURE PLUS FATIGUE STRENGTH OF WASPALOY HAVING DIFFERENT AGING TREATMENTS AND/OR MOLYBDENUM CONTENTS

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4218

CM-1

## SUMMARY

An investigation was conducted to determine if the combined stress-rupture plus fatigue strengths of three groups of Waspaloy with different aging treatments and/or molybdenum contents could be correlated with their resultant stress-rupture ductilities and notch-rupture strengths.

Fatigue tests were run at 1500° F with direct tensile cyclic stresses superimposed upon direct tensile mean stresses. Mean tensile stresses were selected from 1500° F stress-rupture data to produce stress-rupture failure times of about 10, 100, and 500 hours. Cyclic tensile stress levels were chosen to equal 12.5 to 90 percent of the mean tensile stresses.

A possible direct relation between combined stress-rupture plus fatigue strength and stress-rupture ductility of Waspaloy was indicated. However, no clear relation between combined stress-rupture plus fatigue strength and notch-rupture strength was found. If heat treatment and/or composition alone (i.e., without regard to their effects upon basic properties such as ductility, etc.) are considered, the results indicate that the double-aging heat treatment (compared to a single age) increases the combined stress-rupture plus fatigue strength of Waspaloy and that the double-aging treatment plus increased molybdenum content causes further improvement in the combined stress-rupture plus fatigue strength of Waspaloy.

## INTRODUCTION

Waspaloy is of interest as a gas turbine-bucket alloy because of its low strategic material content and its relatively good stress-rupture properties. The developer of this alloy had investigated the stress-rupture strength, stress-rupture ductility, and notch-rupture strength of three lots of Waspaloy; these lots had different aging treatments and/or molybdenum contents. For 1500° F, the data revealed that the three lots possessed fairly similar stress-rupture strengths but differed in both notch-rupture strength and stress-rupture ductility. Two of these lots, group A (single aged) and group B (double aged), which were from the same heat and contained 3 percent molybdenum, were notch strengthened; the third lot (group C) which was double aged and contained 7 percent molybdenum, either had the same strength or was slightly weaker when notched. The first lot of Waspaloy possessed the lowest stress-rupture ductility whereas the third lot had the highest stress-rupture ductility. Since the third lot had the best stress-rupture ductility but not the best notch-rupture strength, stress-rupture ductility and notch-rupture strength might not be directly related.

4218

One might hypothesize that among groups of material having comparable stress-rupture properties, the group exhibiting either or both the greatest stress-rupture ductility or notch-rupture strength would have the greatest time to failure in combined stress-rupture and fatigue (particularly where the fatigue component is quite large); hence, a preliminary study of the foregoing three groups of Waspaloy was carried out to determine if a correlation might exist between combined stress-rupture plus fatigue life and stress-rupture ductility and/or notch-rupture strength.

In this investigation, endurance tests were run at 1500° F with direct tensile vibratory stresses superimposed upon direct tensile mean stresses for three lots of Waspaloy. The amplitude of the cyclic stresses was as great as 90 percent of the mean stresses.

## MATERIALS, APPARATUS, AND PROCEDURE

Pratt & Whitney (who developed Waspaloy) furnished heat-treated stress-rupture specimens. These specimens were from the same lots and had the same heat treatments developed by Pratt & Whitney for the specimens referred to in the INTRODUCTION. The chemical analyses and the description of the heat treatments furnished with the specimens are given in tables I and II, respectively. Grain size and initial hardnesses obtained at the NACA Lewis laboratory are also presented in table II. For convenience, the designations A, B, and C will continue to be used for the single aged - 3 percent molybdenum, double aged - 3 percent molybdenum, and double aged - 7 percent molybdenum groups, respectively (tables I and II).

The specimens used in this investigation are illustrated in figure 1. The surface finish of the specimen test section was 5 to 10 microinches root mean square.

Commercial direct tensile stress fatigue machines operating at approximately 2000 rpm (fig. 2) were used. A description of these machines together with the operating procedure is presented in references 1 and 2.

Combined stress tests were run at the Lewis laboratory on specimens at 1500° F with direct tensile cyclic stresses superimposed upon direct tensile mean stresses. The mean tensile stresses were selected to yield 1500° F stress-rupture lives of approximately 10, 100, and 500 hours at zero vibratory stress. The mean stresses selected to give these above approximate lives differed somewhat for each of the three groups of specimens. The amplitudes of the cyclic tensile stresses were chosen to equal 12.5, 25, 50, 67, and 90 percent of the mean tensile stresses. The stress-rupture ductility, the notch-rupture, and a portion of the stress-rupture data used herein are those already referred to in the INTRODUCTION.

A statistical survey of all tests showed that during any one test, the average values of the maximum and minimum loads (i.e., mean loads) were generally within 1 percent of the desired loads and the extreme values of the maximum and minimum loads were generally within 5 percent of the desired loads. (In general, the extreme values of the maximum or minimum unit stresses were within 1500 psi of the desired values with the greater number of the tests controlled within 1000 psi.)

Samples of as-received Waspaloy were examined to determine the microstructure of groups A, B, and C after heat treatment and prior to testing.

Fractured specimens were examined macroscopically and classified according to the type of failure (stress-rupture, stress-rupture plus fatigue, and fatigue) as described in reference 2. Microspecimens were mounted to show typical intergranular or transgranular cracking and to show fracture surface appearance for each of the three groups of Waspaloy.

Diameters of the failed specimens were determined at the failure zone. These data were used to compute the percent reduction in area at failure. Hardness measurements, obtained in Rockwell-A units and converted to Rockwell-C units, were taken on a transverse section 1/16 to 1/8 inch below the fracture surface.

## RESULTS AND DISCUSSION

### Combined Stress-Rupture Plus Fatigue Tests

The metallurgical data presented in table II show that group C Waspaloy (7 percent molybdenum and double aged) had higher stress-rupture ductility as mentioned previously and somewhat higher hardness than groups A and B (3 percent molybdenum alloy, single aged and double aged, respectively).

Both 1500° F stress-rupture and notch-rupture data are plotted in figure 3. It can be noted from this figure that the NACA stress-rupture data tend to lie somewhat above the Pratt & Whitney data for groups A and C, whereas for group B the data lie on the same curve. The difference in the case of groups A and C are likely random effects. Hence, a single rupture curve has been drawn for each group. A study of this figure indicates that groups A and B are notch strengthened in stress rupture, while group C is either unaffected or slightly notch weakened. The stress-rupture properties of the three groups can be considered essentially the same in view of the small observed differences.

4218

The results of this investigation are presented in figure 4 as a plot of the mean stress against time to failure at 1500° F with the cyclic stress ratio held constant. (The cyclic stress ratio is defined as the ratio of the amplitude of the cyclic stress to the mean stress.) In order to conveniently evaluate the data presented in figure 4, the data have been cross-plotted in figure 5 as cyclic stress ratio against time to failure at 1500° F and constant mean stress. A study of figure 5 indicates that for the conditions studied, stress ratios of a given magnitude generally caused greater reductions in the life of group A (notch strengthened) than in group B (notch strengthened) and had least effect upon group C (slightly notch weakened or unaffected). At the low mean stress (20,000 psi) and high cyclic stress ratios (0.50 to 0.90) groups B and C appeared to have considerably better resistance to combined stress than group A.

Consideration of the foregoing results suggests that a capacity for notch-rupture strengthening does not necessarily result in improved combined stress-rupture plus fatigue strength. In fact, a tendency towards notch weakening may not necessarily be expected to be harmful.

As can be noted from table II, the stress-rupture ductility of group C was appreciably better than of groups A or B and B was slightly better than A. Further, as indicated previously, group C had the best combined stress-rupture plus fatigue strength, group B had intermediate strength, and group A had the lowest strength. Thus, there is indication of a possible relation between stress-rupture ductility and combined stress-rupture plus fatigue strength.

