THE SPRING RESEARCH ASSOCIATION

THE FATIGUE PROPERTIES OF BERYLLIUM-COPPER STRIP

by

S. D. Gray, A.P.(Sheff), A.I.M.

Report No. 205

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SUMMARY

Fatigue tests have been carried out on three sizes of half hard and tempered (aged) nominal 2% beryllium-copper strip, namely 0.25 mm (0.010 in), 0.50 mm (0.020 in) and 0.9 mm (0.037 in), to compare the effect of strip thickness on fatigue properties, and to compare the general performance with that reported in published data. S/N curves have been produced for zero and 300 N/mm^2 (19.4 tonf/in^2) initial stresses, enabling the construction of modified Goodman diagrams. Data on the S/N curves have been statistically analysed allowing best fit (50% confidence) and 95% confidence lines to be plotted.

At zero initial stress the three sizes possessed almost identical fatigue properties, however, increases in initial stress resulted in a divergence of fatigue properties, until at 1000 N/mm^2 (64.7 tonf/in^2), the 0.5 mm strip revealed the highest fatigue strength. Approximate data obtained by extrapolation indicated that the material under examination was as good as, and in some cases better than, that publicised in the literature for reverse bending conditions.

(August 1972)

CONTENTS

Page No.

CONTENTS cont.

9. Figures

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1. INTRODUCTION

Beryllium-copper is the most expensive of all the common copper alloys currently being used for springs, and in recent years has found increasing engineering applications because of its high strength and hardness combined with good conductivity and corrosion resistance. Beryllium-copper is a precipitation hardening alloy and may therefore be cold formed into springs in its softer conditions and subsequently heat treated between 320 and 350°C to produce the optimum mechanical and fatigue properties.

In the form of strip, such alloys are used in the manufacture of diaphragms, bellows, clips and contacts; however, despite the fact that such materials have been used commercially for many years, very little information is available on the fatigue properties of thin strip. A programme of research was therefore drawn up by The Spring Research Association, on behalf of Johnson-Matthey and Company Limited, Hatton Garden, London EC1, and their associate Mallory Metallurgical Products Ltd., Exhibition Grounds, Wembley, to compare the fatigue properties of nominal 2% Be-Cu strip in three thicknesses, namely 0.9 mm (0.037 in), 0.5 mm (0.020 in) and 0.25 mm (0.010 in).

2. MATERIALS

Beryllium-copper strip specimens, 0.25 mm, 0.5 mm and 0.9 mm thick, approximately 50 mm in length and 17.5 mm wide were supplied by Mallory Metallurgical Products, having been subjected to the following processes:-

(a) Cold rolled to half-hard condition
(b) Heat treated for two hours at 335°C
(c) Process pickled to remove scale

Prior to testing each specimen was checked for surface damage, the sheared edges were then polished and the whole thoroughly cleaned.

The chemical compositions of the strip are given in Table I.

3. EXPERIMENTAL PROCEDURE

3.1 Load Testing

Fatigue testing was carried out on a strip fatigue testing rig, recently designed, developed and thoroughly tested by the Association, for accurately fatigue testing thin strip of less than 0.25 mm (0.010 in), bending one side of zero (Fig. 1).

In essence, specimens were held at each end by two smooth grips suitably radiused to prevent fretting. Having adjusted the grips to a gauge length of 30 mm, the whole was then vertically load tested to establish the necessary deflection to give the required stress.

3.2 Fatigue Testing

Following specimen calibration the unit was positioned in one station of an eight station forced motion multiple spring testing machine (Fig. 2).

3.3 Mechanical Testing

Full tensile data were produced for each of the conditions tested, and the results are recorded in Table III.

The strips were then fatigue tested at two initial stress levels of zero and 300 N/mm^2 (19.6 tonf/in^2). It will be noted that 0.9 mm strip was only tested at zero initial stress level as this was a preliminary test prior to testing the more important smaller gauges. By varying the stress range applied to each specimen the endurance could be measured and used to construct S/N curves, Figs. 3, 4 and 5. Results from the broken strips were analysed statistically to provide the appropriate regression lines for 95% and 50% confidence.

4. DISCUSSION AND RESULTS

4.1 Fatigue Strength

From Fig. 6 it can be seen that all three sizes of Be-Cu strip possessed very similar fatigue properties for 10^7 cycles at zero initial stress, the 0.25 mm and 0.5 mm strip having identical strengths at 580 N/mm^2 (37.6 tonf/in^2) with the 0.9 mm showing 630 N/mm^2 (40.8 tonf/in^2). An increase in the initial stress caused a gradual divergence of Goodman diagrams, the 0.5 mm strips showing superior properties, at higher initial stress levels. Limited life data showed the results for 10^6 and 10^7 cycles to be the same; however, 10^5 cycles revealed a marked separation in properties at zero initial stress with the previously observed divergence at higher initial stress levels. One unusual feature observed was the high fatigue strength of 0.9 mm strip at zero initial stress, and in an attempt to justify this occurrence further properties are discussed later.

In order to place the resultant properties in perspective, it would be necessary to determine the fatigue properties under reverse bending conditions; however, to do this further research into testing rigs would be required. An approximation of the reverse bending stresses can be achieved, however, by extrapolating the existing Goodman diagrams to produce a schematic stress relationship diagram, and whilst not an acceptable method for predicting working stresses due to possible errors, it gives an indication of how the range of permissible stress variation changes as the maximum value of stress decreases. Hence by this method it was possible to obtain a comparison between results obtained and those published in related literature.

From Fig. 7 it can be seen that a reverse bending (zero mean) fatigue stress for 0.25 and 0.5 mm Be-Cu strip, of ±380 N/mm^2 (24.6 tonf/in^2) can be obtained, AB and BC, as opposed to DE and EF for 0.9 mm of ±430 N/mm^2 (27.8 tonf/in^2). Table II lists the fatigue and mechanical properties of nominal 2% Be-Cu strips for 10^7 and 10^8 cycles, and it can be observed that all the materials tested in this investigation showed superior properties with higher fatigue strengths ranging from 5.3 N/mm^2 (3.4 tonf/in^2) to 10.2 N/mm^2 (6.6 tonf/in^2), when compared with the only available 10^7 cycles data(1). A general comparison with the remaining data in Table II at 10^8 cycles, would again tend to suggest that the material under investigation was still superior(2)(3).

4.2 The Effect of Chemical Composition on Mechanical and Fatigue Properties

Of the three standard commercial Be-Cu alloys, i.e. 2%, 0.4% and 1% Be, the nominal 2% Be is the most common. In proprietary materials the beryllium content may range from about 1.5% to as much as 2.7%, depending on the properties desired and the ultimate service condition.

Although other additions such as cobalt and nickel are added to control precipitation, beryllium is the most influential element, affecting the mechanical properties quite markedly. Compositions ranging from 1.6 to 2.0% Be for half-hard and tempered strip have revealed changes of 224 N/mm^2 (14.5 tonf/in^2) in U.T.S.$^{(1)}$ Additions of Be in excess of 1.92% have little effect on the mechanical properties and in excess of 2%, may adversely affect the microstructure of the material.

