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Young's moduli of iron–carbon–chromium alloy castings

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The effects of chromium on the anisotropy of Young's modulus and the thermoelastic coefficient of iron–cementite alloy castings were investigated at temperatures up to 773 K. From regression analysis, the Young's moduli of cementite and pearlite were evaluated as functions of carbon and chromium concentrations. The Young's moduli and thermoelastic coefficients of iron–carbon–chromium alloy castings are highly anisotropic. Chromium decreases the ΔE effect due to the ferromagnetism of cementite and increases the Young's moduli of cementite and pearlite. An Elinvar property is observed in the alloy Fe–4 wt% C–4 wt% Cr below the Curie temperature.

1. Introduction

The anisotropy of Young's modulus and the thermal expansion of pure cementite has been demonstrated in previous work [1]. The Young's modulus of cementite in the direction $\langle 0\,1\,0 \rangle$ is larger than that in the direction normal to $\langle 0\,1\,0 \rangle$, and larger than that of pure iron. Cementite has a positive thermoelastic coefficient in the direction normal to $\langle 0\,1\,0 \rangle$ below the Curie point and a minimum Young's modulus in the direction $\langle 0\,1\,0 \rangle$ around the Curie point, which reflects the anisotropy of the magnetostriction of cementite [2–5]. It is also indicated that the Fe–3.23 wt% C alloy casting shows an Elinvar property below the Curie temperature, resulting from the fact that the positive thermoelastic coefficient of cementite counterbalances a negative thermoelastic coefficient of the iron matrix [1].

In the present work Young's modulus and its temperature dependence were examined for iron–carbon–chromium alloy castings to elucidate the effects of chromium on the Young's modulus and its anisotropy in the alloy castings and cementite, and on the composition of iron–carbon–chromium alloys exhibiting an Elinvar property.

2. Experimental procedure

Iron–carbon–chromium alloy castings with different carbon and chromium contents (Table I) were prepared from electrolytic iron, electrode graphite and electrolytic chromium. Mixtures of these materials were induction-melted in alumina crucibles under an argon atmosphere and then were cast into two kinds of steel moulds to produce square-section castings with dimensions 25 mm × 25 mm × 200 mm and round-bar castings of 10 mm diameter. The former castings, which had a columnar structure grown normal to the inner faces of the mould, were annealed at 1173 K for 24 to 60 h and then were air-cooled. Specimen A 2 mm thick, 10 mm wide and 100 mm long for the measurement of Young's modulus was cut off from the location in the castings shown in Fig. 1a. The longitudinal axis of the specimen is normal to the $\langle 0\,1\,0 \rangle$ direction of eutectic cementite. Round-bar castings were zone-melted at a zone-travelling speed of 0.03 mm sec^{-1} by a floating zone-melting method. The castings were annealed at 1173 K for 24 h and air-cooled. Specimen B (2 mm × 10 mm × 60 mm) was cut off from the location exclusive of the initial transient zone and final molten zone in these zone-melted bars as shown in Fig. 1b, where the carbon and chromium distributed uniformly, and its longitudinal axis was parallel to the $\langle 0\,1\,0 \rangle$ direction of eutectic cementite. The Young's moduli of Specimens A and B were measured by a flexural vibration method in the temperature range up to 773 K. For the regression analysis of Young's moduli of iron–carbon–chromium alloy specimens to evaluate those of cementite, the volume fractions of eutectic cementite in the specimens were measured by the point-counting method and the chromium concentration in cementite was determined by electron microprobe analysis.

3. Results and discussion

Young's moduli of Specimens A and B at elevated temperatures are shown in Figs 2 and 3, respectively. When Specimens A have low carbon and chromium concentrations, their Young's moduli are smaller than that of pure iron [1] shown by a broken curve, while

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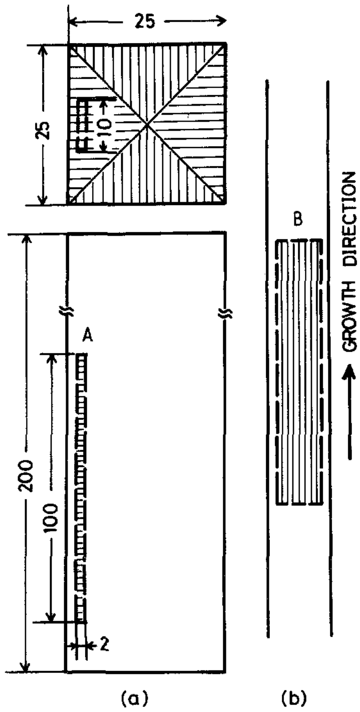

Figure 1 Locations of specimens for Young's modulus measurement on (a) steel mould castings and (b) zone-melted bars. Dimensions in mm.

