Effects of Titanium in Alnico 8-Type Magnet Alloys*

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Alnico 8-type magnet alloys containing more than 5% Ti have been well-known to have very high coercive forces, particularly when the isothermal field treatment is applied. As a primary approach in this research to explore its cause, the transformations, microstructures and magnet characteristics were investigated in a series of Alnico 8-type alloys with various titanium contents. The critical temperatures of the transformations including magnetic transition were determined as a function of titanium content. It may be reasonably concluded that the mechanism of magnetic hardening in these alloys is similar to that in Alnico 5-type alloys containing no titanium.

It was shown that when the alloys were subjected to isothermal field treatment, the coercive force obtained depended largely upon the temperature of the treatment, and slightly upon the treating time. In each of the specimens, the optimum temperature of the treatment was found to exist about 50°C below the critical temperature of the two-phase separation reaction and to raise as the titanium content was increased. In addition, the magnetic anisotropy induced by the heat treatments in a magnetic field seems rather to decrease in magnitude with increasing titanium content. Furthermore, the electron microscopic observation has revealed that the precipitate particles developed by the optimal treatment are likely to increase in both size and dimension ratio with increasing titanium content.

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I. Introduction

Many attempts have been made to improve the properties of Alnico alloys by the addition of titanium, and it has been found that its addition particularly contribute to the increase in coercive force of the alloys. Among those works, it is most noteworthy that Luteijn and de Vos⁽¹⁾ reported that remarkable magnet characteristics of $BH_c = 1300$ Oe and $(BH)_{\max} = 11.0$ MG Oe could be attained with a columnar specimen of Ticonal X (34% Co, 14% Ni, 7% Al, 5% Ti, 4% Cu and balance Fe) by isothermal treatment in a magnetic field. Recently Planchard et al.⁽²⁾ have achieved a much higher coercivity, 2000 Oe, with Alnico-type alloys containing greater amounts of Co and Ti than Ticonal X. Such a high value of coercivity seems to be comparable with the highest one that can be estimated from the theory of ferromagnetic single-domain particles. These results have suggested the possibility of the practical production of magnets with higher energy products than 10 MG Oe, thus stimulating an increasing interest in Alnico 8-type alloys containing a large amount of titanium; Alnico 8 is the name of a typical commercial magnet alloy, which is nominally composed of 35% Co, 14.5% Ni, 7% Ti, 5% Cu and the balance Fe, comparable with Ticonal X.

Now, the following questions would arise proposed about Alnico 8-type alloys: How can such type alloys have coercivities considerably higher than Alnico 5, and why can the high coercivity be achieved only through

isothermal treatment in a magnetic field? In order to solve the Alnico 8 problem, it is necessary to clarify the transformations and the resulting structure in the Alnico 8-type alloys. However, little has been known about the metallurgical aspects of Alnico 8-type alloys^{(3)~(5)}. In the present study, experiments were carried out to investigate the effects of titanium on the transformations and the microstructures of Alnico 8-type alloys of various compositions. As a first step to make clear the above questions, the magnet characteristics were measured, and metallurgical considerations were given to the results. Particularly the effect of titanium on the factors involved in the isothermal treatment in a magnetic field were examined in detail.

II. Experimental Procedure

Specimens of Alnico 8-type alloys were melted *in vacuo* with a high-frequency induction furnace and injection cast into a quartz tube 3 or 5 mm in diameter. The compositions of the specimens were varied in such a way as to contain 1~7.5% titanium and other elements in similar proportion to that of Alnico 8. The results of chemical analysis are shown in Table 1. All the ingots were annealed in argon at about 1200°C to promote homogeneity. Then specimens were prepared into suitable shapes for the respective measurements.

Metallographic investigation was carried out mainly by micro-examination of specimens quenched from various temperatures. Particularly the details of the two-phase structures containing fine precipitate particles were examined by means of an electron microscope, where the oxide replica method was adopted⁽⁶⁾. Also measurements of resistivity at elevated temperatures were made at a

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(1) A. J. Luteijn and K. J. de Vos: Philips Res. Rep., 11 (1956), 489.

(2) E. Planchard, C. Bronner and J. Sauze: Proceeding of *Journées Internationales des Applications du Cobalt*, Brussels, (1964), 134.

(3) A. J. J. Koch, M. G. vd Steeg and K. J. de Vos: Conf. Magnetism and Mag. Materials, (1956), 173.

