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Publication Date
1977-06-01

Presented at the Proceedings of the
1977 International Magnetics Conference,
Los Angeles, CA, June 6 - 9, 1977

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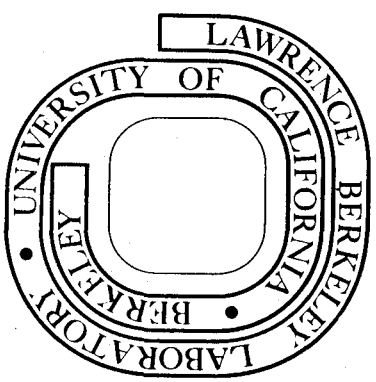
June 1977

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48



DISCLAIMER

PHASE DIAGRAM OF Fe-Cr-Co PERMANENT MAGNET SYSTEM*

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ABSTRACT

The miscibility gap of the α phase in Fe-Cr-Co permanent magnet alloys is constructed using mechanical hardness and Curie temperature measurements. It is found that the miscibility gap of the Fe-Cr binary system develops into Fe-Cr-Co ternary system, and that the addition of cobalt raises the decomposition temperature, and extends the difference in concentrations between the iron rich phase (α_1) and the chromium rich phase (α_2). For instance, the α phase of an Fe-31%Cr-23%Co alloy exhibits a miscibility gap below 670°C, and decomposes into the α_1 phase of 65%Fe-32%Co-3%Cr and the α_2 phase of 69%Cr-21%Fe-10%Co at 600°C.

INTRODUCTION

Fe-Cr-Co alloys reproduce the magnetic properties of many of the Al-Ni-Co system, and can be forged or machined at certain stages in their manufactures. The magnetic hardening of those alloys is performed by aging after solution treatment. Upon aging, an iron rich phase (α_1) and a chromium rich phase (α_2) are finely precipitated from the α phase.[1] The Fe-Cr-Co ternary phase diagram has been studied by Köster and Hofmann.[2] However, since they did not take into account the existence of miscibility gap in the Fe-Cr binary system proposed by Williams [3], the ternary diagram at low temperature has not been defined yet. The present work describes the establishment of the miscibility gap of the α phase in Fe-Cr-Co permanent magnet alloys using mechanical hardness and Curie temperature measurements.

EXPERIMENTAL

In this work a wide range of compositions of the alloys was used as shown in Fig.1. The alloys were melted from 99.9% electrolytic iron, 99.9% electrolytic chromium and 99.5% cobalt in an induction furnace in argon and taken up by a quartz tube to be about 5 mm inside diameter. The alloys were heated at 1300°C