TABLE I Chemical compositions of alloys

No.	Alloy	Carbon (wt %)	Chromium (wt %)
1	Fe–2Cr–0.6C	0.57	1.87
2	Fe–4Cr–0.5C	0.44	3.83
3	Fe–2C–2Cr	2.09	1.96
4	Fe–2C–4Cr	1.91	3.45
5	Fe–3C–2Cr	3.02	1.93
6	Fe–3C–4Cr	3.04	3.71
7	Fe–3C–6Cr	3.04	5.26
8	Fe–4C–2Cr	4.06	1.87
9	Fe–4C–4Cr	3.97	3.88
10	Fe–3.9C–5Cr	3.89	4.96
11	Fe–3.7C–7Cr	3.64	6.84

the Young's moduli of Specimens B are higher than that of iron†. This means that the Young's modulus of an iron–carbon–chromium alloy is highly anisotropic as indicated for pure iron–cementite alloys [1]. Chromium increases the Young's moduli of iron–cementite alloy castings and its effect is more significant in Specimens A with higher carbon concentrations. Below the Curie temperature (shown by arrows) the slopes of Young's modulus–temperature curves for Specimens A are reduced by the magnetostric-

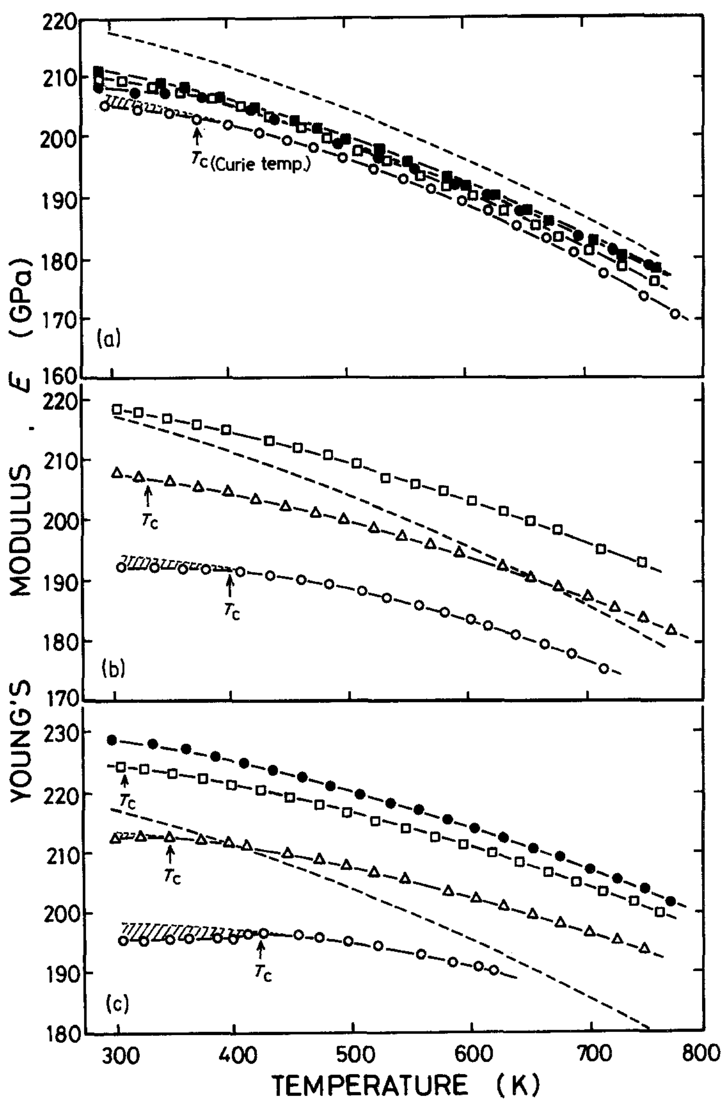

Figure 2 Temperature dependence of Young's modulus of Specimens A in iron–carbon–chromium alloy castings on different carbon and chromium levels. (a): (●) Fe–0.6C–2Cr, (■) Fe–0.5C–4Cr, (○) Fe–2C–2Cr, (□) Fe–2C–4Cr, (– – –) pure iron [1]. (b): (○) Fe–3C–2Cr, (△) Fe–3C–4Cr, (□) Fe–3C–6Cr, (– – –) pure iron. (c): (○) Fe–4C–2Cr, (△) Fe–4C–4Cr, (□) Fe–3.9C–5Cr, (●) Fe–3.7C–7Cr, (– – –) pure iron.

†Young's moduli of Fe–3.23 wt % C and Fe–4.31 wt % C alloy specimens were 225 and 245 GPa, respectively, at room temperature in the previous work [1], which were higher than those shown in Fig. 3 in the present work. The former values were reduced to the latter ones after the annealing at 1173 K for 10 h followed by air-cooling.

