Thermal Expansion and Temperature Dependence of Young's Modulus in Fe-Cr Alloys*

By Hakaru Masumoto**, Shôhachi Sawaya**
and Michio Kikuchi**

Thermal expansion within a temperature range of $-150^{\circ}\sim 900^{\circ}\text{C}$ and Young's modulus within a temperature range of $-150^{\circ}\sim 700^{\circ}\text{C}$ and the rigidity modulus at room temperature of Fe-Cr alloys containing 0~59.10% chromium have been measured. It has been found that the mean linear coefficient of thermal expansion at $0^{\circ}\sim 40^{\circ}\text{C}$ show minimum values of 9.94×10^{-6} and 10.60×10^{-6} in the annealed alloys containing 19.90% and 54.10% chromium, respectively, thereby revealing the Invar property. Fe-Cr alloys with a concentration range of about 17~39% chromium exhibit the Elinvar property, the highest transition temperature being 230°C in an alloy containing nearly 25% chromium. The negative minimum value of the temperature coefficient of Young's modulus at $0^{\circ}\sim 40^{\circ}\text{C}$ is -6.81×10^{-5} in an alloy containing 19.43% chromium. The Elinvar property is also observed in the Fe-54.10% Cr alloy with a negative minimum value of -9.60×10^{-5} at $0^{\circ}\sim 40^{\circ}\text{C}$.

(Received August 4, 1970)

I. Introduction

Many studies have been carried out on the physical properties of Fe-Cr alloys^{(1)~(3)}, whereas little has been known about Young's modulus changes with temperature, with the single exception Nishiyama's work which was carried out on alloys containing 0~14% Cr at room temperature⁽⁴⁾. Therefore, as a part of extensive studies about Elinvar alloys, the present authors have investigated Fe-Cr alloys so as to clarify the temperature dependence of not only thermal expansion but also of Young's modulus and of rigidity modulus in the binary system.

II. Experimental Procedure

The alloying materials used were electrolytic Fe and Cr. The chemical compositions of these materials are tabulated in Table 1. In the preparation of the specimens, electrolytic Fe was first melted in an alumina crucible under the flow of hydrogen by using a high-frequency induction furnace and then stirred thoroughly with electrolytic Cr to produce a homogeneous molten alloy. The molten alloy casted in an iron mold 10mm in inner diameter was made into wires 2 and 0.5mm in diameter by means of swaging and of cold drawing at room temperature. Then pieces 100mm long

were cut from the 2mm diameter wire to measure the thermal expansion, density and Young's modulus. Pieces 150mm long were also cut from the 0.5mm diameter wire to measure the rigidity modulus.

The specimens investigated were of 23 kinds, all of which were heated in a vacuum at 1000°C for 1 hr with subsequent cooling at about 300°C/hr .

Thermal expansion measurements were carried out in the range of $-150^{\circ}\sim 900^{\circ}\text{C}$ by a vertical-type dilatometer⁽⁵⁾ and a horizontal-type dilatometer, while the density was determined by weighing in water. The resonance frequency of vibration (700~900 Hz) of the specimens was measured at temperatures between $-150^{\circ}\sim 700^{\circ}\text{C}$ by means of a vibrator-controlled oscillator system⁽⁶⁾. Young's modulus E and its temperature coefficient e were calculated from the measured values of the resonance frequency of vibration, the thermal expansion coefficient α and the density D . Although there are various methods to support the specimen at the nodal point of vibration to measure the resonance frequency of vibration, the method used to suspend the specimen with a thin molybdenum wire was especially employed for the high-temperature measurement. The rigidity modulus G was determined from the measurement of a specimen 0.5 mm in diameter at room

Table 1 Chemical compositions of iron and chromium used (wt%)

Metals	Fe	Cu	Al	Mn	Si	C	S	P
Electrolytic Fe		0.004	Trace	0.005	0.005	0.005	0.005	0.004
" Cr	0.21	—	0.06	—	0.07	0.03	0.02	0.01

* This paper was presented at the 1969 Spring Meeting of the Japan Institute of Metals. Reported originally in Japanese in J. Japan Inst. Metals, 34 (1970), 847; The 43rd Report from The Foundation: The Research Institute of Electric Magnetic Alloys, Sendai, Japan.

** The Foundation: The Research Institute of Electric and Magnetic Alloys, Sendai, Japan.

(1) A. B. Kinzel and R. Franks: *The Alloys of Iron and Chromium*, McGraw-Hill, N. Y., (1940), 57.