Reductions in area at failure (dynamic ductility) in combined stress-rupture plus fatigue tests plotted against time to failure are presented in figure 6. A study of this figure indicates that group C is generally most ductile followed in ductility by groups B and A over the range of cyclic stress ratios and mean stress levels studied. Further, it can be noted that the ductilities of the three groups decreased as cyclic stresses increased and tended to become quite small (1 to 2 percent) and about the same order of magnitude at the higher cyclic stress ratios. This particular behavior is quite interesting since it demonstrates that while differences in dynamic ductility (as measured herein) become very small, combined stress-rupture plus fatigue strengths still may differ considerably for the three groups. Hence, one might conclude that combined stress-rupture plus fatigue strength is not directly related to dynamic ductility.

If the heat treatment and/or composition of the alloys studied in this investigation are considered alone (i.e., without regard to their resultant effects upon the basic properties of ductility, etc.), the following observations may be made: Double aging has improved the combined stress-rupture plus fatigue strength of the Waspaloy with the 3 percent molybdenum content. Additional molybdenum in conjunction with the double-age heat treatment further improved the combined stress-rupture plus fatigue properties.

## Metallurgical Evaluation of Failed Specimens

The structures of the three groups of Waspaloy after heat treatment and prior to testing are presented in figure 7. Groups A and B have about the same grain size, while group C average grain size is slightly finer. Group C has a duplex grain structure and pronounced spheroidization of the grain boundaries. Inasmuch as a nonuniform grain size structure has generally been considered to cause reduced life in turbine buckets, the possibility of a duplex grain structure causing reduced life under conditions of combined stress-rupture plus fatigue may be raised. However, group C with a duplex grain structure is indicated as having as good or better strength than the groups with a uniform grain structure.

The macroscopic appearance of the specimens at failure is summarized in table III. Photomicrographs illustrating the three types of failure are presented in figure 8. There did not appear to be any significant difference in the macroscopic failure behavior associated with the three groups of Waspaloy.

Stress-rupture fracture appears to have been initiated intergranularly and then progressed in a predominately transgranular fashion. This was the case for all three groups of Waspaloy. Intergranular initiation of fracture is illustrated in figure 9(a) for groups A and B; figures 9(b) and (c) illustrate intergranular initiation of cracking in group C, where the surface grains were fine and coarse, respectively. The progression of fracture through groups A and B and through group C is illustrated in figures 10(a) and (b), respectively.

The fatigue areas fractured transgranularly in all three groups of Waspaloy. Fatigue fracture of groups A and B is illustrated in figure 11(a) and of group C in figure 11(b). Intergranular failure along the sides of fatigue-failed specimens was quite prevalent.

Stress-rupture plus fatigue failures combined the metallographic features of both stress-rupture failed specimens and fatigue failed specimens.

The microstructures of the failed specimens do not offer any apparent explanation for the differences in the combined stress strengths of the three groups of Waspaloy.

The hardnesses at failure are presented in figure 12. These data do not show any pronounced trend between the hardness at failure and cyclic stress ratio; however, group C hardness values are higher than groups A and B.

## SUMMARY OF RESULTS

This investigation, conducted to determine if the combined stress-rupture plus fatigue strengths of three groups of Waspaloy could be correlated with either their stress-rupture ductilities or notch-rupture strengths, yielded the following results:

1. No clear relation occurred between combined stress-rupture plus fatigue strength and notch-rupture strength. Contrary to what might be expected, a group of specimens with least notch-rupture strength properties (slightly notch weakened or unaffected) had the best combined stress-rupture plus fatigue properties.

2. A possible relation between combined stress-rupture plus fatigue strength and stress-rupture ductility was observed. However, no relation between combined stress-rupture plus fatigue strength and dynamic ductility (ductility at failure in combined stress) was observed.

3. If the heat treatments and/or compositions of the alloys studied in this investigation are considered alone (i.e., without regard to their resultant effects upon the basic properties of ductility, etc.), the following may be observed: Double aging has improved the combined stress-rupture plus fatigue strength of the Waspaloy with the 3 percent molybdenum content. Additional molybdenum, in conjunction with the double-aging treatment further improved the combined stress-rupture plus fatigue properties.

4. The high molybdenum (7 percent) Waspaloy group had a duplex grain structure; this type of structure might be questioned as having a deleterious effect upon resistance to combined stress-rupture plus fatigue. However, this group generally exhibited best combined stress strength.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 10, 1957

## REFERENCES

1. Ferguson, Robert F.: Effect of Magnitude of Vibratory Load Superimposed on Mean Tensile Load on Mechanism of and Time to Fracture of Specimens and Correlation to Engine Blades. NACA RM E52I17, 1952.

2. Hoffman, Charles A.: Strengths and Failure Characteristics of AMS 5765A (S-816) Alloy in Direct Tensile Fatigue at Elevated Temperatures. Proc. ASTM, vol. 56, 1956, pp. 1063-1080.

TABLE I. - CHEMICAL COMPOSITION

| Group | C | Co | Fe | Mn | Mo | Cu | Si | Ti | Cr | Al | Ni |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A and B | 0.04 | 14.18 | 0.55 | 0.89 | 2.97 | 0.12 | 0.57 | 2.70 | 20.10 | 1.25 | Bal. |
| C | .062 | 13.87 | .41 | .74 | 7.32 | .01 | .64 | 2.47 | 19.61 | 1.01 | Bal. |

TABLE II. - METALLURGICAL DATA

| Group | Supplier's data | | | | | | | | NACA data | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Heat treatment | Temperature, 1500° F; Mean stress, psi | | | | | | | Initial grain size (ASTM) | Initial hardness, Rockwell C |
| | | 32,500 | | 27,500 | | 25,500 | | | | |
| | | Ductility, percent reduction in area, at failure | Time to failure, hr | Ductility, percent reduction in area, at failure | Time to failure, hr | Ductility, percent reduction in area, at failure | Time to failure, hr | | | |
| A | Solution treated:<br>1975° F - 2 hr; air cooled<br>Aged:<br>1400° F - 16 hr; air cooled | 6.0 | 20.5 | 7.9 | 159.2 | 5.9 | 148.2 | 1-4 | 32.5 |
| B | Solution treated:<br>1975° F - 2 hr; air cooled<br>Aged:<br>1550° F - 4 hr; air cooled<br>1400° F - 16 hr; air cooled | 6.7 | 35.4 | 8.5 | 138.0 | 7.1 | 153.5 | 1-4 | 32.5 |
| C | Solution treated:<br>1975° F - 2 hr; air cooled<br>Aged:<br>1550° F - 4 hr; air cooled<br>1400° F - 16 hr; air cooled | 9.8 | 36.9 | 12.9 | 54.2 | [a]7.6 | [a]606.2 | [b]2-3, [b]8 | 34.1 |

[a]15,000 psi mean stress.

[b]Duplex grain structure.

TABLE III. - SPECIMEN APPEARANCE AT FAILURE

[Group A, 3 percent molybdenum - single age; group B, 3 percent molybdenum - double age; group C, 7 percent molybdenum - double age.]

| Cyclic stress ratio | Group A | | | Group B | | | Group C | | |
|---|---|---|---|---|---|---|---|---|---|
| | $^{a}\sigma_M$ | | | $\sigma_M$ | | | $\sigma_M$ | | |
| | 22,800 | 29,000 | 38,000 | 20,000 | 28,000 | 40,000 | 21,500 | 29,500 | 40,500 |
| 0 | S-R | S-R | S-R | S-R | S-R | S-R | S-R | S-R | S-R |
| .125 | S-R | S-R | S-R | S-R | S-R | S-R | S-R | S-R | S-R |
| .250 | S-R | S-R + F | S-R | S-R | F | S-R + F | S-R + F | S-R + F | S-R |
| .50 | S-R + F | S-R + F | S-R + F | F | F | S-R + F | F | F | F |
| .67 | F | F | S-R + F | F | F | S-R + F | F | F | F |
| .90 | F | S-R + F | S-R + F | F | F | F | F | F | --- |

[a]Mean stress, $\sigma_M$; stress rupture, S-R; stress rupture plus fatigue, S-R + F; fatigue, F.