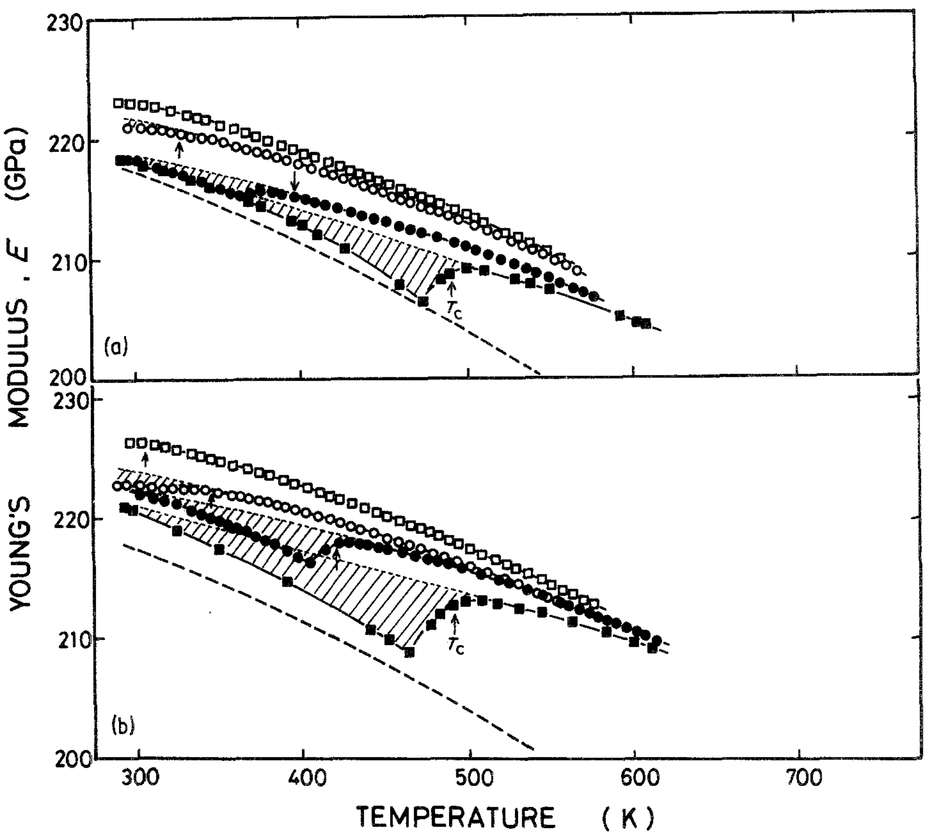

Figure 3 Temperature dependence of Young's modulus of Specimen B in iron–carbon–chromium alloy castings on different carbon and chromium levels. (a): (●) Fe–3C–2Cr, (○) Fe–3C–4Cr, (□) Fe–3C–6Cr, (■) Fe–3.23% C [1], (---) pure iron [1]. (b): (●) Fe–4C–2Cr, (○) Fe–4C–4Cr, (□) Fe–3.9C–5Cr, (■) Fe–4.31% C [1], (---) pure iron.

tion of cementite, and the specimens Fe–3C–2Cr, Fe–4C–2Cr and Fe–4C–4Cr show nearly constant Young's moduli in the temperature range up to the Curie temperature, while Young's moduli of Specimens B show a minimum around the Curie temperature. This indicates that the contribution of the magnetostriction of cementite to the Young's modulus is also anisotropic.

The tie lines which connect the compositions of eutectoid and massive cementite in equilibrium for Fe–C–Cr alloys are given in Fig. 4. Employing the lever rule and the tie lines, volume fractions of massive cementite in the iron–carbon–chromium alloys were evaluated assuming that the densities of massive cementite and eutectoid in the alloys were equal to those of pure cementite and pure eutectoid in iron–carbon alloy. The volume fractions of massive cementite obtained from the lever rule are plotted against those determined by the point-counting method in Fig. 5, showing a fairly good accordance between them. The chromium concentration in pearlite is calculated using the volume fraction of massive cementite and chromium concentrations in the cementite and alloy.

For the regression analysis of Young's moduli of iron–carbon–chromium alloys, parallel and series models of massive cementite and pearlite were employed. In the case of Specimen A, the growth direction of ledeburite is normal to the longitudinal axis of the specimen where tensile and compressive stresses are applied in the measurement of Young's

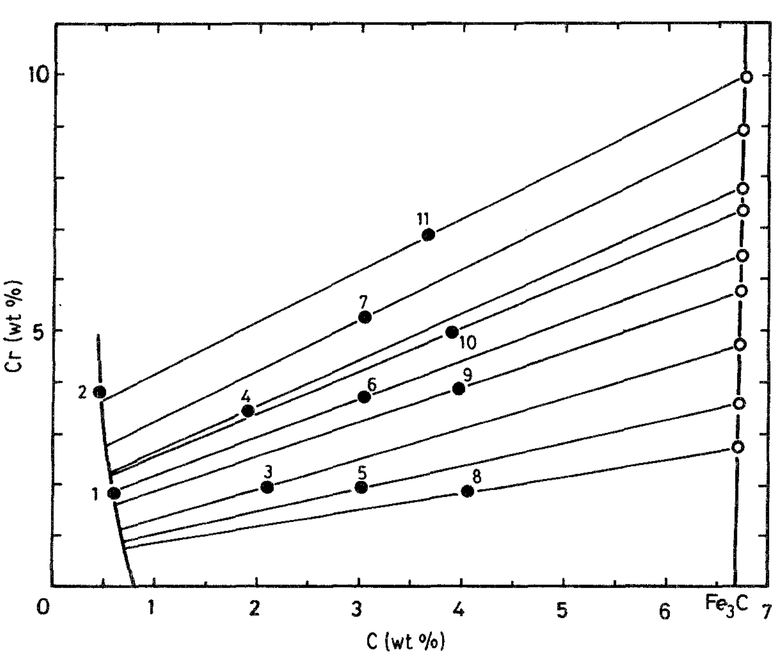

Figure 4 The tie lines connecting the compositions of eutectoid and massive cementite in the alloy castings. Numbers by points indicate Alloy No. in Table I.

