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THE ELASTIC PROPERTIES
OF METALLIC ALLOYS

*par M^Mrs. R. Cabarat, L. Guillet
et R. Le Roux*

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THE ELASTIC PROPERTIES OF METALLIC ALLOYS.*

1162

By R. CABARAT,† PROFESSOR L. GUILLET,‡ and R. LE ROUX.§

(Translated by H. W. L. PHILLIPS, M.A., MEMBER.)

SYNOPSIS.

The object of this investigation was to study the effect of constitution on the elastic modulus and logarithmic decrement in copper-tin and copper-zinc alloys. The method employed consisted in setting up by electrostatic means longitudinal vibrations in the specimens, thereby submitting them to very small strains at a high frequency, all measurements being made in free air. In the two systems, the δ and γ phases, which have multi-atomic cells, are shown to have high moduli of elasticity with low values for the internal friction, whereas the curve showing the relationship between the latter property and the composition shows maxima for the phases β (body-centred cubic) and ϵ (hexagonal). Changes of the decrement with composition follow closely those of the electrical conductivity. The experimental data are discussed in the light of current theory.

I.—INTRODUCTION.

MEASUREMENTS of physical properties have often been used to obtain confirmation of the constitution of alloy systems as determined by thermal analysis or crystallographic methods. Little use has, however, been made of the elastic properties in this connection. In the case of brittle alloys, experimental difficulties are very great, and the majority of investigators have limited their work to a study of the changes occurring in solid solutions. For example, Chevenard and Portevin¹ showed that, at constant temperature, the modulus of elasticity varied linearly with the chemical composition, while the internal friction, as estimated by the logarithmic decrement of the decay of the amplitude of the vibration, varied in a manner similar to that shown by the electrical conductivity. In 1936, one of the authors,² using a dynamic method due to Le Rolland and Sorin,³ showed that exceptionally high values of the elastic modulus were reached in the case of certain inter-metallic compounds of which the structure had been established, and these results were later confirmed by the work of Köster⁴ and by that of Druyvesteyn and Meyering.⁵ Very recently, in 1946, the present

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Some years ago, one of the authors, working in the Testing Laboratory of the Conservatoire National des Arts et Métiers, developed a new apparatus for determining the elastic properties, complying fully with these requirements, in which the test-piece was submitted to longitudinal vibrations produced electrostatically.¹² The chief object of the present investigation was to show that this apparatus could be used in correlating changes in the elastic properties with constitution. The alloys of copper with tin and of copper with zinc were chosen for study because their constitution is now sufficiently well established.

where σ = Poisson's ratio, z = number of half wave-lengths in the whole rod, r = radius of rod, L = length of rod. Taking a value of 0.37 for Poisson's ratio, it can be shown that for test-pieces of dimen-

sions used in this research $(1 + e)^2 = 1.0086$ approximately. Thus the error introduced by neglecting the Rayleigh correction is extremely small. Boyle and Sproule¹⁴ have shown that an additional correction may be needed to cover the effect of coupling between the longitudinal waves in the rod and the transverse waves which they engender. The correction, however, is negligible if $\frac{2\nu}{L}$ does not exceed 0.55, a condition which is met in the case of rods of the dimensions given vibrating in the fundamental mode. Stokes¹⁵ has shown that the velocity of propagation is lowered by internal friction, the formula being :

$$V = \sqrt{\frac{E}{d} - \left[\frac{4}{3}(1 + \sigma) \frac{n\pi}{d\lambda} \right]^2}$$

where n is the coefficient of internal friction. Here again, for the frequency used, the correction is negligible. Röhrich¹⁶ has taken thermal conductivity into account, and has shown that an adiabatic modulus E' should be used in the formulæ, related to E by the expression :

$$\frac{E}{E'} = 1 - \frac{\alpha^2 T E}{dc}$$

where α = linear coefficient of expansion, T = absolute temperature, and c = specific heat at constant pressure. The correction is again very small.