4218

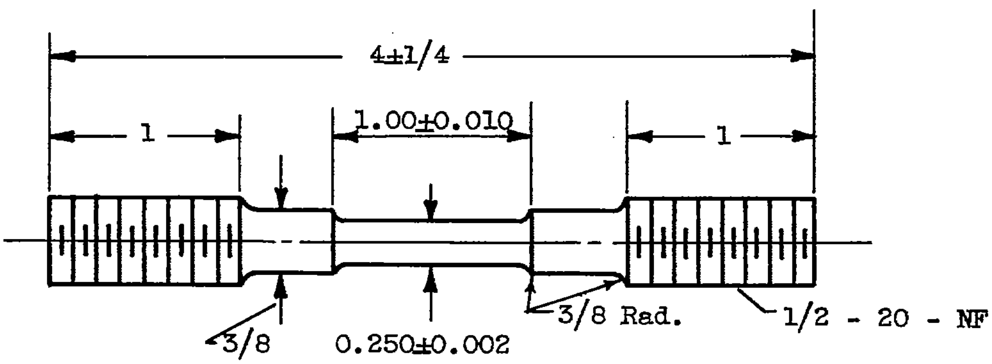


Figure 1. - Fatigue specimen. (All dimensions in inches.)

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CM-2 back

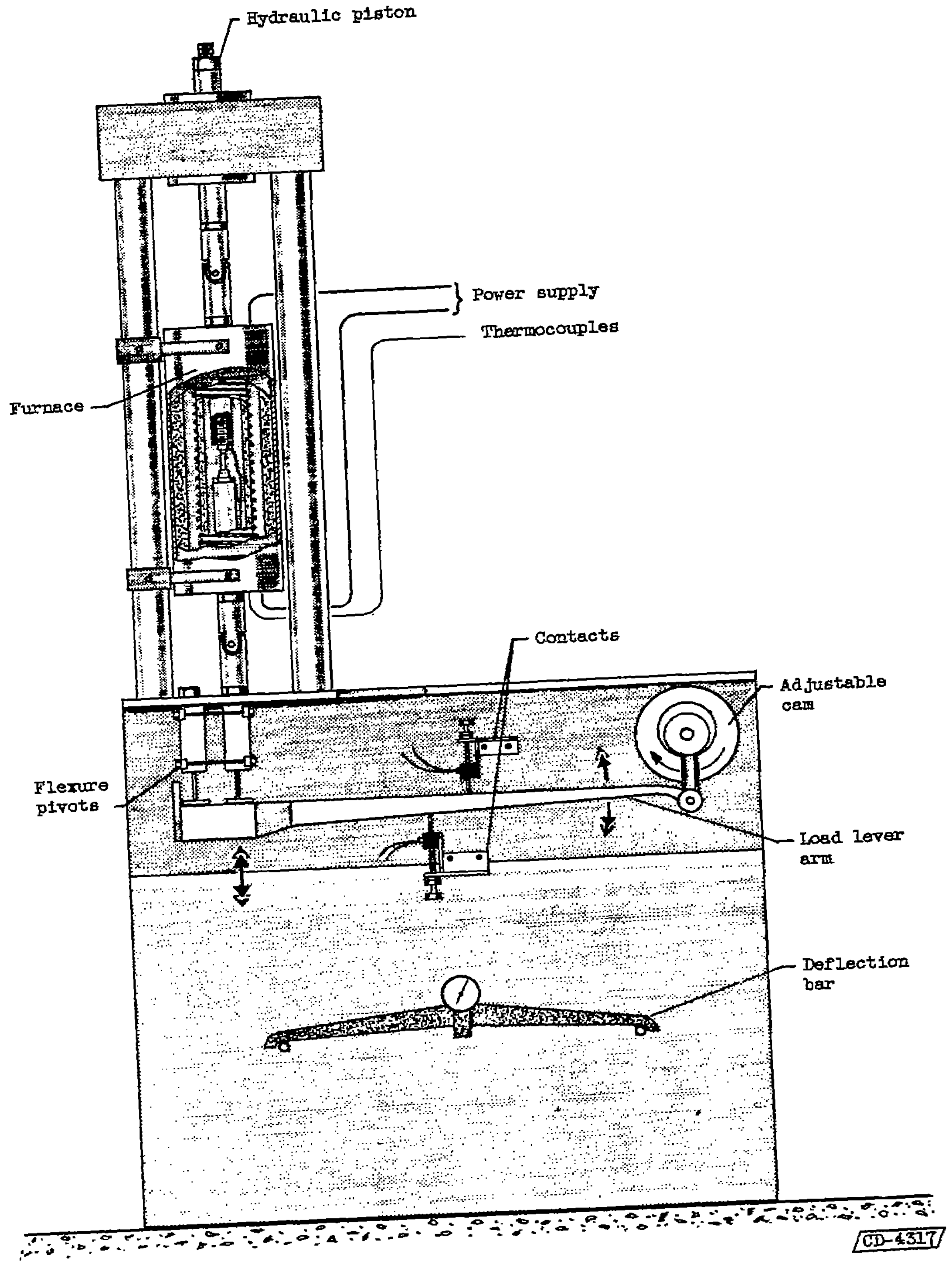


Figure 2. - Direct tensile stress fatigue machine.

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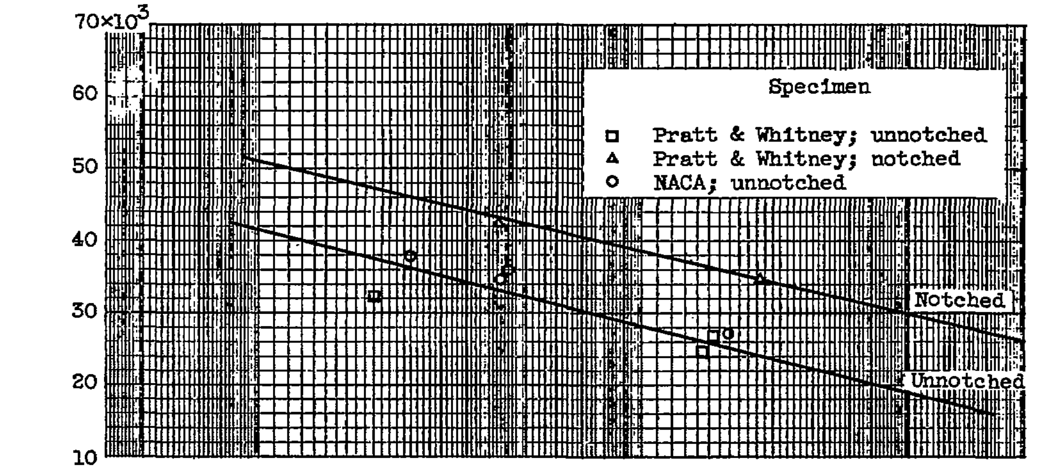
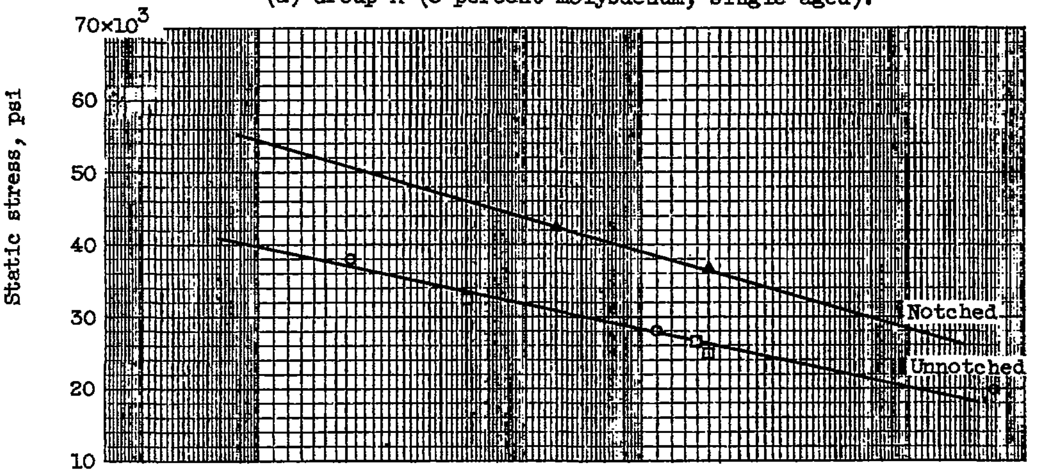
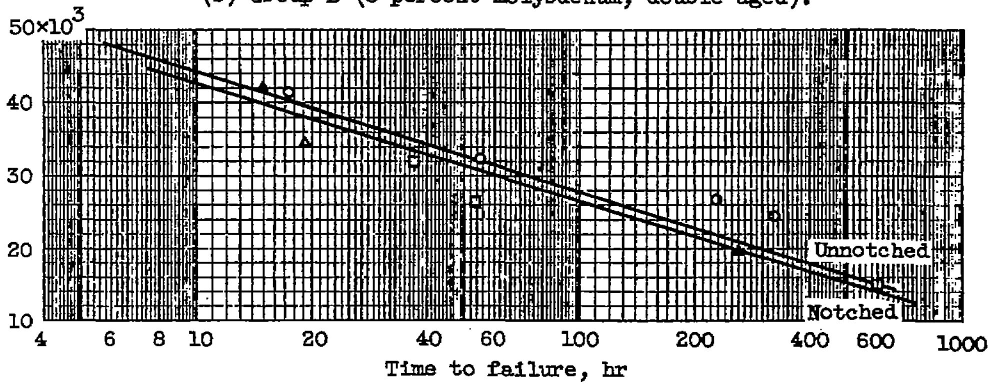