(2) Y. Matsunaga: *Ôyô-Kinzokugaku-Taikai*, Vol. 6, Seibundô-Shinkô-Sha, Tokyo, (1963), 6.

(3) Edited by The Japan Institute of Metals and The Iron and Steel Institute of Japan, *Tekkô-Zairyô-Binran*, Maruzen, Tokyo, (1967), 607.

(4) Z. Nishiyama: *Sci. Rep. Tohoku Univ.*, 18(1929), 359.

(5) H. Masumoto and T. Kobayashi: *J. Japan Inst. Metals*, 12-6 (1948), 1; *Sci. Rep. RITU*, A-2(1950), 856.

(6) Y. Shirakawa and I. Oguma: *J. Japan Inst. Metals*, 24(1960), 63; *Sci. Rep. RITU*, A-18 Suppl. (1966), 523.

temperature by means of the torsional pendulum method⁽⁷⁾. The hardness Hv was determined by the micro-Vickers hardness tester (load : 500 g).

III. Results and Discussion

The experimental results are summarized in Figs. 1~5 and Tables 2~3. The thermal expansion curves at

$-150^{\circ}\sim 900^{\circ}\text{C}$ for Fe-Cr alloys containing less than 59.10% Cr are shown in Fig. 1. The curves indicate a distinct knee at the magnetic transformation point T_c and form nearly a straight line at temperatures above and below T_c , with an inclination which is larger in the former than in the latter. The anomalous change corresponding to the phase transformation is not revealed in the curves (cf. Fig. 2)⁽⁸⁾. Figure 3 shows the tempera-

Table 2 Young's modulus E and its temperature coefficient e , linear coefficient of thermal expansion α , rigidity modulus G and its temperature coefficient g , Vickers hardness Hv, and density D in the annealed state of Fe-Cr alloys

Alloy No.	Cr (%)	$E (\times 10^5 \text{ kg/cm}^2, 20^{\circ}\text{C})$	$e (\times 10^{-5}, 0^{\circ}\sim 40^{\circ}\text{C})$	$\alpha (\times 10^{-6}, 0^{\circ}\sim 40^{\circ}\text{C})$	$G (\times 10^5 \text{ kg/cm}^2, 20^{\circ}\text{C})$	$g (\times 10^{-5}, 0^{\circ}\sim 40^{\circ}\text{C})$	Hv (20°C)	$D (\text{g/cm}^3, 20^{\circ}\text{C})$
3	9.65	20.37	-14.30	12.63	7.82	-14.50	102	7.79
8	18.48	20.74	-9.60	10.42	7.84	-9.81	134	7.72
10	19.43	20.77	-6.81	10.23	7.88	-7.00	142	7.72
11	19.90	20.78	-8.63	9.94	7.88	-10.10	145	7.72
12	20.42	20.80	-9.50	9.96	7.89	-10.25	150	7.72
13	21.40	20.85	-13.58	10.05	7.90	-13.79	152	7.72
22	52.30	22.21	-14.70	10.71	8.03	-14.90	287	7.50
23	53.20	22.27	-12.20	10.70	8.04	-12.50	293	7.49
24	54.10	22.31	-9.60	10.60	8.04	-9.85	296	7.48
25	55.10	22.36	-11.20	10.62	8.05	-11.72	300	7.48
26	59.10	22.57	-15.70	10.68	8.06	-15.83	317	7.45

Table 3 Temperature coefficients of Young's modulus of Fe-Cr alloys in various states

Cr contents (%)	Cold-worked	Cooling rate after heating at 1000°C for 1 hr		
		170°C/sec (quenched)	300°C/hr (annealed)	10°C/hr (annealed)
		$(\times 10^{-5}, 0^{\circ}\sim 40^{\circ}\text{C})$		
14.50	-15.13	-14.10	-12.50	-10.80
19.43	-9.70	-8.70	-6.81	-5.70
24.35	-20.01	-18.80	-17.30	-14.81

Fig. 1 Thermal expansion of Fe-Cr alloys.

Fig. 2 Equilibrium diagram of Fe-Cr alloys.

ture dependence of E at temperatures below 700°C for Fe-Cr alloys containing less than 59.10% Cr. As can be seen in the figure, the phase transformation point T and the knee T' are observed in the curves at temperatures below T_c . These values of T_c , T and T' are plotted in Fig. 2 with the open circles, of which T_c and T coincide well with the transformation points reported in the previous studies.

