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A.R.C. Technical Report

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Fatigue Tests on Notched Extruded Aluminium Alloy (DTD 364B) having a Theoretical Stress Concentration Factor of 3.65

by

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FATIGUE TESTS ON NOTCHED EXTRUDED ALUMINIUM ALLOY (DTD 364B) HAVING A THEORETICAL STRESS CONCENTRATION FACTOR OF 3.65

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W.A.P. Fisher

SUMMARY

Fatigue tests were made in axial tension at ratios of mean to alternating stress of 1.1, 2, and 3, and at fixed mean stresses of 8800, 14,000 and 18,000 lb/in.^{2}. The tests provide data on the fatigue of alloy to DTD 364B (now L65) with a comparatively high stress concentration and also on the notch sensitivity of this material.

LIST OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

1 INTRODUCTION

In aircraft structures the effective stress concentration factor often exceeds a value of 3.0. Insufficient information has existed for making design fatigue estimates for stress concentration factors of this order, particularly for various mean stresses such as may occur in wing spars. The present limited programme of tests was arranged with a view to providing a basis for such calculations.

Fatigue tests in axial tension were made on flat bars in material to DTD 364B (see Appendix) for a range of mean stress from 8000 to 18,000 lb/in.^{2}. The bars had notches machined on each side at the central cross section, giving a theoretical stress concentration factor of 3.65. For practical testing reasons, the mean stress always exceeded the alternating stress; thus the case of zero mean stress was not covered.

For estimating the appropriate notch sensitivity index, a 'machined finish' datum for similar material was taken from tests[1] on machined bars for various mean stresses and an isolated value for a highly polished bar test[2] made by Vickers Armstrong (Weybridge). From the present tests a value for the notch sensitivity index, $\frac{K_f - 1}{K_t - 1}$, was found which is compared with that deduced from tests[1] (also by Vickers Armstrong) on round bars with unloaded holes ($K_t = 2.65$) having a somewhat greater notch radius.

2 DESCRIPTION OF TEST SPECIMEN

The specimens were all machined from one batch of extruded 3" x 1" bar to Specification DTD 364B (see Appendix).

A sketch of the specimen is given in Fig.1. The pin jointed lug ends ensured axial loading. To avoid failure at the end holes, the latter were fitted with tapered steel bushes having a 0.003 inch interference.

The notch dimensions were chosen with parameter ratios $D/d = 1.5$ and $r/d = 0.047$, D being the full width of the bar, d the distance between the bases of the notches, and r the notch radius. Curves obtained photo-elastically by Frocht[3] give, for these ratios, and for axial tension, a value $K_t = 3.65$.

3 METHOD OF TEST

The specimens were tested in a short base 20 ton Avery-Schenck machine.

For unbroken specimens, the test was stopped at or before 25 million cycles.

4 SCOPE OF TESTS

Sufficient tests were made to give endurance curves at the following ratios of mean to alternating stress, denoted by β.

$$\beta = 1.1, \quad \beta = 2, \quad \beta = 3,$$

i.e., $$R = 0.0476, \quad 0.33 \text{ and } 0.5$$

where $R = \frac{\text{Min stress}}{\text{Max stress}}$.

Additional tests were made at constant mean stresses of 8800, 14,000 and 18,000 lb/in.^{2}.

4.1 Mechanical properties

Two static tensile tests were made as a check on the mechanical properties of the material.

5 TEST RESULTS

The results of static tensile tests are given in Table 1.

The fatigue test results are shown in Table 2 and in Fig.2. The full lines in Fig.2 are the endurance curves for constant stress ratio β, and the broken curves for mean stresses, f_m, of 8800, 14,000 and 18,000 lb/in.^{2}.

6 DISCUSSION OF RESULTS

The static tensile tests show a ratio of 0.1% proof stress to U.T.S. of 89%.

Owing to fairly low scatter in the fatigue tests, the combination of tests at constant β with tests at constant mean stress made it possible to draw in curves from only 30 tests. The one serious discrepancy is the result for specimen No. 8 which has been disregarded in view of those for Nos. 9 and 10.

A feature of the endurance curves is that from 10^6 cycles and beyond they are almost horizontal (specimens which exceeded 2 million cycles were unbroken at 10 million). This feature contrasts with the characteristic continuously falling curves for joints, where fretting plays an important role in promoting failure.

