Effect of Addition of Cobalt or Nickel on the Strain Gauge Factor and Electrical Properties of Iron-Chromium Alloys*

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The present investigators already measured the strain gauge factor K and electrical properties for the wires of Fe-Cr alloys containing less than 50% chromium, and obtained the largest value of 6.2 in K for the alloy containing 20% chromium. So they have further investigated the influence of the addition of less than 70% cobalt or 65% nickel on their properties. Although K of Fe-Cr alloys shows some decrease with increasing cobalt or nickel content, the electrical resistivity ρ increases considerably, while the mean temperature coefficient of electrical resistivity C_f and the mean thermo-electromotive force relative to copper E_{mf} decrease and reach comparatively small values. The results on Fe-15%Cr-35%Co and Fe-10%Cr-20%Ni alloys show that K is 3.9 and 3.7, ρ is 88.6 and 86.0 $\mu\Omega\text{-cm}$, C_f is 2.6×10^{-4} and 3.0×10^{-4} , and E_{mf} is -0.1 and $-4.7 \mu\text{V}/^\circ\text{C}$, respectively.

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I. Introduction

In the preceding study⁽¹⁾ the present authors measured the strain gauge factor, K , at room temperature for wire specimens of Fe-Cr alloys containing less than 50% chromium which had been prepared by cold working of about 98% reduction. The results of measurements showed a large value of K over a wide composition range of chromium with the highest value of 6.2 at 20% chromium. However, the temperature coefficient of electrical resistivity, C_f , and the thermo-electromotive force relative to copper, E_{mf} , were measured to be 32.7×10^{-4} and $+11.0 \mu\text{V}/^\circ\text{C}$, respectively, which were considerably larger than those of the commonly-used strain gauge material.

Therefore, the present study was intended to examine the effect of the addition of cobalt or nickel as the third element on the strain gauge factor and other properties of Fe-Cr alloys. Köster⁽²⁾ and Wever et al.⁽³⁾ have studied the phase diagrams on the iron side of Fe-Cr-Co and Fe-Cr-Ni alloys around room temperature, respectively, as shown in Figs. 1 and 2. Fig. 1 shows that the Fe-Cr-Co alloys containing less than 70% cobalt and 30% chromium consist largely of the α and ϵ phases, but no consideration is given to the σ phase. On the other hand, Fig. 2 shows that the α and γ phases account for a major composition of the Fe-Cr-Ni alloys containing less than 65% nickel and 30% chromium and part of the σ phase is revealed in the high chromium composition range.

Fig. 1 Equilibrium diagram at 20°C of Fe-Cr-Co alloys

Fig. 2 Equilibrium diagram at 20°C of Fe-Cr-Ni alloys

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

(1) H. Masumoto and N. Nakamura : J. Japan Inst. Metals, **32** (1968), 681; Trans. JIM, **10** (1969), 124; The 20th Report of The Foundation : The Research Institute of Electric and Magnetic Alloys, Sendai, Japan.

Although these phase diagrams which represent the equilibrium state of the alloys are not directly related to the cold-worked state of the alloys in the present experiment, the diagrams are shown in this paper in view of their significance, as reference data, in carrying out the present experiment.

(2) W. Köster : Arch. Eisenhütt., **6**(1932), 113.

(3) F. Wever and W. Jellinghaus : Mitteil. Kaiser Wilhelm-Inst. für Eisenforschung, **13** (1931), 93 ; *Stainless Iron and Steel* (J. H. G. Money Penny), **2** (1954), 161.

Table 1 Results of chemical analysis of metals used

Metals	Fe (%)	Co (%)	Ni (%)	C (%)	S (%)	Si (%)	Mn (%)	Cu (%)	Pb (%)
Co (mt)	0.150	99.59	0.140	0.007	0.004	0.025	0.012	—	—
Ni (el)	0.0007	0.18	—	—	0.0002	0.0004	0.0000	0.0005	0.0000

II. Specimens and Experimental Procedures

The alloying materials, iron and chromium, were of the same kinds as described in the preceding paper⁽¹⁾, but the metallic cobalt and electrolytic nickel used were of the purities shown in Table 1. In the same way as mentioned previously⁽¹⁾, out of the alloying materials totaling 100 g, iron, cobalt or nickel was loaded in an alumina crucible and melted with a high-frequency induction furnace while blowing hydrogen gas on the surface of metals to prevent oxidation. Chromium was then added to the melt and stirred thoroughly for homogenization. In the case of Fe-Cr-Ni alloys, 0.5% manganese and 0.3% silicon were added to the melt so as to increase its workability. The alloy was cast into an iron mold 10 mm in diameter and 12 cm in length, and its ingot was forged at about 1000°C to a cylindrical rod 5 mm in diameter. At the intermediate stage of the subsequent cold swaging and drawing, the rod was annealed at 1000°C to obtain three kinds of wires with a diameter of 1 mm (for measurement of ρ), 0.5 mm (for measurement of E_{mf}) and 0.06 mm (for measurement of K) in a cold-worked state of about 98% reduction. Finally the pieces 10 cm, 1 m and about 70 cm in length were cut out from the wires, respectively, and their values in ρ , C_f , E_{mf} and K were measured in the same way as described in the preceding paper⁽¹⁾. Since the result of the tensile test provides useful information, the measurement was performed on some of the alloys by the Instron-type testing machine.