The beryllium content of the materials under investigation ranged from 1.72 to 1.83% and consequently for identical heat treatments have resulted in mean UTS values of 1293 and 1321 N/mm^2 (83.7 and 85.5 tonf/in^2) respectively, with corresponding differences in proof stress data (Table III).

Although changes in tensile strength are evident, Table IV showed the hardness values to be relatively constant before and after ageing on all three sizes of material.

The effect of beryllium content on the fatigue properties is not so marked as that on tensile strength; changes of less than ± 48 N/mm^2 (3.1 tonf/in^2) have been recorded for contents from 1.6 to 1.7% Be and 1.92 to 2% Be.$^{(1)}$

4.3 Maximum Permissible Operating Stress

Static bend tests carried out on all three sizes of strip indicated that signs of plastic deformation began to occur when specimens were subjected to an approximate bending stress of 1300 N/mm^2 (84.2 tonf/in^2), which is approximately the UTS of the material, and thus it can be concluded that design limitations should be based on the ultimate tensile strength and not proof stress data.

4.4 The Effect of Grain Size

Grain size in cold worked copper alloys has an important effect on static working stress, formability and surface condi~~tion~~, and directly influences the ~~fatigue~~ properties of copper base materials.

Grain size is controlled by the rolling mill process and final anneals, and is specified according to average grain diameter in millimetres.

Fig. 8 shows the structure of the 0.9 mm specimens in the longitudinal and transverse direction at magnifications of x 100 and x 400. Examination will reveal the large variation in grain size from 0.005 mm to 0.075 mm diameter, with a mean reading of 0.0185 mm (Table V). Although variations in grain size are not uncommon, such large variations should be avoided if possible, especially where fatigue properties are important. The microstructures illustrated show an α solid solution with fine particles of γ precipitated within the grains. Larger precipitates observed were merely those of cobalt-beryllium, the excess Co having affinity for Be.

Fig. 9 shows the microstructures of 0.5 mm strip, the greater degree of work hardening resulting in a much higher concentration of mechanical twins. A mean grain size of 0.019 mm diameter was recorded, but as observed the grain size variation was not so acute, being 0.005 to 0.05 mm.

A similar grain size variation was observed for 0.25 mm strip, 0.005 to 0.07 mm; however, the average size was slightly less at 0.0155 mm (Fig. 10).

In general grain sizes of the order of 0.025 mm are obtained and found acceptable for Be-Cu strip, and this would explain the better properties of all the materials under test, which had a much smaller grain size.

Results from this investigation have not clearly indicated why the largest strip size should possess the most superior fatigue properties at zero initial stress level, further work is therefore necessary.

5. CONCLUSIONS

1. At zero initial stress the fatigue properties of 0.25, 0.5 and 0.9 mm beryllium copper strip are almost identical.

2. With increasing initial stress, 0.5 mm strip showed superiority in fatigue properties.

3. Approximate reverse bending zero mean stress data obtained by extrapolation showed the material under test to possess higher fatigue strengths, in the order of 5.3-6.6 N/mm^2, than those indicated in general non-ferrous literature.

4. Bend tests at very high maximum stress levels have indicated that the limiting design parameter for springs made from Be-Cu strip is not the tensile elastic limit, but the actual tensile strength.

6. RECOMMENDATIONS

1. The surface condition of thin Be-Cu strip will directly influence the fatigue properties, thus various thicknesses of strip should be tested with following surface conditions:-

   (a) Highly polished

   (b) Shot peened with steel shot

   (c) Shot peened with glass beads

   (d) Shot peened with alumina

2. The need for a fine uniform grain size is paramount for superior fatigue properties, and thus the effect of grain size should be examined.

3. Due to the increasing demand for thin strip, smaller sizes such as 0.012 mm (0.005 in) should be tested.

7. REFERENCES

1. "The Mechanical Properties of Copper Beryllium Alloy Strip" A.S.T.M. Special Tech. Pub. No. 367.

2. "Beryllium-Copper"
Copper Development Association Publication No. 54.

3. "Beryllium Copper"
Kawecki Berylco Industries, Tech. Pub. 304 2 - TD 40.

TABLE I **CHEMICAL COMPOSITION OF BE-CU STRIP**

STRIP THICKNESS	CHEMICAL COMPOSITION %										
	Be	Co	Fe	Si	Al	Bi	Pb	Sn	Zn	Ni	Cu
0.25 mm	1.83	0.21	0.09	0.12	0.04	0.001	0.002	0,005	0.001	0,005	Bal
0,5 mm	1.72	0,19	0.09	0.09	0.06	0.001	0,002	0.001	0.002	0.005	Bal
0.9 mm	1.78	0.19	0.08	0.13	0.05	0.001	0.002	0.001	0.002	0.200	Bal

TABLE II

COMPARATIVE DATA FOR HALF HARD BE-CU STRIP
(REVERSE BENDING R = -1)   AGED AT 330°C

REFERENCE	% BERYLLIUM	FATIGUE STRENGTH		CYCLES	U.T.S.		PROOF STRESS		ELONGATION %	FATIGUE RATIO	SPECIMEN THICKNESS	
		N/mm^2	$tonf/in^2$		N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$			mm	in
1	1.80 (Actual)	327 297	21.2 19.2	10^7 10^8	1316	85.2	1188 (0.2%)	76.9 (0.2%)	4.6	0.248 0.23	0.8	0.032
2	2.0 (Nominal)	256	16.6	10^8	1382	89.5	1236 (0.1%)	80.0 (0.1%)	5.5	0.19	-	-
3	2.0 (Nominal)	287	17.9	10^8	1310	84.8	1186 (0.2%)	76.8 (0.2%)	-	0.21	-	-

TABLE III

TENSILE DATA FOR BE-CU STRIP

STRIP THICKNESS	U.T.S.		PROOF STRESS						ELONGATION % (On 2 in G.L.)
			0.1%		0.2%		0.5%		
	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	
0.25 mm strip (1)	1341	87.0	1125	73.0	1203	78.0	1280	83.0	3
0.25 mm strip (2)	1311	85.0	1095	71.0	1172	76.0	1265	82.0	5
0.25 mm strip (3)	1311	85.0	-		-		-		3
0.50 mm strip (1)	1302	84.5	1110	72.0	1158	75.0	1241	80.5	4
0.50 mm strip (2)	1289	83.5	1050	68.0	1141	74.0	1218	79.0	5
0.50 mm strip (3)	1289	83.5	1080	70.0	1158	75.0	1218	79.0	3
0.90 mm strip (1)	1250	81.0	1050	68.0	1095	71.0	1172	76.0	4
0.90 mm strip (2)	1258	81.5	1032	67.0	1111	72.0	1202	78.0	5
0.90 mm strip (3)	1265	82.0	1065	69.0	1111	72.0	1202	78.0	4

TABLE IV VICKERS HARDNESS TESTS ON BE-CU STRIP

STRIP THICKNESS	HARDNESS VICKERS	
	BEFORE AGEING	AFTER AGEING
0,25 mm	217 (HV 2,5)	394 (HV 5)
0,50 mm	216 (HV 5)	397 (HV 10)
0.90 mm	218 (HV 5)	392 (HV 10)

TABLE V GRAIN SIZE OF BE-CU STRIP

STRIP THICKNESS	GRAIN SIZE (mm)*
0,25 mm	0,0155 (0,005 - 0,07)
0,50 mm	0,0190 (0.005 - 0.05)
0,90 mm	0.0185 (0,005 - 0.075)

* The results recorded are a mean of measurements taken from the x, y and z axes of the material. The figures shown in brackets give an indication of the grain size variation.