The results are re-plotted in Fig.3 showing constant endurance curves with mean stress as abscissa and alternating stress as ordinate. The curves for 10^6 and for 10^7 cycles are nearly coincident. On such a diagram, tests at constant β lie on a straight line through the origin. The lines for $\beta = 1.1$, 2 and 3 are indicated. The curve for repeated loading (i.e. 0 to max) can be deduced from the line $\beta = 1$.

Also plotted in Fig.3 from a report by Vickers-Armstrong (Aircraft) Ltd. are the curves for 10^7 cycles for turned bars (production finish) made from similar material and a point V for polished bars with a surface finish of 7 micro-inches. The broken line through V is an estimated portion of the 'polished bar' curve and is used here as a reference curve for estimating the fatigue strength reduction factor K_f.

7 FATIGUE STRENGTH REDUCTION FACTOR AND NOTCH SENSITIVITY INDEX

As distinct from the theoretical stress concentration factor K_t, the ratio of the experimental fatigue strengths (in terms of nominal stresses) for a polished bar and for a notched specimen is known as the fatigue strength reduction factor, K_f. For steels, K_f is defined as the ratio of the respective endurance limits. As aluminium alloys do not show a definite endurance limit, a specific endurance, such as 10^7 cycles, is used instead.

For a given stress ratio β, let the alternating stress for 10^7 cycles for a polished bar be denoted by f_a and the alternating stress giving 10^7 cycles for a notched bar by f_{an}. Then K_f is defined as f_a/f_{an}. This definition (i.e. for a constant stress ratio) implies that the mean stress at the base of the notch is raised by the same factor as the alternating stress.

Curve A, Fig. 3, shows the predicted stresses found from the 'polished bar' curve by dividing f_a and f_m by the full theoretical stress concentration factor 3.65. The fatigue strength according to this curve would be about 1/1.265 of that shewn by the experimental results, suggesting a value of K_f equal to $K_t/1.265$, i.e. 2.9. The notch sensitivity index, $q = \frac{K_f - 1}{K_t - 1}$, is therefore about 0.72. Results[1] for a cylindrical bar with a transverse hole, in material to the same specification, are shown as points K and L in Fig. 3. In this case, K_t was 2.65 and it is found by measurement on the diagram that K_f is 2.34. These figures give q = 0.81.

For the present tests, taking $K_f = 2.9$ (i.e. q = 0.72) irrespective of mean stress gives the 'reduced' curve B which touches the 10^7 cycle curve at $\beta = 1.1$ but is conservative for higher values of β. The departure of the experimental points from curve B at high values of β is in agreement with other results for notched test pieces, which have been discussed by K. Gunn[4] and by H.L. Cox[5]. The maximum stress at the base of the notch is limited by local plastic deformation, resulting in a limitation of the effective mean stress (see line marked 'Yield boundary' in Fig. 3).

For values of β from 0 to 1 the present tests provide no information. But the positions of points K and L make it seem probable that in this part of the diagram the 10^7 curve would conform closely to the 'reduced' theoretical curve B for mean stresses down to zero. It is concluded that for an endurance of 10^7 cycles a notch sensitivity index of 0.72 for these specimens is valid for mean stresses from 0 to 10,000 lb/in.^{2} and is conservative for higher mean stresses.

The notch sensitivity index, though dependent on the type of material, cannot be regarded as a physical property. It depends, for instance, on the absolute size of the notch root radius. The value 0.72 for the present tests (root radius 0.064") and that of 0.81 for the transverse holes (radius 0.0937") show the expected trend of increasing notch sensitivity with increase in notch radius. For large unloaded holes, an index approaching unity might well be necessary. With loaded holes, as is well known, the effects of fretting make fatigue strength estimates based on K_t totally unsafe.

8 CONCLUSIONS

Fatigue data on notched specimens of DTD 364 (or L.65) have been presented. It is shown that the fatigue strength for 10^7 cycles and mean stress less than 10,000 lb/in.^{2} may be estimated as follows:

(i) For a known value of K_t the value of K_f is determined by the equation

$$K_f - 1 = q(K_t - 1)$$

where q may be taken as 0.72 for a notch radius of about 0.064" or 0.81 for a notch radius of about 0.09"; for a notch radius greater than 0.1" a value of q approaching unity might be appropriate.

