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The Resistance of Aluminium and Beryllium Bronzes to Fatigue and Corrosion-Fatigue

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Summary.—The investigation of the fatigue and corrosion-fatigue resistance of special bronzes (Gough and Sopwith, 1937³) is extended to include (1) aluminium bronze (D.T.D.160), (2) beryllium bronze (2·25 per cent. Be), each in two heat-treated conditions.

In neither material is the fatigue or corrosion-fatigue resistance appreciably higher in the heat-treated condition than in the condition as received. The fatigue strength in air of the beryllium bronze is almost independent of the ultimate stress, which varied from 32 to 81 ton/in.².

1. *Introduction.*—In an earlier paper (Gough and Sopwith, 1937³) the results were given of fatigue and corrosion-fatigue tests on some special bronzes. The bronzes investigated were :—

- (1) Phosphor bronze (B.S.S.369A).
- (2) Aluminium bronze (D.T.D.160).
- (3) Beryllium bronze (British manufacture).
- (4) Superston bronze (D.T.D.197).

All four materials were tested “as received”; in the case of two of the materials, aluminium bronze and beryllium bronze, this condition was not such as would be used in practice. It was, however, considered desirable to test these materials in the condition extruded and drawn as received, as well as in the heat-treated condition, since the condition which produces the highest ultimate stress and fatigue limit in air is not necessarily the best under corrosion-fatigue conditions. It was stated that it was intended later to test each of these materials in two heat-treated conditions. The present paper describes the results of these tests.

2. *Particulars of Materials.*—The aluminium bronze used in the previous tests, although supplied to Specification No. D.T.D.160, contained 1·4 per cent. zinc and 0·15 per cent. iron, as against the specified maximum impurity content of 0·75 per cent., and was also somewhat low in aluminium (8·89 per cent. as against 9 to 9·8 per cent. as specified). A fresh batch of this material in the form of $\frac{3}{4}$ -in. diameter bar was therefore obtained. The beryllium bronze was that used for the previous work.

The heat-treatments adopted were as follows :—

- Aluminium bronze .. (1) Heated 1 hr. at 880 deg. C., quenched in water.
 (2) As (1), reheated 1 hr. at 600 deg. C., cooled in free air.
- Beryllium bronze .. (1) Solutionised (40 mins. at 810–820 deg. C., quenched in cold water).
 (2) Fully heat-treated (as (1), reheated 1 hr. at 360 deg. C., quenched in cold water).

Chemical analyses and microscopical examinations of the materials were carried out in the Metallurgy Division of the Laboratory. The results of the analyses are given in Table 1, and of the microscopical examination in the following extract from the Metallurgy Division Report, and Figs. 1 to 4.

“ Longitudinal sections taken from the butt ends of the four (fatigue test) specimens were prepared for microscopical examination.

“ The structure of the beryllium bronze HMX 3J, Fig. 1, consists of grains of α (light), surrounded by γ (dark), precipitated during the heat-treatment at 360 deg. C. The α grains also show signs of incipient precipitation of γ . This structure is typical of fully heat-treated material of this composition.

“ The structure of the beryllium bronze HMX 6J, Fig. 2, consists of a groundmass of α in which β is dispersed in strings, a characteristic effect of hot working.

“ The aluminium bronze quenched from 880 deg. C. shows a characteristic structure seen in Fig. 4, consisting of α (white) and ‘ martensitic ’ β (dark). On reheating at 600 deg. C. the β constituent is partly absorbed, as shown in Fig. 3.”

For convenience of reference, the heat-treatments will be referred to in the remainder of this paper as Q (quenched) and QR (quenched and reheated).

TABLE 1
Chemical Composition of Materials

Per cent.	Material and Reference Mark		
	Aluminium Bronze KDK		Beryllium Bronze HMX
	Spec. D.T.D.160	Actual	
Copper	Remainder	90.62	97.26
Aluminium	9.0 to 9.8	9.27	—
Iron	} Total impurities } ≥ 0.75	0.07	0.10
Zinc		0.09	—
Nickel		—	0.30
Beryllium		—	2.25
Manganese		—	trace

The results of tensile, hardness and notched-bar tests are given in Table 2.