(a) Group A (3 percent molybdenum, single aged).

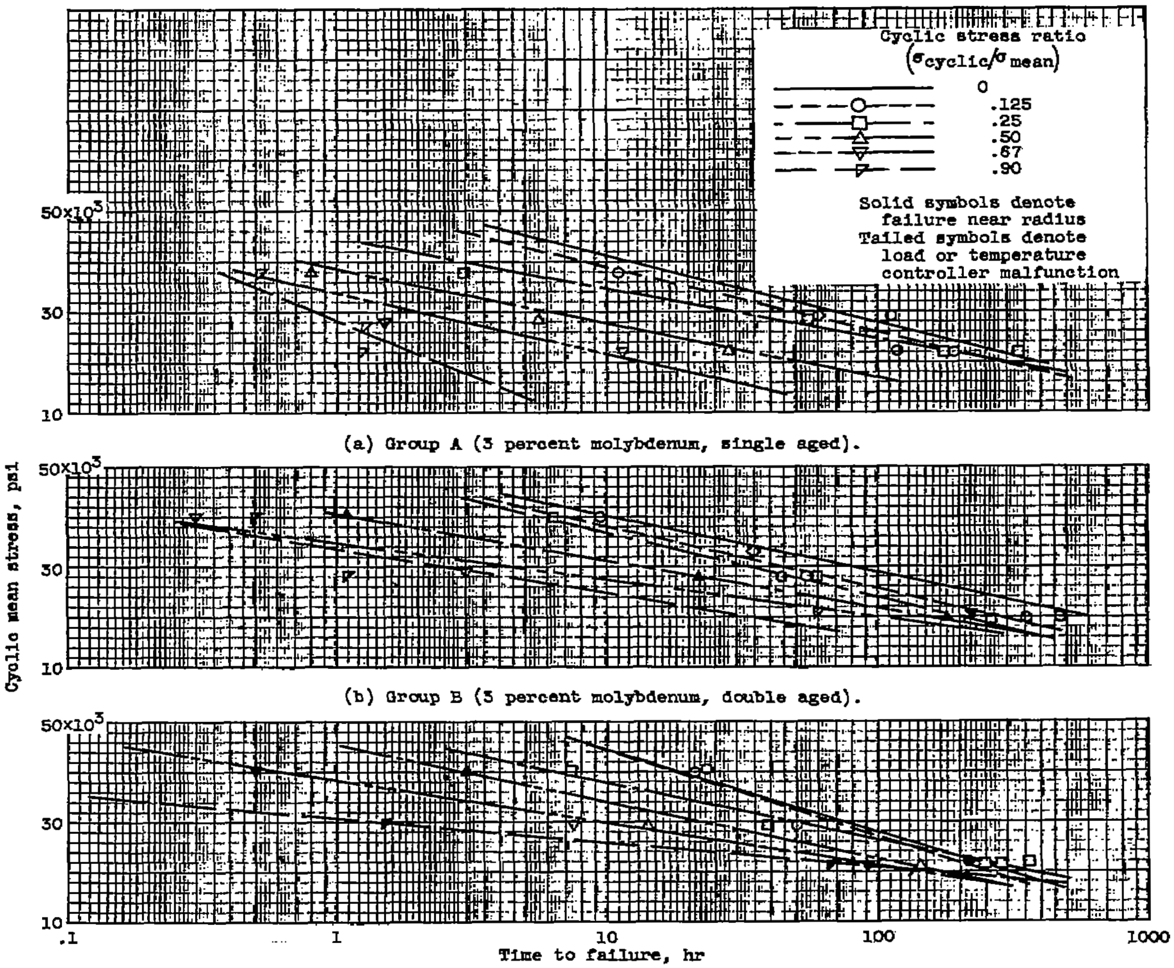



(b) Group B (3 percent molybdenum, double aged).




(c) Group C (7 percent molybdenum, double aged).

Figure 3. - Variation of time to failure at 1500° F with static stress.