III. Results of Measurements and Consideration

1. Strain gauge factor

Figs. 3 and 4 illustrate the composition dependence of K for the Fe-Cr-Co and Fe-Cr-Ni alloys in a cold-worked state of about 98% reduction, respectively, in which the closed circles represent the specimen compositions. As can be seen from Fig. 3, the value of K for Fe-Cr alloys decreases comparatively rapidly at the beginning and then gradually with increasing cobalt addition. The highest value of 6.2 in K for the Fe-Cr system with 20% chromium changes along the $\overline{AB}$ line of Fe:Cr=4:1 with the cobalt content and becomes about 3.0 at 65% cobalt. It can be understood that the $\overline{AB}$ line coincides roughly with the critical solution line of the α phase in the equilibrium

phase diagram over the composition range of more than about 30% cobalt.

As shown in Fig. 4, the value of K for Fe-Cr alloys generally decreases rapidly with increasing nickel content. In this case, the highest value of 6.2 in K for the Fe-Cr system decreases to a minimum in the vicinity of the $\alpha+\gamma$ phase, followed by a slight increase up to the composition range of about 13%

Fig. 3 Strain gauge factor at room temperature of Fe-Cr-Co alloys in a cold-worked state of about 98% reduction

Fig. 4 Strain gauge factor at room temperature of Fe-Cr-Ni alloys in a cold-worked state of about 98% reduction

• present investigators ○ Yamamoto et al.⁽⁴⁾

chromium and 20% nickel in the γ phase range, and then decreases linearly. The open circles shown in Fig. 4 represent the compositions of Fe-Cr-Ni alloys measured by Yamamoto et al.⁽⁴⁾ under the same condition as used by the present authors. The results in both cases are in good agreement with each other. The results of measurements by Bertodo⁽⁵⁾ do not agree with those of the present authors because the specimens of the former contained a large quantity of impurities and were in an annealed state.

2. Electrical resistivity and its temperature coefficient

The values in ρ at 20°C and in C_f at 0°~40°C for

- (4) M. Yamamoto, T. Nakamichi, N. Yokoyama and N. Hayashi : J. Japan Inst. Metals, **31**(1967), 696; M. Yamamoto, T. Nakamichi and N. Yokoyama : J. Japan Inst. Metals, **31** (1967), 702; Sci. Rep., RITU, (50th Anniversary vol.), A18, Suppl. (1966), 486.
 (5) R. Bertodo : Proc. Instn. Mech. Engrs., **173** (1959), 605; **178** (1964), 907.

Fe-Cr-Co and Fe-Cr-Ni alloys were measured, the results of which are shown in Figs. 5 and 6, respectively. As can be seen from Fig. 5, ρ of iron increases drastically at the beginning and then slowly with increasing chromium and cobalt contents and attains a value greater than $90\mu\Omega\text{-cm}$ in the composition range of more than about 23% cobalt and about 17% chromium. As shown in Fig. 6, the addition of chromium and nickel increases substantially the ρ value of iron in the α phase range, while in the other phases the amount of the increase slows down and the value reaches a value greater than $90\mu\Omega\text{-cm}$ as in the case with Fe-Cr-Co alloys. The open circles in the

Fig. 5 Electrical resistivity at 20°C and its mean temperature coefficient in the temperature range 0° to 40°C for Fe-Cr-Co alloys in a cold-worked state of about 98% reduction

Fig. 6 Electrical resistivity at 20°C and its mean temperature coefficient in the temperature range 0° to 40°C for Fe-Cr-Ni alloys in a cold-worked state of about 98% reduction

• present investigators ○ Yamamoto et al.⁽⁴⁾

figure indicate the specimens compositions measured by Yamamoto et al.⁽⁴⁾ under the same condition as used by the present authors, and their measured values are in good agreement. For C_f of Fe-Cr-Co alloys, the values on the Fe-Cr and Fe-Co sides decrease rapidly at the beginning and then slowly with increasing cobalt or chromium content, as shown in Fig. 5. The minimum values of C_f are shown in the composition range of about 7~16% chromium and about 33~40% cobalt. As shown in Fig. 6, the value of C_f of Fe-Cr-Ni alloys increases rapidly in the α phase range but decreases gradually in the other phase ranges with increasing chromium or nickel content.

