The Measurement of the Young's Modulus of Metals and Alloys by an Interferometric Method. III : The Influence of Heat-Treatment on the Young's Moduli of Fe-Al Alloys, and the Young's Moduli of Ni-Al, Al-Cu Alloys and German Silver in the Annealed State

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The Measurement of the Young's Modulus of Metals and Alloys by an Interferometric Method. III

The Influence of Heat-Treatment on the Young's Moduli of Fe-Al Alloys, and the Young's Moduli of Ni-Al, Al-Cu Alloys and German Silver in the Annealed State*

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Synopsis

The measurement described in the earlier papers of this series has been extended to the study of the influence of heat-treatment on the Young's moduli of Fe-Al alloys having the composition up to 14.75 per cent aluminium. It becomes clear that the Young's modulus of ordered Fe_3Al (13.8 per cent aluminium) is smaller than that of disordered one. This result is contrary to the cases of Cu_3Au and Ni_3Mn. Moreover, measurement has been done on the static Young's moduli of Ni-Al alloys (up to 5.17 per cent aluminium), several specimens of Al-Cu alloys and german silver. The Young's modulus vs. composition curve of Ni-Al alloys seems to be akin to the curve peculiar to Ni-alloys, such as Ni-Cu and Ni-Mn systems.

I. Introduction

In the first two parts of this series[1], which will be referred to as I and II, an account was given of the apparatus for measuring the Young's moduli of metals and alloys, of the experimental results on Ni-Cu alloys, and of those on Ni-Mn alloys. The existence of superlattice Fe_3Al in Fe-Al alloy system discovered by Bradley and Jay[2] induced us to extend the measurement of the Young's moduli to these alloys. The Young's moduli in the ordered state of the typical superlattice alloys such as Cu_3Au and CuZn, which show no change in the crystal structure by the formation of superlattice, are larger than those in the disordered state, and the temperature dependence of the Young's moduli is quite similar to that of their own degree of order. A qualitative theory of the temperature dependence of the Young's modulus of β-brass (CuZn) proposed by one of us showed a fair agreement with the experimental result[3]. The basic idea of the theory which assumes that there is no change in the crystal structure and no difference of atomic distance between the ordered alloy and disordered one is as follows: the difference between the Young's modulus in the

* The 728th report of the Research Institute for Iron, Steel and Other Metals.
Read at the semi-annual meeting of the Japan Institute of Metals held at Tokyo, April 1, 1952.

(1) T. Fukuroi and Y. Shibuya, Sci. Rep. RITU., A **2** (1950), 748, 829. (Parts I and II)

(2) A. J. Bradley and A. H. Jay, Proc. Roy. Soc., A **136** (1932), 210; J. Iron and Steel Inst., **125** (1932), 339.

(3) Y. Shibuya, Sci. Rep. RITU., A **1** (1949), 161.

ordered state and that in the disordered one is due to the change in the force constants between the neighbouring atoms resulting from the site-interchanges of atoms. On the other hand, the superlattice alloys such as CuAu[4] and CuPd[4] seem to show an opposite behaviour. In the cases of CuAu and CuPd the crystal structures change slightly in the former and considerably in the latter because of the formation of superlattice. This is also the case for Fe_3Al[2],[5]. Moreover, the mechanism of atomic site-interchange for the case of Fe_3Al is not so simple[2] as for the case of Cu_3Au or CuZn. Therefore the interpretation of the behaviour of the Young's modulus of CuAu, CuPd or Fe_3Al is beyond the scope of the elementary theory.

