Magnetic field dependence of $\gamma$-$\alpha$ equilibrium temperature in Fe-Co alloys

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Abstract. We have investigated effect of magnetic field on $\gamma$(austenite)$\rightarrow$$\alpha$(ferrite) (ferrite) equilibrium temperature $T_0$ in Fe-$x$Co alloys with $x = 0, 10, 20, 30$ mol%. The $\alpha$-phase at $T_0$ is paramagnetism for $x = 0$ and 10, while it is ferromagnetism for $x = 20$ and 30. We have found that $T_0$ increases almost proportional to magnetic field for the Fe-20Co and Fe-30Co alloys, while it does almost proportional to square of magnetic field for pure Fe and the Fe-10Co alloy. The increase in $T_0$ by applying magnetic field of 10 T is about 7 K for pure Fe, 18 K for the Fe-10Co alloy, 24 K for the Fe-20Co alloy and 20 K for the Fe-30Co alloy. The results are discussed on the basis of the Clausius-Clapeyron equation.

1. Introduction
Solid-solid phase transformations are usually classified into two groups from a viewpoint of atom diffusion: diffusionless (martensitic) and diffusional transformations. For both transformations, their characteristics are known to be influenced by external fields such as temperature and pressure. Magnetic field is one of such fields, and especially effective for changing the transformation temperature when there is a large difference in magnetization between the high- and low-temperature phases. In fact, concerning martensitic transformations, the effects of magnetic field have been intensively studied in some iron based alloys by Sadovsky et al.[1] and Kakeshita et al. [2,3] Through the studies, the field dependence of transformation temperature and also transformation kinetics have been quantitatively clarified until now. On the other hand, concerning diffusional transformation, the effect of magnetic field has not been so clarified yet because there are not so many investigations.

The $\gamma$(austenite)$\rightarrow$$\alpha$(ferrite)$\rightarrow$ transformation in Fe-based alloys is one of representative diffusional transformations, in which the transformation temperature is considerably influenced by magnetic field[4-7], because there exists a large difference in magnetization between the two phases. Among various Fe-based alloys, Fe-Co system is especially of interest because the Curie temperature $T_c$ of the $\alpha$-phase becomes higher than the $\gamma$-$\alpha$ equilibrium temperature $T_0$ when Co content exceeds about 15 mol% while $T_c$ is below $T_0$ when Co content is below about 15 mol%. Then we can expect that properties of field dependence of $T_0$ in the former case differ from the latter case. However, as far as the authors are aware, there is no report which clearly shows such behavior.

In the present study, therefore, we have examined the $\gamma\rightarrow\alpha$ and $\alpha\rightarrow\gamma$ transformation temperatures in Fe-$x$Co alloys with $x = 0, 10, 20, 30$ under various magnetic field by electrical resistivity measurements. The results are discussed on the basis of the Clausius-Clapeyron equation.
2. Experimental Procedure

Ingots of Fe-Co alloys with Co content of 10, 20, 30 mol% were prepared by arc melting. They were homogenized in vacuum for 72 h at 1273 K followed by quenching into iced water. From each ingot, a rectangular specimen of 20 mm in length, 2 mm in width and 0.5 mm in thickness was cut out. Platinum lead wires with a diameter of 0.1 mm was attached by spot welding at both ends of each specimen, and its resistivity was measured by a direct current four probe method under a magnetic field of up to 10 T applied along the long side of the specimen, where a direct current of 100 mA was passed through the specimen in the same direction. Temperature of the specimen was monitored by an R-type thermocouple welded at the center of each sample. The heating and cooling rates for the resistivity measurements were 1 K/min.

3. Results

Figure 1 (a) and (b) show temperature dependence of electrical resistivity of the Fe-20Co alloy measured in the heating and cooling processes, respectively, under various magnetic field strengths indicated in the figure. As shown in Fig. 1, transformation start temperatures $T_{\alpha\rightarrow\gamma}$ and $T_{\gamma\rightarrow\alpha}$ are determined as the onset of abrupt increase of the resistivity in the heating process and decrease of the resistivity in the cooling process, respectively. Similar result has been obtained for the Fe-30Co alloy. Concerning pure Fe and Fe-10Co alloy, the behavior of resistivity at transformation temperatures was different. That is, the $\alpha\rightarrow\gamma$ transformation has been detected as a decrease in the heating curve and the $\gamma\rightarrow\alpha$ one as an increase in the cooling curve. Such a different behavior in resistivity at the transformation temperature will be attributed to the different magnetic properties of the $\alpha$-phase at the transformation temperature. That is, the $\alpha$-phase is paramagnetic at the transformation temperature in case of the pure Fe and Fe-10Co alloy while it is ferromagnetic in case of the Fe-20Co and Fe-30Co alloys. The magnetic order of the $\alpha$-phase in the Fe-20Co and Fe-30Co alloys will be responsible for the decrease in resistivity associated with the $\gamma\rightarrow\alpha$ transformation.