(4) G. Vallier, C. Bronner and R. Peffen: Cobalt, 34 (1967), 10.

(5) C. Bronner, J. Sauze and E. Planchard: Cobalt, 36 (1967), 123.

(6) K. J. de Vos: Philips Res. Rep., 18 (1963), 405.

rate of about $10^{\circ}\text{C}/\text{min}$ on specimens of 3 mm diameter and 80 mm length, to determine the critical temperature of the two-phase separation transformation; it can be most accurately determined according to a knick on the resistivity-vs.-temperature curve obtained. Thermomagnetic analyses were made by means of a magnetic balance with very small specimens, which may allow the measurement to be performed at a very rapid rate. Besides, with a specimen of 5 mm diameter and 16 mm length set into a bottle type of magnet, a I - H loop was measured within the limit of an external field of 5000 Oe by a Cioffi-type recording fluxmeter. From this loop, a saturation induction $4\pi I_s$ (by extrapolating I -vs.- $1/H^2$), a residual induction B_r , a coercive force $1H_c$ and a maximum energy product $(BH)_{\text{max}}$ were obtained.

Table 1 Chemical compositions of specimens

Specimen No.	Composition (wt%)					
	Ti	Al	Ni	Co	Cu	Fe
1	1.05	7.75	15.02	36.54	2.55	Res.
2	2.10	7.30	14.69	35.81	2.62	"
3	3.10	7.45	14.91	35.44	2.49	"
4	3.64	7.08	14.47	35.47	2.70	"
5	4.36	7.02	14.31	35.06	2.82	"
6	5.48	6.95	14.36	34.33	2.54	"
7	6.39	6.92	13.82	33.62	2.83	"
8	7.52	6.92	13.85	33.56	2.48	"

III. Behaviours of Transformations

Fig. 1 shows a constitutional diagram in the solid state for a series of the alloys investigated in this work, which were determined from the various measurements above described; the Ti content in the specimens is shown on the abscissa. The transformations occurring in the solid state of the Alnico 8-type alloys are very similar to those of Alnico 5, that is $\alpha \rightleftharpoons \alpha + \gamma$ (A_4 and A_3 transformations) and $\alpha \rightleftharpoons \alpha_1 + \alpha_2$ (two-phase separation transformation or miscibility gap reaction). As a result, the diagram consists of four regions, α , $\alpha + \gamma$; $\alpha_1 + \alpha_2 + \gamma$ and $\alpha_1 + \alpha_2$, as shown in Fig. 1. The phase boundaries separating these regions indicate how the critical temperatures of the transformations change with the Ti content. Besides, Curie points are shown corresponding to a homogeneous

α phase state of specimens, which have been determined by thermomagnetic analyses.

1. A_4 and A_3 transformations

All the alloys consist of a homogeneous α (bcc) phase at higher temperatures. At temperatures below about $1300^{\circ}\sim 1200^{\circ}\text{C}$, however, they precipitate the γ (fcc) phase to transform into a two-phase state of $\alpha + \gamma$ which is called the A_4 transformation. Then, below about 800°C the γ phase transforms again into the α phase, the A_3 transformation. The A_3 transformation cannot be prevented even by an extremely drastic quenching, but takes place in a martensitic form of transformation. Moreover, the γ phase may precipitate also when the specimen is quenched from a homogeneous α region at higher temperatures, followed by annealing above the A_3 temperature.

The A_4 temperature has been determined by micro-examination of the quenched specimen during cooling from the α phase region. It is seen in Fig. 1 that the A_4 temperature considerably falls with increase in Ti content. On the other hand, the A_3 temperature has been determined by micro-examination of the specimen quenched on the way of heating, after a solution treatment in the α phase region followed by quenching to room temperature. The heating time was 48 hr at each temperature. The A_3 temperature rises slightly with the Ti content. From the above results, it can be concluded that the phase region where the γ phase is existing becomes narrower as the Ti content increases. This seems to be reasonable in accordance with the well-known fact that the titanium element is an α former in the ferrous alloys.