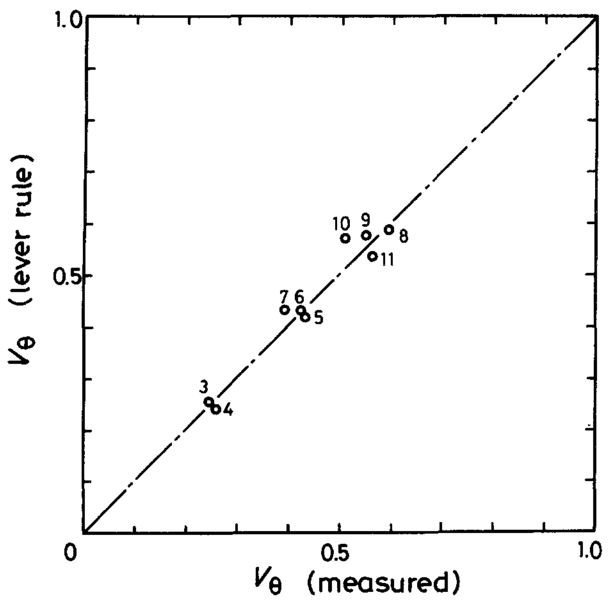

Figure 5 Relationship between the volume fraction of massive cementite obtained from the lever rule and that determined by the point-counting method.

modulus. From the arrangement of the ledeburitic lamellae in Specimen A, the Young's modulus of the specimen is given as an average of the values given by the following equations for parallel and series models, because eutectic cementite is plate-like:

$$E = E_c V_c + E_p V_p \quad (1)$$

$$E = \frac{1}{(V_c/E_c) + (V_p/E_p)} \quad (2)$$

where E, E_c and E_p are the Young's moduli of the casting, massive cementite and pearlite, respectively, and V_c and V_p are the volume fractions of massive cementite and pearlite, respectively. In Equation 1 and 2, E_c and E_p are given as a function of chromium concentration in each phase. For Specimen B, the parallel model is applied from the arrangement of the ledeburitic lamellae which are parallel to the longitudinal axis of the specimen.

The Young's moduli of cementite and pearlite obtained by regression analysis for Specimens A and B are shown in Fig. 6 as functions of temperature and chromium concentrations in these phases. In Specimens A, with increasing chromium concentration, the Young's modulus of cementite increases markedly and that of pearlite increases slightly. The Curie temperature of the cementite is lowered with increasing chromium concentration and becomes below room temperature with a chromium concentration higher than 8 wt % [5]. The contribution of magnetostriction to the Young's modulus, which is observed for cementites with chromium concentrations lower than 8 wt % and is shown by shaded area in the figure, decreases with an increase in chromium concentration. In Specimens B, the magnetic contribution to the Young's modulus is large around the Curie temperature and is reduced with lowering temperature and with increasing chromium concentration. It is noted that the temperature dependence of Young's modulus of paramagnetic cementite in Specimens A and B is reduced with decreasing chromium concentration and that the cementite with chromium concentration less than 2 wt % in Specimen A has a small temperature dependence of Young's modulus above the Curie point. The result is similar to the temperature dependence for pure cementite given by Drapkin and Fokin [6].

The contour lines of Young's modulus of iron-carbon-chromium alloy castings at room temperature