TABLE 2
Mechanical Properties of Materials

Material	Aluminium Bronze		Beryllium Bronze	
Heat Treatment	QR	Q	QR	Q
Reference Mark	KDK 1 to 3	KDK 5 to 6	HMX 3 to 5	HMX 6 to 8
<i>Tensile Tests</i>				
Ultimate stress ton/in. ²	32·8	36·8	81·2	32·2
Yield stress "	—	—	—	—
Proportional limit "	3·4	3·0	24	5·4
0·1 per cent. proof stress "	8·6	8·4	60·6	11·0
0·15 per cent. proof stress "	9·3	9·6	65·9	11·4
Young's modulus <i>E</i> lb/in. ²	$15·6 \times 10^6$	$15·0 \times 10^6$	$19·2 \times 10^6$	$17·6 \times 10^6$
Elongation on $4\sqrt{A}$ per cent.	51	$28\frac{1}{2}$	1	63
Reduction of area " "	43	26	4	66
<i>Izod Impact Tests</i>				
Energy absorbed ft. lb.	58·1 to 66·0	43·0 to 44·0	—	—
Mean "	61·0	43·8	—	—
<i>Brinell Tests</i>				
Hardness number "	105 to 113	133 to 144	380 to 397	108 to 132
Mean "	108	137	390	121

The aluminium bronze complies with the specification D.T.D.160 as regards composition and, in the quenched (Q) condition, as regards mechanical properties (about 35 ton/in.² ultimate stress and 126 to 179 Brinell number). The two heat-treatments of the beryllium bronze have produced material of widely varying mechanical properties—the quenching and reheating (QR) a very high ultimate stress with practically no ductility and the quenching (Q) a low ultimate stress with very high ductility.

3. *Apparatus and Specimens.*—The fatigue and corrosion-fatigue tests were carried out in rotating-beam machines of the N.P.L. type, a uniform bending moment being produced over the whole length of the test portion of the specimen by means of equal upward and downward loads applied to points on its enlarged outer end. The frequency of operation was about 2,200 stress cycles per minute, as in all previous corrosion-fatigue work at N.P.L.; the endurance basis adopted was 50 million cycles.

The apparatus used for the corrosion-fatigue tests was that previously described (Gough and Sopwith, 1933²), in which the specimen is surrounded during test by a fine mist of salt solution (3 per cent. common salt in distilled water) injected by means of compressed air.

The form of specimen used was that shown in Fig. 1a of the paper mentioned for the aluminium bronze and Fig. 1b for the beryllium bronze; in each case the diameter of the test portion was 0·275 in. and its length about 1 in.

4. *Results of Fatigue Tests.*—The results of the fatigue tests in air and in salt-spray are given in Tables 3 and 4 and, plotted logarithmically, in Figs. 5 and 6. The deduced values of the fatigue and endurance limits are summarised in Table 5, together with those previously obtained for the same and other materials.

TABLE 3

Results of Fatigue Tests in Air and Salt Spray on Aluminium Bronze (Ref. Mark KDK)

Heat Treatment	Fatigue Tests in Air			Corrosion-Fatigue Tests in Salt Spray		
	Specimen	Range of Applied Stress (ton/in. ²)	Endurance (millions)	Specimen	Range of Applied Stress (ton/in. ²)	Endurance (millions)
QR	1A	±16	1.04	2A	±16	0.63
	1B	±14	1.40	3B	±12.5	2.56
	1C	±12	8.01	2B	±12	2.93
	1E	±11	5.96	2D	±11	4.82
	1F	±10	40.67	2C	±10	9.10
	1G	±9.5	50.63*	2F	±9	11.56
				3A	±9	17.01
			2G	±8	40.69	
			3C	±7.5	52.98*	
Q	4A	±20	0.16	5A	±16	0.73
	4B	±16	0.65	5B	±12	5.66
	4C	±14	3.81	5C	±10	19.46
	4D	±12	24.78	5E	±9	31.57
	4F	±11.5	44.55	5F	±8.5	55.57
	4G	±11	55.21*			

* Specimens unbroken

TABLE 4

Results of Fatigue Tests in Air and Salt Spray on Beryllium Bronze (Ref. Mark HMX)

Heat Treatment	Fatigue Tests in Air			Corrosion-Fatigue Tests in Salt Spray		
	Specimen	Range of Applied Stress (ton/in. ²)	Endurance (millions)	Specimen	Range of Applied Stress (ton/in. ²)	Endurance (millions)
QR	3A	±30	0.47	4E	±25	2.03
	3B	±25	3.21	4G	±22	1.29
	3C	±22	1.48	4A	±20	10.93
	3D	±20	10.62	4B	±19	8.58
	3G	±19.5	37.96	4C	±18	7.40
	3F	±19	74.29*	4F	±17	17.27
	3E	±18	50.71*	4D	±16	49.00
Q	6A	±30	0.016	7A	±20	1.52
	6B	±20	0.51	7B	±18	2.54
	6D	±18	12.91	7C	±16	10.62
	6F	±17.5	31.66	7D	±15	21.74
	6E	±17	51.57*	7E	±14	32.02
	6C	±15	56.56*	7F	±13	62.03

* Specimens unbroken.