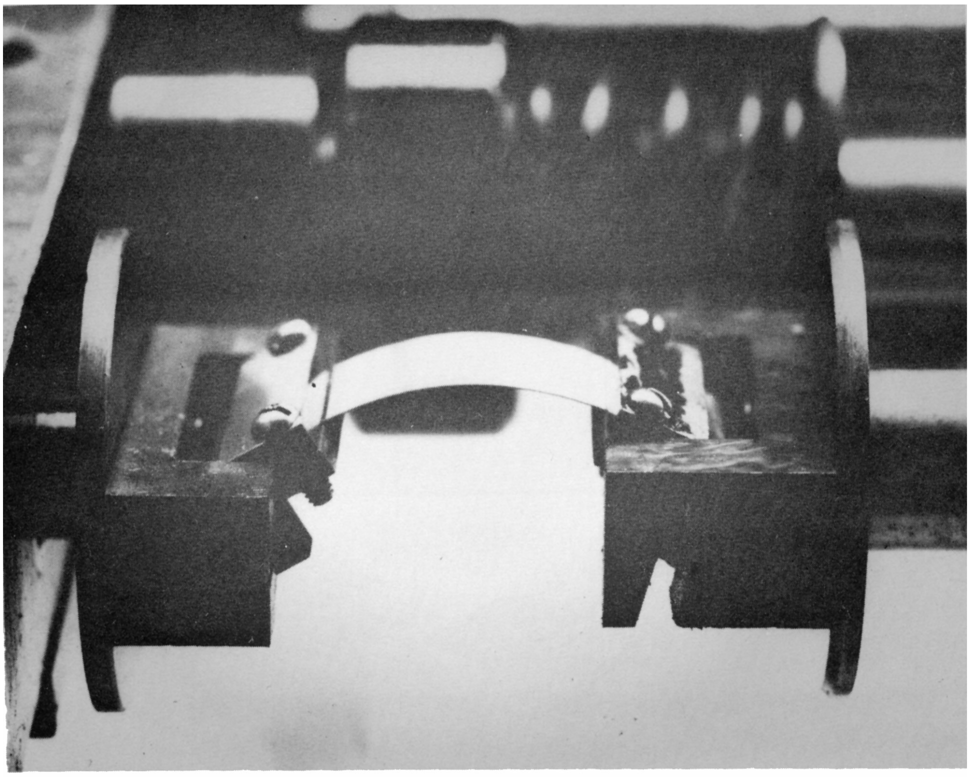


FIG. 1 STRIP FATIGUE TESTING RIG

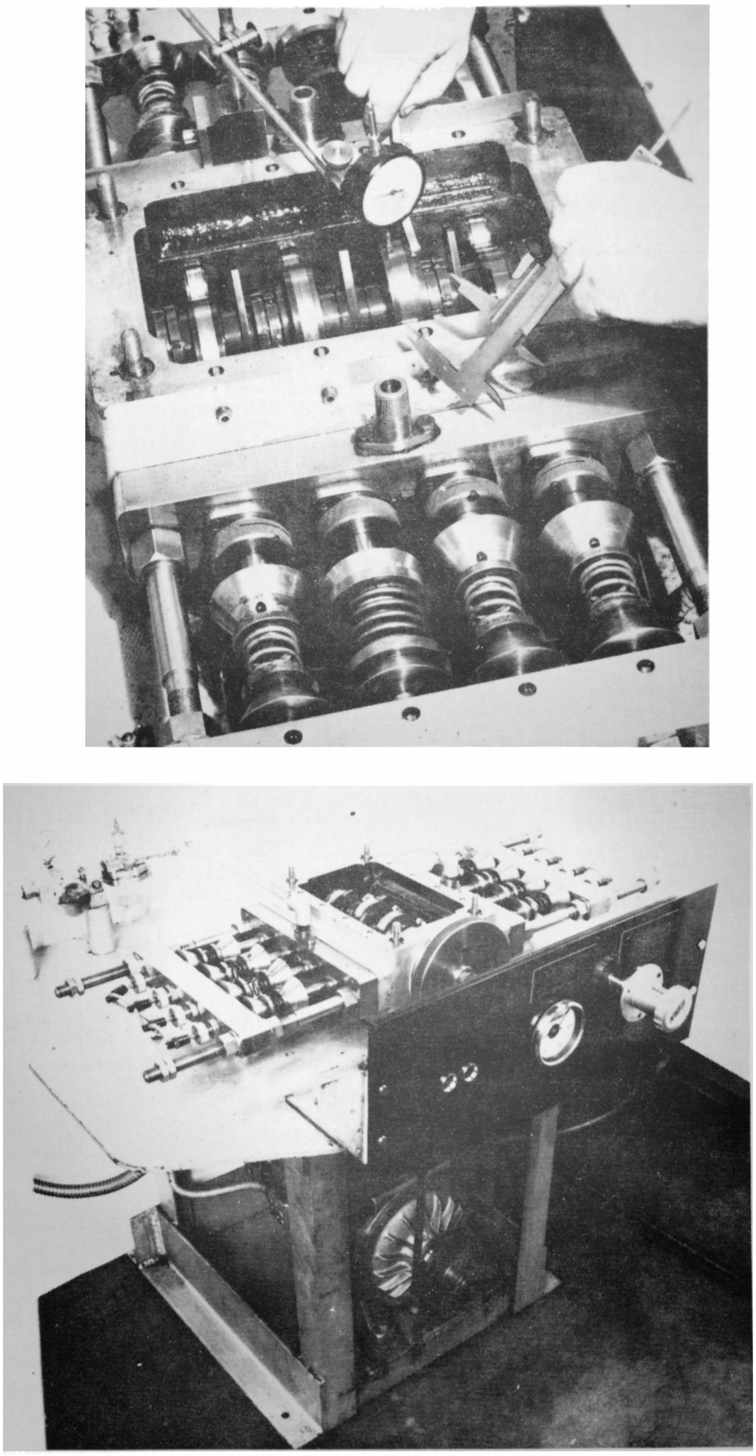


FIG. 2 FORCED MOTION MULTIPLE SPRING TESTING MACHINE

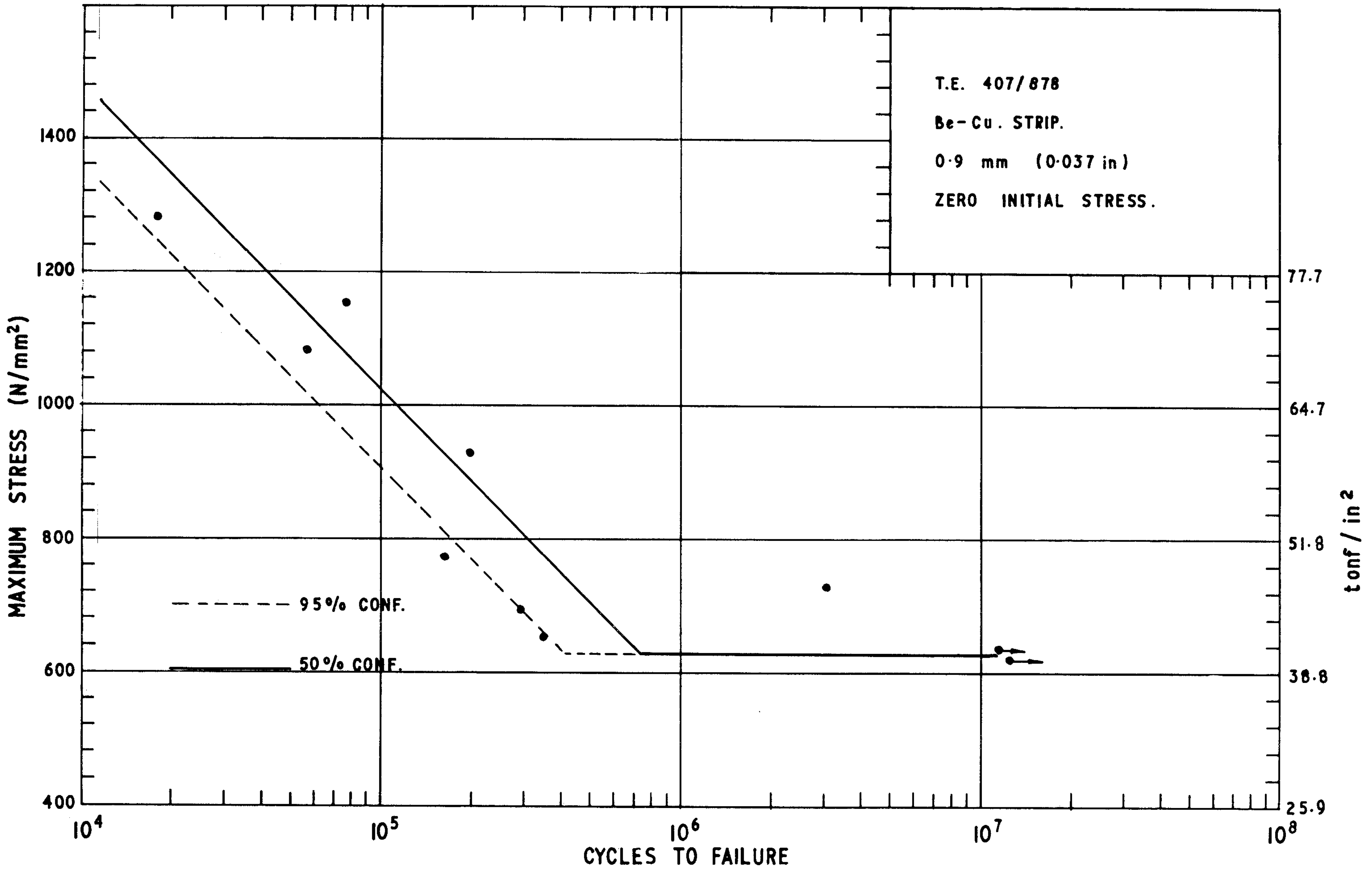


FIG. 3 S/N CURVE FOR 0·9 mm Be - Cu STRIP.