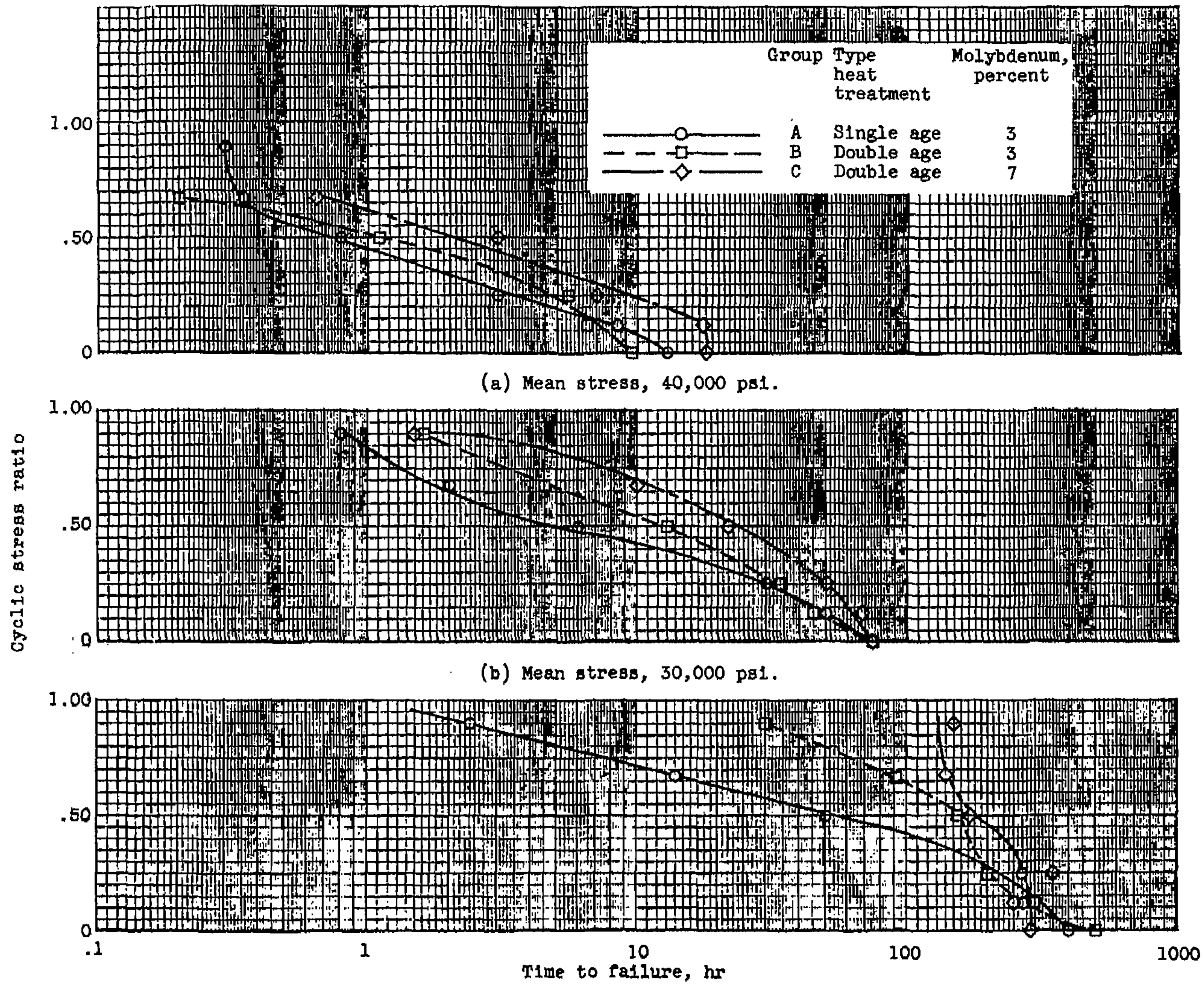



(a) Group A (3 percent molybdenum, single aged).

(b) Group B (3 percent molybdenum, double aged).

(c) Group C (7 percent molybdenum, double aged).

Figure 4. - Variation of time to failure with cyclic mean stress at constant stress ratio and 1500° F.

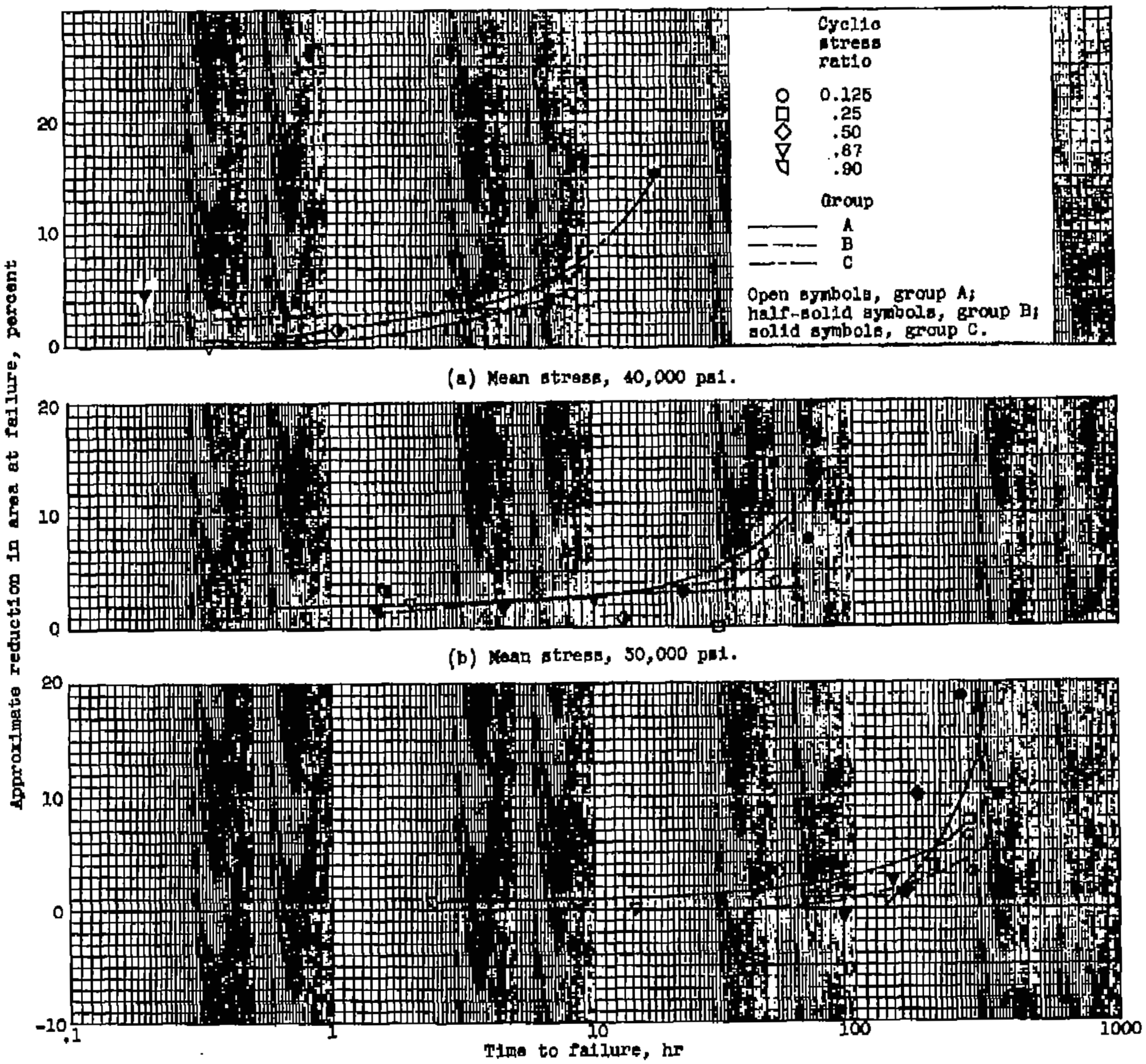



(a) Mean stress, 40,000 psi.

(b) Mean stress, 30,000 psi.

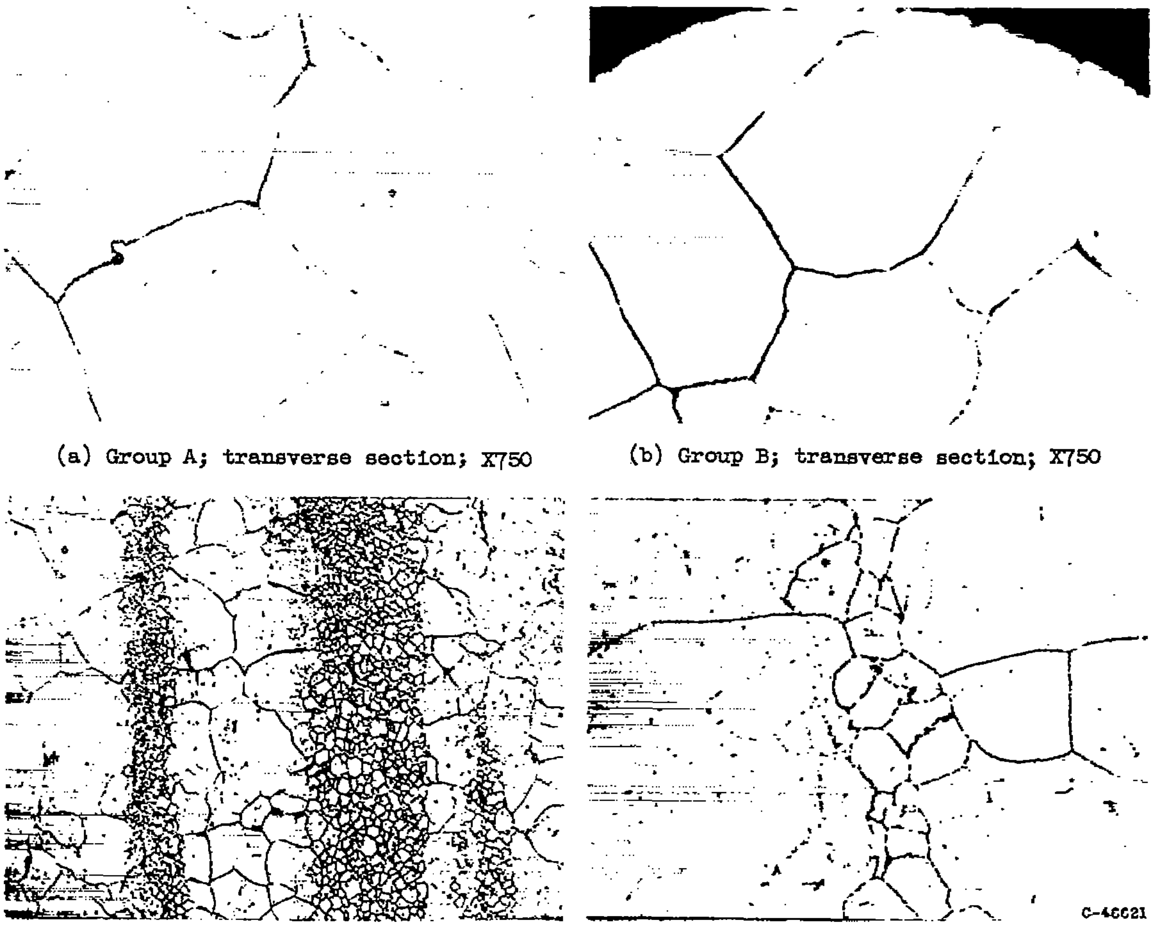
(c) Mean stress, 20,000 psi.