5. *Discussion of Results.*—The results of fatigue tests in air indicate that the fatigue limit particularly in the aluminium bronze, is not reached at an endurance of 50 million cycles, and the values have therefore been recorded as endurance limits on that basis. The endurance limits for the present (9.3 per cent.) aluminium bronze in the heat-treated conditions (about $\pm 11\frac{1}{2}$ ton/in.²) in the quenched and ± 10 ton/in.² in the quenched and reheated condition are considerably lower than that of the (8.9 per cent.) aluminium bronze previously tested in the condition as received (extruded and drawn— $\pm 14\frac{1}{4}$ ton/in.²), although there is little difference in the ultimate stresses.

The fatigue test results in air on the beryllium bronze are interesting. Normally the effect of heat-treatment on a material tested in the polished condition is to increase its fatigue strength almost in proportion to its ultimate tensile stress, the endurance ratio (ratio of fatigue limit to ultimate stress) decreasing slightly as the ultimate stress increases. In the beryllium bronze, however, there is little variation in fatigue strength ($\pm 16\frac{1}{4}$ to $19\frac{1}{2}$ ton/in.²) for a wide variation in ultimate stress from 32 to 81 ton/in.². There is thus a very marked decrease in endurance ratio as the ultimate stress increases. A notch-sensitive material would be expected to behave in this way when a high degree of stress concentration is present, due to a sharp change of form. The reason in the present case may be similar, due to internal stress or to flaws set up during the heat-treatment. No indication was, however, observed of the presence of such flaws. The value of 0.54 for the endurance ratio of this material in the soft state is exceptionally high for a non-ferrous metal.

The log S-log N curves (Figs. 5 to 8) for the corrosion-fatigue tests are, in the case of the aluminium bronze in both conditions and the beryllium bronze in the quenched condition, straight lines, with some very slight initial curvature at endurances below about 2 million in one case (Fig. 5). This agrees with all previous corrosion-fatigue tests at N.P.L. The results on the quenched and reheated beryllium bronze show some scatter, but are probably fairly represented by the curve shown (Fig. 7), having a fairly pronounced curvature up to about 10 million cycles. In neither of the two materials did heat-treatment (either quenching alone, or quenching and reheating) give a corrosion-fatigue endurance limit as high as that of the material in the extruded and drawn condition as received. The endurance ratio of the aluminium bronze does not vary much with heat-treatment over the small range of ultimate stress covered; that of the beryllium bronze, however, as in tests in air, varies widely. In the two heat-treated conditions, the endurance limit in salt spray is about 80 per cent. of that in air, the extruded and drawn condition giving a value 7 per cent. higher than that in air. The small effect of heat-treatment on the corrosion-fatigue resistance is to be expected as the latter is affected more by composition and internal stress than by the ultimate stress or air fatigue limit*. In this case, moreover, as pointed out above, the air fatigue limit also was almost independent of heat treatment.

Table 5 summarises the results of corrosion-fatigue tests on all the materials investigated at the N.P.L.; the ferrous and non-ferrous metals are each arranged in order of corrosion-fatigue resistance. The conclusion reached in the previous paper is not affected by the results of the present tests, viz., that the corrosion-fatigue resistances of the bronzes compare favourably with those of the stainless steels. The value for beryllium bronze, extruded and drawn, is still the highest figure recorded.

Acknowledgments.—The work described above was carried out in the Engineering Division of the National Physical Laboratory, and was completed in 1940. Publication was not considered desirable at that date; the paper is now published (1949) on the recommendation of the Aeronautical Research Council and by permission of the Director of the Laboratory. The author's thanks are due to Messrs. Jas. Booth & Co. (1915), Ltd., for the supply of the materials and to Dr. H. Sutton for the heat-treatment.