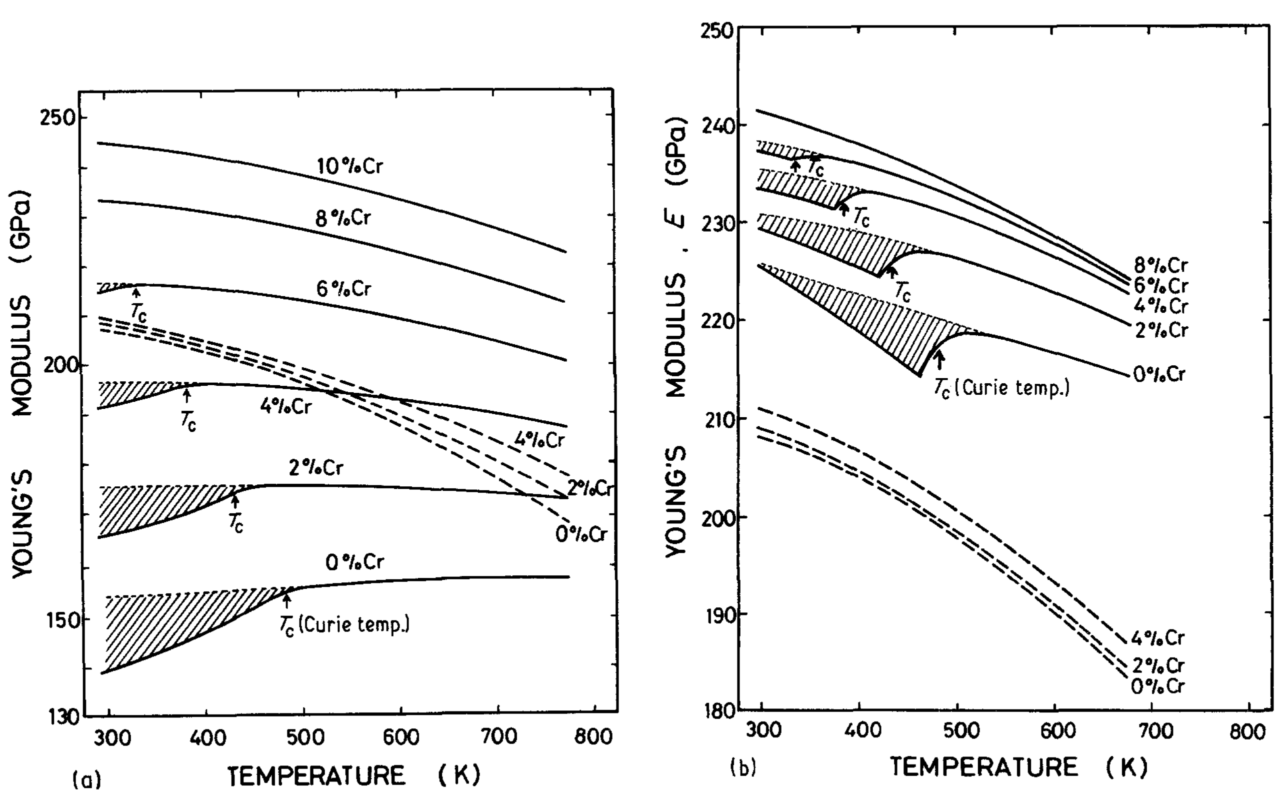

Figure 6 The Young's moduli of (——) cementite and (- - -) pearlite obtained by regression analysis for (a) Specimens A and (b) Specimens B as functions of temperature and chromium concentrations in these phases.

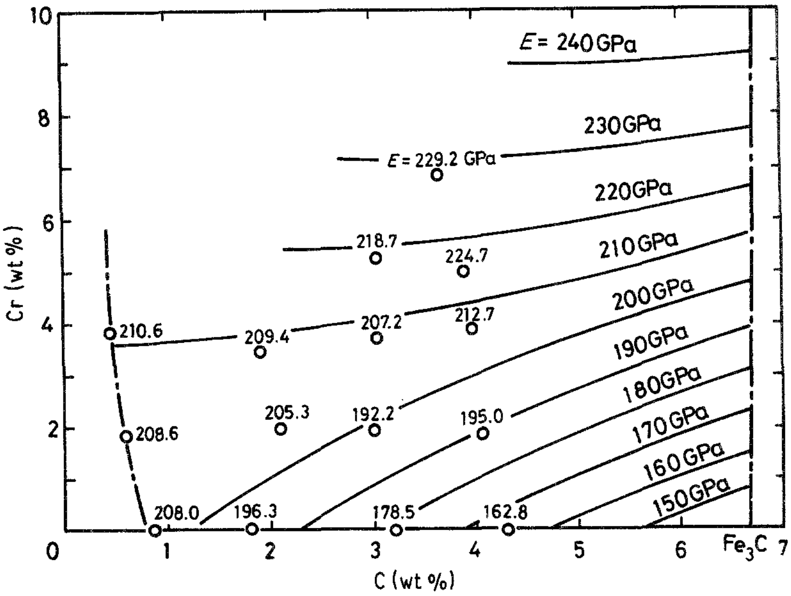

Figure 7 The contour lines of Young's modulus for Specimens A at room temperature. (O) Experimental values.

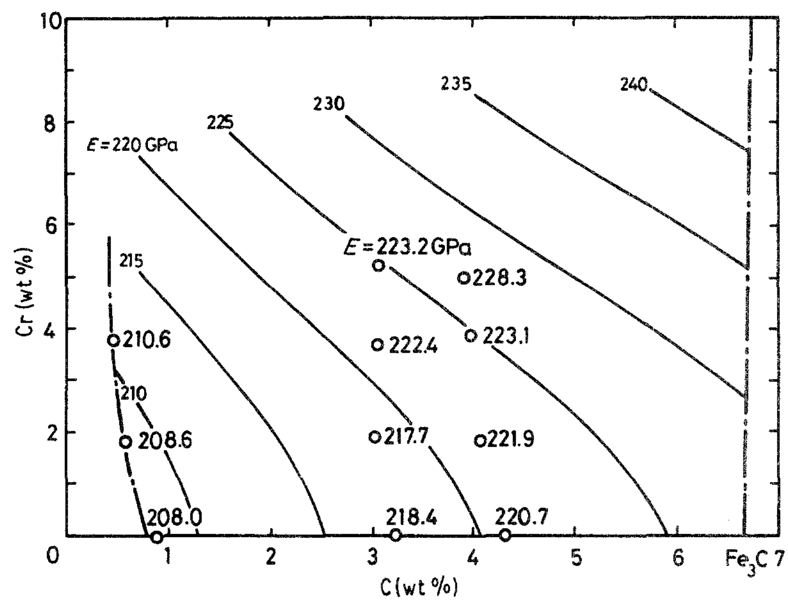

Figure 8 The contour lines of Young's modulus for Specimens B at room temperature. (O) Experimental values.