If the test-piece, of length L , is vibrating at a frequency F_0 , with a node at the middle, the wave-length λ is given by the expression :

$$\lambda = 2L = \frac{V}{F_0} \quad \dots \dots \dots (2)$$

Combining equations (1) and (2) :

$$E = (2F_0 L)^2 d \quad \dots \dots \dots (3)$$

In the apparatus shown diagrammatically in Fig. 1, a cylindrical test-piece 140 mm. long and 8-12 mm. in dia. is held vertically between two adjustable electrodes A and B by means of three hardened steel needles at the node, i.e. the mid-point of its length. The diameter of the test-piece need not be exactly specified, but must be uniform. The two electrodes A and B form, with the flat ends of the test-piece, the plates of an electric condenser. The electrode A is coupled, through an amplifier, to the output of a low-frequency heterodyne oscillator, and exerts a periodic electrostatic attraction on the test-piece, thereby setting up in it longitudinal vibrations. The electrode B functions as an electrostatic microphone. Potential variations set up in it by the vibration of the test-piece are amplified and applied to a cathode-ray

oscillograph, and may be measured by means of a thermionic voltmeter. The test-piece itself must be at earth potential.

The vibrations in the specimen only become appreciable when the frequency of the applied voltage is equal to the frequency of free vibration of the specimen. The variable condenser of the oscillator is therefore rotated until resonance is obtained. At this point the amplitude of the vibrations reaches a sharp maximum, and the corresponding

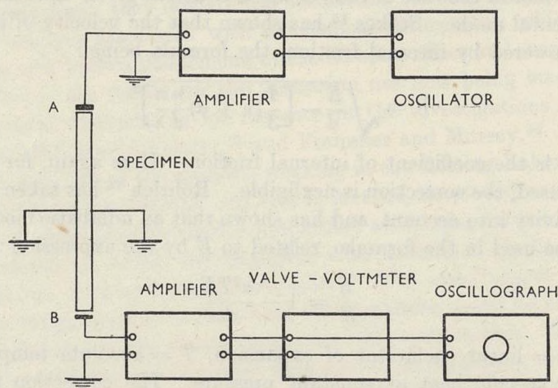


FIG. 1.—Diagram of the Apparatus Used for Measuring the Elastic Modulus and Internal Friction.

frequency F_0 is read off from the dial of the condenser, which has previously been calibrated. The value of the modulus is then determined by means of equation (3). The frequency, which is checked by comparison with a standard provided by the Laboratoire National de Radioélectricité, can be read to ± 5 cycles per second, involving a relative error of 5×10^{-4} . The length can be measured to ± 10 microns, involving a relative error of 6×10^{-5} , while the error involved in determining the density is 1 to 2.5×10^{-3} . The values calculated for the modulus are therefore subject to an error of the order of 0.36%. Successive determinations of the modulus made on the same specimens have, in fact, given results differing by less than 0.4%.

The logarithmic decrement of the decay of the amplitude of successive vibrations is usually taken as a measure of the internal friction of the material. Its value is given by the expression :

$$\delta_0^n = \log_e \frac{A_0}{A_1} = \frac{1}{n} \log_e \frac{A_0}{A_n}$$

where A_0 = initial amplitude, A_1 = amplitude after one complete

oscillation, A_n = amplitude after n complete oscillations, and e = base of natural logarithms.

In practice, δ may be calculated from observations of the time for the amplitude A_n to fall to a definite fraction of A_m , but it may also be determined from the breadth of the resonance curve when the specimen is in forced vibration (Fig. 2), and this method has been used in the present investigation. It is easy to show that if ΔF is the breadth of the resonance curve at an amplitude of $\frac{A_m}{\sqrt{2}}$ then :

$$\delta = \pi \frac{\Delta F}{F_0}$$

where F_0 is the resonance frequency. The error of the determination is rather higher than that given above for the modulus, and it is probable that it is of the order of 5%.

Fig. 3 (Plate XLII) gives a general view of the apparatus. It should be mentioned that all measurements were made in free air.

