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# The Nature of the K-state in the System of Iron and Aluminium\*

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## Synopsis

The electrical resistivity and the thermal expansion have been measured with iron-aluminium alloys containing from 9.75 to 11.66 % aluminium, by treating them isothermally at the temperatures between 200° and 300°C and also by cooling them to -183°C from quenched state, K-state and Fe<sub>3</sub>Al-ordered state. According to the results obtained, the alloys containing more than 10.65 % aluminium, which show the characteristics of the K-state at first, transform into the Fe<sub>3</sub>Al phase after passing through the K-state during the isothermal treatment. Further, the amount of the K-state in the alloys containing from 10.5 to 10.9 % aluminium decreases at -183°C, and the alloys of more than 10.9 % aluminium show the characteristics of the Fe<sub>3</sub>Al phase at that temperature. Thus, it can be concluded that the K-state observed at room temperature is essentially of the Fe<sub>3</sub>Al superstructure. However, the alloys containing less than 10.5 % aluminium remain as the K-state even at -183°C. The difference in the nature between the alloys containing more and less than 10.5 % aluminium remains to be clarified.

## I. Introduction

Thomas<sup>(1)</sup> found an anomaly in the electrical resistance of iron and aluminium alloys containing about 10 wt. % aluminium, and named this anomalous state "K-state" because of the complexity of the phenomenon hardly explainable at that time. Independent of Thomas, one of the present authors<sup>(2)</sup> reported anomalies in the physical properties of iron-aluminium alloys in the same concentration range in the same year, and proposed the phenomenon to be related to a short-range order, Fe<sub>13</sub>Al<sub>3</sub>. From these results, it may be defined that the K-state in the system of iron and aluminium is an anomalous state having its central composition of Fe<sub>13</sub>Al<sub>3</sub>. The result in common with each other is that the alloys in the concentration range of about 11~13 % aluminium are composed of the K-state and the Fe<sub>3</sub>Al-ordered state at lower temperatures, but only of the Fe<sub>3</sub>Al-ordered state at higher temperatures; with the rise of temperature, the characteristics of the K-state and then those of the Fe<sub>3</sub>Al phase appear in succession. Similar anomalies in electrical resistance were found by Yano<sup>(3)</sup> in nickel and chromium alloys, and later by some workers in a number of some other

\* The 1245th report of the Research Institute for Iron, Steel and Other Metals. Reported in Japanese in the J. Japan Inst. Metals, 30 (1966), 930.

- (1) H. Thomas, Z. Metallkde., 41 (1950), 185; Z. Phys., 129 (1951), 219.
- (2) H. Saitô, J. Japan Inst. Met., B-14 (1950), No. 5, 1; 6 (in Japanese).
- (3) J. Yano, Nippon Nickel Review, 19 (1941), 17.

alloy systems. Lately, some observations have also been reported of the K-state in the systems of iron and aluminium<sup>(4,5)</sup>, nickel and chromium<sup>(6,7)</sup> and nickel and tungsten<sup>(8)</sup> by X-ray analysis and of nickel, iron and molybdenum<sup>(9)</sup> by electronmicroscopy, confirming that the state is of the short-range order\*. The existence of  $\text{Fe}_{13}\text{Al}_3$  phase was supported by Rassmann et al.<sup>(10)</sup> from the measurements of magnetic properties and thermal expansion, and roentgenographically by Taylor et al.<sup>(7)</sup> and Ebel et al.<sup>(11)</sup> Davies, however, reported that the K-state was structurally of  $\text{Fe}_3\text{Al}$  type according to X-ray analysis.

Therefore, it is very important to determine whether the K-state is a phase of the short-range order of  $\text{Fe}_3\text{Al}$  or of  $\text{FeAl}$  or a special phase called the K-state or  $\text{Fe}_{13}\text{Al}_3$ . In the present study, the electrical resistance and the volume change of the iron-aluminium K-state alloys were measured simultaneously in the temperature range from  $300^\circ$  to  $-183^\circ\text{C}$ , and its nature was considered from the results thus obtained.

## II. Specimens and methods of measurement

As elements of the alloys, electrolytic iron of 99.9 % purity and aluminium of 99.99 % purity were used. To prepare an alloy, 2 kg of the metals mixed in suitable proportion was melted in a high frequency furnace and cast into an iron mould. After a homogenizing treatment at  $1200^\circ\text{C}$  for 9 hr, the ingot was forged and rolled into a plate, 1 mm thick, and then specimens, 1 mm $\times$ 1 mm $\times$ 100 mm, were cut from it.

The specimens were annealed at  $1000^\circ\text{C}$  for 2 hr in vacuo and then cooled in furnace. The annealed specimens were sealed in vacuo in a silica tube, 1.5 mm in inner diameter, and again annealed at  $850^\circ\text{C}$  (the temperature higher than Curie point) for 2 hr and then quenched in water. For the isothermal treatment, two methods were used: For the treatments at temperatures from  $200^\circ$  to  $300^\circ\text{C}$ , the specimens were immersed into a salt-bath (1  $\text{NaNO}_3$  + 1  $\text{NaNO}_2$ ). In this case the oxidation of the specimen surface was negligibly small. For the treatments above  $300^\circ\text{C}$ , the specimens were sealed again in a silica tube in vacuo and heated in an electric furnace or in a salt-bath.