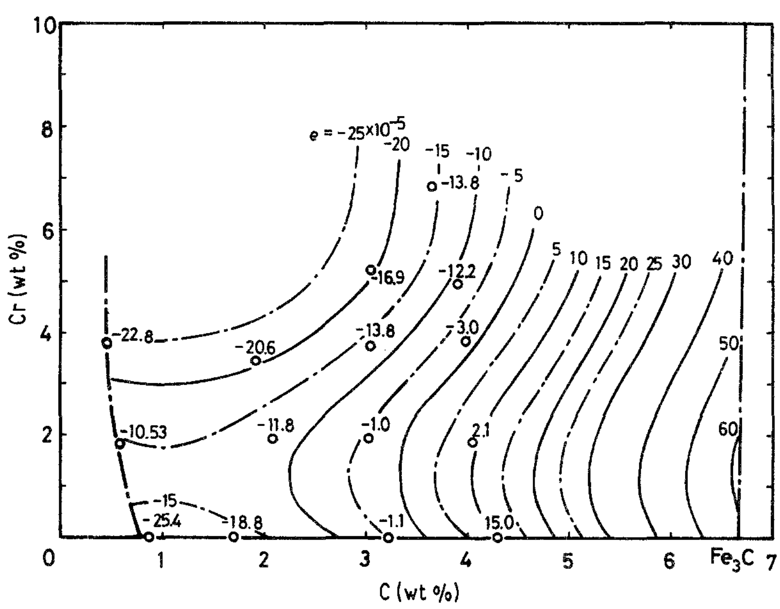

Figure 9 The contour lines of thermoelastic coefficient *e* evaluated in the temperature range from room temperature to 373 K for Specimens A. (O) Experimental values.

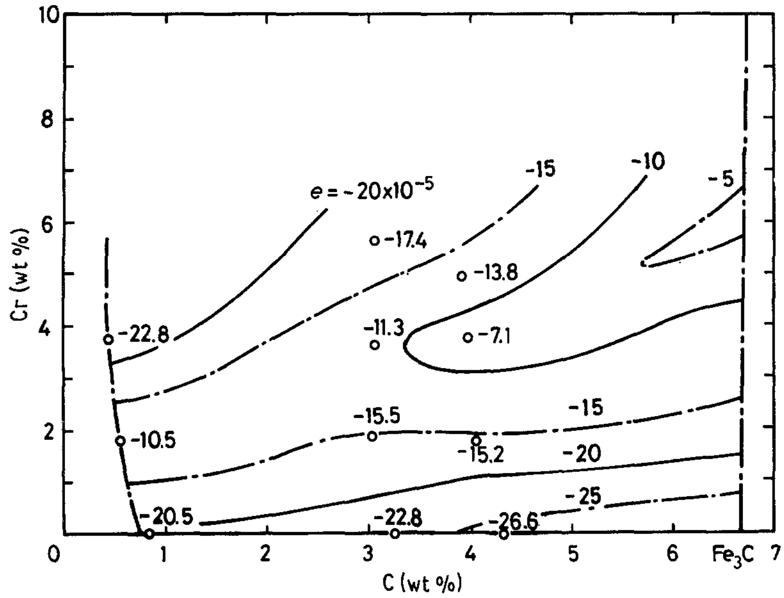

Figure 10 The contour lines of thermoelastic coefficient e evaluated in the temperature range from room temperature to 373 K for Specimens B. (O) Experimental values.

are obtained by regression analysis and are represented in Figs 7 and 8 for Specimens A and B, respectively. In Specimens A, when the chromium content is high the contour lines are roughly parallel to the horizontal axis, indicating that the Young's moduli of the alloy castings depend principally on the chromium content and are independent of the carbon content. In Specimens B, the contour lines are given by the oblique curves and thus the Young's moduli of the alloy castings are affected by both carbon and chromium content.