3. Thermo-electromotive force relative to copper

Figs. 7 and 8 show the values of E_{mf} at 0°~40°C for Fe-Cr-Co alloys and Fe-Cr-Ni alloys, respectively. As can be seen from Fig. 7, the positive value of E_{mf} decreases monotonously with the addition of cobalt to Fe-Cr alloys and becomes nil at a certain composition between 30~40% cobalt, after which the value becomes negative and its absolute value increases gradually. In the case of Fe-Cr-Ni alloys, as shown in Fig. 8, the positive value of E_{mf} of Fe-Cr alloys decreases abruptly with the addition of nickel and

Fig. 7 Mean thermo-electromotive force relative to copper in the temperature range 0° to 40°C for Fe-Cr-Co alloys in a cold-worked state of about 98% reduction

Fig. 8 Mean thermo-electromotive force relative to copper in the temperature range 0° to 40°C for Fe-Cr-Ni alloys in a cold-worked state of about 98% reduction

becomes nil at a composition near the critical solid solution curve of the γ phase. After entering the γ phase, the value followed a complicated change ranging from about $-4\mu\text{V}/^\circ\text{C}$ to about $+1\mu\text{V}/^\circ\text{C}$.

Based on the above results, the composition dependence of strain gauge characteristics was obtained with Fe-Cr-Co alloys containing 15% chromium and Fe-Cr-Ni alloys containing 10% chromium, respectively. The results are shown in Figs. 9 and 10. As is evident from these figures, the alloys composed of 50% iron, 15% chromium and 35% cobalt and of 70% iron, 10% chromium and 20% nickel are 3.9 and 3.7 in K , 88.6 and $86.0\mu\Omega\text{-cm}$ in ρ , 2.6×10^{-4} and 3.0×10^{-4} in C_f and -0.1 and $-4.7\mu\text{V}/^\circ\text{C}$ in E_{mf} , respectively. This indicates that these alloys show the decrease in K as compared with Fe-Cr alloys, but the other

properties are greatly improved.

Fig. 11 shows the relationship between the changes in electrical resistivity and length at room temperature for wire specimens of the 50% Fe-15% Cr-35% Co and 70% Fe-10% Cr-20% Ni alloys in a cold-worked state of about 98% reduction. The linear portion of the resistance vs. length curve accounts for about 0.9 % in the length change in the former alloy and about 0.65% in the latter, which are much larger than the linear limit of 0.3~0.5 obtained on Fe-Cr binary alloys. Since a large tensile strength is required for alloy wires used in the strain gauge, the tensile test was performed on the wires of the above-mentioned

two alloys (1 mm in diameter and about 10 cm in length) and the values obtained were as large as 160 and 130 kg/mm², respectively. They were also found to have good workability. Therefore, it seems possible to put these alloys to practical use for various purposes.

IV. Conclusions

Strain gauge characteristics were measured of Fe-Cr-Co alloys containing less than 30% chromium and 70% cobalt and Fe-Cr-Ni alloys containing less than 30% chromium and 65% nickel after cold-working of about 98% reduction. The results obtained are as follows:

(1) The value of K for Fe-Cr alloys decreases rapidly at the beginning and then slowly with the addition of cobalt. The highest value of 6.2 in K for the Fe-Cr system with 20% chromium changes along a line with Fe:Cr=4:1 with increasing cobalt content and becomes about 3.0 at 65% cobalt. In the case of the addition of nickel to Fe-Cr alloys, the value of K decreases generally with increasing nickel content. The highest value of 6.2 in K at 20% chromium in the Fe-Cr system decreases to a minimum value at a composition near the $\alpha+\gamma$ -phase and then increases slightly up to a composition near 13% chromium and 20% nickel in the γ phase, after which it decreases again.

(2) With the addition of chromium and cobalt or chromium and nickel to iron, the electrical resistivity increases and attains a value greater than 90 $\mu\Omega$ -cm, which is much larger than that of Fe-Cr binary alloys.

(3) With the addition of cobalt or nickel to Fe-Cr alloys, the temperature coefficient of electrical resistivity decreases to a minimum value and then increases.

(4) With the addition of cobalt or nickel to Fe-Cr alloys, the thermo-electromotive force relative to copper decreases to zero value, after which the value changes into a negative sign and then increases in its absolute value.

(5) The characteristics of the alloys consisting of 50 %Fe-15%Cr-35%Co and of 70%Fe-10%Cr-20%Ni are obtained respectively as follows: 3.9 and 3.7 in the strain gauge factor, 88.6 and 86.0 $\mu\Omega$ -cm in the electrical resistivity, 2.6×10^{-4} and 3.0×10^{-4} in temperature coefficients of electrical resistivity and -0.1 and $-4.7 \mu\text{V}/^\circ\text{C}$ in the thermo-electromotive force relative to copper.

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Fig. 9 Strain gauge characteristics of Fe-Cr-Co alloys containing 15% chromium

Fig. 10 Strain gauge characteristics of Fe-Cr-Ni alloys containing 10% chromium

Fig. 11 Relation between changes of resistance and length at room temperature for Fe-15%Cr-35%Co and Fe-10%Cr-20%Ni alloys in a cold-worked state of about 98% reduction