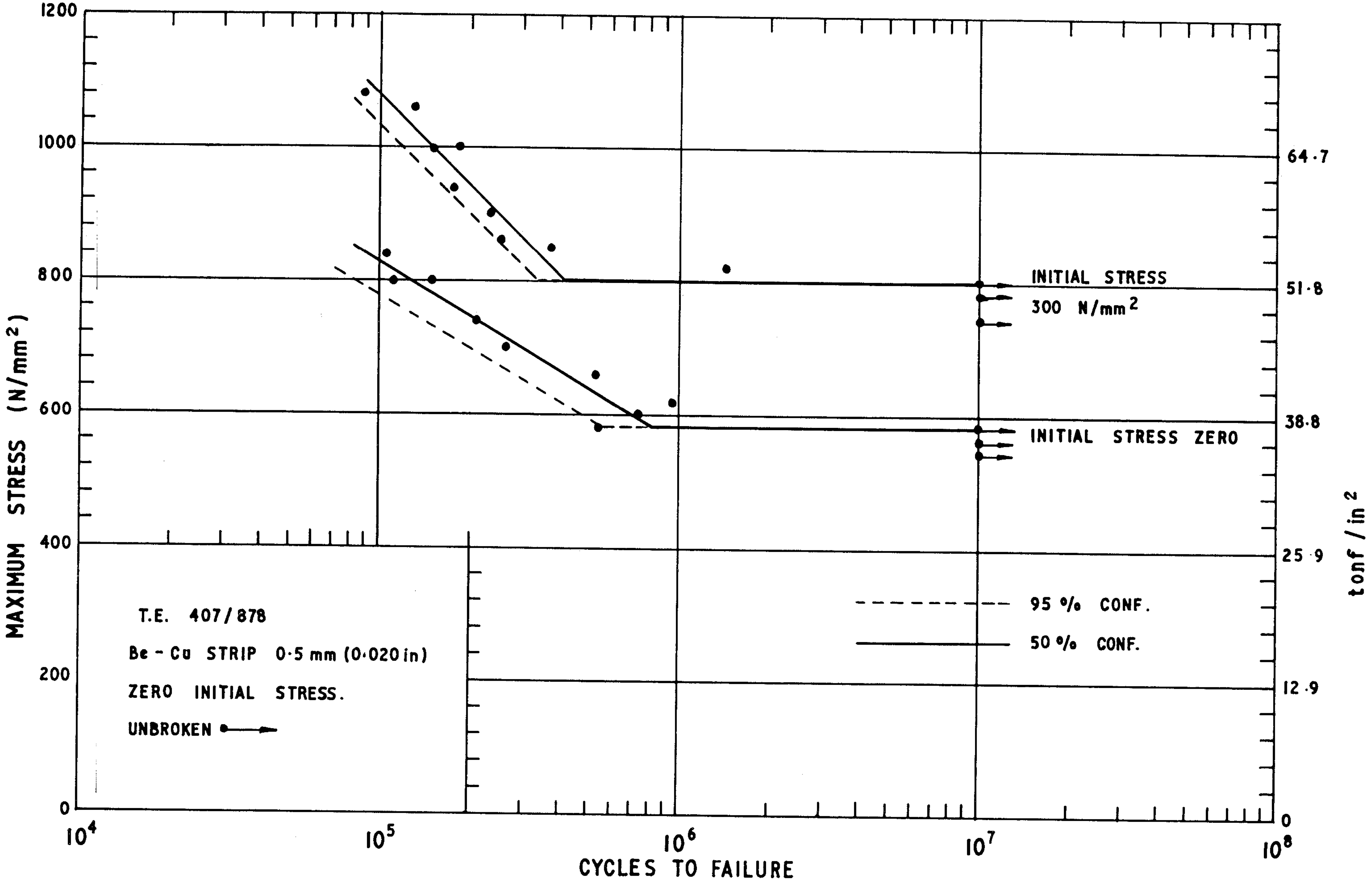


FIG. 4 S/N CURVE FOR 0·5 mm Be - Cu STRIP.

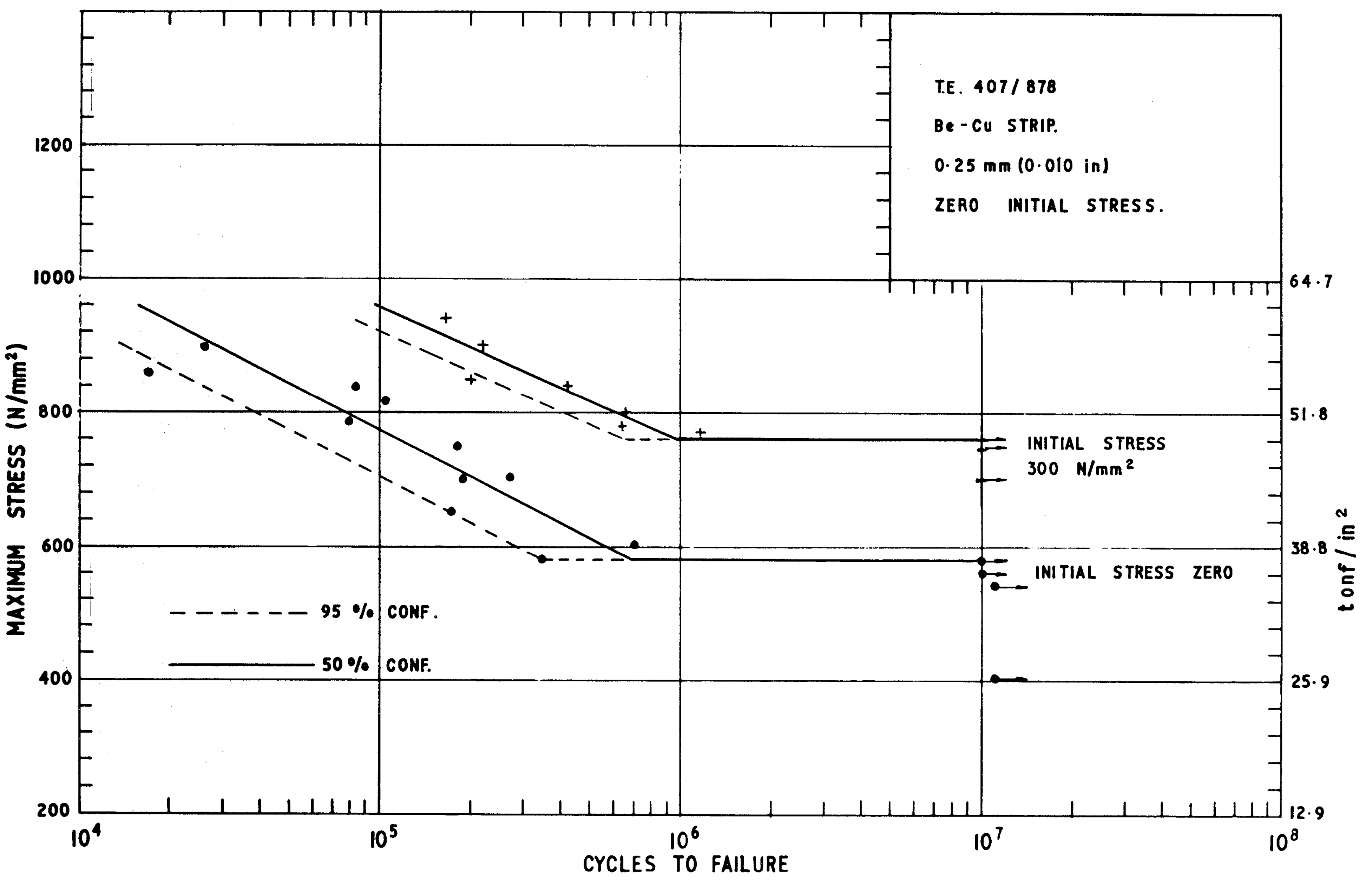


FIG. 5 S/N CURVE FOR 0·25 mm Be-Cu STRIP.