According to the results of chemical analysis, the aluminium contents in the specimens were 9.75, 9.90, 10.44, 10.65, 10.74, 10.99, 11.13, 11.57, and 11.66 wt. %.

The electrical resistance was measured by a potentiometer with the sensitivity

- (4) R.G. Davies, *J. Phys. Chem. Solids*, **24** (1963), 985.
- (5) A. Taylor and R.M. Jones, *J. Phys. Chem. Solids*, **6** (1958), 16.
- (6) O. Bear, *Naturwiss.*, **43** (1956), 298.
- (7) A. Taylor and K. Hinton, *J. Inst. Met.*, **81** (1952), 169.
- (8) H.G. Baer, *Z. Metallkde.*, **56** (1965), 79.
- (9) F. Pfeifer und I. Pfeifer, *Z. Metallkde.*, **55** (1964), 398.
- (10) G. Rassmann and H. Wich, *Z. angew. Phys.*, **13** (1961), 172.
- (11) H. Ebel, J. Heinrich und H. Wilfert, *Z. angew. Phys.*, **15** (1963), 189.

\* In this paper, "the short-range order" means not only a usual short range order, but also the heterogeneously ordered state.

of 10<sup>-7</sup>V, connected with iron lead wires in the vacuum electric furnace, during the isothermal annealing at various temperatures or at room temperature after the isothermal annealing for various hours. For the measurement of the resistance at the temperatures lower than room temperature, the specimens held in small knife edges were immersed in liquid air (-183°C), half-congealed methyl alcohol (-116°C) and a mixture of methyl alcohol and dry ice (-72°C).

Using the specimens connected to lead wires, the volume change was measured simultaneously with the electrical resistance by a dilatometer of horizontal type.

### III. Results of measurements

#### 1. Changes in electrical resistivity and volume at room temperature and at high temperatures

##### (a) Electrical resistivity

Fig. 1 shows the equilibrium resistivity at various temperatures obtained with 11.13% aluminium alloy after the isothermal annealing at each temperature. The time required to reach an equilibrium stage becomes shortened with the rise of annealing temperature; 4 hours are sufficient at 490°C, but even 90 hours or more are insufficient at 226°C. As seen in the figure, it forms S-curve<sup>(1)</sup>, which is characteristic of the K-state alloy.

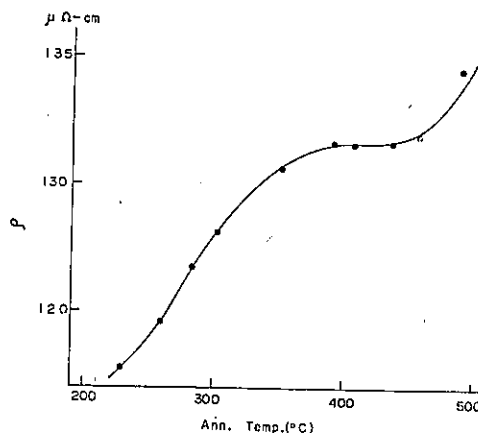


Fig. 1. Equilibrium electrical resistivity of 11.13% Al alloy at each temperature.

As an example of the change in resistivity of the iron-aluminium alloys measured at room temperature after the isothermal annealing at 200°~300°C for varying time, Fig. 2 shows the relative change during the isothermal annealing at 220°C; the ordinate represents the percentage change in resistivity comparing with that of the quenched state. As shown in the figure, the resistivity of all the alloys decreases at the beginning and then increases. In the alloys of 9.75 and 9.90% aluminium, the decrease of resistivity at the beginning stage continues for about 40 min. The resistivities of 9.75, 9.90 and 10.44% aluminium alloys do not

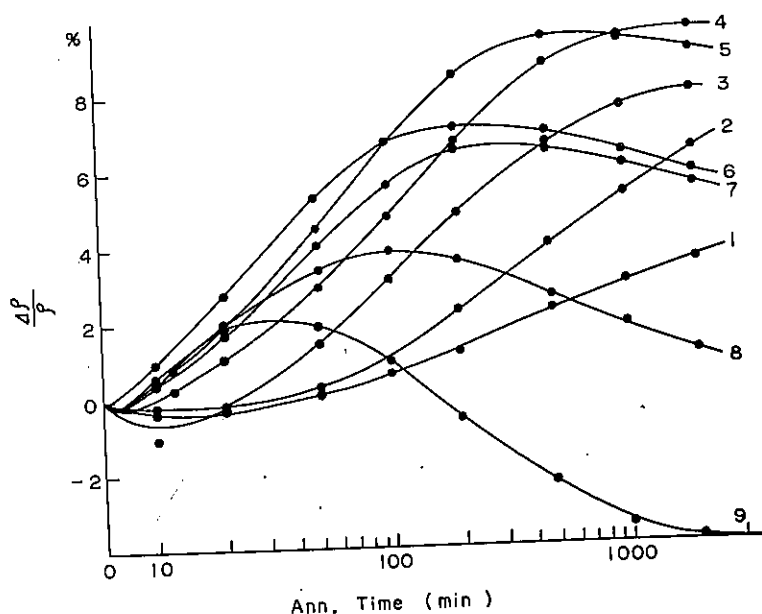


Fig. 2. Relaxation curves of electrical resistivity of Fe-Al alloys during the isothermal annealing at 220°C.  
1: 9.75, 2: 9.90, 3: 10.44, 4: 10.65, 5: 10.74, 6: 10.99, 7: 11.13, 8: 11.57, 9: 11.66 % Al.