(ii) Using the 'polished bar' curve shewn in Fig. 3 the curve for the notched specimen (10^7 cycles) is determined by dividing both f_a and f_m by K_f.

The above procedure is conservative for mean stresses exceeding 10,000 lb/in.^{2} and is applicable only to purely geometric stress concentrations (i.e. when there is no fretting).

LIST OF REFERENCES

No.	Author(s)	Title, etc.
1	Anon.	Part two of final report on experience of fatigue at Weybridge. Ministry of Supply S. & T. Memorandum No. 2/55. July, 1954.
2	Anon.	Unpublished report by Vickers-Armstrong (Aircraft) Ltd., Weybridge.
3	Frocht, M.M.	A photoelastic investigation of stress concentration due to small fillets and grooves in tension. NACA Technical Note No. 2442. August, 1951.
4	Gunn, K.	Fatigue of notched test pieces. Aeronautical Quarterly <u>6</u> p.277. 1955.
5	Cox, H.L.	Stress concentration in relation to fatigue. Proc. International Conference on Fatigue Metals p.214. Institution of Mechanical Engineers. 1956.

APPENDIX 1

EXTRUDED ALUMINIUM ALLOY BAR TO SPECIFICATION DTD 364B (NOT EXCEEDING 6" DIAMETER OR MINOR SECTIONAL DIMENSION)

Specified chemical composition

Copper - Not less than 3.5 nor more than 4.8 per cent.
Silicon - Not more than 1.5 per cent.
Magnesium - Not less than 0.3 nor more than 0.6 per cent.
Manganese - Not less than 0.4 nor more than 1.2 per cent.
Iron - Not more than 1.0 per cent.
Titanium - Not more than 0.3 per cent.
Aluminium - The remainder.

Specified heat treatment

Solution treated, straightened and artificially aged, i.e. heated to 510° ± 5°C, quenched, aged by heating at one of a range of temperatures between 155° and 205°C for a specified period, and again quenched in water or cooled in air.

Specified minimum strengths

	Test pieces* representing:-		
	Extruded sections not greater than $\frac{3}{8}$" thickness.	Extruded sections greater than $\frac{3}{8}$" but less than 1" in thickness or greater than 4" and not more than 6" in diameter, minor sectional dimension or thickness.	Extruded sections not less than 1" nor more than 4" in thickness.
	Not less than:	Not less than:	Not less than:
0.1 per cent proof stress	24 tons per sq in.	26 tons per sq in.	28 tons per sq in.
Ultimate tensile stress	28 tons per sq in.	30 tons per sq in.	32 tons per sq in.
Elongation	8 per cent	8 per cent	8 per cent

*For bars up to and including $1\frac{1}{8}$" diameter or minor sectional dimension the tensile test piece shall be machined concentrically from the test sample. Above this diameter or minor sectional dimension the longitudinal axis of the specimen shall be not less than $^{9}/16$" from the surface of the test sample.

TABLE 1

Results of static tensile tests

Specimen	0.1% proof stress (T/in.^{2})	U.T.S. (T/in.^{2})	Young's mod.	Elongation (per cent)
A	29.8	33.2	10.5×10^6	8.3
B	30.0	33.7	10.5×10^6	10