Figure 5. - Variation of time to failure with cyclic stress for constant mean stress and 1500° F.




(c) Mean stress, 20,000 psi.

Figure 6. - Variation of reduction in area at failure with time to failure.



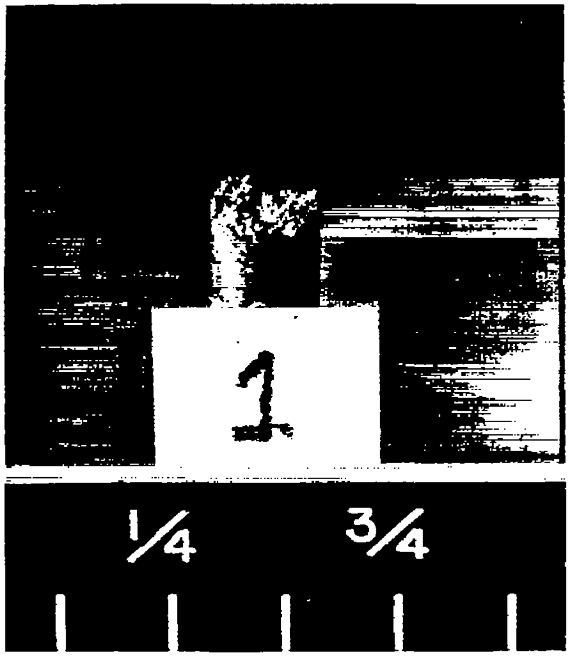

(a) Group A; transverse section; X750

(b) Group B; transverse section; X750

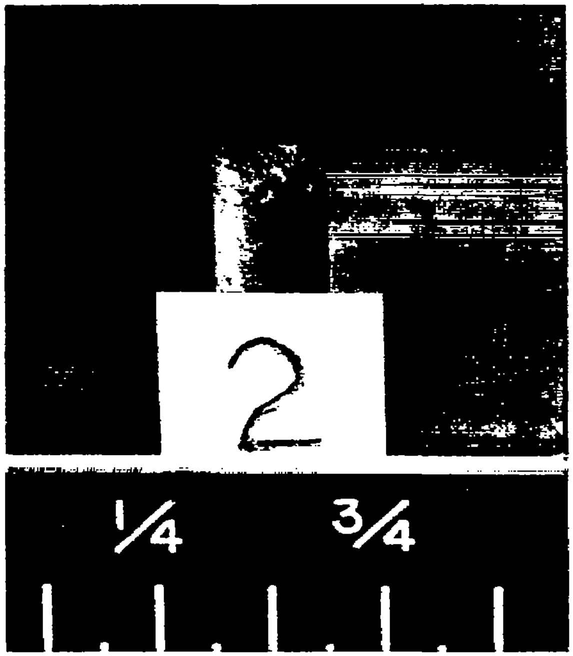
(c) Group C; longitudinal section; X100

(d) Group C; longitudinal section; X250

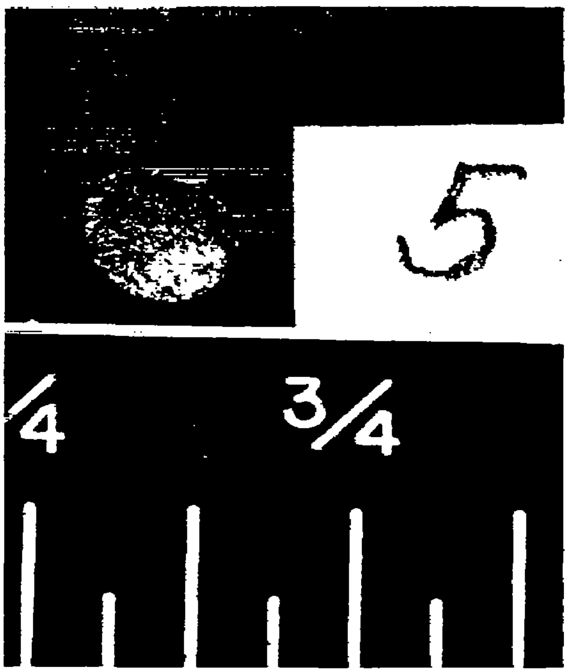
Figure 7. - Structure after heat treatment and prior to testing; electrolytically etched with $HCL+HNO_3+H_2O$. Magnification reduced 42 percent in reproduction.




(a) Stress-rupture failure; X3




(b) Stress-rupture plus fatigue failure; X3.5

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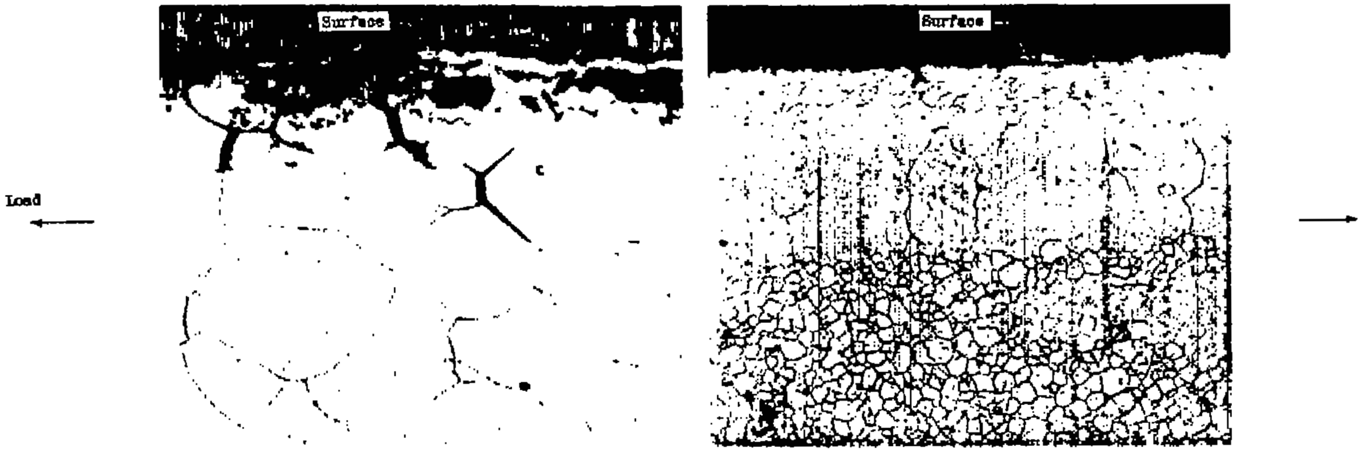
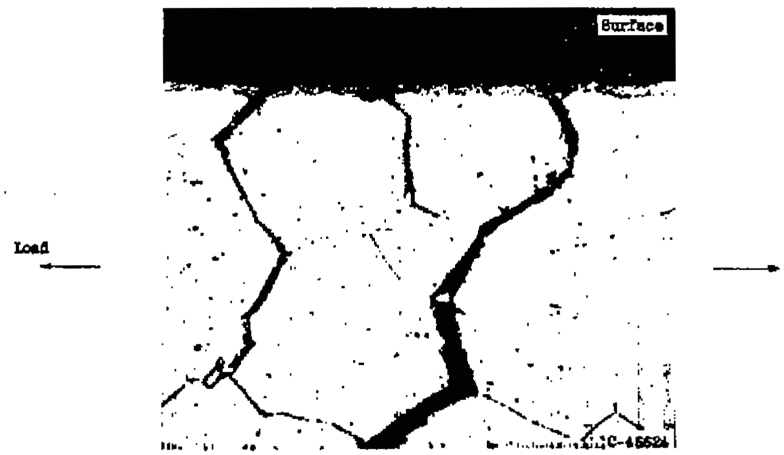
(c) Fatigue failure; X3.5