reach their final values even after the isothermal annealing for 2000 min. In the case of the 10.74 % aluminium alloy, the decrease of the resistivity at the initial stage continues only for 2 min and then increases rapidly, reaching a maximum after 600 min. It decreases thereafter to an equilibrium value. This decrease of resistivity after attaining a maximum in the iron-aluminium alloys has been found for the first time by the present investigation, the amount of this decrease becoming larger with the increase of aluminium content. As already mentioned in (I), in the concentration range from 11.6 to 13.9 % aluminium, the characteristics of the K-state (or  $\text{Fe}_{13}\text{Al}_3$  phase) and the  $\text{Fe}_3\text{Al}$  superstructure appear in succession with the rise of temperature. Thus, it can be considered that the decrease of resistivity after attaining a maximum is due to the transformation of the K-state into the  $\text{Fe}_3\text{Al}$  phase after prolonged isothermal treatment.

When treated isothermally at such a high temperature as 300°C, the increasing rate of resistivity becomes greater in all cases. In the case of the 10.65% aluminium alloy, the resistivity also attains an equilibrium value, but thereafter it shows no longer any decrease. Moreover, the higher the aluminium content in these alloys, the greater become the increasing rate and the final value.

Electric resistivities at room temperature of iron-aluminium alloys after the quenching,  $\rho_{23^\circ\text{C}}$ , and after the isothermal annealing at 270°C for 140 hr,  $\rho_{23^\circ\text{C}}^{\text{A}}$ , are shown in Fig. 3. While  $\rho_{23^\circ\text{C}}$  increased linearly with the aluminium content showing that the alloys in the measured concentration range comprise a homogeneous solid

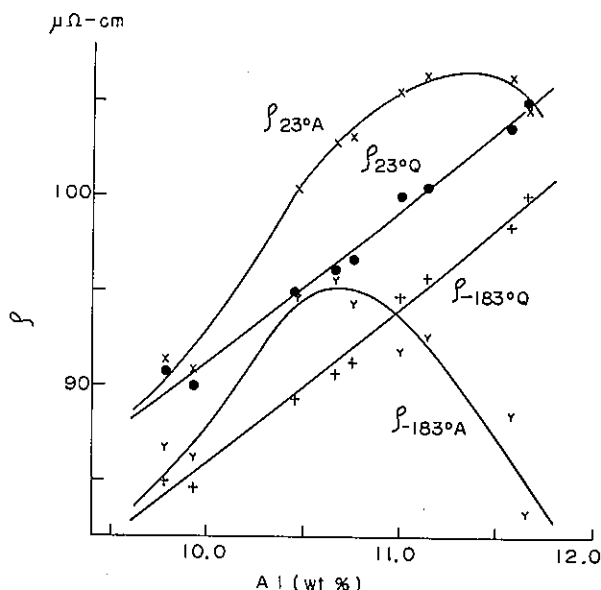


Fig. 3. Electrical resistivity vs. concentration curves of Fe-Al alloys.

$\rho_{23^{\circ}Q}$ : measured at 23°C after quenching,  $\rho_{23^{\circ}A}$ : measured at 23°C after the isothermal annealing of 270°C  $\times$  140 hr,  $\rho_{-183^{\circ}Q}$ : measured at -183°C after quenching,  $\rho_{-183^{\circ}A}$ : measured at -183°C after the isothermal annealing.

solution after quenching,  $\rho_{23^{\circ}A}$  begins to increase exponentially with the aluminium content and then decreases transforming into the  $Fe_3Al$  long-range order after passing through a maximum at about 11.3% aluminium, and  $\rho_{23^{\circ}A}$  in the 11.66% aluminium alloy becomes somewhat smaller than  $\rho_{23^{\circ}Q}$ .

$\Delta\rho_{23^{\circ}} = \rho_{23^{\circ}A} - \rho_{23^{\circ}Q}$ , that is, the equilibrium-increased amount of resistivity in iron-aluminium alloys by the formation of the K-state is shown in Fig. 4. It must be noticed that the figure does not represent the true amount in increase, because the resistivity in the alloys containing more than 10.74% aluminium decreases after the prolonged isothermal treatment as seen in Fig. 2. As seen in Fig. 4,  $\Delta\rho$  in the concentration below 10.65% aluminium increases exponentially with the aluminium content, and then decreases rapidly after passing through a maximum at about 10.74% aluminium (about  $Fe_{13}Al_3$ ), and finally reaches a small negative value in the 11.66% aluminium alloy.

In Fig. 5, tangent values,  $d\rho/dt$ , at the point of  $\Delta R/R = 0.5\%$  obtained from the resistivity-annealing time curves at room temperature after isothermal treatments for various hours are shown. As seen in the figure,  $d\rho/dt$  is almost constant in the aluminium content less than 9.75%, but when the aluminium content increases, the value varies so rapidly that it can not be measured in the alloys of more than 11% aluminium.