* See, for example, Gough, 1932.²

TABLE 5
Summary of Results of Fatigue and Corrosion-Fatigue Tests

Material	Ref. Mark	Ultimate Stress ton/in. ²	Fatigue Limit in Air ton/in. ²	Endurance Limits in Salt Spray ton/in. ²			Stress Ratio†	Endurance Ratios		Ratio of Endurance Limits in Air and Salt Spray
				10 ⁷ Cycles	2 × 10 ⁷ Cycles	5 × 10 ⁷ Cycles		In Air	In Salt Spray	
		<i>T</i>	<i>F_B</i>			<i>f_B</i>		<i>F_B/T</i>	<i>f_B/T</i>	<i>f_B/F_B</i>
<i>Non-ferrous Metals</i>										
Beryllium Bronze as received	HMX	41.8	±16.3	±18.4	±18.0	±17.4	0.92	0.39	0.42	1.07
Beryllium Bronze QR	HMX	81.2	±19.4*	±17.8	±16.8	±15.9	0.85	0.24	0.20	0.82
Beryllium Bronze Q	HMX	32.2	±17.4*	±16.0	±14.8	±13.6	0.79	0.54	0.42	0.78
Superston Bronze	HFP	51.7	±22.7	±18.9	±16.9	±14.6	0.68	0.44	0.28	0.64
Phosphor Bronze	HJO	27.6	± 9.8	±13.7	±12.8	±11.7	0.79	0.35	0.42	1.19
Aluminium Bronze (8.9 per cent.) as received	HNE	35.7	±14.3	±12.8	±11.4	± 9.8	0.68	0.40	0.27	0.68
Aluminium Bronze (9.3 per cent.) Q ..	KDK	36.8	±11.4*	±11.0	± 9.8	± 8.7	0.71	0.31	0.24	0.76
Aluminium Bronze (9.3 per cent.) QR ..	KDK	32.8	± 9.9	± 9.9	± 8.9	± 7.8	0.70	0.30	0.24	0.79
Duralumin	EXA	28.2	± 9.2	± 4.5	± 4.0	± 3.4	0.67	0.33	0.12	0.37
Magnesium Alloy (2.5 per cent. Al) ..	EXB	16.4	± 6.8	± 1.7	± 1.0	—	0.17	0.41	(0.10)	(0.25)
<i>Ferrous Metals</i>										
18/8 Cr.-Ni. Steel	EWZ	66.3	±23.8	±17.5	±16.7	±15.8	0.87	0.36	0.24	0.67
17/1 Cr.-Ni. Steel	FAP	54.5	±32.8	±15.0	±13.8	±12.3	0.76	0.60	0.23	0.38
15 per cent. Cr. Steel	FAO	43.3	±24.8	±11.2	±10.3	± 9.1	0.73	0.57	0.21	0.37
0.5 per cent. C. Steel	EOY	63.2	±25.0	± 5.0	± 3.9	± 2.8	0.44	0.40	0.044	0.11

* Endurance limits—5 × 10⁷ cycles.

† For tenfold increase of endurance.

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- | <i>No.</i> | <i>Author</i> | <i>Title, etc.</i> |
|------------|-------------------------------|---|
| 1 | H. J. Gough | Corrosion-fatigue of Metals. <i>J. Inst. Met.</i> 49, p. 39. (1932.) |
| 2 | H. J. Gough and D. G. Sopwith | Some Comparative Corrosion-fatigue Tests Employing Two Types of Stressing Action. <i>J.I. & S. Inst.</i> 127, p. 301. (1933.) |
| 3 | H. J. Gough and D. G. Sopwith | The Resistance of some Special Bronzes to Fatigue and Corrosion-fatigue. <i>J. Inst. Met.</i> 160, p. 143. (1937.) |
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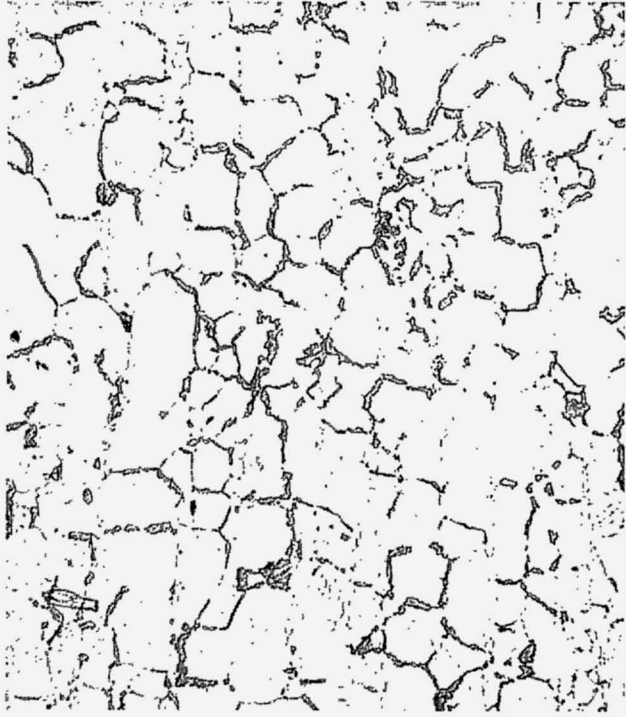