Thermoelastic coefficients defined by $e = \Delta E/E\Delta T$ (where ΔE is a change in Young's modulus E with a change in temperature (ΔT) on the Young's modulus-temperature curves shown in Figs 2 and 3) for Fe–C–Cr alloy castings were calculated in the temperature range from room temperature to 373 K and are given by contour lines in Figs 9 and 10 for Specimens A and B, respectively. The contour lines for Specimens A are shown by roughly vertical curves with a nose at a chromium content around 1 wt %, and the thermoelastic coefficients are expressed principally as a function of carbon content. With increasing chromium content, the carbon content of the alloy castings

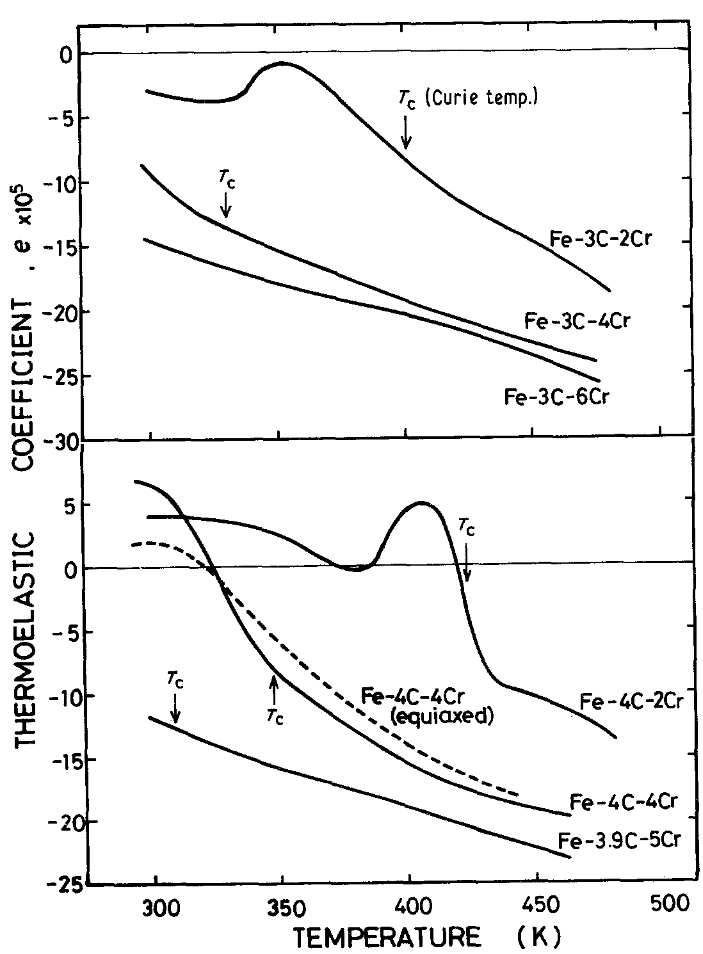

Figure 11 The variation of thermoelastic coefficient for Specimens A with temperature.

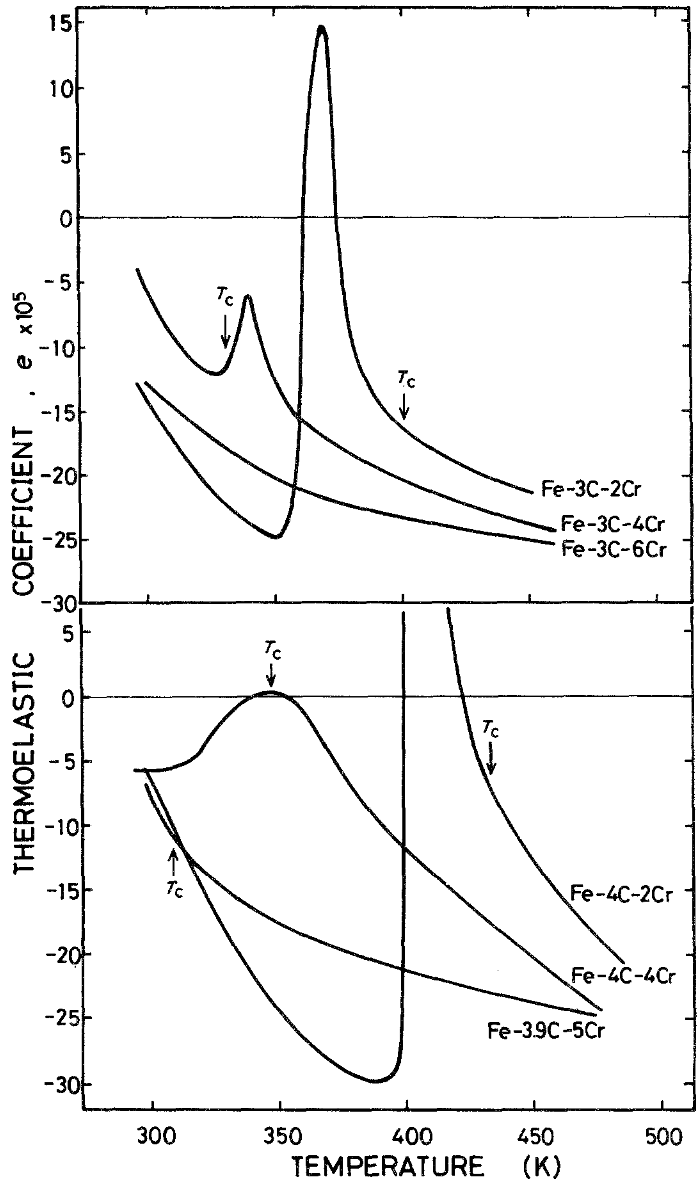

Figure 12 The variation of thermoelastic coefficient for Specimens B with temperature.

exhibiting an Elinvar property, that is $e \simeq 0$, decreases from 3.5 wt % and becomes a minimum at 1 wt % Cr content and then increases. In Specimens B the contour lines lie horizontally, indicating that the thermoelastic coefficients depend mainly on the chromium content. The thermoelastic coefficient for Specimens B, remains negative and the composition of the alloy castings having a small thermoelastic coefficient is limited within a narrow band of very high carbon content and the chromium content of 4 to 6 wt %.