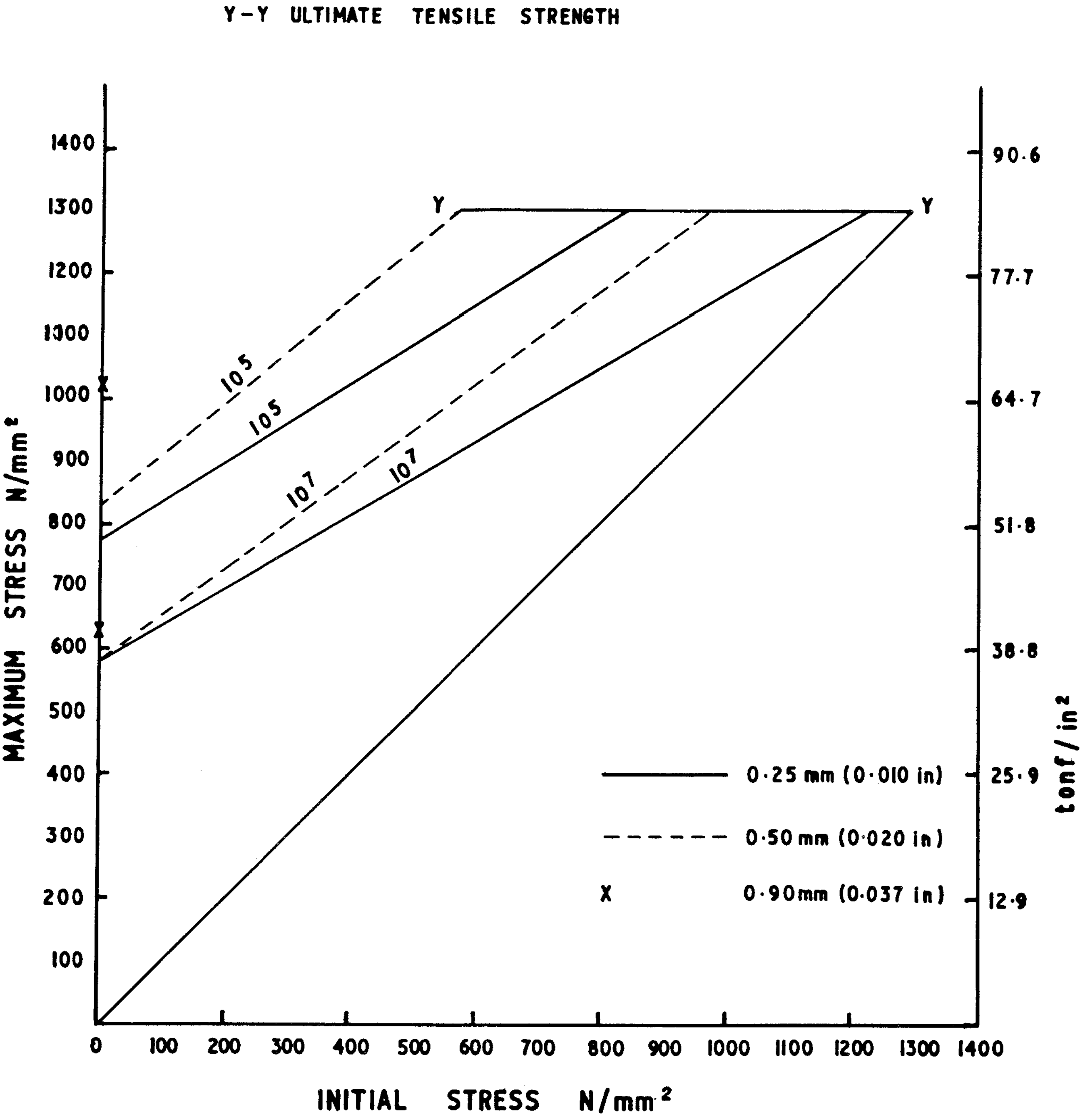


FIG. 6 MODIFIED GOODMAN DIAGRAMS FOR Be-Cu STRIP. (50 % CONFIDENCE)