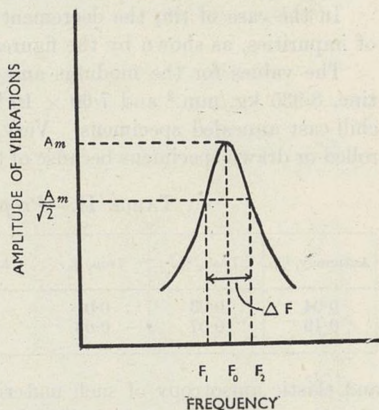


FIG. 2.—Resonance Curve.

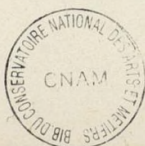
III.—ELASTIC CONSTANTS OF PURE METALS.

The value of the decrement for pure copper given in Tables III and IV, namely 79.4×10^{-4} , is higher than that usually quoted in the literature. The authors have found, however, that the decrement is appreciably affected by the oxygen content of the metal, as the values given in Table I show.

TABLE I.—*Properties of Copper.*

Oxygen, %.	Log. decrement, δ , $\times 10^4$.	Specific Resistance, ohms/cm. ² /cm., at 20° C.	Temp. Coeff. of Resistivity, $\frac{1}{\rho} \times \frac{d\rho}{d\theta} \times 10^5$.
0.017	79.4	1.695	399
0.024	78.3	1.695	400
0.044	54.6	1.695	399

It will be seen that the decrement decreases with increasing oxygen content, whereas the electrical resistivity and the temperature coeffi-



cient of resistivity (the latter measured over the range 20°–57° C.) remain constant. The test-pieces used for these experiments had been annealed for 15 hr. at 600° C. and had a grain-size of 300 grains/mm.²

In the case of tin, the decrement also falls with increasing content of impurities, as shown by the figures quoted in Table II.

The values for the modulus and decrement given in Table IV for zinc, 8.935 kg./mm.² and 7.60×10^{-4} , respectively, were measured on chill-cast annealed specimens. Very scattered values are obtained on rolled or drawn specimens because of the markedly preferred orientation

TABLE II.—*Properties of Tin.*

Antimony, %.	Lead, %.	Iron, %.	Arsenic, %.	Copper, Silver.	Log. decrement, $\delta, \times 10^4$.
0.04	0.03	0.01	trace	traces	75
0.19	0.07	0.06	0.005	traces	51.2

and elastic anisotropy of such material. Values measured on a single crystal, produced by recrystallization, of which the glide planes were inclined at an angle of 32° to the axis of the specimen, were 12.039 kg./mm.² for the modulus and 3.5×10^{-4} for the logarithmic decrement.

IV.—ELASTIC CONSTANTS OF COPPER-TIN ALLOYS.

Except for alloys containing less than 10% tin, which could be rolled, the alloys were chill cast. Cast α bronzes are somewhat unsound, because of their long solidification interval and high gas content, so that values of the elastic constants determined on such materials are subject to considerable scatter, particularly so in the case of the logarithmic decrement. In general the alloys were annealed for 100 hr. at the maximum temperature compatible with the equilibrium diagram, and were then cooled at an average rate of 1° C./min. An exception was made in the case of alloys containing 30–50% tin: here, because of the slowness of diffusion, an annealing time of 1000 hr. was adopted. All specimens were examined for soundness by radiographic means, and by comparing the experimentally determined value d_e of the density with the value d_c calculated from lattice-parameter measurements. The values are given in Table III, and the modulus and decrement are shown plotted against atomic percentage of tin in Figs. 4 and 5.

It is generally accepted that in the copper-tin system there are three intermediate solid-solution ranges, designated δ , ϵ , and η' , as indicated in Figs. 4 and 5. Only the first of these phases corresponds with a stationary point, a maximum, on the modulus-composition curve, but

all three correspond with stationary points on the decrement-composition curve, δ and η' with minima and ϵ with a maximum. It is interesting to note that the shape of the decrement-composition curve is very similar to that of the electrical conductivity-composition curve.¹⁷

TABLE III.—Elastic Properties of Copper-Tin Alloys.