The Young's moduli of annealed Fe-Al alloys were, hitherto, measured by Kubo[6], and Masumoto and Saito[7]. In the measurement of the Young's modulus the former used the dynamical method and the latter resorted to the statical method named König's one which differs somewhat in principle from the statical one we used. The influence of heat-treatment on the Young's moduli in zero-magnetic field of this series has been, however, reported nowhere with the exception of that in regard to Fe_3Al by Kubo[6]. Hence we have been interested in the behaviour of the Young's moduli in zero-magnetic field of Fe-Al alloys subjected to annealing or quenching. Unfortunately, however, the measurement was confined only to that on the specimens having the composition less than 14.75 per cent aluminium in weight. This was mainly due to the difficulty of working the specimens of high aluminium content. Moreover, for some reasons we could not measure the Young's modulus in the quenched state of the specimens having the composition less than 9.16 per cent aluminium.

According to our previous experiments on Ni-Cu (I) and Ni-Mn alloys (II), the dependence of the Young's moduli of nickel-solid solutions on the solute-composition shows a minimum in the region adjacent to nickel. Ni-Al alloys form solid solutions up to about 14 per cent aluminium. Therefore we performed a measurement on the Young's moduli of annealed specimens of these solid solutions in order to ascertain the existence of a minimum in the Young's moduli. The specimens we prepared were confined to those having the composition less than 5.17 per cent aluminium for the same reason as in the case of Fe-Al alloys.

Furthermore measurements were performed on the Young's moduli of a number of specimens of Al-Cu alloys and german silver.

The measuring apparatus and procedure were quite the same as decribed in the reference I, and the detailed account of the apparatus used for vacuum-quenching was given in the reference II.

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(4) H. Roehl, Zeit. f. Phys., **69** (1931), 309; Ann. d. Phys., **18** (1933), 155.
(5) A. Osawa and T. Murata, Nippon Kinzoku Gakkai-Shi (in Japanese), **5** (1941), 259.
(6) T. Kubo, Nippon Sûgaku-Butsuri Gakkai-Shi (in Japanese), **16** (1942), 426.
(7) H. Masumoto and H. Saito, Nippon Kinzoku Gakkai-Shi (in Japanese), **8** (1944), 359.

II. Specimens and their heat-treatment

In the preparation of the alloy specimens we followed the procedure described in the earlier papers I and II. The dimension of all specimens was also approximately standardized to the length of 8 cm, the thickness of 0.1 cm and the width of 0.5 cm.

The result of chemical analysis of impurities in Fe-Al, Ni-Al and Al-Cu alloys is shown in Table 1.

Table 1. Composition of alloys in weight per cent.

(i) Fe-Al*

No. of specimen		No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11
Charge	Fe	98	96	94	94	92	90	86.5	88	86	87	84
	Al	2	4	6	6	8	10	13.5	12	14	13	16
Analysis	Fe	balance	bal.	bal.	bal.	bal.	bal.	bal.	bal.	bal.	bal.	bal.
	Al	2.37	3.54	5.16	7.16	8.05	9.16	11.53	11.97	12.84	13.12	14.75
	Si	0.023	0.067	0.033	0.067	0.037	0.055	0.23	0.089	0.14	0.17	0.23
	Mn	0	0.053	0	0.044	0	trace	trace	trace	trace	trace	trace
	Cu	0		0		0	trace					
	C		0.058		0.055			0.15	0.13	0.16	0.10	0.15

* The three groups of specimens, i. e. the first group (Nos. 2 and 4), the second group (Nos. 1, 3, 5 and 6) and the third one (Nos. 7, 8, 9, 10 and 11) were made of electrolytic iron and aluminium from different sources respectively.

(ii) Ni-Al

No. of specimen		No. 1	No. 2	No. 3	No. 4	No. 5
Analysis	Ni	balance	bal.	bal.	bal.	bal.
	Al	0.39	0.64	2.49	4.86	5.17
	Fe	0.021	0.021	0.027	0.027	0.030
	Si	0.005	0.016	0.051	0.070	0.075
	Co	0.52	0.63	0.56	0.56	0.51

(iii) Al-Cu**

No. of specimen		No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Charge	Al	100	97	97	93	87	75	40	30
	Cu	0	3	3	7	13	25	60	70
Analysis	Al	balance	bal.	bal.	bal.	bal.	bal.		
	Cu	0.018	2.63	2.63	7.80	13.03	27.47		
	Fe	0.26	0.28	0.28					
	Zn	0.021	0.023	0.023	0.11	0.11	0.070		
	Si	0.11	0.12	0.12	0.29	0.30	0.26		
	Mn	0.009	0.008	0.008	0	0	0		

** The two groups of specimens, i. e. the first group (Nos. 1, 2 and 3) and the second one (Nos. 4, 5, 6, 7 and 8) were prepared at different times. The result on specimens Nos. 7 and 8 was plotted in Fig. 4 with the charged values of copper.