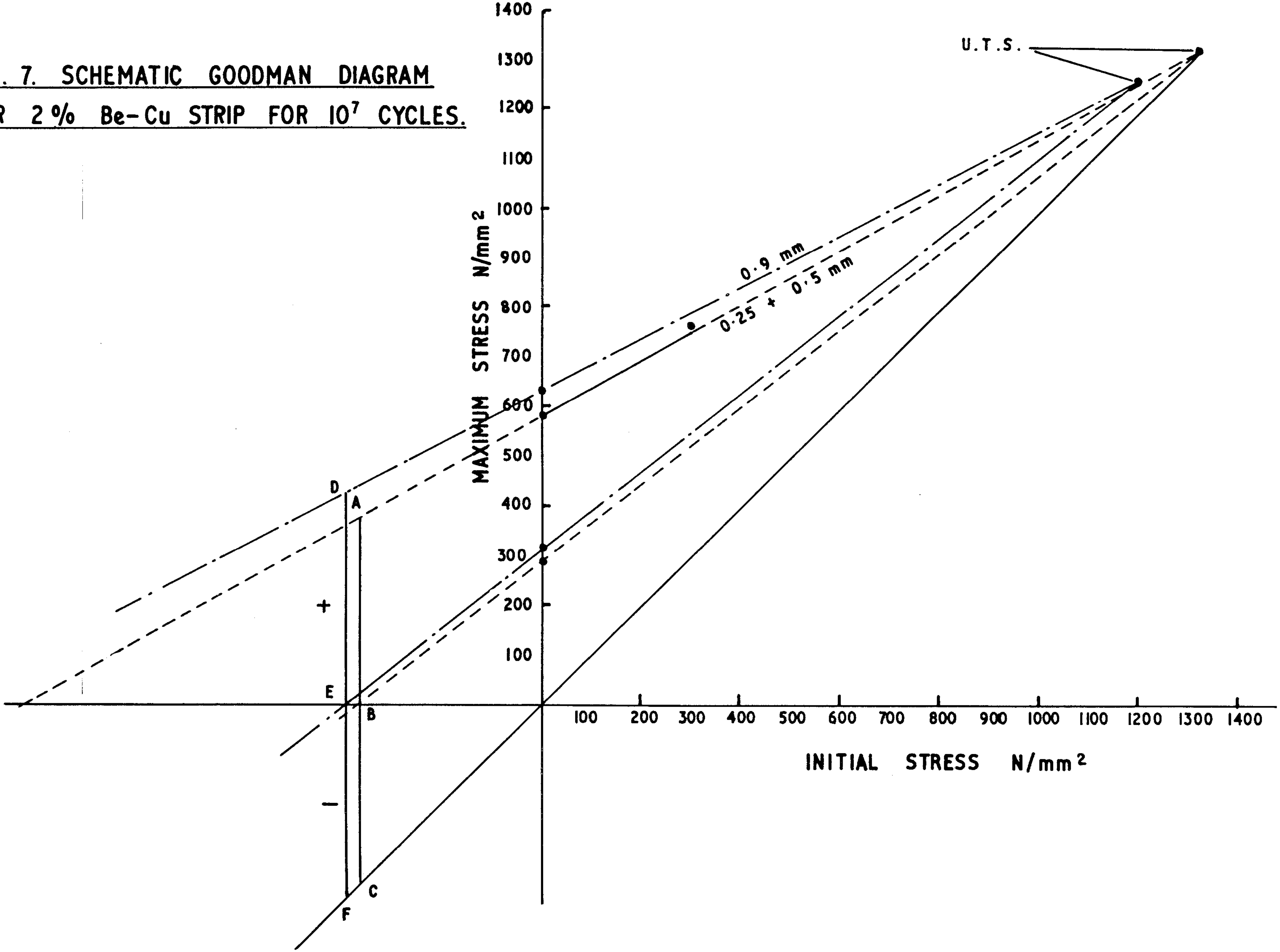
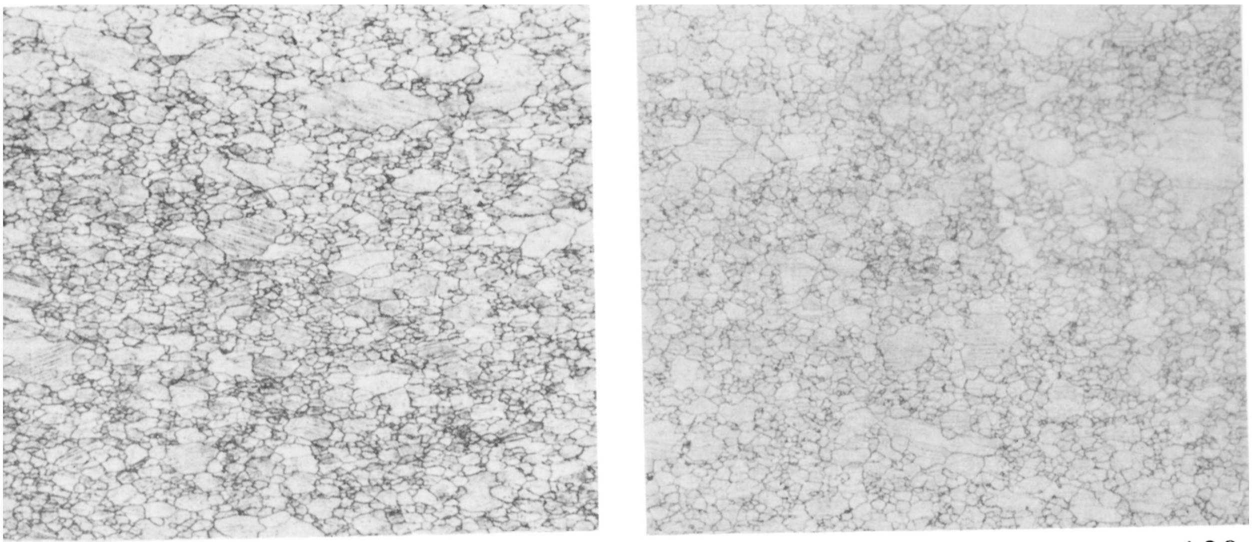
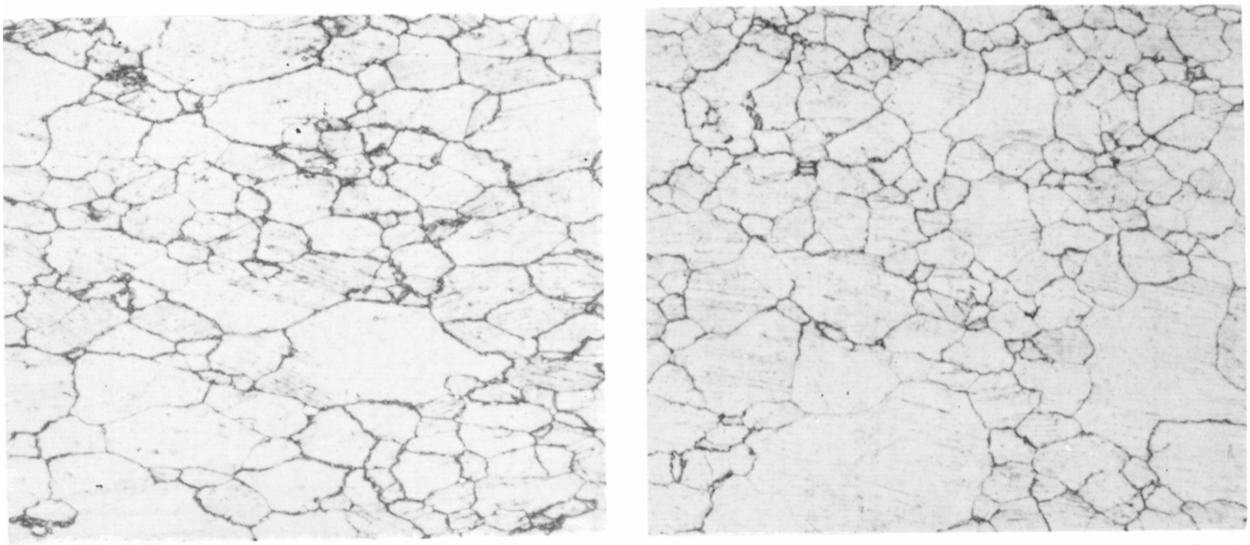