Fig. 6 shows the relative change of resistivity measured during the isothermal annealing at 230°C. As shown in the figure, the change in resistivity during

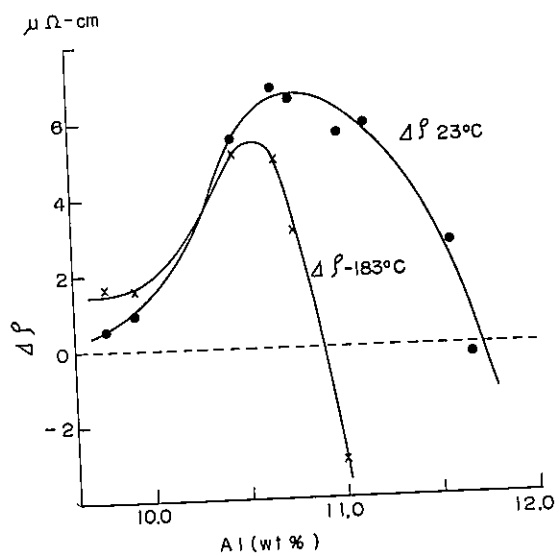


Fig. 4. Increasing amount of electrical resistivity of Fe-Al alloys measured at 23°C and -183°C after the isothermal annealing of 270°C  $\times$  140 hr.

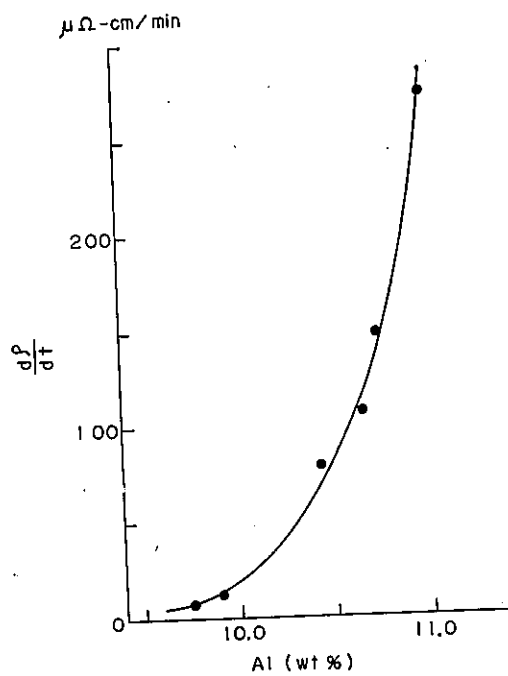


Fig. 5. Growing velocity of the K-state during the isothermal annealing at 230°C.

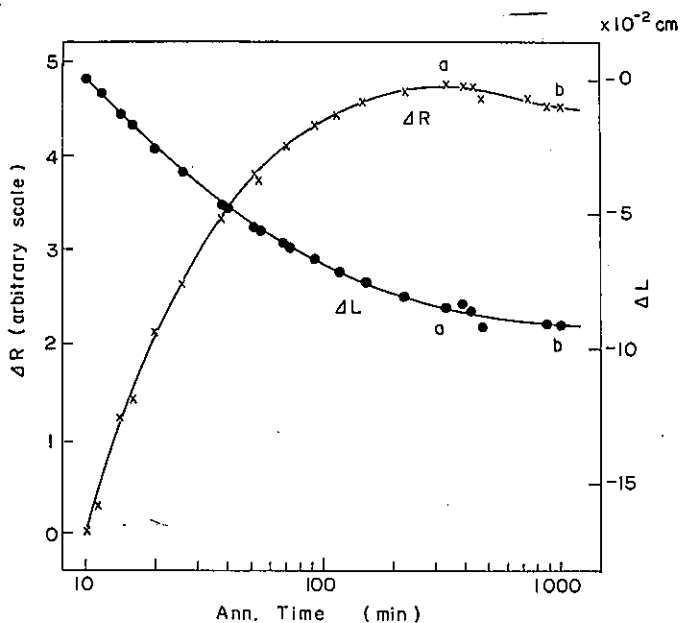


Fig. 6. Relative change of electrical resistivity and volume of 11.13 % Al alloy during the isothermal annealing at 230°C.

the isothermal treatment at 230°C is almost similar to that measured at room temperature after isothermal treatments for varying times (Fig. 2). Thus, it can be confirmed that the maximum observed after the treatment for about 300 to 400 min (a) corresponds to the formation of the K-state, and that the decrease of resistivity after the prolonged treatment (b) is due to the transformation of the K-state into the  $\text{Fe}_3\text{Al}$  superstructure.

#### (b) Thermal expansion

The change in volume in the 11.13 % aluminium alloy during the isothermal annealing at 230°C measured simultaneously with the electrical resistivity is also shown in Fig. 6. As shown in the figure, the volume of the alloy first decreases in inverse proportion to the change of resistivity and reaches its final value, showing no anomaly at the annealing time marked with a or b in the resistivity curve, in which the K-state reaches its maximum or the K-state begins to transform into the  $\text{Fe}_3\text{Al}$  superstructure. This phenomenon seems to be essential to elucidate the nature of the K-state.