The specimen of Fe-Al alloys prepared to size were annealed at 1,000°C for one hour in high vacuum, then cooled in the furnace to 700°C, and from there cooled to room temperature with the cooling rate of 50°C per hour.

Quenching of Fe-Al specimens was done with the following procedure: they were kept at 1,000°C for an hour in high vacuum, then cooled in the furnace to

900°C, and water quenched at that point according to the quenching procedure described in detail in the reference II.

The Ni-Al specimens annealed at 700°C for 3 hours in high vacuum were allowed to cool to room temperature in the furnace.

The Al-Cu specimens were annealed at 400°C for 3 hours in high vacuum and cooled to room temperature in the furnace.

The german silver specimens were annealed at the temperatures between 400° and 600°C in accordance with their composition and cooled to room temperature in the furnace.

III. Experimental results

(i) Young's moduli of Fe-Al alloys

The composition dependence of Young's modulus in the non-magnetized state of annealed Fe-Al specimens together with that of quenched specimens is shown in Fig. 1. The Young's moduli of annealed specimens decrease with the increase of aluminium content. The decreasing rate seems to become reduced at about 7 per cent aluminium and to become marked again at about 9 per cent aluminium. Then there appears a minimum at about 12.5 per cent aluminium. For the sake of comparison, the earlier results obtained by Kubo(6), and Masumoto and Saito(7) together with ours are shown in Fig. 2. At any rate it can be seen that the Fe_3Al phase affects Fe-Al alloys so as to decrease their Young's moduli.

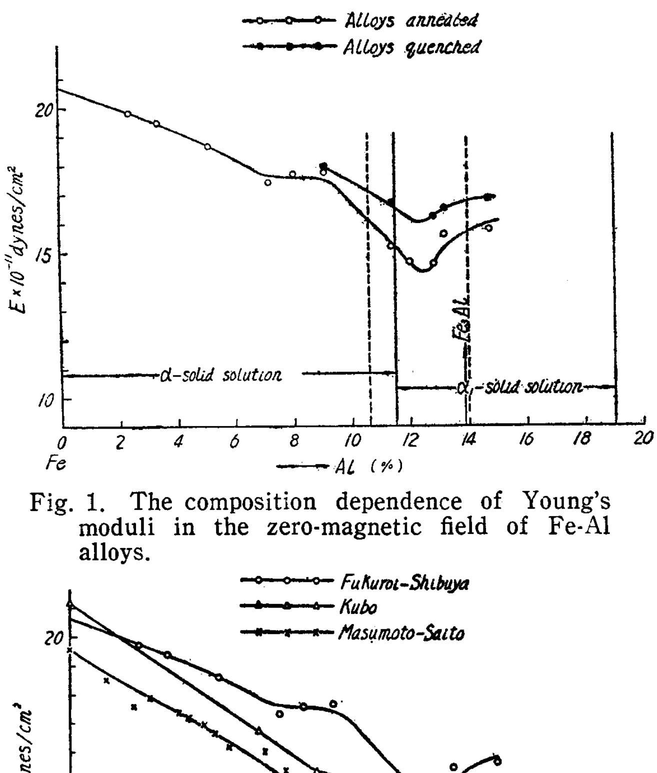

Fig. 1. The composition dependence of Young's moduli in the zero-magnetic field of Fe-Al alloys.