FIG. 7. SCHEMATIC GOODMAN DIAGRAM FOR 2% Be-Cu STRIP FOR 10^7 CYCLES.

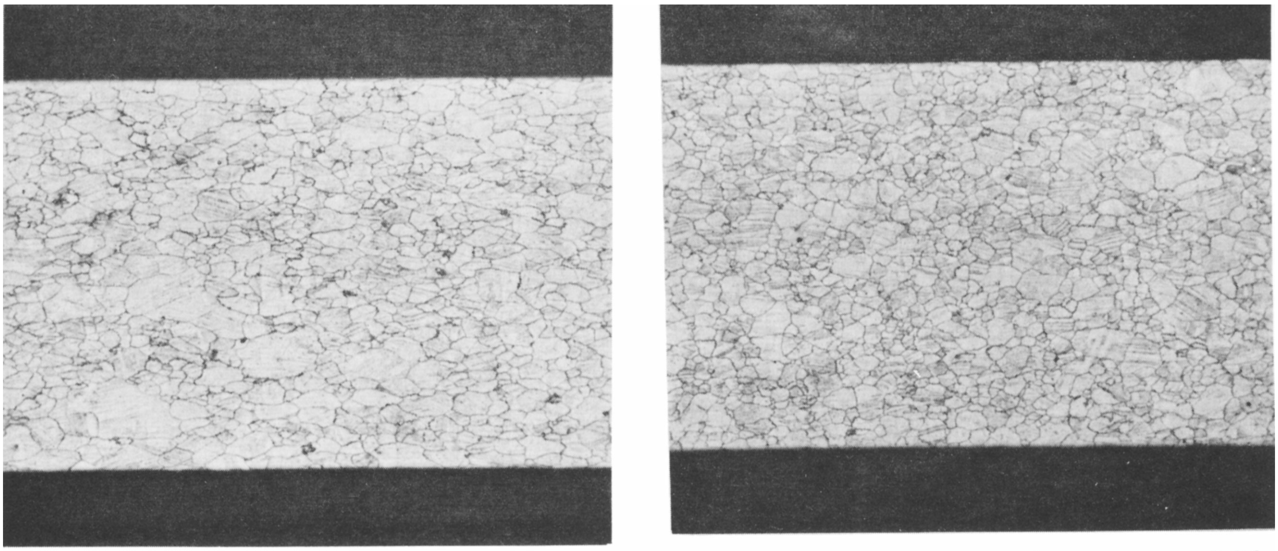


a Longitudinal Section x 100 b Transverse Section x 100

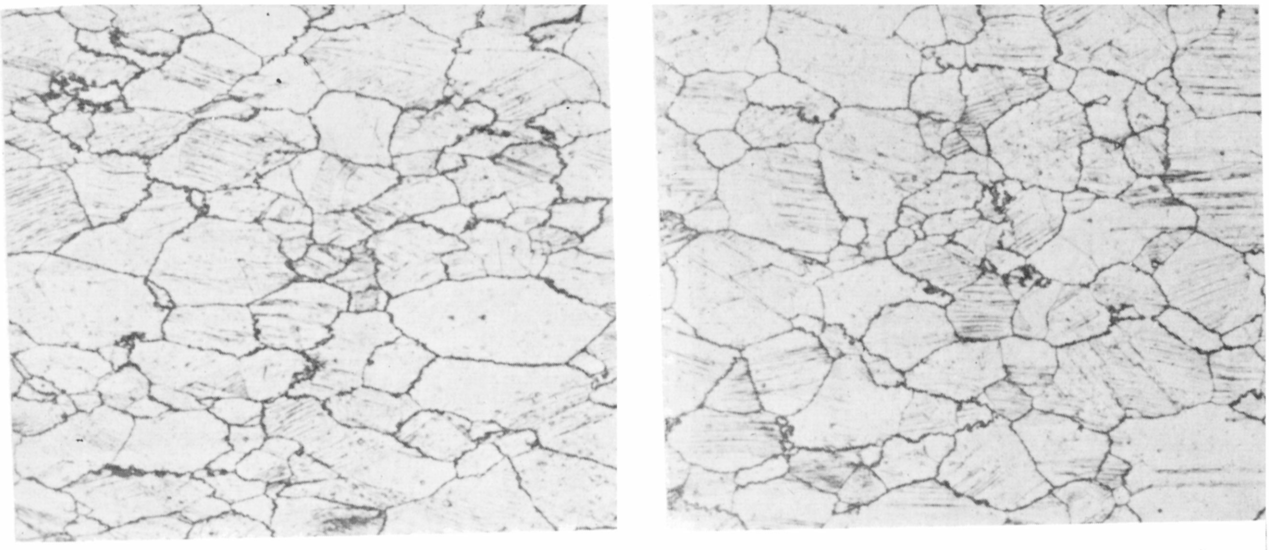


c Longitudinal Section x 400 d Transverse Section x 400

FIG. 8 MICROSTRUCTURE OF 1.78% BE-CU STRIP 0.9 mm (0.037 in)
ETCHANT FERRIC CHLORIDE

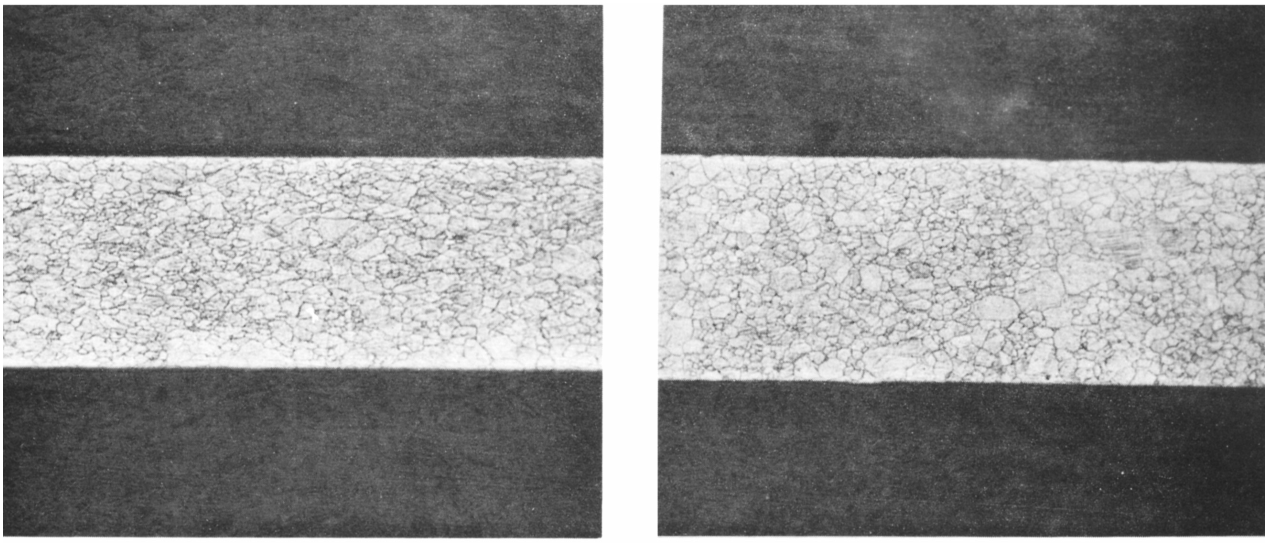