### 2. Changes in electrical resistance and volume at low temperatures

#### (a) Electrical resistivity

The resistivity change in the 11.13 % aluminium alloy has been measured while cooling down to  $-183^\circ\text{C}$  from the quenched state, the state marked with (a) in Fig. 6, that is, the K-state, and also the state at the beginning of the transformation into  $\text{Fe}_3\text{Al}$  superstructure from the K-state (b). The results of these



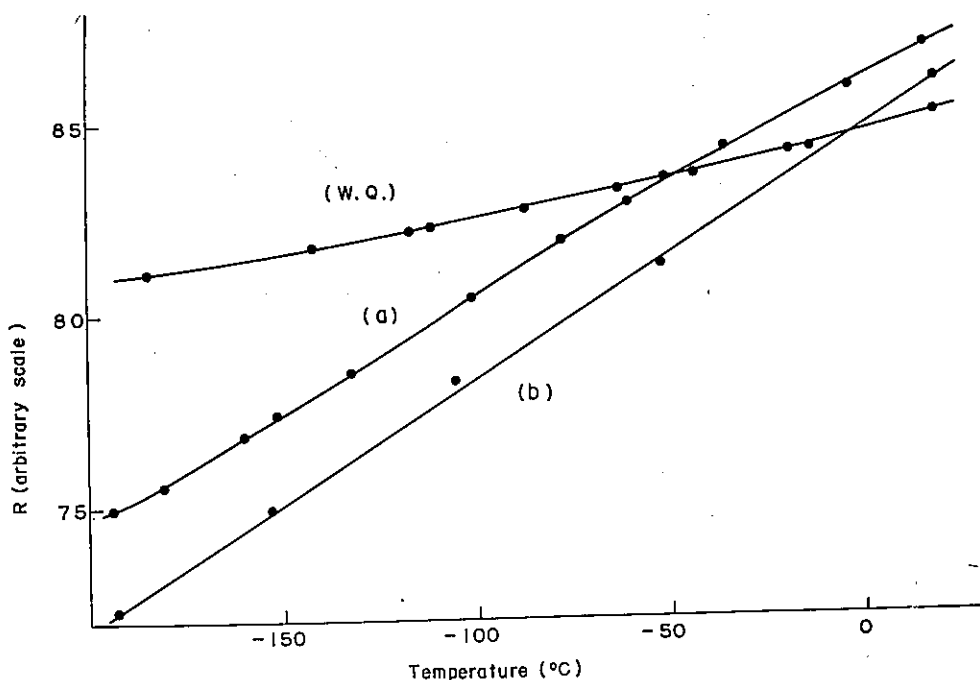


Fig. 7. Temperature change of electrical resistivity of 11.13 % Al alloy during cooling to  $-183^{\circ}\text{C}$  from quenched state (WQ), K-state (a) and  $\text{Fe}_3\text{Al}$ -ordered state (b), respectively.

measurements are shown in Fig. 7. As shown in the figure, the temperature coefficient of resistivity is smallest in the quenched state (WQ) and largest in the state transformed into  $\text{Fe}_3\text{Al}$  superstructure (b). As a result, it can be made clear that the state showing a larger resistivity at  $230^{\circ}\text{C}$  or at room temperature than that of the quenched state vanishes at  $-50^{\circ}\text{C}$  and in fact the condition reverses at the temperature. It is very significant that the residual resistivity in the K-state alloy having a large resistivity at room temperature is smaller than that of the quenched alloy having a small resistivity at room temperature, and also that the residual resistivity in the same alloy varies depending upon the state after various treatments.

The temperature change of resistivity for all the specimens was measured after quenching and isothermal annealing at  $270^{\circ}\text{C}$  for 140 hr, some of the results obtained being shown in Fig. 8. In the alloys shown in the figure, those containing 9.90 and 10.44 % aluminium remain in the K-state after the isothermal treatment, and that of 11.66 % aluminium transforms into the  $\text{Fe}_3\text{Al}$  superstructure after passing through the K-state. As seen in Fig. 8, the resistivity at room temperature of the former increases more after the isothermal treatment than after the quenching, but the temperature coefficient of resistivity changes a little, and the increasing amount of resistivity at room temperature might be held even at  $0^{\circ}\text{K}$ .