FIG. 1. Specimen HMX 3J. Quenched and Reheated.

Beryllium Bronze—Etched in Alcoholic Ferric Chloride $\times 150$.



FIG. 2. Specimen HMX 6J. Quenched.



FIG. 3. Specimen KDK 3G. Quenched and Reheated.

Aluminium Bronze—Etched in Alcoholic Ferric Chloride $\times 150$.

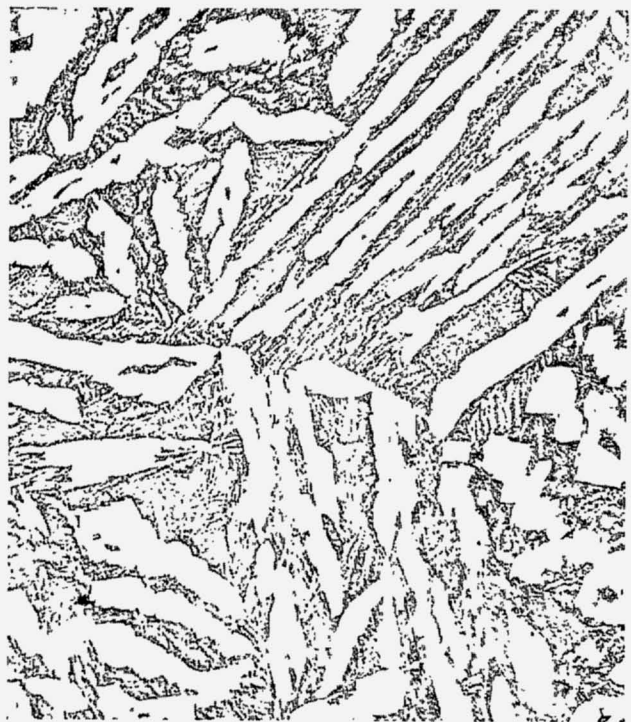


FIG. 4. Specimen KDK 6C. Quenched.

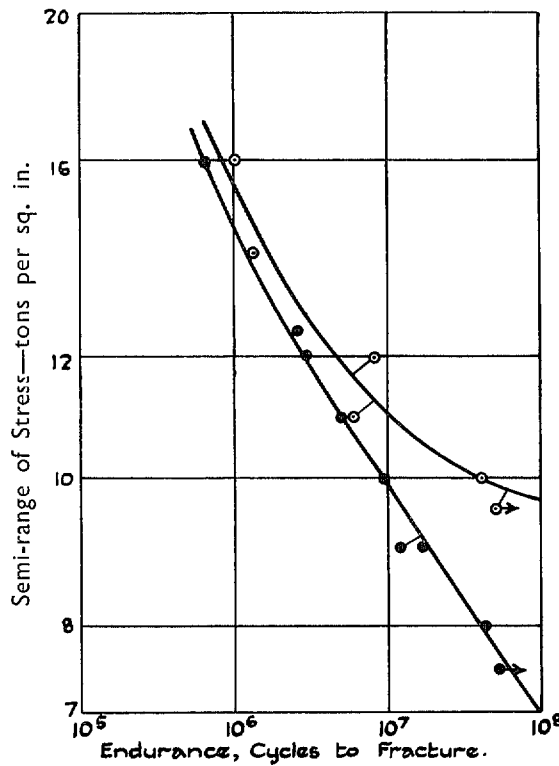


FIG. 5. Aluminium Bronze—Quenched and Reheated.

