

THE CHANGE IN THE ELASTICITY OF ALUMINUM WIRE WITH CURRENT AND EXTERNAL HEATING.

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THIS paper is the third of a series upon the effect of temperature on the elasticity of wires and deals with aluminum. The apparatus is the same as that used in work with copper and mild steel wires already described in the *PHYSICAL REVIEW*.¹ Upon these metals very exhaustive tests were made, the necessity of this being evident from the great variation in the results that had been reported. The treatment of the specimens of aluminum and the methods employed to secure a wide variation in the conditions have been the same as are fully described in former papers. In general the results have been the same. Consequently this paper is restricted to a brief discussion of the effects peculiar to aluminum and to a discussion of certain general conclusions regarding the effect of temperature on the elasticity of metals.

The tests have been made upon two samples of aluminum wire known commercially as "soft" and "hard." The former is annealed wire and bends easily, the latter is unannealed and is stronger and stiffer. The wires and their chemical analyses were secured through the kindness of Mr. H. M. Hall, superintendent of the United States Aluminum Co., Massena, N. Y. Below are tabulated the analyses, certain physical constants and data regarding the tests.

Chemical Analyses and Constants.

	Soft Aluminum.	Hard Aluminum.
Iron44 per cent.	.32 per cent.
Silicon24 " "	.22 " "
Copper03 " "	.07 " "
Aluminum	99.29 " "	99.39 " "
Diameter	1.24 mm.	1.44 mm.
Breaking load	22. kg.	38. kg.
Coefficient of expansion000025	.000025
Length	57.7 cm.	57.5 cm.
Permanent load	1,114. g.	1,114. g.
Added load	1,048. g.	1,048. g.
Total load per sq. mm.	1.8 kg.	1.3 kg.
Maximum current	23. amp.	
Maximum current per sq. mm.	19.1 amp.	

¹ *PHYS. REV.*, N. S., Vol. 2, 431, 1913; Vol. 5, 373, 1915.

Aluminum will not stand very heavy loads. The percentage accuracy of the determinations of Young's modulus is consequently not as high as has been the case when the loading and resulting total stretch were considerably greater. The curves may however be regarded as giving the change in the modulus to an accuracy of one per cent. The error in the measurement of the temperature is of course greatest at high temperatures but probably does not exceed ten or at the most fifteen degrees.

TESTS UPON SOFT ALUMINUM WIRE.

The specimen of soft aluminum wire was first subjected to loads of two and four kilograms and a temperature of about 250° C. This treatment straightened out the kinks and lengthened the wire several millimeters. The weights were then made of appropriate sizes and two series of readings were taken with external heating. Series 2, Fig. 1,

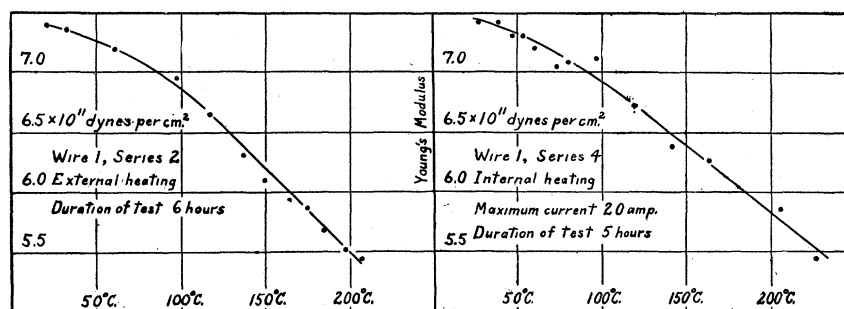


Fig. 1.

Effect of current and external heating upon the Young's modulus of a soft aluminum wire.

shows how the rate of decrease of the modulus increased rapidly with increase of temperature until it became uniform at about 100° C. The third series was with decreasing temperature and was similar in character. Series 4, Fig. 1, differs only in the manner of heating, an electric current in the wire itself being used.¹

A comparison of these results with those shown in series 5, Fig. 2, shows that a permanent change in the properties of the specimen resulted from the treatment in test 4. In this test the temperature reached was higher than before, resulting in some stretching of the wire. The annealing was consequently more thorough. Series 5 was with external heating, increasing and decreasing temperature, and may be regarded as giving the change of Young's modulus with temperature for a thoroughly annealed aluminum wire.

¹ In all figures dots represent observations with increasing temperature, crosses those with decreasing temperature.