Tin, at.-%.	Density.		Length, <i>L</i> , mm.	Frequency, <i>F</i> ₀ , c./s.	Modulus, <i>E</i> , kg./mm. ²	Breadth of Resonance Curve,* ΔF , c./s.	Log. decrement, δ , $\times 10^4$.
	Measured <i>d</i> ₀ .	Calculated <i>d</i> _c .					
0	9.058	9.02	139.94	13,262	12,730	33.5	79.4
1.8	9.040	9.02	139.72	13,460	13,036	6.5	15.4
2.6	8.990	9.02	140.10	13,140	12,423	1.3	3.11
3.2	8.984	9.02	140.14	13,040	12,216	2.3	5.54
5.6	9.128	9.03	139.93	12,887	12,102	1.8	4.36
15.1	9.040	...	132.22	13,640	11,989	2.5	5.76
20.0	9.084	9.05	129.57	15,001	13,993	1.45	3.04
22.6	9.096	...	135.78	14,005	13,412	4.4	9.87
24.5	9.120	9.10	138.94	12,157	10,609	9.2	23.8
31.6	8.852	...	133.50	12,698	10,368	3.05	7.55
34.9	8.519	...	136.10	12,630	10,264	2.05	5.1
40.0	8.452	...	132.90	12,969	10,238	2.85	6.91
41.8	8.370	...	138.00	11,903	9,207	3.3	8.70
44.5	8.400	8.20	134.48	12,453	9,606	6.5	16.4
68.1	7.837	...	135.92	10,814	6,904	10.3	29.9
100.0	7.320	7.35	137.54	9,847	5,475	23.5	75

* Corresponding to an amplitude $\frac{A_{\max.}}{\sqrt{2}}$

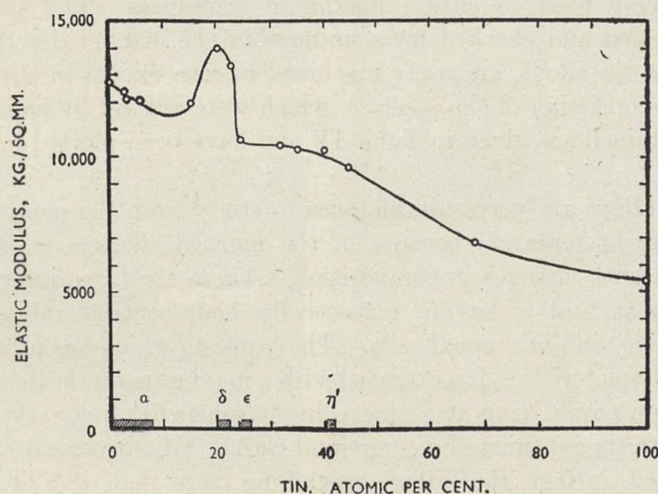


FIG. 4.—Variation of Elastic Modulus with Chemical Composition: Copper-Tin Alloys.