The variation of thermoelastic coefficient with temperature is shown for several alloy castings in Figs 11 and 12. In the figures, the Curie temperature of eutectic cementite in the castings is indicated by arrows. The Curie temperatures of eutectoid cementite, which can be estimated from the chromium concentration in pearlite (see Fig. 4), for Fe–3C–2Cr and Fe–4C–2Cr alloys are 350 and 320 K, respectively, and those for others lie below room temperature, because the chromium concentration of eutectoid cementite is much higher than that of eutectic cementite. The effect of magnetostriction of the eutectoid cementite on the thermoelastic coefficients in the above-mentioned two alloys should be, however, negligibly small because of the small volume fraction of eutectoid cementite in these alloys. In Specimens A, magnetostriction of eutectic cementite increases the thermoelastic coefficient and, with decreasing temperature from the Curie point, the thermoelastic coefficient for the alloys Fe–3C–2Cr and Fe–4C–2Cr shows a maximum and then a minimum. A similar temperature dependence of the thermoelastic coefficient was observed in Specimens B. However, the thermoelastic coefficient–temperature curves for the alloys Fe–3C–2Cr and Fe–4C–2Cr have a relatively sharp peak and a deep valley. Positive thermoelastic coefficients are observed in the Specimens A of Fe–4C–2Cr and Fe–4C–4Cr alloys, at temperatures below 373 and 323 K, respectively. On the other hand, the thermoelastic coefficients for the Specimens B of these alloys are negative in the same temperature ranges. If these alloy castings have a homogeneous equiaxed eutectic structure where the arrangement of eutectic cementite is macroscopically isotropic, the Young's moduli are estimated from the following equation:

$$E_{\mathrm{hom}} = (2E_{\mathrm{a}} + E_{\mathrm{b}})/3 \qquad (3)$$

where E_{hom}, E_{a} and E_{b} are the Young's moduli of the specimens with homogeneous equiaxed eutectic structure, Specimens A and Specimens B, respectively. In

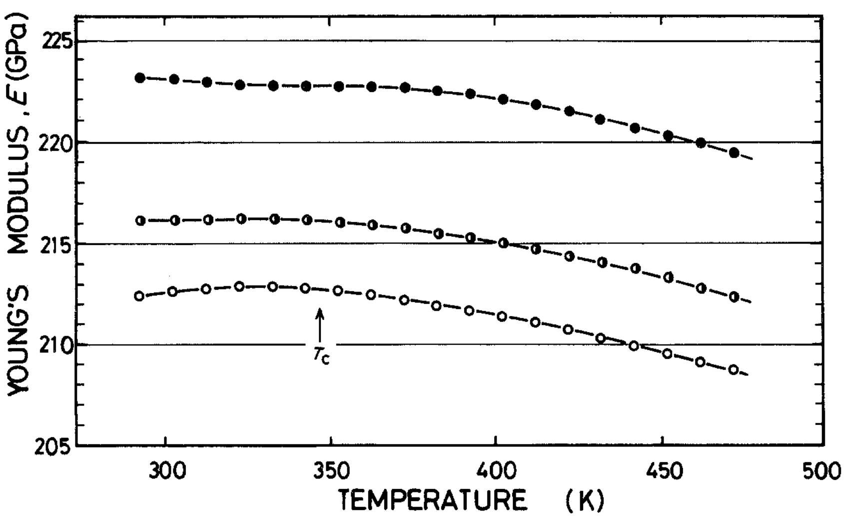

Figure 13 The Young's modulus of the alloy Fe–4C–4Cr with (◑) a homogeneous equiaxed eutectic structure, estimated from the Young's moduli of Specimens (○) A and (●) B of the alloy castings.

Fig. 13, the estimated Young's modulus of the alloy Fe–4C–4Cr is plotted against temperature. The thermoelastic coefficients shown by a broken curve in Fig. 11 approach zero below the Curie temperature.

4. Conclusion

The Young's moduli of iron–carbon–chromium alloy castings were measured at elevated temperatures up to 773 K. From a regression analysis of the Young's modulus of the alloy castings, the Young's moduli of cementite and pearlite were evaluated as functions of carbon and chromium concentrations. The Young's modulus and thermoelastic coefficient are highly anisotropic, especially below the Curie temperature, reflecting the anisotropy of the magnetostriction of cementite. Chromium decreased the effect of ferromagnetism of cementite on the Young's modulus (the ΔE effect) and increases the Young's moduli of cementite and pearlite. An Elinvar property is observed in the alloy Fe–4C–4Cr below the Curie temperature.

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