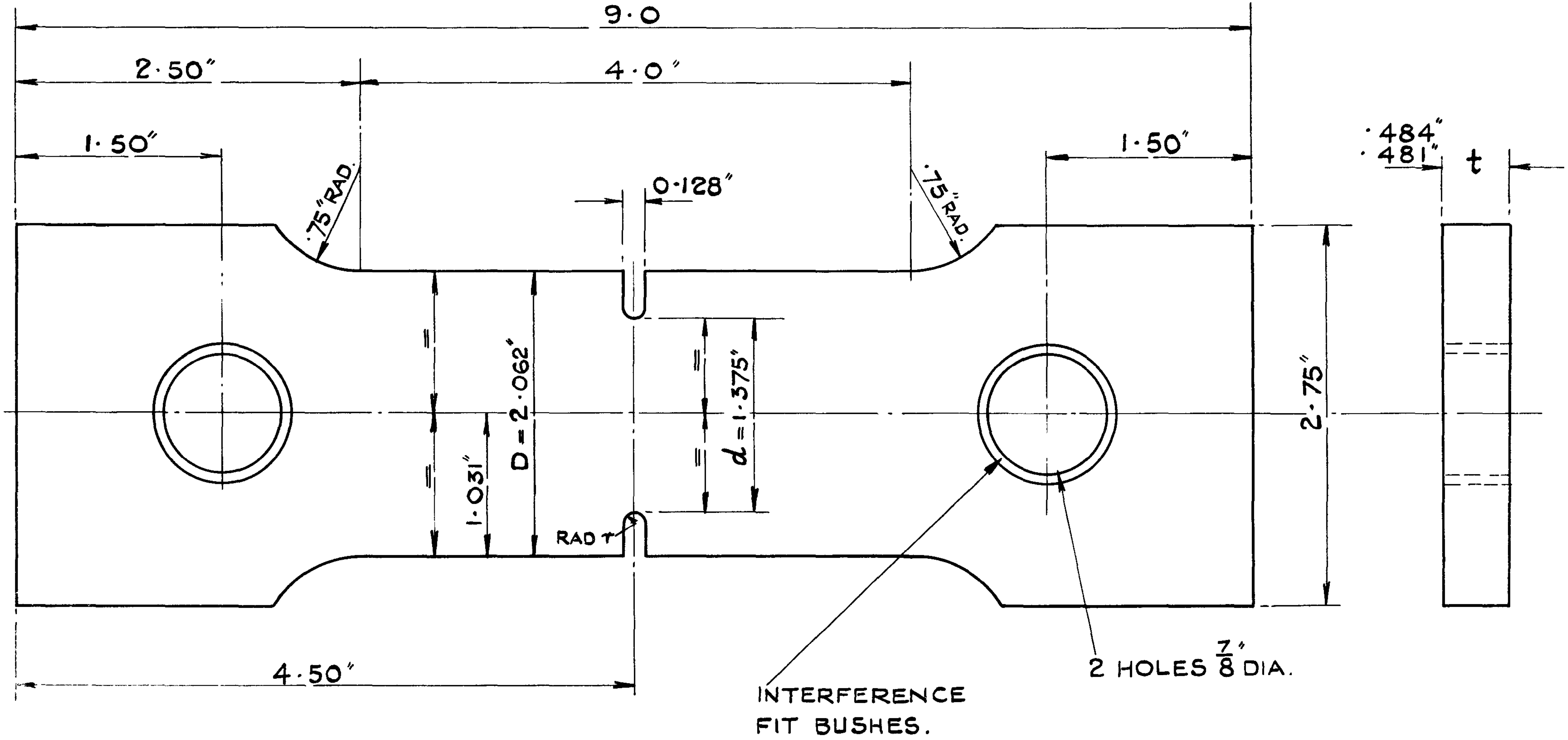
TABLE 2

Fatigue test results

Type 2B - DTD 364

Test No.	Stress (lb/in.^{2})	No. of cycles
	Tests at $\beta = 1.1$	
1	11,000 ± 10,000	139,300
2	8,800 ± 8,000	391,900
3	7,700 ± 7,000	14,780,600
4	7,700 ± 7,000	10,890,000
5	6,600 ± 6,000	25,416,300 unbroken
	Tests at $\beta = 2$	
6	18,000 ± 9,000	54,800
7	16,000 ± 8,000	93,500
8	12,000 ± 6,000	18,615,400 unbroken
9	12,000 ± 6,000	199,400
10	12,000 ± 6,000	383,600
	Tests at $\beta = 3$	
11	21,000 ± 7,000	52,200
12	18,000 ± 6,000	120,200
13	15,000 ± 5,000	295,500
14	12,000 ± 4,000	25,708,400 unbroken
15	12,000 ± 4,000	27,774,600 unbroken
	Tests at 8,800 lb/in.^{2} mean stress	
16	8,800 ± 8,000	391,900
17	8,800 ± 6,000	1,145,700
18	8,800 ± 6,000	1,927,100
	Tests at 14,000 lb/in.^{2} mean stress	
19	14,000 ± 12,700	36,700
20	14,000 ± 12,000	41,600
21	14,000 ± 8,000	122,900
22	14,000 ± 6,000	296,400
23	14,000 ± 5,000	499,300
24	14,000 ± 5,000	463,600
25	14,000 ± 4,500	25,151,100 unbroken
26	14,000 ± 4,000	21,358,700 unbroken
	Tests at 18,000 lb/in.^{2} mean stress	
27	18,000 ± 9,000	54,800
28	18,000 ± 6,000	120,200
29	18,000 ± 4,500	394,300
30	18,000 ± 4,000	24,572,600 unbroken

WT.2078.C.P.460.K3 - Printed in England



$D/d = 1{\cdot}5$

$r/d = 0{\cdot}047$

MATERIAL :- D.T.D. 364 B

N.B. STRESSES ARE ALL BASED ON NETT CROSS SECTIONAL AREA $d \times t = 0{\cdot}665$ IN?