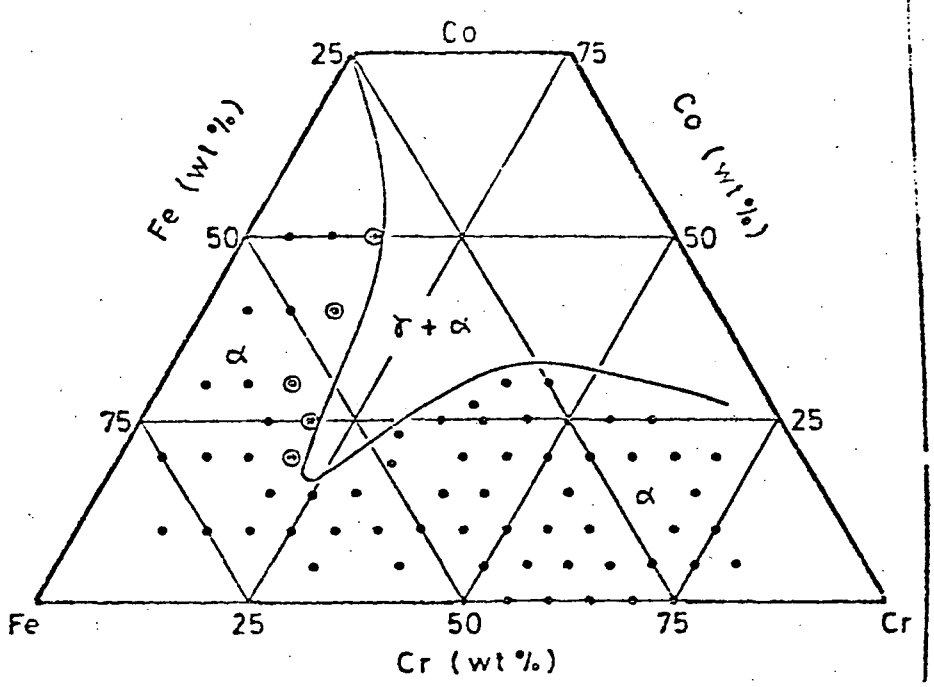

Fig.1 Phase diagram of Fe-Cr-Co alloys quenched from 1300°C. (Alloys marked by ⊙ were cold-swaged at 60% reduction after the quenching)

for 1 hour in argon and quenched in ice water. Structure of the alloys marked by ⊙ in Fig.1 consisted of a residual austenite γ and an α phase in the quenching state from 1300°C. To complete transformation of the γ phase to the α phase, these alloys were cold-swaged after the quenching. The other alloys consisted of the single α phase in the quenching state. It is expected that the alloys would contain no more than 0.3% metallic impurities, 0.04% total carbon and nitrogen.

In order to construct the miscibility gap, the processes of aging and recovery were followed by mechanical hardness and Curie temperature measurements, and microstructural work was done. In order to measure the hardness, the alloys were cut into small blocks 3 mm long as specimens, which were aged at 510°C for 50 hours in vacuum, and then step-heated at elevated temperatures above 510°C in a salt bath. Hardness measurements were made using a Vickers hardness tester with 1 kg load. In order to measure the Curie temperature, the alloys were also cut into chips as specimens, which were aged at 640°C, 620°C and 600°C. The Curie temperature was measured with an automatic magnetic balance in a magnetic field of 3 kOe.

RESULTS AND DISCUSSION

Typical results for hardness of the alloys aged and step-treated are given in Fig.2. The hardness was increased by the aging, and then decreased by the step-