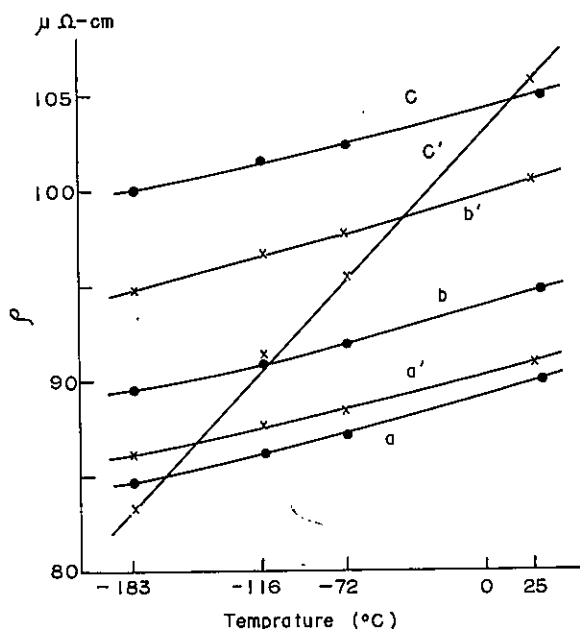


Fig. 8. Some examples of the temperature change of electrical resistivity of Fe-Al alloys below room temperature after quenching and the isothermal annealing of  $270^{\circ}\text{C} \times 140$  hr. a, b, c: measured after quenching, a', b', c': measured after the isothermal annealing of  $270^{\circ}\text{C} \times 140$  hr, a, a': 9.90, b, b': 10.44, c, c': 11.66 % Al.

On the contrary, in the alloys containing more than 10.74 % aluminium, the increasing amount of resistivity at room temperature due to the isothermal treatment decreases and the temperature coefficients become larger with the aluminium content, resulting in a decrease of the residual resistivity as is shown in the 11.66 % aluminium alloy in Fig. 8.

In Fig. 3, the resistivities,  $\rho_{-183^{\circ}\text{Q}}$  and  $\rho_{-183^{\circ}\text{A}}$ , obtained at  $-183^{\circ}\text{C}$  for iron-aluminium alloys after the quenching and after the isothermal annealing at  $270^{\circ}\text{C}$  for 140 hr, respectively, are also shown in comparison with those obtained at  $23^{\circ}\text{C}$ . From the results shown in the figure, it must be noticed that the alloys are in a perfect disordered state at these temperatures after the quenching and their temperature coefficients are almost constant, because the curves to the concentration of  $\rho_{-183^{\circ}\text{Q}}$  and  $\rho_{23^{\circ}\text{Q}}$  are almost parallel with each other.  $\rho_{-183^{\circ}\text{A}}$  begins to increase in the way similar to  $\rho_{23^{\circ}\text{A}}$  and then rapidly decreases after passing through a maximum at about 10.7 % aluminium content, and becomes smaller than  $\rho_{-183^{\circ}\text{Q}}$  in the concentration above 10.95 % aluminium. The difference between  $\rho_{-183^{\circ}\text{A}}$  and  $\rho_{-183^{\circ}\text{Q}}$ , that is, the amount of the K-state at  $-183^{\circ}\text{C}$ ,  $\Delta\rho_{-183^{\circ}}$ , is also shown in Fig. 4 in comparison with  $\Delta\rho_{23^{\circ}}$ . In the concentration below 10.4 % aluminium,  $\Delta\rho_{-183^{\circ}}$  first increases with the aluminium content just as does  $\Delta\rho_{23^{\circ}}$ , but after reaching its maximum at about 10.5 % concentration of aluminium, it decreases showing

that the alloys of more than 10.9% aluminium transform into the  $\text{Fe}_3\text{Al}$  superstructure, because  $\Delta\rho_{-183^\circ}$  in the above-mentioned concentrations becomes negative. It is very important that while the alloys in the concentration range from 10.95 to 11.66% of aluminium are in the K-state at  $23^\circ\text{C}$ , they are in  $\text{Fe}_3\text{Al}$  ordered state at  $-183^\circ\text{C}$ . The relations between the temperature coefficient of resistivity and the alloying concentration at  $-183^\circ\text{C}$  can be obtained as shown in Fig. 9. It must be noticed that the temperature coefficients at low temperatures are almost constant irrespective of the aluminium content after quenching, but after the isothermal treatment, it increases continuously with the aluminium content. Any effect due to the existence of the K-state is not observed.

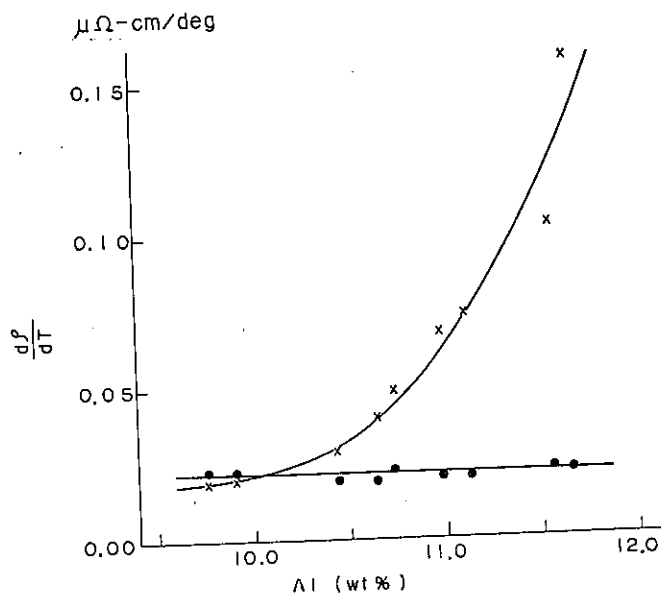


Fig. 9. Temperature coefficient of electrical resistivity of Fe-Al alloys after quenching and the isothermal annealing of  $270^\circ\text{C}\times 140$  hr.