a Longitudinal Section x 100 b Transverse Section x 100



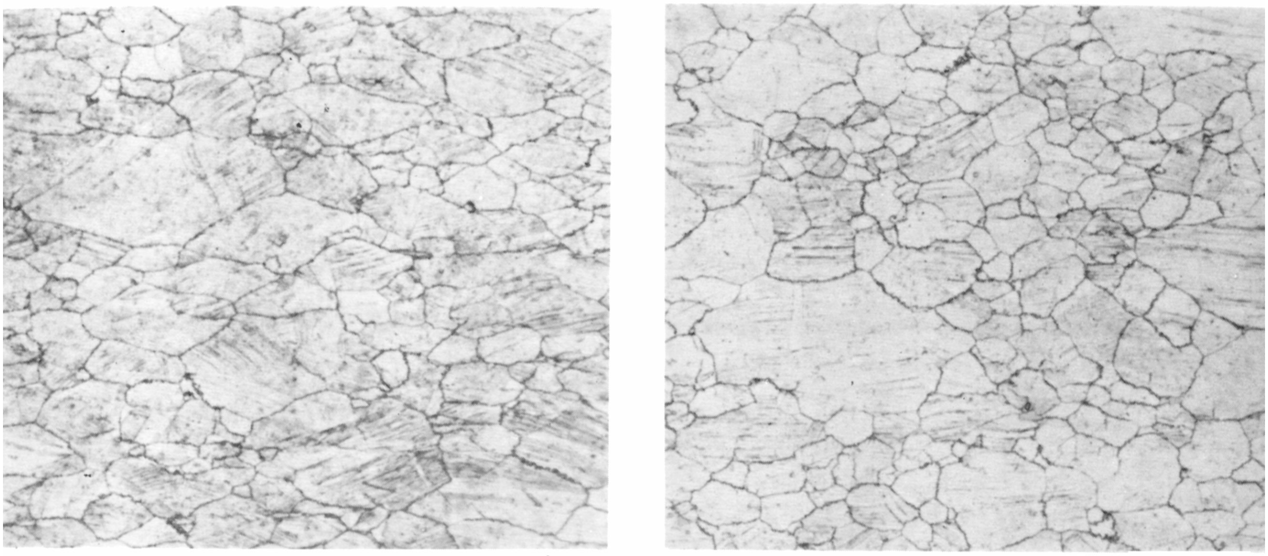
c Longitudinal Section x 400 d Transverse Section x 400

FIG. 9 MICROSTRUCTURE OF 1.72% BE-CU STRIP 0.5 mm (0.020 in)
ETCHANT FERRIC CHLORIDE



a Longitudinal Section x 100

b Transverse Section x 100



c Longitudinal Section x 400

d Transverse Section x 400

FIG. 10 MICROSTRUCTURE OF 1.83% BE-CU STRIP 0.25 mm (0.010in)
ETCHANT FERRIC CHLORIDE