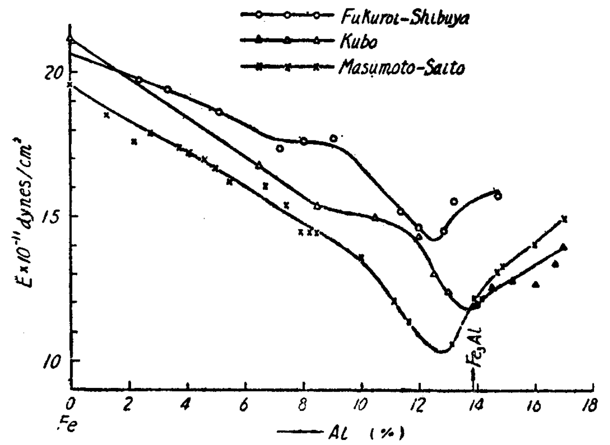

Fig. 2. Relations between the Young's modulus in the non-magnetized state and the composition of annealed Fe-Al alloys obtained by different researchers.

Young's moduli of quenched Fe-Al specimens having the composition between 9.16 and 14.7 per cent aluminium are also shown in Fig. 1. The Young's moduli of quenched Fe-Al alloys in this composition region are larger than those of annealed specimens. Some consideration on these results will be discussed in the following section.

(ii) Young's moduli of Ni-Al alloys

The composition dependence of Young's moduli in the zero magnetic field of Ni-Al alloys is shown in Fig. 3. The measured points are so scanty that it may appear rather rash to connect them with a continuous curve. However, the characteristic behaviour of the Young's moduli of Ni-alloys previously observed in the case of Ni-Cu and Ni-Mn alloys seems to reveal itself also in this case. This point will be touched briefly in the next section.

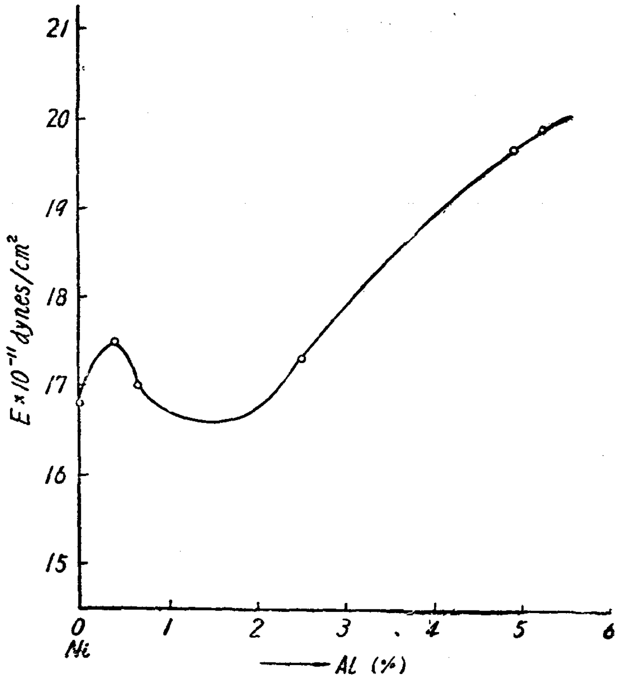

Fig. 3. The composition dependence of Young's moduli in the zero magnetic field of annealed Ni-Al alloys.

(iii) Young's moduli of Al-Cu alloys

The relation between the Young's moduli of annealed Al-Cu specimens and their composition is shown together with the data obtained by Guillet(8), and Köster and Rauscher(9) in Fig. 4. The linear increase of the Young's modulus in the region adjacent to aluminium with the addition of copper to aluminium can be seen in the figure. Owing to the difficulty of preparing the specimen, the measured points with regard to the specimens having higher content of copper were very scanty.