(b) Thermal expansion

In Fig. 10 are shown the results on the thermal expansion measured simultaneously with the electrical resistivity of the 11.13% aluminium alloy in Fig. 7, which was cooled down to  $-183^\circ\text{C}$  immediately after quenching and also after heating at  $230^\circ\text{C}$  until the resistivity reached its maximum due to the K-state (a) and began to transform into the  $\text{Fe}_3\text{Al}$  superstructure (b) (cf. Fig. 6). As seen in the figure, the thermal expansion coefficient does not show any difference despite the state of the alloy, and the volume difference at room temperature might be held to  $0^\circ\text{K}$ .

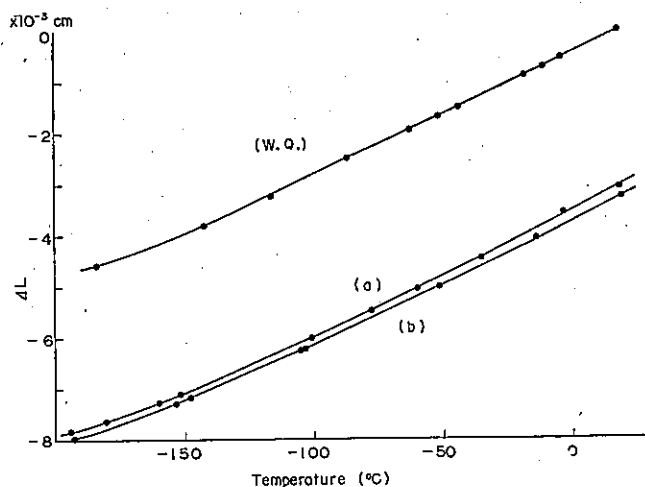


Fig. 10. Linear expansivity curves of 11.13 % Al alloy below room temperature cooled from quenched state (WQ), K-state (a) and  $\text{Fe}_3\text{Al}$ -ordered state (b).

#### IV. Discussion

Some of the results in the present investigation are similar to those obtained previously by other workers: First, the equilibrium resistivity-temperature curve obtained with 11.13 % aluminium alloy after isothermal annealings at various temperatures forms S-curve, which is the typical in the K-state alloy (Fig. 1)<sup>(1)</sup>. Second, the effect due to the K-state is largest in the concentration range of about 10.7 to 10.8 % aluminium ( $\text{Fe}_{13}\text{Al}_3$ ) (Figs. 3 and 4)<sup>(1,2)</sup>. Third, the volume of iron-aluminium alloys contracts with the growth of the K-state (Fig. 6)<sup>(11)</sup>. The decrease of electrical resistivity at the initial state of the isothermal annealing after quenching may be explained by the annihilation of excess vacancies produced by quenching<sup>(12)</sup>.

The followings are the unique results obtained by the present investigation.

##### 1. K-state at high temperatures

As shown in Fig. 2, the alloys containing less than 10.65 % aluminium remain in the K-state after the isothermal annealing at 220°C, but those of more than 10.74 % aluminium transform into the  $\text{Fe}_3\text{Al}$  long-range order superstructure after passing through the K-state. These anomalous behaviours in iron-aluminium alloys have been found for the first time by the present investigation. Thomas<sup>(1)</sup> also measured the change of electrical resistivity of iron-aluminium alloys in the K-state during isothermal annealing, but could not observe this phenomenon because the temperatures were limited below 200°C at which the growing velocity of the K-state was too slow to be observed and above 300°C at which the velocity was too fast to be measured. Behaviours similar to that in Fig. 2 were found in

(12) L.A. Kudryavtseva, L.M. Panova, L.Ya. Popov and V.F. Sukhovorov, *Phys. Met. and Metallog.*, 15 (1963), No. 3, 108.

nickel-chromium alloys<sup>(13,14)</sup> and other alloys<sup>(15)</sup>, and explained the phenomenon to be the transformation of the K-state into the  $\text{Ni}_2\text{Cr}$  superstructure<sup>(13)</sup>.

It is of great significance that in Fig. 5  $d\rho/dt$  at the time when the electrical resistivity of the iron-aluminium alloys increased by 0.5 %, that is, the growing velocity of the K-state<sup>(16)</sup> shows a monotonous curve in the whole measured concentration range, without any anomalous difference between the alloys remaining in the K-state and those transforming into the  $\text{Fe}_3\text{Al}$  superstructure by isothermal treatment. According to these results, it can be confirmed that the essential difference between the K-state and the  $\text{Fe}_3\text{Al}$  superstructure does not exist in the initial stage of nucleus-growing but exists only in their final stages.

As shown in Fig. 6, it deserves attention that any change of volume is not observed during the transformation of the K-state into the  $\text{Fe}_3\text{Al}$  long-range order (a-b). Thus, it is warrantable that the transformation between the two states is not caused by a rearrangement of atoms.