We have evaluated the equilibrium temperature $T_0$ as the average of $T_{\alpha\rightarrow\gamma}$ and $T_{\gamma\rightarrow\alpha}$ for convenience. The field dependence of $T_0$ thus obtained for the present alloys is shown in Fig. 2. In the figure, the change in $T_0$, $\Delta T_0= T_0(H)-T_0(H=0)$, is plotted by solid marks. Obviously, $T_0$ increases with increasing magnetic field for all the alloys. It should be noted in the figure that $\Delta T_0$ is almost proportional to square of magnetic field for pure Fe and the Fe-10Co alloy, while it is almost proportional to magnetic field for the Fe-20Co and Fe-30Co alloys as expected before. The increase in $T_0$ by the application of $\mu_0 H = 10$ T is about 7 K for pure iron, 18 K for the Fe-10Co alloy, 24 K for the Fe-20Co alloy and 20 K for the Fe-30Co alloy.

![Figure 1. Temperature dependence of electrical resistivity in an Fe-20Co alloy under various magnetic fields (0, 3, 5, 7, 10 T) near the $\alpha\rightarrow\gamma$ (a) and $\gamma\rightarrow\alpha$ (b) transformation temperatures. The resistivity is successively shifted by 0.2 $\mu$Ωm to separate each curve from others.](image-url)
4. Discussion
In this section we will discuss the effect of magnetic field on $T_0$ of Fe-Co alloys based on the Clausius-Clapeyron equation. The equation under a magnetic field is expressed as

$$dH = \frac{\Delta M}{\Delta S},$$

where $\Delta M$ and $\Delta S$ are, respectively, the difference in magnetization and entropy between the two phases. The value of $\Delta S$ under magnetic fields are approximated by $\Delta S$ under zero magnetic field, which was reported by Normanton et al.[8]. In evaluating $\Delta M$, we can neglect the magnetization of the $\gamma$-phase, because the magnetization of the $\gamma$-phase is very small compared with that of the $\alpha$-phase. The magnetization of the $\alpha$-phase in Fe-Co alloys at high temperatures is not reported yet, so we have calculated it by assuming the Weiss mean-field theory like previous reports [4,5]. In the calculation, the total angular momentum number has been assumed to be $1/2$ and the spontaneous magnetization at $0$ K ($M_0$) has been evaluated from the Slater-Pauling curve. We also need Curie temperature $T_c$, and we have used the value estimated previously by Inden [9]. The values of latent heat, $M_0$, $T_c$ and $T_0$ thus obtained are summarized in Table 1. Using these values, we have calculated the magnetization of the $\alpha$-phase under various magnetic fields, which is partly shown in Fig. 3, where the temperature is normalized by $T_c$.

Putting the values of $\Delta S$ and $\Delta M$ into the Clausius-Clapeyron equation, the field dependencies of the shift of $\gamma$-$\alpha$ equilibrium temperatures ($\Delta T_0$) have been calculated for the present alloys, and the results are shown by lines in Fig. 2. The calculated value is almost in good agreement with experimental result for pure iron and Fe-10Co alloy. On the other hand, the calculated value is obviously smaller than the experimentally obtained value for the Fe-20Co and Fe-30Co alloys. The

![Figure 2. Change in the $\alpha$-$\gamma$ equilibrium temperature, $\Delta T_0 = T_0(H) - T_0(0)$, by the application of magnetic field $H$, where $T_0(0)$ is the equilibrium temperature under zero magnetic field. Marks are obtained experimentally by resistivity measurements, and lines are calculated from the Clausius-Clapeyron equation.](image)
deviation between the calculations and experimental results probably comes from underestimation of magnetization for the Fe-20Co and Fe-30Co alloys. For further discussion, the magnetization of the $\alpha$-phase should be measured experimentally, and such measurements are now in progress.

5. Conclusions
The $\gamma\alpha$ equilibrium temperature $T_0$ of pure Fe-20Co and Fe-30Co alloys increases linearly with increasing magnetic field. On the other hand, that of pure Fe and Fe-10Co alloys increases nearly proportional to square of magnetic field. The difference arises form the magnetic state of the $\alpha$-phase at $T_0$: it is ferromagnetic for Fe-20Co and Fe-30Co alloys while paramagnetic for pure Fe and Fe-10Co alloys. The field dependence of the equilibrium temperature obtained by experiments is slightly larger than the value calculated on the basis of the Weiss mean-field theory. Such difference should be solved by measuring accurate magnetization of the $\alpha$-phase at high temperatures.

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