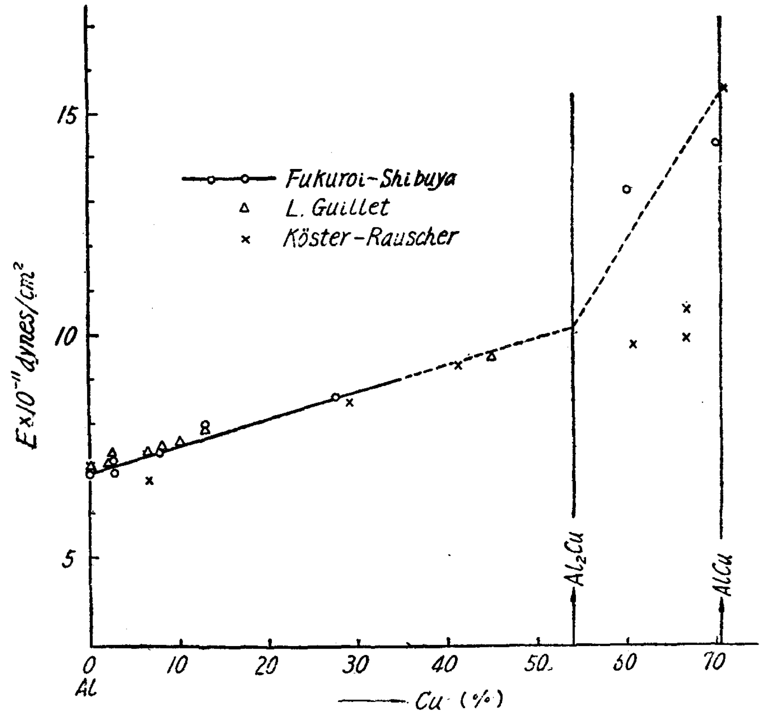

Fig. 4. The composition dependence of Young's moduli of annealed Al-Cu alloys.

(iv) Young's moduli of german silver

The result obtained with a number of german silver specimens is shown in Table 2 together with their composition.

(8) L. Guillet, Fils, Rev. Mét., **36** (1939), 497.
(9) W. Köster and W. Rauscher, Zeit. f. Metallkde., **39** (1948), 111.

Table 2. Composition in weight per cent and Young's moduli of german silver.

No. of Specimen	Composition (Chemical Analysis)						$E\times10^{-11}$ (dynes/cm^2)
	Ni	Zn	Mn	Pb	Sn	Cu	
1	14.55	32.54	0.14	0.02	0.008	balance	12.5
2	14.88	33.05	0.13	0.03	0.008	bal.	12.4
3	17.96	32.61	0.04	0.02	0.008	bal.	11.9
4	19.47	32.37	0.12	0.02	0.008	bal.	14.1
5	20.08	28.18	0.08	0.02	0.008	bal.	11.7
6	20.17	27.20	0.10	0.02	0.010	bal.	11.6
7	21.53	26.71	0.07	0.02	0.008	bal.	13.9
8	24.49	24.84	0.12	0.02	0.008	bal.	13.0

IV. Consideration on the results

As is clearly seen in Fig. 1, the Young's moduli of Fe-Al alloys in the composition region adjacent to Fe_3Al are smaller in the annealed state than in the quenched state. This may be due to the existence of Fe_3Al-phase in these alloys, the Young's modulus of which is smaller in the annealed state (it may be regarded as highly ordered state) than in the quenched state, i.e. the disordered one. According to the phase-diagram of Fe-Al alloys obtained by Osawa and Murata[5], at room temperature alloys having the composition between 0 and 11.5 per cent aluminium form α-solid solutions which crystallize with a body-centred cubic lattice and those having the composition between 11.5 and 19 per cent aluminium form α_1-solid solutions which contain the superlattice Fe_3Al in them. The difference of the Young's moduli between the two states, however, appears down to 9 per cent aluminium. Consequently the difference in the Young's moduli in the two states which occurs in the composition region 9 to 11.5 per cent aluminium must be attributed to some other origin. Although the ΔE-effect of iron is very small compared with that of nickel, the ΔE-effect of Fe-Al alloys in the composition region near Fe_3Al is of the same order as that of nickel[10]. Therefore it is likely that the ΔE-effect in Fe-Al alloys due to the internal stresses introduced in the specimens by quenching may be responsible for such a remarkable change in the Young's modulus as in Fe-Al alloys of 9 to 11.5 per cent aluminium.