## 2. K-state in low temperature range

As shown in Figs. 3 and 4, the K-state of iron-aluminium system exists in the concentration range from 9.5 to 11.7 % aluminium at 23°C, but at -183°C this range is limited below 10.9 % aluminium and beyond it the alloys are assumed to be in the  $\text{Fe}_3\text{Al}$  superstructure phase. As seen in Figs. 7, 8 and 9, the temperature coefficient of electrical resistivity shows a remarkable difference depending upon the heat treatment. In the relation between the coefficient and the alloying concentration, the coefficients measured become very large and show a considerable difference between the K-state and the  $\text{Fe}_3\text{Al}$ -ordered state, and any discrepancy between two states was not observed despite the fact that they are almost the same after quenching. Thus, it can be concluded that the alloys containing 11 to 11.7 % aluminium are essentially in the  $\text{Fe}_3\text{Al}$  ordered state at low temperatures, although they show an apparent K-state at room temperature owing to the large temperature coefficient of electrical resistivity. Further investigations are yet to be carried out as to the reason why the temperature coefficients of electrical resistivity in the same iron-aluminium alloy at low temperatures differ according to the quenched state, the K-state and the ordered state, and why the coefficients in the alloys of the same K-state containing less than 10.5 % aluminium are smaller. According to the results by one of the present authors<sup>(2)</sup>, the electrical resistivity vs. temperature curves of  $\text{Fe}_3\text{Al}$  superstructure alloys in the temperature range from room temperature to the order-disorder transformation temperature are concave toward the temperature axis, and those after quenching are smaller than those after slow cooling. Accordingly, it can be considered that the lattice vibration of the  $\text{Fe}_3\text{Al}$  superstructure alloys is specially violent, but it must be noticed that as

(13) R. Nordheim and N.J. Grand, *J. Inst. Met.*, **12** (1953/54), 440.

(14) H.G. Baer, *Z. Metallkde.*, **49** (1958), 614.

(15) W. Köster, *Z. Metallkde.*, **51** (1960), 716.

(16) L.P. Weiberg and S.L. Quimby, *J. Phys. Chem. Solids*, **24** (1963), 1251.

seen in Fig. 10, the thermal expansion coefficients do not show any great difference among the disordered state, the K-state and the ordered state. Therefore, it is difficult to relate this anomaly of electrical resistivity to the lattice vibration, and the change in band structure must be taken in consideration as in the case of nickel-chromium alloys<sup>(17)</sup>.

### 3. Nature of the K-state

As mentioned above, it is evident that a part of the K-state at room temperature of the alloys containing more than about 11% aluminium is only apparent owing to the large temperature coefficients of electrical resistivity. It can be concluded, therefore, that the K-state in the iron-aluminium alloys containing more than 11% aluminium is essentially in the beginning stage of the  $\text{Fe}_3\text{Al}$  superstructure (short-range order). But the alloys containing less than 10.9% aluminium is known to be in the K-state even at  $-183^\circ\text{C}$ . It is an important problem whether at much lower temperatures there is any essential difference between the two alloys containing more and less than 11% aluminium or not. On this respect a further investigation is being carried out.

### Summary

The changes in electrical resistivity and volume of iron-aluminium alloys containing 9.75 to 11.66% aluminium have been measured during and after isothermal annealing and in the temperature range from room temperature to  $-183^\circ\text{C}$ , and the following results were obtained:

(1) The equilibrium electrical resistivity vs. annealing temperature curve is of the typical K-state.

(2) At the beginning stage of isothermal annealing at  $200^\circ\sim 300^\circ\text{C}$ , the resistivity of all the alloys decreases for sometime and then increases. The decrease must be caused by annihilation of excess vacancies. While the resistivity of the alloys containing less than 10.65% aluminium does not show any decrease thereafter and reaches its final value, that is, the alloys remain in the K-state in the final stage, the resistivity of the alloys containing more aluminium decreases after passing through a maximum value, and the alloys transform into the  $\text{Fe}_3\text{Al}$  superstructure.

(3) The existence range of the K-state at room temperature is limited to the concentration range from 9.6 to 11.6% aluminium and its maximum is found at the concentration of about 10.7% aluminium (about  $\text{Fe}_{13}\text{Al}_3$ ).

(4) The growing velocity of the K-State does not show any discontinuity between the alloys which remain finally in the K-state and those which transform into the  $\text{Fe}_3\text{Al}$  superstructure, and the velocity becomes faster as the concentration approaches  $\text{Fe}_3\text{Al}$ .

(5) Below room temperature, the temperature coefficient of electrical

(17) W. Köster und P. Rocholl, Z. Metallkde., 48 (1957), 485.

resistivity of an iron-aluminium alloy is smallest after quenching, and is largest in the  $\text{Fe}_3\text{Al}$  ordered state. In regard to the coefficient and the concentration, however, the curve is continuous between the two states. On the contrary, the thermal expansion coefficient is almost constant regardless of its state.

(6) The existence range of the K-state at  $-183^\circ\text{C}$  is limited to the concentration range from 9.6 to 10.9% aluminium, beyond which the alloys are in the  $\text{Fe}_3\text{Al}$  superstructure phase. The amount of the K-state at  $-183^\circ\text{C}$  in the alloys of less than 10.5% aluminium is almost the same as that at room temperature.

(7) Summarizing the preceding results, it can be concluded that the K-state in the iron-aluminium alloys containing more than 10.9% aluminium is essentially of the  $\text{Fe}_3\text{Al}$  superstructure. The nature of the alloys containing less than 10.9% aluminium has not been made clear.

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