Figure 8. - Three types of failure of Waspalloy. Magnification reduced 17 percent in reproduction.



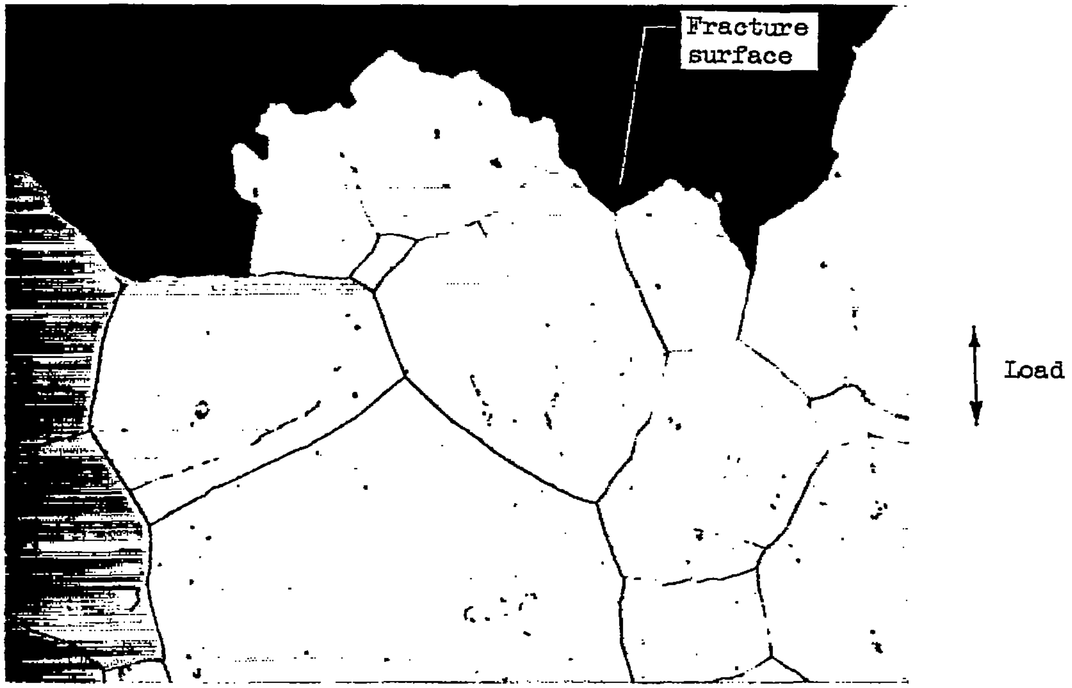

(a) Specimens of groups A and B.

(b) Specimens of group C where fine grains occur along surfaces.

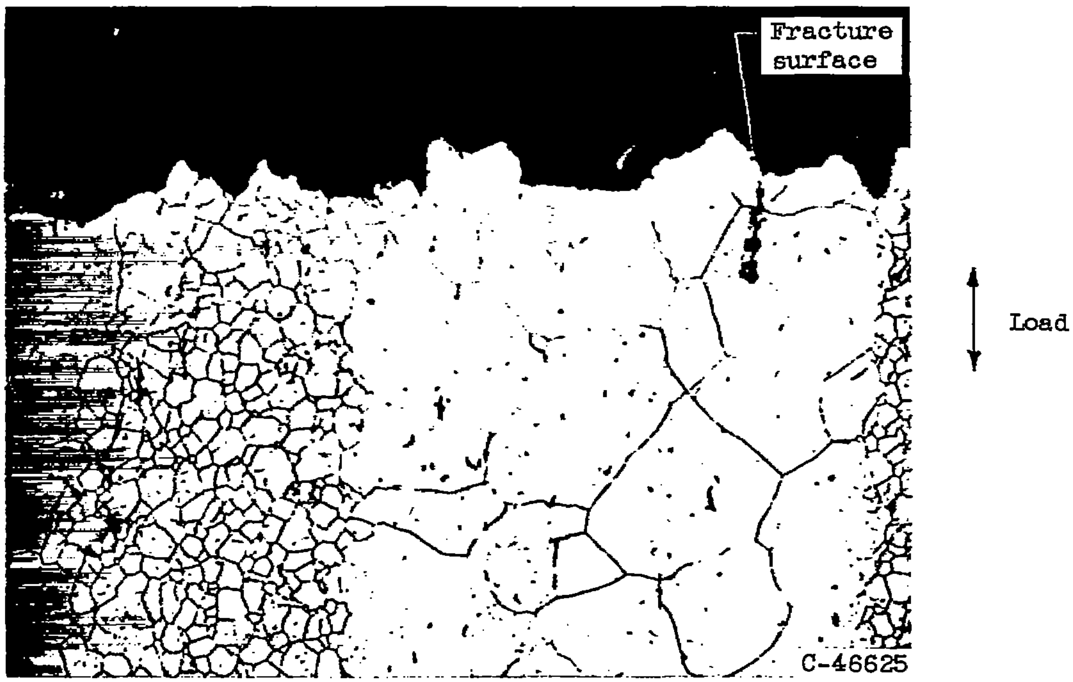



(c) Specimens of group C where coarse grains occur along surfaces.

Figure 9. - Intergranular cracking along side surfaces. Electrolytically etched with $HCL+HNO_3+H_2O$; X250. Magnification reduced 42 percent in reproduction.