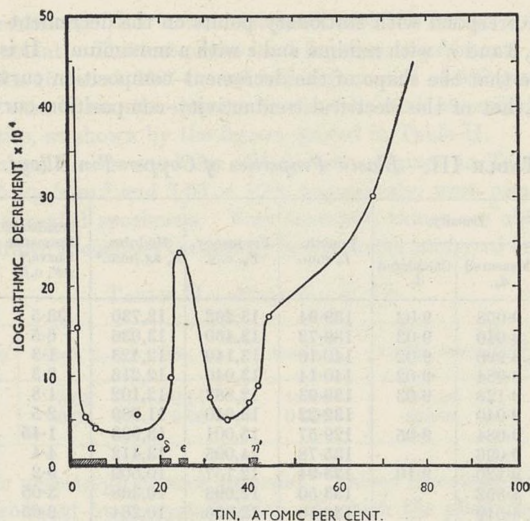
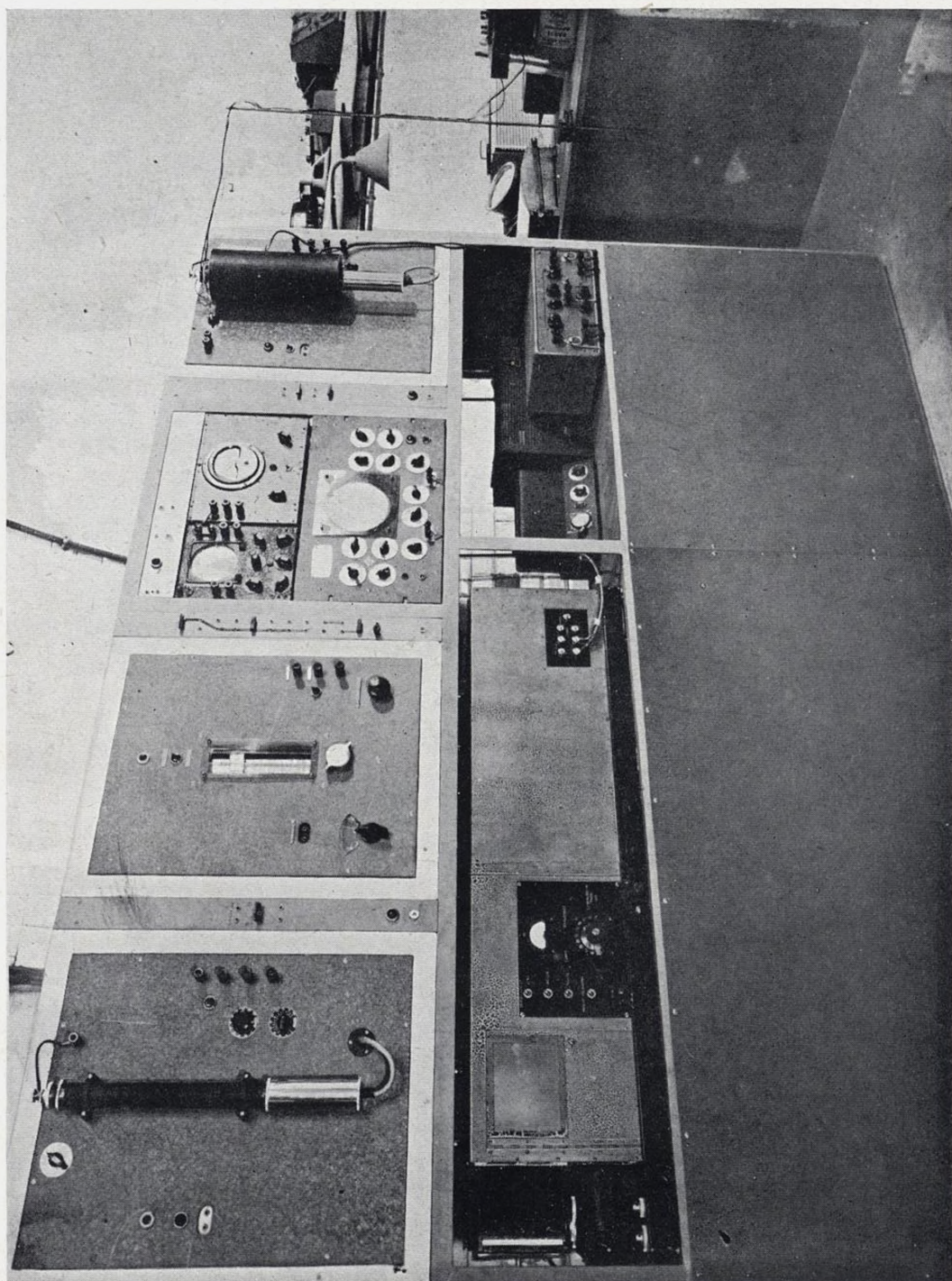


Fig. 5.—Variation of Decrement with Chemical Composition: Copper-Tin Alloys.

V.—ELASTIC CONSTANTS OF COPPER-ZINC ALLOYS.