FIG.1. TEST SPECIMEN

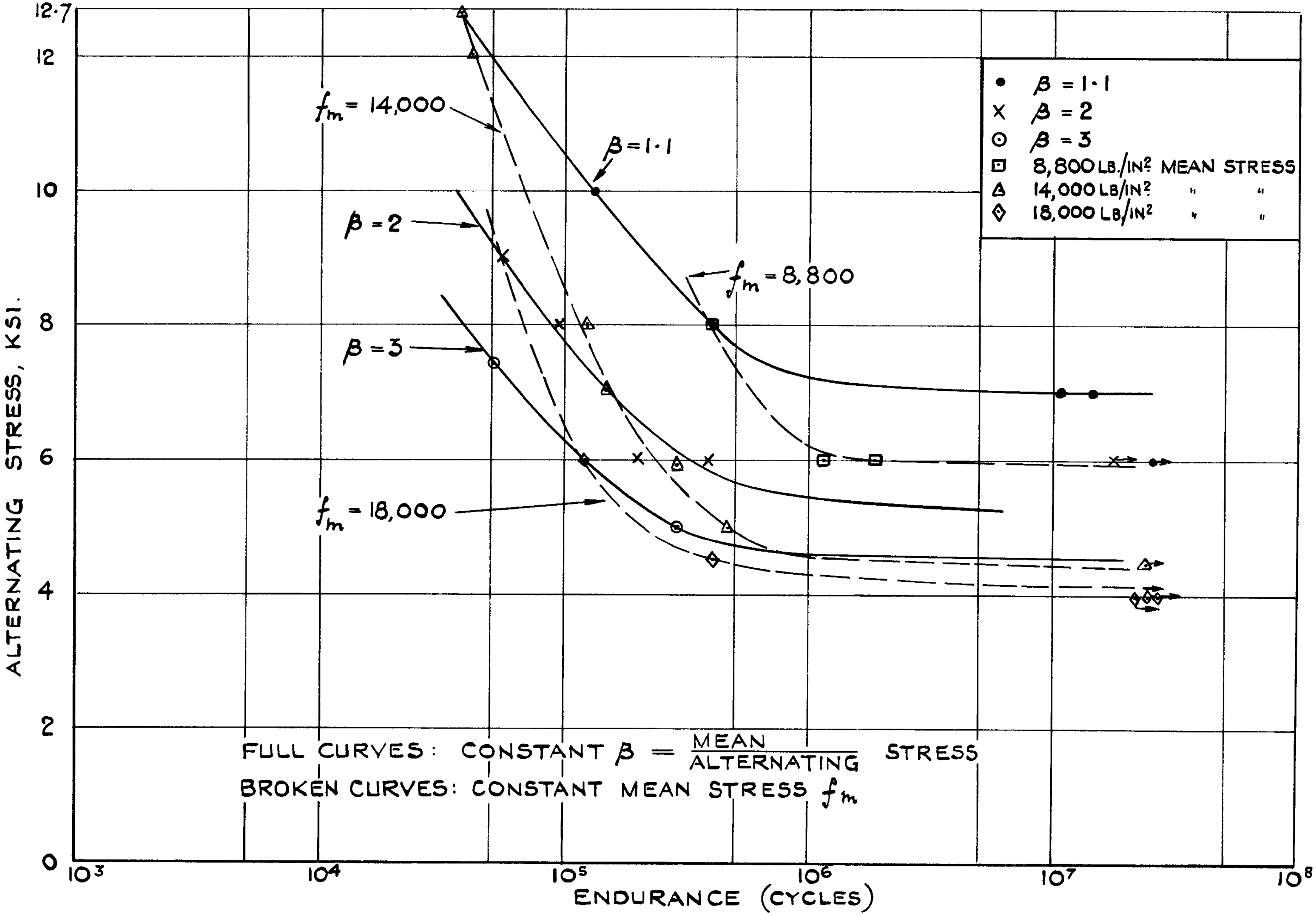


FIG. 2. TEST RESULTS.