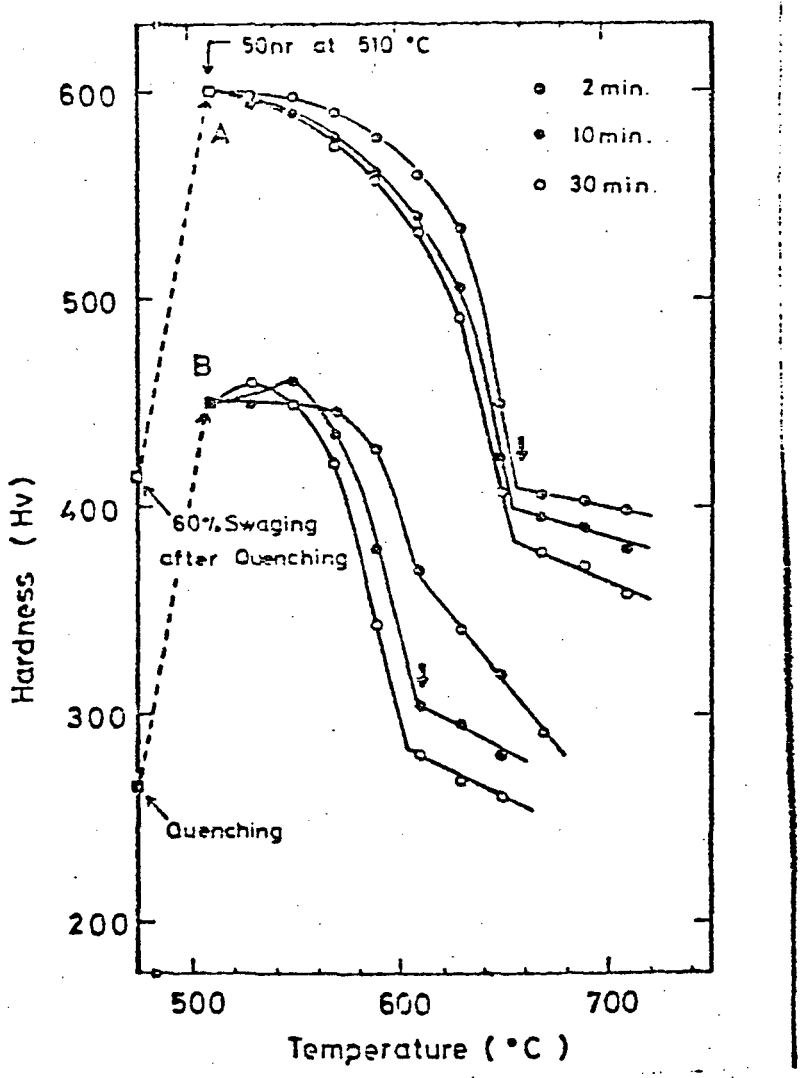

Fig.2 Hardness recovery of aged Fe-15%Cr-40%Co alloy (A) and aged Fe-40%Cr-5%Co alloy (B) step-heated at successively higher temperature.

heating show a bend at a certain temperature. An Fe-15% Cr-40%Co alloy aged at 640°C, below the temperature at the bend, had a two-phase structure $\alpha_1 + \alpha_2$. It was estimated that the decrease was associated with dissolution of the $\alpha_1 + \alpha_2$ phases precipitated by the aging, and that the temperature at the bend was a transformation temperature ($\alpha = \alpha_1 + \alpha_2$). Fig.3 shows the transformation temperature obtained from the results of the hardness in the Fe-Cr-Co alloys. The miscibility gap was given by lines drawn at the transformation temperature. However, the miscibility gap in high chromium field could not be obtained by the hardness measurements, since the high chromium alloys did not show the bend clearly. The miscibility gap in this field was constructed by Curie temperature measurements as follows.

Curie temperatures of the high chromium alloys consisting of the single α phase are shown in Fig.4. The Curie temperature decreased with increasing chromium content, and came to 0°C at about 70%Cr. The magnetization as a function of temperature of an Fe-31%Cr-23%Co alloy is shown in Fig.5. The specimen A was quenched from 1300°C, while the specimens B and C were aged at 640°C after the quenching. The magnetization curves for the aged specimens B and C have a bend