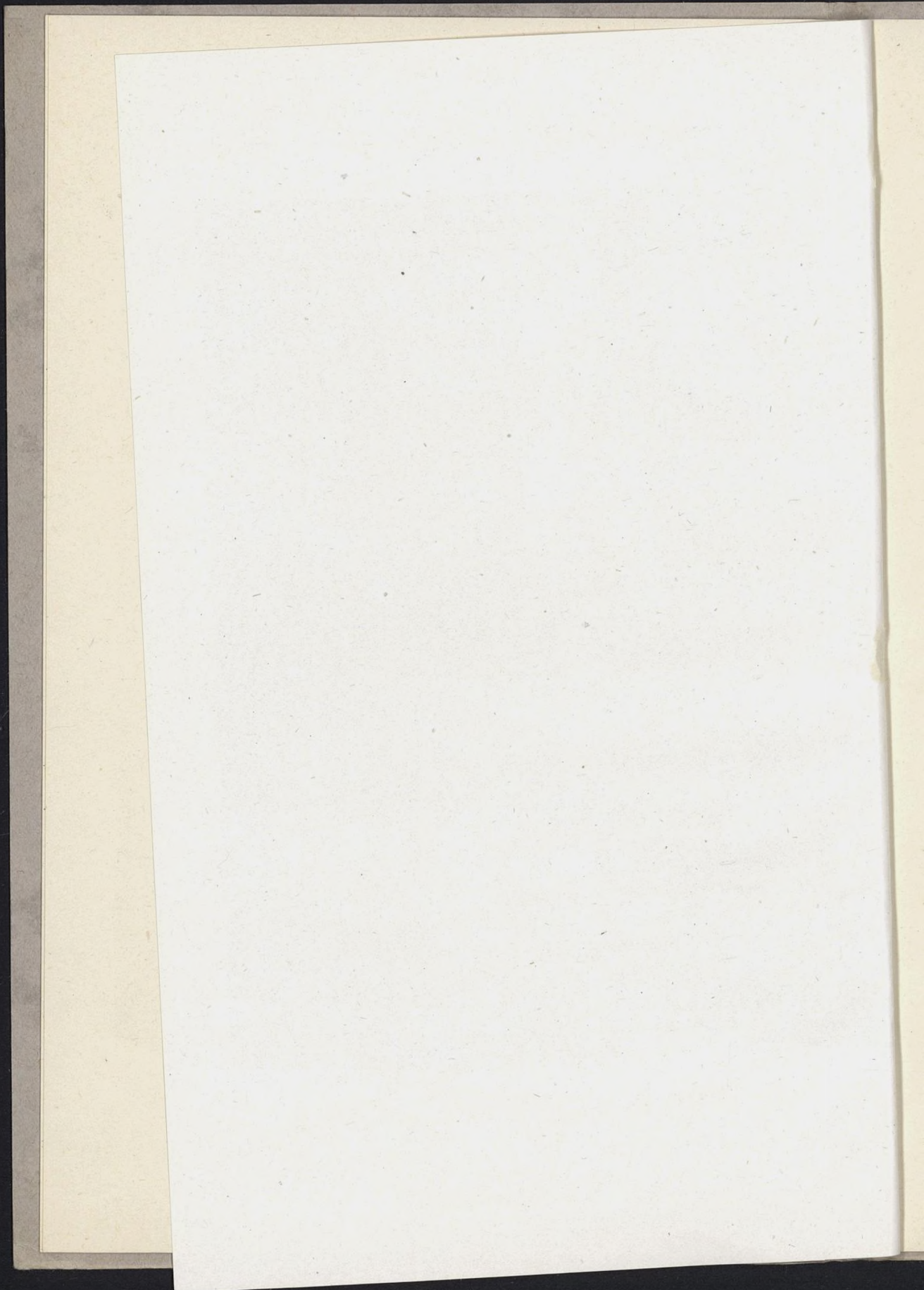
Alloys were prepared from electrolytic copper and zinc. From 0 to 35% of zinc, test specimens were prepared from rolled bars, but with higher percentages of zinc, sand castings were made, the Durville process being used to ensure maximum soundness. The specimens were annealed and checked for soundness in the manner described for the copper-tin alloys, and were machined to size, except in the case of the alloys consisting of the γ phase, which were ground by hand. The results obtained are given in Table IV and have been plotted in Figs. 6 and 7.