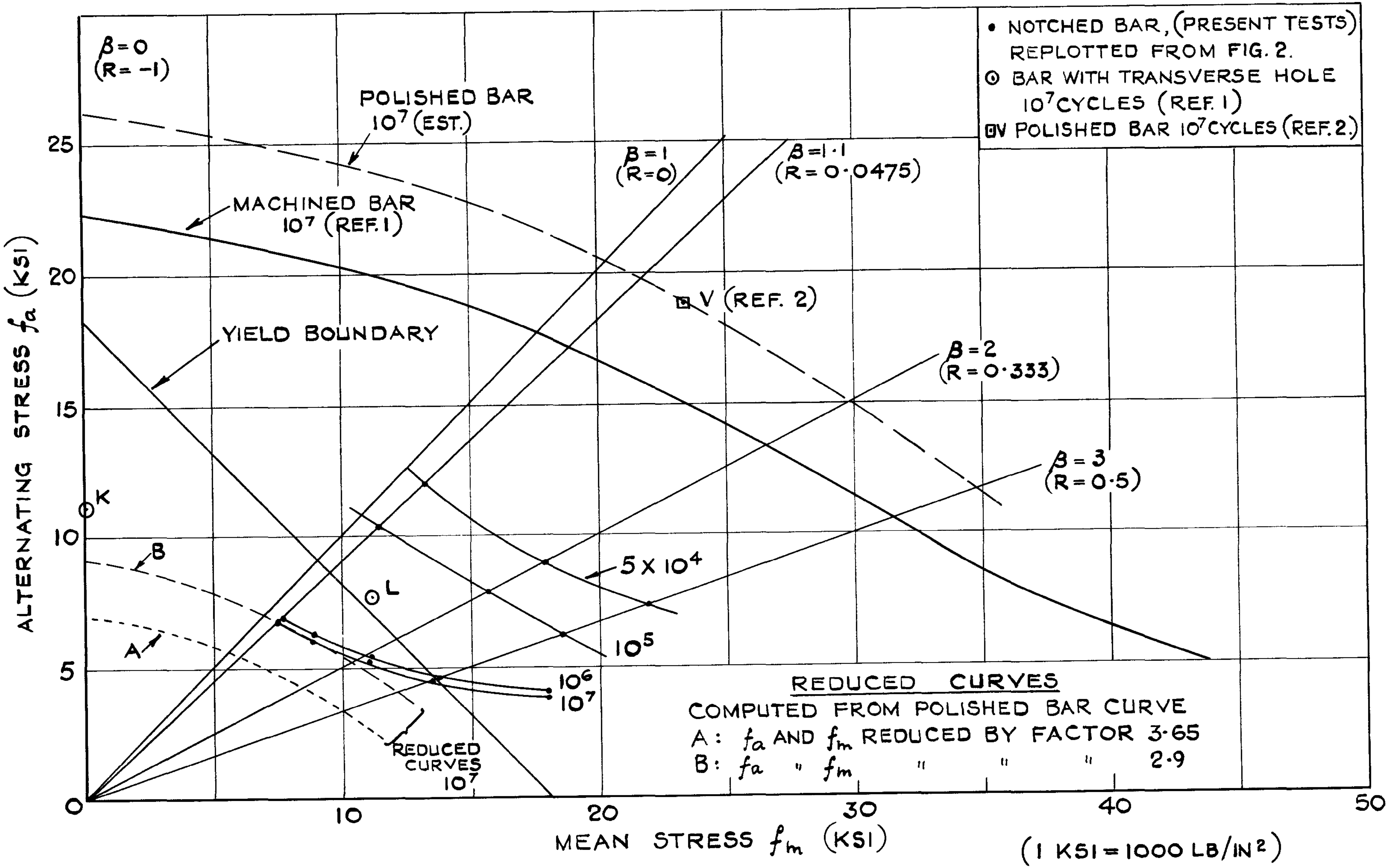


FIG. 3. EFFECT OF MEAN STRESS (CONSTANT ENDURANCE CURVES)

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