(7) H. Masumoto and H. Saitô : J. Japan Inst. Metals, 16 (1952), 126.

(8) M. Hansen : *Constitution of Binary Alloys*, McGraw-Hill, N. Y., (1958), 525; R. P. Elliott : *Constitution of Binary Alloys*, McGraw-Hill, (1965), 345; Y. Imai, M. Izumiyama and T. Masumoto : J. Japan Inst. Metals, 30 (1966), 284.

Fig. 3 Temperature dependence of Young's modulus of Fe-Cr alloys.

The composition dependence of Young's modulus E and its temperature coefficient e , thermal expansion coefficient α , density D and hardness H_v at room temperature in Fe-Cr alloys is represented in Fig. 4. As shown in the figure, the curves of E and H_v are slightly bent in the vicinity of the 20% Cr concentration, while at the same Cr concentration the curves of D indicate a fairly large bend. The value of α shows a fairly large minimum value at about 20% Cr and a very small minimum value at about 54% Cr. Under the three conditions of annealing, water quenching and cold working, the value of e has a negative minimum value at these concentrations. The smallest negative value in the annealed state is -6.81×10^{-5} in the Fe-19.43% Cr alloy and -9.60×10^{-5} in the Fe-54.10% Cr alloy. The values of e at room temperature for the three alloy specimens with 14.50~24.35% Cr subjected to the various heat treatments are tabulated in Table 3, from which it is self-evident that e becomes smaller with a decrease in cooling rate.

The measured data on the rigidity modulus G and its temperature coefficient g in the annealed state are shown in Fig. 5. As shown in the figure, the shape of the curves for the composition dependence of G and g are in close resemblance with those for the composition dependence of E and e , respectively, in which g takes a negative minimum value of -7.00×10^{-5} at a concentration of about 20% Cr and -9.85×10^{-5} at about 54% Cr. The various properties of Fe-Cr alloys in composition near to 20 and 54% Cr are shown in Table 2.

The above results have made it clear that the Invar and Elinvar properties are revealed in Fe-Cr alloys containing about 20 and 54% Cr. However, the cause of

Fig. 4 Relation between Young's modulus and its temperature coefficient, linear coefficient of thermal expansion, density and Vickers hardness and composition in Fe-Cr alloys.

Fig. 5 Rigidity modulus and its temperature coefficient in Fe-Cr alloys.

these anomalies remains unaccounted for as the subject of detailed research in the future.

IV. Conclusions

Measurements of thermal expansion and Young's modulus between low and high temperatures, and the rigidity modulus, density and hardness at room temperature were performed on 23 kinds of Fe-Cr alloys containing 0~59.10% Cr.

The results obtained are as follows:

(1) The curves for the composition dependence of Young's modulus, density and hardness at room temperature show a knee in Fe-Cr alloys containing about 20% Cr.

(2) The thermal expansion curves have a pronounced knee at the magnetic transformation point, and the inclination of the curves above and below the knee against the temperature axis is smaller in the low temperature range. The mean thermal expansion coefficient at $0^{\circ} \sim 40^{\circ}\text{C}$ takes a minimum value of 9.94×10^{-6} at the concentration of 19.90% Cr and 10.62×10^{-6} at 54.10% Cr, thereby revealing a weak Invar property in the alloys.

(3) The Young's modulus vs. temperature curves show a knee corresponding to the magnetic transformation point and the phase transformation point below the magnetic transformation point, besides which an anomaly exists at a relatively low temperature in the concentration range of ca. 17~ca. 39% Cr and the highest transition temperature of 230°C is attained at the concentration of about 25% Cr. Below this temperature

the alloys exhibit the Elinvar property, and the negative minimum value of the temperature coefficient of Young's modulus is -6.81×10^{-5} at the concentration of 19.43% Cr. The alloy with 54.20% Cr which shows a negative value of -9.60×10^{-5} is also found to have the Elinvar property.

(4) The composition dependence of rigidity modulus and its temperature coefficient at room temperature follows a change nearly similar to that of Young's modulus and its temperature coefficient.

Acknowledgments

The authors wish to express their sincere gratitude to Mr. N. Nakamura of their research institute for his co-operation in the measurements of Fe-Cr alloys and also to the staff of the Research Section, Tohoku Tokushuko K.K. for chemical analysis of the alloys.