These alloys are very suitable ones to study from the point of view of the present research, because of the marked changes in structure associated with changes in composition. There are three intermediate phases, β , γ , and ϵ , having respectively body-centred cubic, multi-atomic cubic, and hexagonal cells. The β phase, which has pronounced metallic characteristics, is associated with a maximum on the decrement-composition curve lying at a zinc content somewhat below that corresponding to the intermetallic compound CuZn. Microscopical examination showed, in fact, that alloys containing more than 48.8 at.-% zinc contained some γ phase. Although alloys consisting of the β phase can be rolled at high temperatures (700° C.), it was thought advisable



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Fig. 3.—General View of Apparatus.



to use cast test-pieces: this phase possesses marked elastic anisotropy,¹⁸ and the presence of even small amounts of preferred orientation leads to low values being obtained for the elastic modulus, and pronounced scatter in the values for the decrement. For these alloys, to ensure a

TABLE IV.—*Elastic Properties of Copper-Zinc Alloys.*

Zinc, at.-%.	Density.		Length, [L, mm.	Frequency, F_0 , c./s.	Modulus, E , kg./mm. ²	Breadth of Resonance Curve,* ΔF , c./s.	Log. decrement, δ , $\times 10^4$.
	Measured d_s .	Calculated d_c .					
0	9.058	9.02	139.94	13,262	12,730	33.5	79.4
4.4	8.913	8.95	139.92	13,460	12,890	4.3	10.1
9.8	9.116	8.85	139.55	13,246	12,665	2.15	5.1
29.7	8.555	8.60	139.60	13,025	11,533	1.75	4.22
34.4	8.565	8.50	139.50	12,760	11,065	1.85	4.55
48.0	8.308	8.35	139.80	12,270	9,968	2.95	7.1
55.1	8.173	...	139.84	14,040	12,846	1.25	2.8
59.9	8.073	8.10	149.90	14,425	15,391	0.76	1.68
61.3	8.063	8.08	149.90	14,427	15,376	0.85	1.88
66.6	7.913	7.95	149.00	14,690	15,457	2.05	4.38
73.0	7.745	...	156.90	13,155	13,453	2.50	5.97
80.2	7.480	7.72	149.22	13,250	11,923	2.00	4.75
92.9	7.495	...	139.77	13,795	11,361	1.85	4.22
100.0	7.266	7.22	139.88	12,415	8,935	3.0	7.60

* Corresponding to an amplitude $\frac{A_{max.}}{\sqrt{2}}$

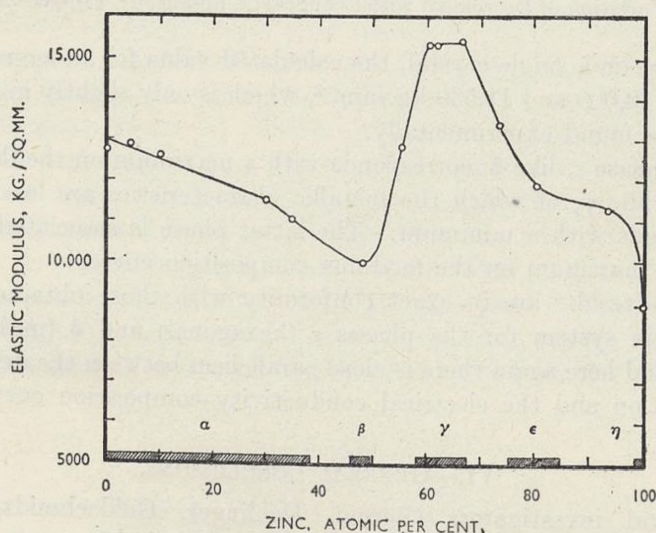


FIG. 6.—Variation of Elastic Modulus with Chemical Composition: Copper-Zinc Alloys.