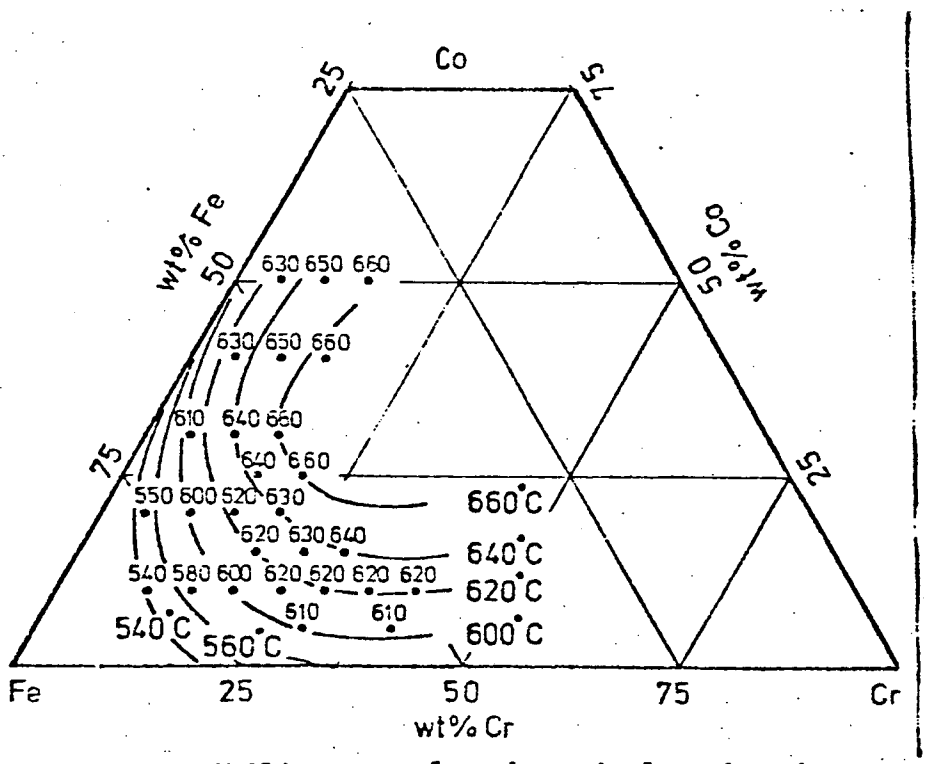

Fig.3 Miscibility gap of α phase in low chromium field.

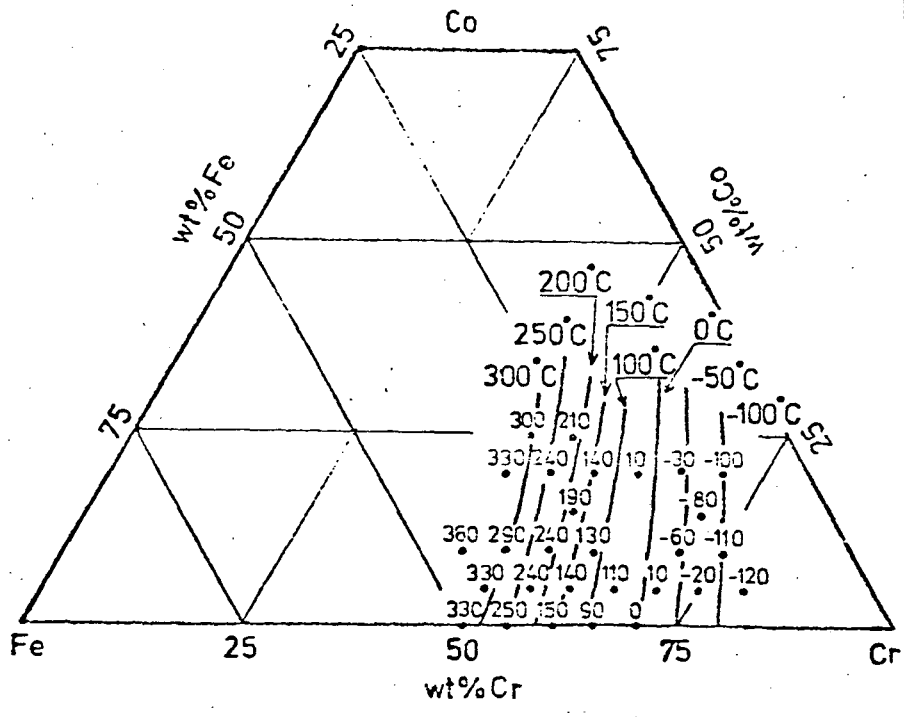

Fig. 4 Curie temperature of high chromium alloys quenched from 1300°C.