Series 6 was taken in the same manner except that the heating was by a current in the wire itself. The curves in the two drawings are practically the same. They show that a cyclic state had been reached in which Young's modulus becomes a function of temperature and is

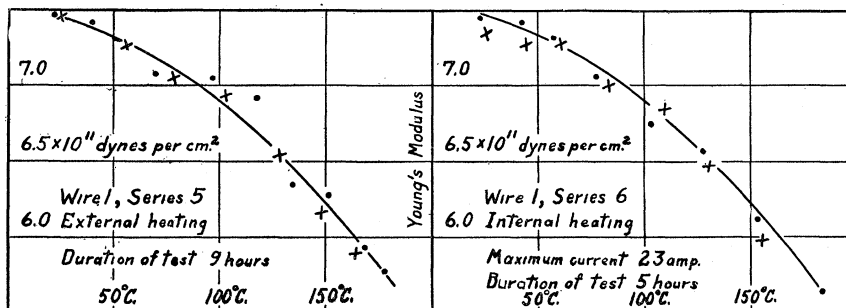


Fig. 2.

Effect of current and external heating upon the Young's modulus of a soft aluminum wire after thorough annealing.

independent of the manner of heating and the thermal route by which any temperature is reached.

Table I. gives the complete data from which series 6 is plotted. This is characteristic of all the data, except that with external heating a longer time was necessary for temperature equilibrium to be reached.

TESTS UPON HARD ALUMINUM WIRE.

The sample of hard aluminum wire was carefully straightened and then tested without any preliminary annealing. Series 1, Fig. 3, shows the almost linear relation between the modulus and temperature. This

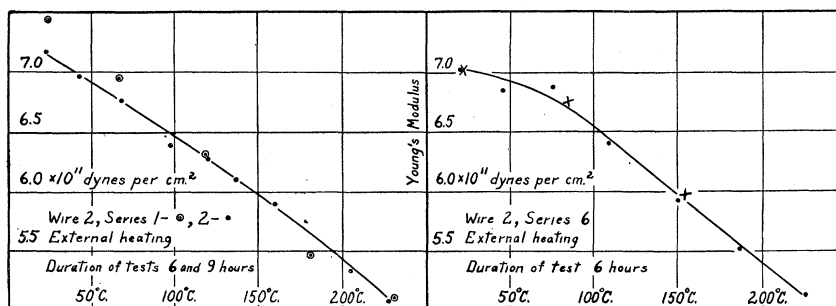


Fig. 3.

Effect of temperature upon the Young's modulus of a hard aluminum wire.

changes slightly with the second heating as shown by the curve of series 2. The next few series of observations were taken under a variety

of conditions, some with heavier weights and at higher temperatures. Just before series 6 the wire was heated to about 400° C. This treatment resulted in a partial annealing and produced the change in the properties of the wire shown by Fig. 3. The similarity of these results to those secured with the soft aluminum specimen lead me to believe that further testing with the consequent thorough annealing would have developed the same final conditions as before.

TABLE I.

Data for Soft Aluminum Wire, Series 6, Internal Heating.

Obs. No.	Time.	Temp.	Stretch.	Current.	No. of Obs.	Young's Modulus $\times 10^{-11}$, Dynes per cm. ²
1	9:00 A.M.	22° C.	.0658 mm.	0 amp.	9	74.5
2	10:00	47	.0660	8	10	74.2
3	10:20	57	.0670	11	9	73.1
4	10:35	78	.0694	14	8	70.6
5	10:50	102	.0726	17	10	67.5
6	11:00	128	.0745	19	11	65.8
7	11:15	154	.0800	21	6	61.2
8	11:25	183	.0870	23	23	56.4
9	11:30	156	.0820	21	7	59.8
10	11:40	131	.0758	19	13	64.6
11	11:50	110	.0717	17	10	68.4
12	12:05 P.M.	83	.0700	14	9	70.0
13	1:00	61	.0673	11	9	72.9
14	1:20	44	.0674	8	11	72.8
15	1:45	25	.0668	0	10	73.4

The results of the tests upon samples of soft and hard aluminum wire may be summarized as follows:

1. Aluminum wire can by thorough annealing be brought to a cyclic condition or steady elastic state in which Young's modulus becomes a function of temperature.¹
2. Within given temperature limits the modulus becomes practically independent of history, the thermal route by which any temperature is reached having no apparent effect on the value of the modulus.
3. Heating by an electric current has no effect other than that caused by the accompanying temperature.
4. The Young's modulus of annealed wire decreases with increase of

¹ Guthe and Sieg, PHYS. REV., Vol. 30, 610, 1910, and Sieg, PHYS. REV., Vol. 31, 421, 1910, in studying the elastic constants of platinum-iridium wires by means of torsional vibrations found that annealing would bring the wires to such a state that results were easily reproducible.

temperature at an increasing rate. The following table is compiled from the results for thoroughly annealed soft aluminum wire.¹

TABLE II.