According to the earlier reports[2, 5], the lattice constants in the annealed state of these alloys in the composition region near Fe_3Al differ from those in the quenched state. The said difference begins to be recognized at the composition of about 10 per cent aluminium and becomes remarkable in the region within two vertical, dotted lines in Fig. 1. The lattice constants of annealed alloy in this region are smaller than those of quenched ones. If we apply the idea of Grüneisen that the Young's modulus of an alloy can be given qualitatively in terms of its lattice constant to the case of superlattice alloys, we should expect that the small lattice constant corresponds to the large Young's modulus. That this is not the case for Fe_3Al is clear as the present measurement together with

(10) M Yamamoto and T. Taniguchi, unpublished paper.

earlier X-ray investigation shows. Furthermore, as described before, the mechanism of atomic site-interchange in Fe_3Al is not so simple as in the typical superlattice alloy such as Cu_3Au or CuZn. Thus neither Shibuya's theory nor Grüneisen's idea can explain the effect of ordering on the Young's modulus of Fe_3Al.

As shown in Fig. 2, the composition dependence of the Young's moduli of Fe-Al alloys hitherto obtained differs from each other. Although the common behaviour of the curves, that is, the first rapid, then slow and again rapid decrease of the Young's modulus with the increase of aluminium content can be seen in the three curves illustrated in the figure, the magnitude and position of the minimum in the Young's modulus differs from each other. It may not be easy to clarify the discrepancy. At any rate it can be safely concluded that the presence of the superlattice Fe_3Al in the Fe-Al alloys causes their Young's moduli to decrease and Fe_3Al belongs to the category of alloys, whose Young's modulus in the disordered state exceeds that in the ordered state.

The minimum in the Young's modulus of Ni-Al alloys seems to be found at the composition of about 2 per cent aluminium in Fig. 3, whereas the minima in the Young's moduli of Ni-Cu and Ni-Mn alloys were found at the composition of about 15 per cent copper and manganese respectively. On the one hand, as the result of chemical analysis given in Table 1 shows, the specimens of very small aluminium content contained cobalt, as an impurity, of much the same order of amount as the solute atom of interest (aluminium). Consequently, the idea that the behaviour of curve near nickel is due to the result of alloying nickel and a small amount of cobalt which has a higher value of Young's modulus than the former may not be unconceivable. On the other hand, we cannot deny decidedly hat this may be due to the difference of valency of solute atoms. At all events we cannot explain clearly this point at the present stage of investigation.

The result that the Young's moduli of Al-Cu alloys in the composition-region adjacent to aluminium increase linearly with the addition of copper is in accordance with the earlier result obtained by Guillet(8), and Köster and Rauscher(9). According to the phase-diagram of Al-Cu alloys(11) Al-Cu alloys having the composition 0 to 54.1 per cent copper (Al_2Cu) consist of two phases, one of which is ω-phase and the other is θ-phase (Al_2Cu). The accepted view that the law of mixing in regard to the Young's moduli holds good in the case of two phase-alloys(12) can be adopted also in this case.

A linear increase of the Young's moduli with the increase of copper content should be expected in the range between Al_2Cu (54.10 per cent copper) and AlCu (70.21 per cent copper). Our measured points coincide roughly with the broken line which joins the values for Al_2Cu and AlCu.

What can be said on the experimental result on the Young's moduli of german silver shown in Table 2 is that the effect of nickel content on the Young's moduli of german silver seems not to be quite simple, even if we take into

(11) For instance, M. Hansen, Der Aufbau der Zweistofflegierungen, (1936), 98.
(12) Y. Shibuya, Sci. Rep. RITU., A 3 (1951), 645.

account the reasonable experimental error (somewhat less than 2 per cent).

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