around 300°C. The quenched specimen A does not show such a phenomenon. This phenomenon was attributed to existence of the α_2 phase which has a lower Curie temperature than the matrix. It was estimated that the temperature at the bend was the Curie temperature of the α_2 phase precipitated by the aging at 640°C. Fig.6 shows the Curie temperature of the α_2 phase of the Fe-31%Cr-23%Co alloy was aged at 640°C, 620°C and 600°C additionally. The Curie temperature decreases with decreasing aging temperature and drops to -20°C at 600°C. The Curie temperatures and their isothermal lines in the Fe-Cr-Co alloys aged at 640°C are given in Fig.7. The α_2 phase having the same composition was precipitated from the alloys on the same isothermal line at constant temperature. Therefore, these isothermal lines correspond to conjugated lines in the miscibility gap. The compositions of the α_2 phase were indicated by intersecting points of the isothermal lines drawn in Fig.4 and Fig.7 respectively. Thus, the miscibility gap at 640°C was given a curve A in the Fig.8, which connects the intersecting points.

The miscibility gap at 620°C and 600°C could be also obtained in the same way.

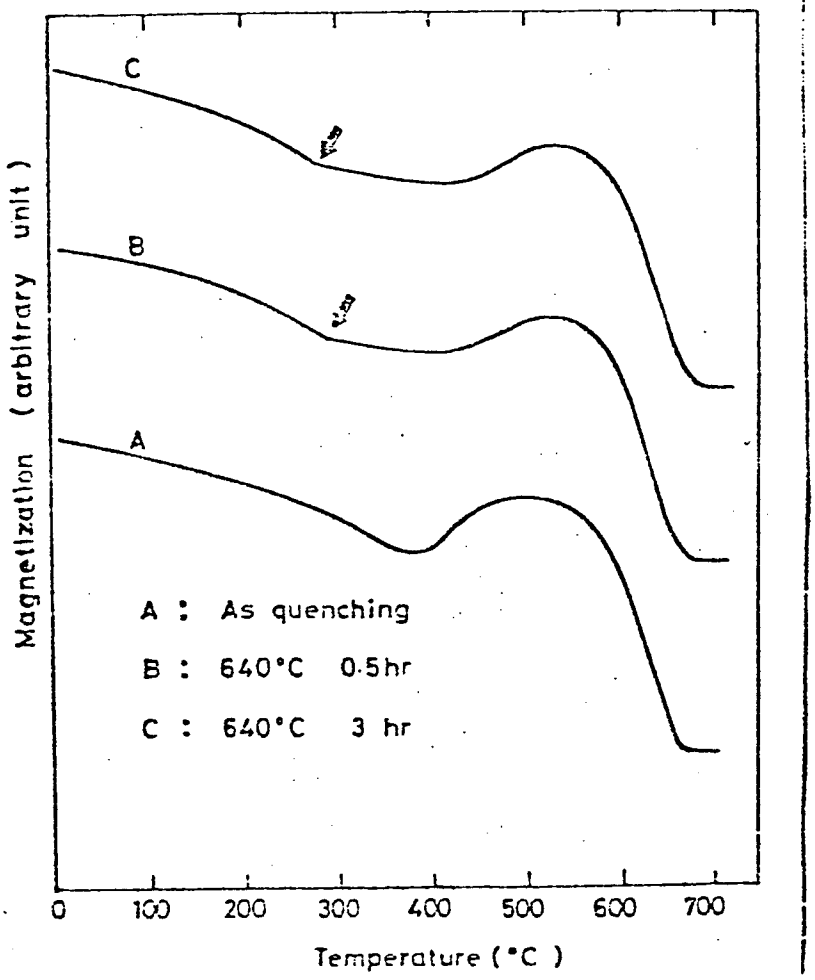

Fig.5 Magnetization vs. temperature, Fe-31%Cr-23%Co alloy.