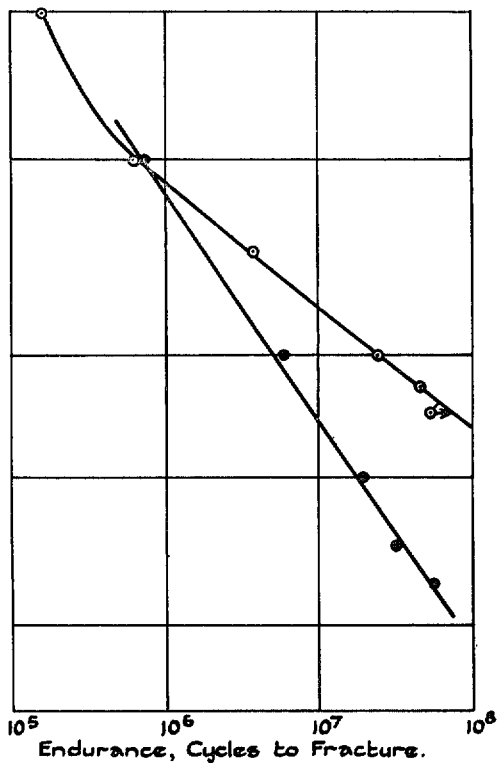


FIG. 6. Aluminium Bronze—Quenched.

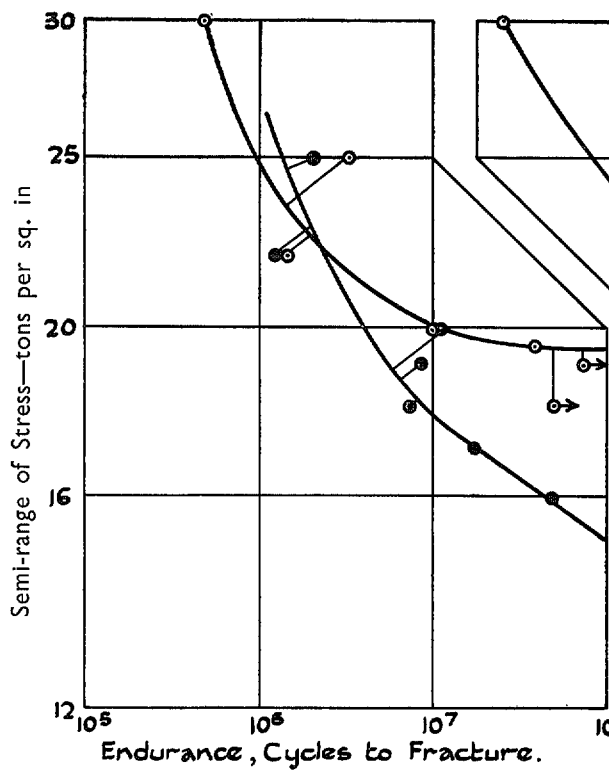


FIG. 7. Beryllium Bronze—Quenched and Reheated.

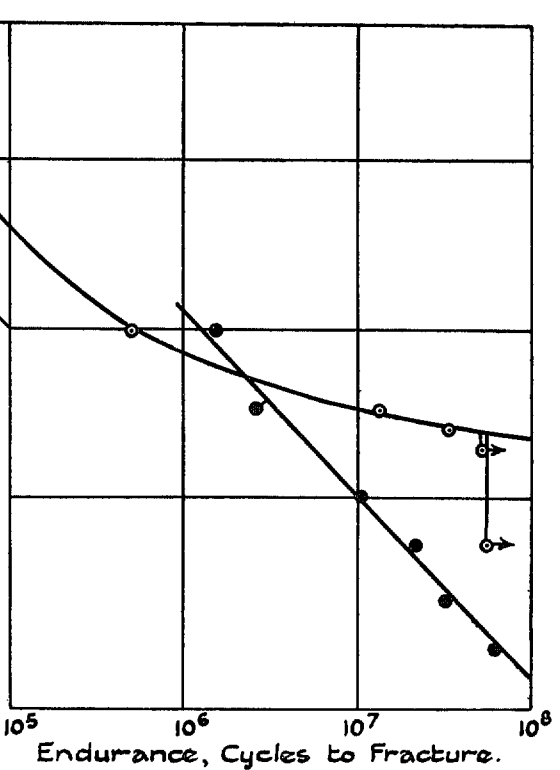


FIG. 8. Beryllium Bronze—Quenched.

———→ Specimen unbroken.
 —○— Tests in air.
 —●— Tests in salt spray.

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