fine grain-size ($600/\text{cm}^2$), an addition of 0.25% titanium was made to the melt, and a graphite mould was used. It is interesting to compare the experimental value of the modulus for the β phase (9968 kg./mm^2) with that calculated, for an aggregate of crystals oriented at random, by means of Bruggeman's formula.¹⁹ From data derived from mea-

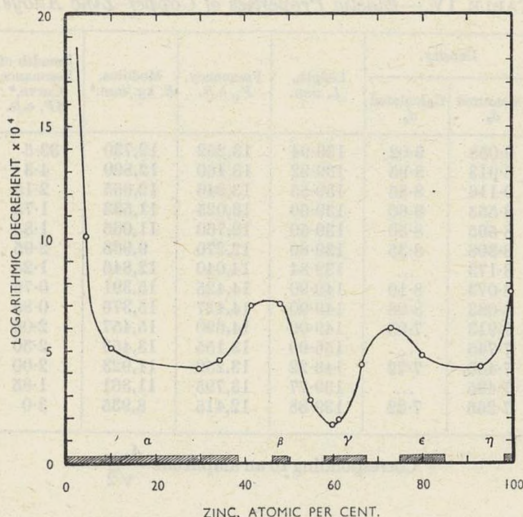


Fig. 7.—Variation of Decrement with Chemical Composition: Copper-Zinc Alloys.

surements on a single crystal, the calculated value for an aggregate lies between 10,000 and 11,530 kg./mm^2 , which is only slightly higher than the value found experimentally.

The phase ϵ , like β , corresponds with a maximum on the decrement curve, while γ , of which the metallic characteristics are less marked, corresponds with a minimum. The latter phase is associated with an absolute maximum on the modulus-composition curve.

These results are in exact conformity with those obtained in the copper-tin system for the phases ϵ (hexagonal) and δ (multi-atomic cubic), and here again there is close parallelism between the decrement-composition and the electrical conductivity-composition curves.

VI.—GENERAL CONCLUSIONS.

Several investigators (Bernal, Dehlinger, Goldschmidt, Hume-Rothery, &c.) have classified the phases present in the copper-tin and copper-zinc systems according to their predominant characteristics,

and have distinguished, in particular, between those which are essentially metallic and those which are homopolar.

CuZn is a typical metallic phase: it is capable of being deformed at high temperatures, and it is associated with a well marked maximum on the electrical conductivity-composition curve. It has a body-centred cubic structure which is perfectly ordered at temperatures below 470° C. The γ phase is entirely different: it is very brittle and its electrical conductivity is little altered by variations in chemical composition. Its unit cell contains 52 atoms and is obviously distorted, because, as Bradley and Thewlis have shown, it can be regarded as having been formed from 27 cells of the β phase with the loss of 2 atoms. It has been suggested by some physicists that in the γ phase the interatomic bonds are of a different type from those in the metals, and more closely resemble those in homopolar bodies. It is interesting to note that these phases are associated with absolute maxima on the modulus-composition curve: this strengthens the view that the modulus is a property related to the atomic linkages.²⁰ It may be mentioned that the ternary alloy containing copper 53, zinc 30.6, and aluminium 15.3 at.-% has the same type of structure, and a modulus of 16,180 kg./mm.², and that the γ phase in copper-aluminium alloys²¹ has a modulus as high as 20,400 kg./mm.²

It is more difficult to explain the results obtained in the case of the logarithmic decrement. The phenomenon of damping is complex: it is partly due to plastic deformation and partly to intercrystalline thermal currents,²² but the relative importance of these two sources of internal friction differs in different phases of a single system.

In the δ and γ phases, it appears probable that the plastic effect is negligible: because of their crystalline structure, the propagation of a dislocation must be almost impossible. Generally speaking, irregularity and disorder in a crystal lattice appear to be associated with a low value for the decrement as compared with that for a regular and ordered lattice. This decrease is met with in solid solutions as compared with pure metals, and in the ordered β phase as compared with the somewhat disordered γ phase with its multi-atomic cell. This view is supported by the marked decrease in the internal friction which accompanies an order-disorder transformation.²³

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