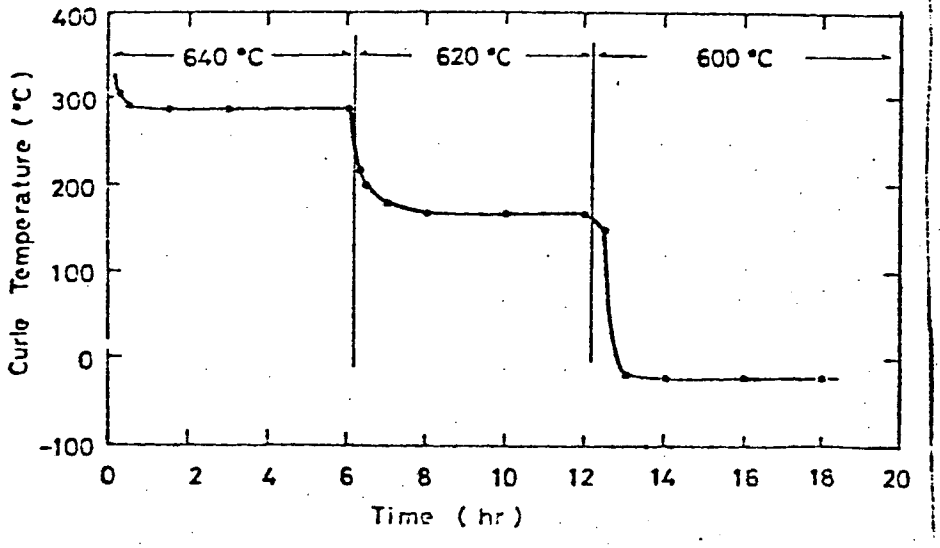

Fig. 6 Curie temperature of α_2 phase of Fe-31%Cr-23%Co alloy aged at 640°C, 620°C and 600°C additionally.

The miscibility gap in Fe-Cr-Co system obtained from the results of the hardness and the Curie temperature measurements is illustrated in Fig. 9. The conjugated concentrations for the α_1 and α_2 phase were denoted by A, B, C and D lines in the figure. Fig. 10 shows the vertical sections along the conjugated lines. It was found that the miscibility gap of the Fe-Cr binary system developed into Fe-Cr-Co ternary system, and that the addition of cobalt raised the decomposion temperature, and extended the difference in concentration between the α_1 phase and the α_2 phase. For instance, the α phase of the Fe-31%Cr-23%Co alloy exhibited a miscibility gap below 670°C and decomposed into the α_1 phase of 65%Fe-32%Co-3%Cr and the α_2 phase of 69%Cr-21%Fe-10%Co at 600°C. The Curie temperature of the α_2 phase in the Fe-31%Cr-23%Co alloy aged at 600°C was -20°C. That of the α_1 phase was estimated to be about 900°C from the value of an Fe-35%Co alloy.[4]