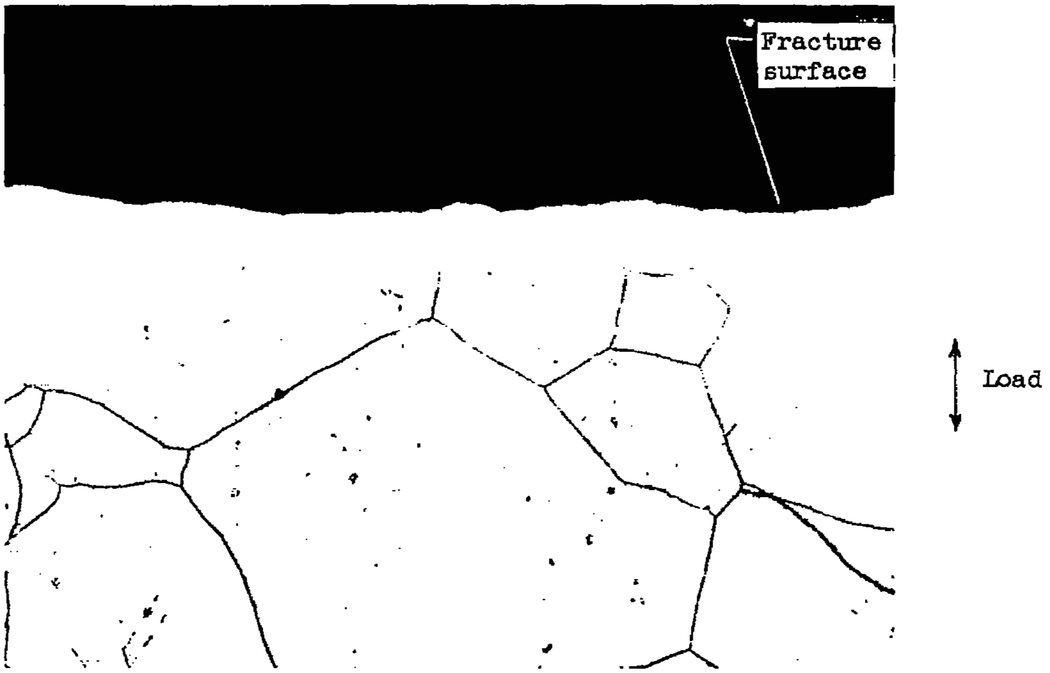



(a) Fracture in specimens of groups A and B.

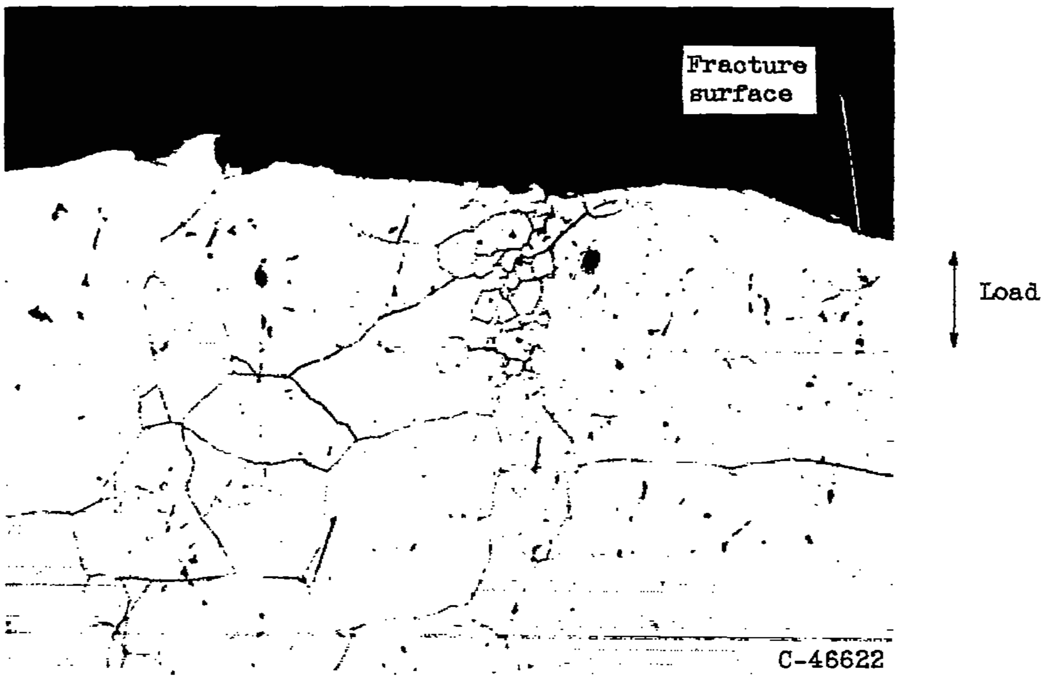



(b) Fracture in specimens of group C.

Figure 10. - Stress-rupture fracture surfaces. Electrolytically etched with $HCL+HNO_3+H_2O$; X250. Magnification reduced 6 percent in reproduction.

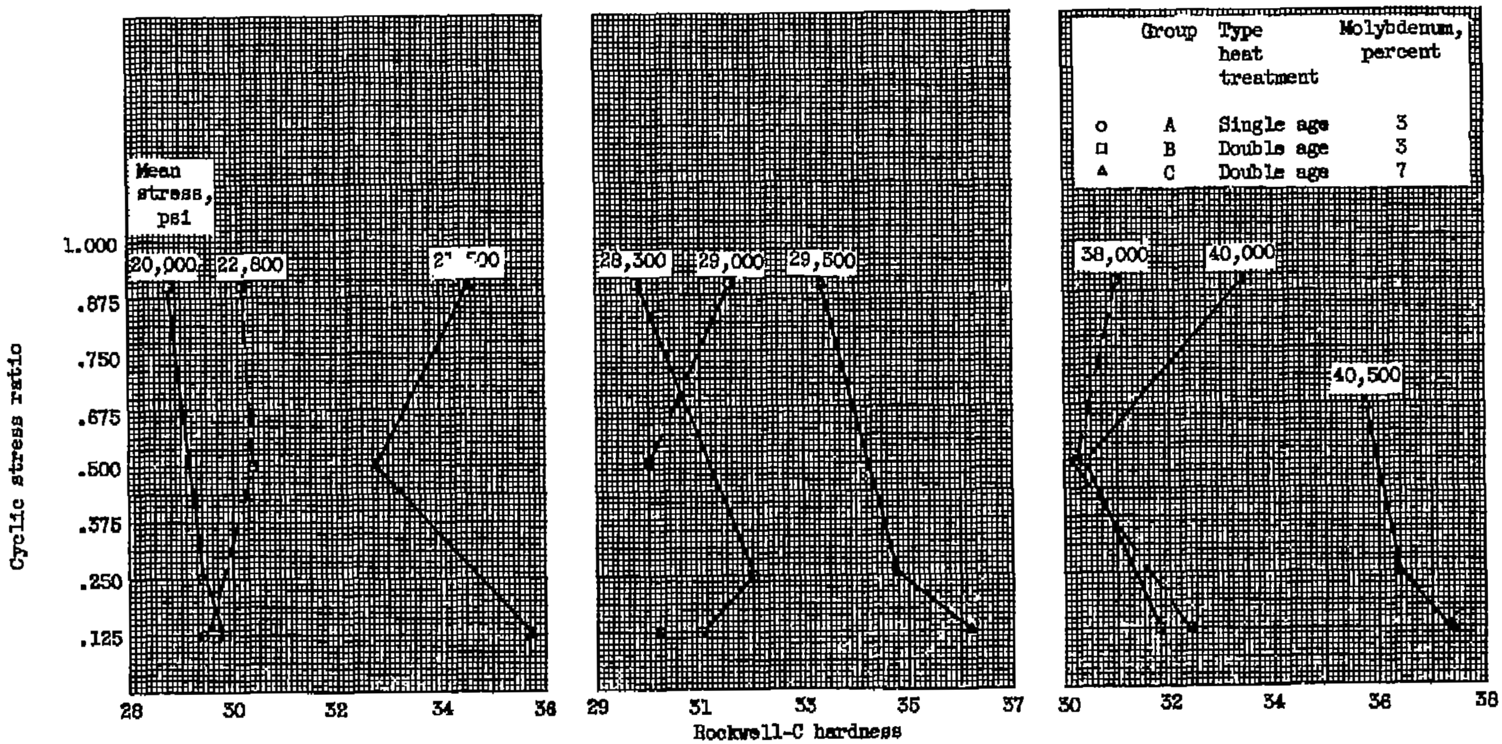



(a) Specimens of groups A and B.




(b) Specimens of group C.

Figure 11. - Fatigue fracture surfaces. Electrolytically etched with $HCL+HNO_3+H_2O$; X250. Magnification reduced 6 percent in reproduction.




(a) Nominal time, 500 hours.

(b) Nominal time, 100 hours.

(c) Nominal time, 10 hours

Figure 12. - Variation of hardness at failure with cyclic stress ratio at constant mean stress.



NACA - Langley Field, Va.