Change of Young's Modulus of a Thoroughly Annealed Aluminum Wire with Increase of Temperature.

Temperature.	Young's Modulus $\times 10^{-11}$, Dynes per cm. ²	$\frac{dE \times 10^{-11}}{dT}$	Total Decrease, Per Cent. of E at 20° C.
20° C.	7.50	.0046	0.0
40	7.40	.0057	1.3
60	7.27	.0072	3.1
80	7.10	.0090	5.3
100	6.90	.0112	8.0
120	6.66	.0135	11.2
140	6.38	.0155	14.9
160	6.06	.0165	19.2
180	5.72	.0170	23.8

5. Hard aluminum wire exhibits an almost constant temperature coefficient of elasticity. Annealing does not materially change the value of Young's modulus but it does however affect the rate of change, increasing the temperature coefficient of elasticity for low temperatures and decreasing it for higher values, the dividing temperature being about 100° C.

GENERAL CONCLUSIONS REGARDING THE EFFECT OF TEMPERATURE UPON THE YOUNG'S MODULUS OF METALS.

When the present series of investigations on the effect of current and external heating upon the Young's modulus of metals was undertaken the literature of the subject revealed great inconsistency and lack of uniformity in the results that had been secured. Although most observers had reported a decrease of elasticity with increase of temperature many did not find this to be the case. So great were the variations in the results that no conclusion could be drawn regarding the true nature of the effect of temperature on Young's modulus.

Two explanations were possible. Either every specimen possessed its own peculiar elastic properties or else the apparatus and methods employed were not sufficiently refined for the very delicate measurements required.

¹ Slotte, Acta. Soc. Scien. Fennicæ, Vol. 26, 1899, for a temperature range of 6° C. to 70° C. reports an almost uniform decrease in the modulus of .16 per cent. per degree. Katzenelsohn, Diss. Berlin, 1887, reports a decrease of .19 per cent. per degree between 0° C. and 100° C.

It was my belief that samples of wire ought by the proper heat treatment to be brought to a condition in which the modulus would be a function of temperature. With this as a criterion the apparatus described in previous papers was developed. The results secured with the cruder forms at once convinced me that a great part at least of the inconsistencies in former work must have been due to poor temperature control and the intrusion of certain factors affecting the accuracy of the determination of the modulus. The greatest difficulties were met when the heating was by an electric current in the wire itself as might have been anticipated from the fact that no satisfactory investigations had ever been carried out with this method of heating.

Copper was chosen for the first tests because of its high electrical conductivity and with the idea that it ought to respond readily to moderate heat treatment. My first paper¹ describes how the copper wire finally reached a cyclic state in which the Young's modulus became a function of temperature, the modulus decreasing at an increasing rate. The experience gained in the study of this metal lead me to believe that there was no reason why other metals should not behave in a similar manner. If any metal were to put this idea to test it seemed as if it would be one possessing such variable and peculiar properties as iron or steel. The second paper¹ describes the results with a mild steel wire. A cyclic state was secured for a temperature range of 20° C. to 475° C. and the general nature of the change of the modulus with temperature proved to be the same as in the case of copper.

Since these experiments were performed almost identical results have been reported by Lea and Crowther² with rods of mild steel, micro-copper, and high-tension brass and by Harrison³ with nickel wire, although in the latter case anomalous effects occur near the critical temperature. Similar results are also to be found in the work of some of the earlier investigators.

In the present paper aluminum has been shown to yield exactly the same type of results as were secured with copper and mild steel. A considerable amount of data is now available and for the metals that have been mentioned the following generalizations appear to be justified:

1. By thorough annealing the metal can be brought to a cyclic state in which Young's modulus becomes a function of the temperature.
2. The Young's modulus of the metal decreases with increase of temperature, the rate of the change increasing with the temperature.

¹ *Loc. cit.*

² Engineering, Vol. 98, 487, 1914.

³ Phys. Soc., Proc., Vol. 27, 8, 1914.

3. When the metal is heated by the passage of an electric current the change in the modulus is a pure temperature effect.

In my own mind it seems so reasonable to expect that other metals will behave in the same manner that I am led to predict that these generalizations will be found to be the laws governing the effect of temperature upon the elasticity of metals.¹ Work is being continued in this laboratory with other metals and it is to be hoped that other investigators will continue with different types of apparatus and under different conditions.

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¹ Dodge, PHYS. REV., N. S., Vol. 5, 76, 1915.