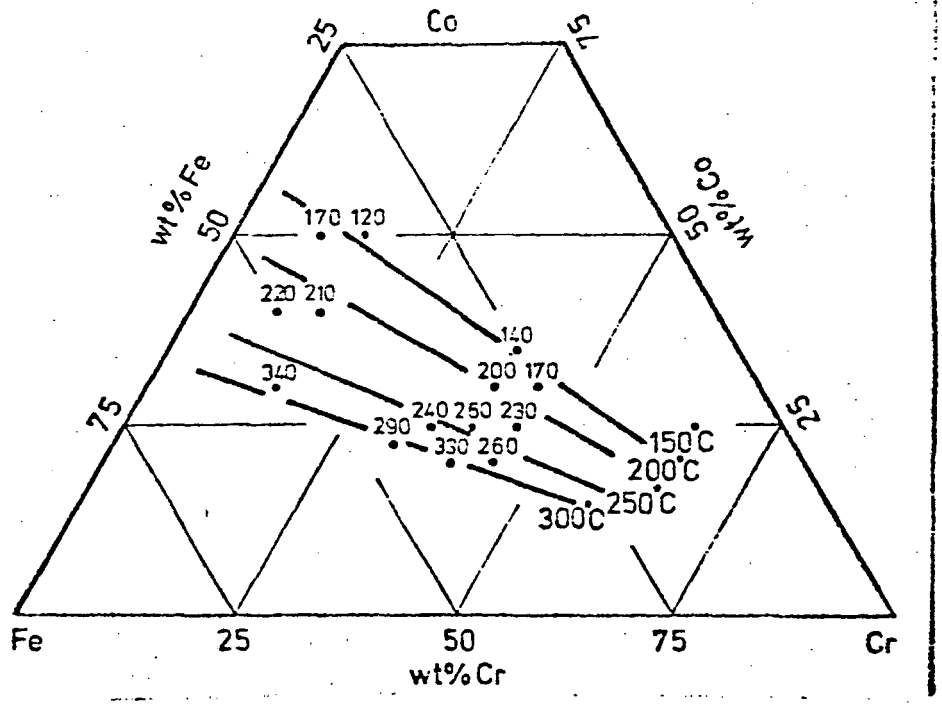

Fig. 7 Curie temperature in Fe-Cr-Co alloys aged at 640°C

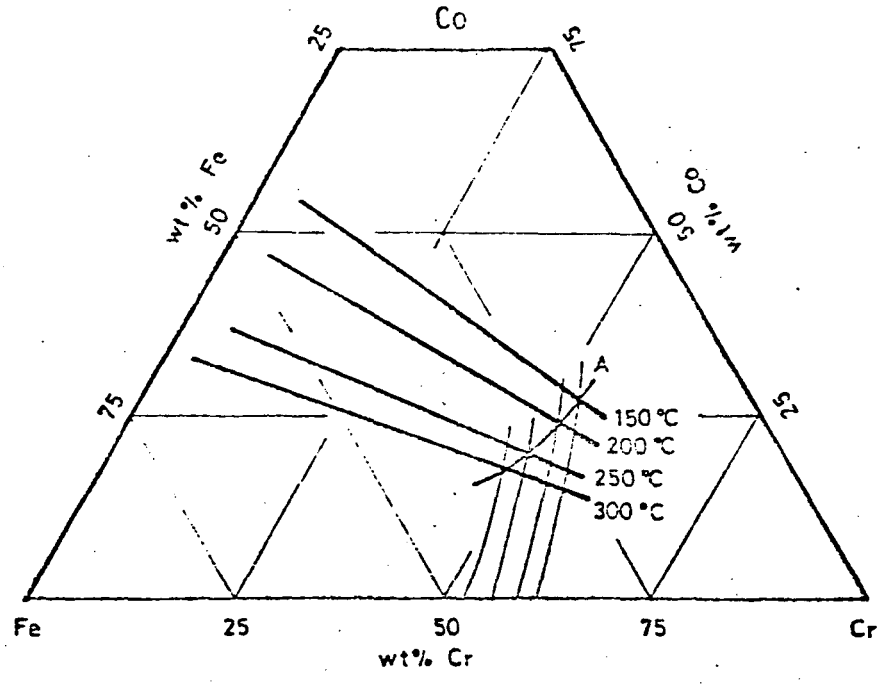

Fig. 8 Miscibility gap of α phase at 640°C in high chromium field.

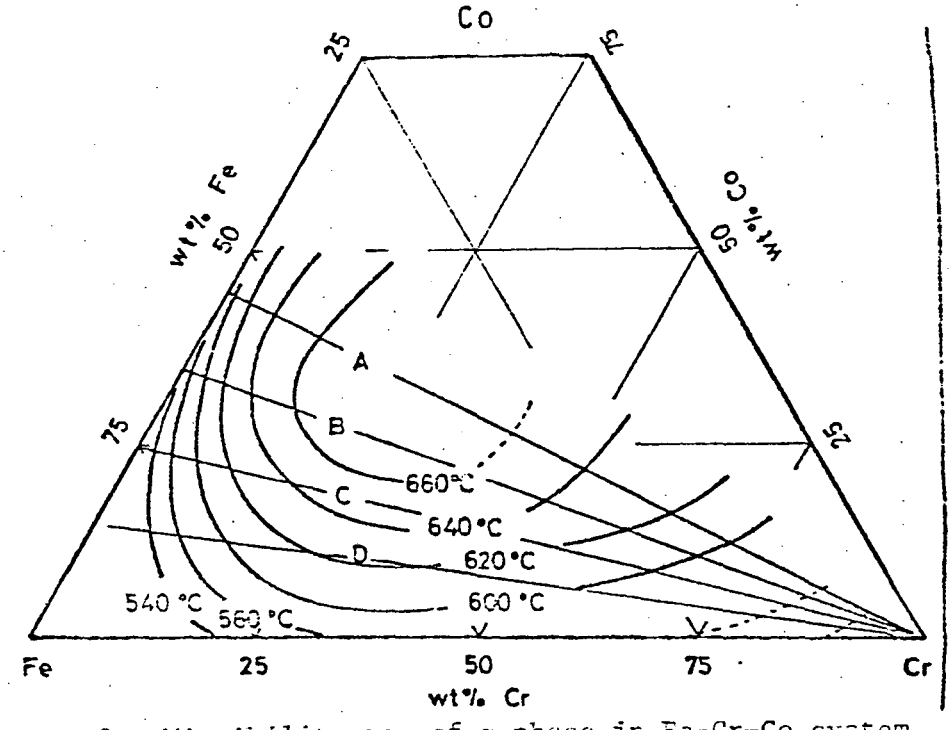

Fig. 9 Miscibility gap of α phase in Fe-Cr-Co system.

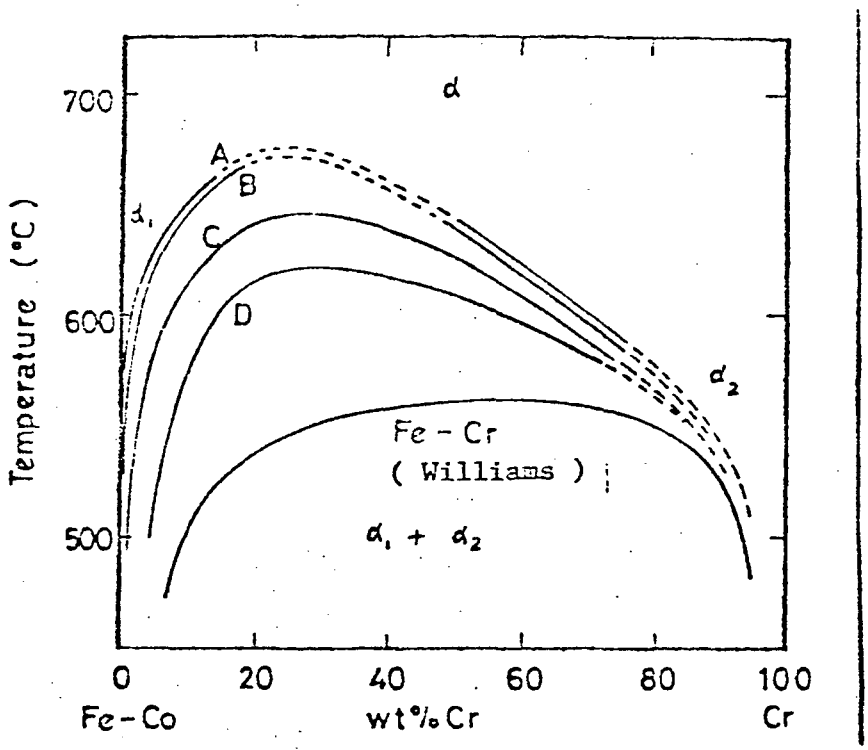

Fig. 10 Vertical sections of miscibility gap along conjugated lines A, B, C and D shown in Fig. 9.

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* Part of this work was supported by the ERDA (M.O and G.T).

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This report was done with support from the United States Energy Research and Development Administration. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the United States Energy Research and Development Administration.

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