2. Two-phase separation transformation

The critical temperature of this transformation has been determined from the measurement of resistivity at elevated temperatures. As shown in Fig. 1, the critical temperature (hereafter, it is denoted as T_c) rises with the Ti content, reaching about 900°C at 7.5% Ti. Since the T_c point lies above the A_3 temperature of the alloys, a three-phase region of $\alpha_1 + \alpha_2 + \gamma$ reveals itself between the two kinds of critical temperatures. However, the $\alpha \rightarrow \gamma$ transformation is much slower in the rate of transformation than the two-phase separation transformation. Accordingly, even if a specimen consisting of a homogeneous α phase is annealed just below the T_c temperature for about 10 min, the γ phase is hardly observable and only the two-phase separation reaction will proceed.

3. Magnetic transition

In Fig. 2, thermomagnetic curves are shown for No. 5 specimen (4.36% Ti) annealed for 48 hr at 700° , 650° and 600°C , respectively. Since the alloy consists of two phases of α_1 and α_2 after the annealing, each curve shows two inflexion points, which correspond to Curie points of the two phases. The lower one indicates a Curie point of the α_2 phase, θ_2 , which falls as the annealing temperature is lowered. A similar behaviour has been observed in the case of Alnico 5⁽⁷⁾. This appears to imply that as the annealing temperature decreases, the equilibrium

Fig. 1 Constitutional diagram in the solid state for Alnico 8-type alloys with various Ti contents.

(7) Y. Iwama: Trans. JIM, 8 (1967), 18.

composition of the α_2 phase involved shifts gradually toward higher contents of Ni, Al and possibly Ti. In Fig. 3, the θ_2 temperatures of all the alloys determined in the same manner as mentioned above are summarized against the Ti content. The descending trend of the θ_2 can be observed with lowering annealing temperature for all the

Fig. 2 Thermomagnetic curves of specimen No. 5 (4.36% Ti) annealed for 48 hr at various temperatures.

Fig. 3 Variation in Curie point of α_2 phase with Ti content of specimens annealed at various temperatures.

alloys. It should deserve particular attention that θ_2 decreases linearly with the Ti content if the specimens are annealed at a certain temperature. This fact seems to suggest that titanium may preferentially dissolve into the α_2 phase, resulting in the decrease of its Curie point. Therefore, when the alloy containing more than 5% Ti is annealed at 600°C, the θ_2 falls below room temperature; that is, the α_2 phase is non-magnetic at room temperature. This is a favourable condition for the Alnicotype magnet alloys⁽⁷⁾, because the α_2 phase forms a matrix comprising ferromagnetic single-domain particles of the α_1 phase, as will be shown later. It does illustrate the meaning of the aging treatment at 600°C which is also very important in the Alnico 8-type alloys.

The other Curie point, which is observed in the higher temperature side in Fig. 2, lies at about 890°C

independent of the annealing temperature. Though it appears to show a Curie point of the α_1 phase, it is not the case. It is because the upper Curie point is situated above its own T_C temperature for almost all the alloys, so that during the measurement with an ordinary heating rate the dissolving reaction, $\alpha_1 + \alpha_2 \rightarrow \alpha$, may probably proceed in some extent before the θ_1 is reached. In order to obtain the accurate θ_1 of the equilibrium α_1 phase, therefore, it is necessary to make a thermomagnetic measurement at a heating rate as rapid as possible, after the specimen is pre-annealed at a specific temperature. Even in the case of Fig. 2 in which thermomagnetic analyses were performed at a fairly rapid rate (over 100 °C/min), it seemed to be still insufficient.

In a similar way, the Curie point of the α phase, θ , must be determined from the thermomagnetic curve which is measured by rapid cooling from a homogeneous α region. As previously noted, the θ 's shown in Fig. 1 have been determined by thermomagnetic analyses with a fairly rapid cooling rate. Nevertheless, since the T_C lies above the θ except for the alloy with less than 2% Ti content, the two-phase separation reaction probably takes place during cooling from the high temperatures before the θ is reached. In such cases, the apparent θ might be somewhat higher than the true θ otherwise obtained.

IV. Heat-Treatments and Magnetic Characteristics

It has been generally recognized that in the case of Alnico 8 or Ticonal X, the isothermal treatment in a magnetic field (hereafter, it will be abbreviated as IFT) at about 800°C is much more effective than the field cooling treatment, which has been exclusively applied to Alnico 5⁽¹⁾⁽⁸⁾. Particularly it can bring about much higher coercivity. Therefore, the IFT has been applied to a series of alloys with different Ti contents, so as to investigate the influences of both the temperature and the time of the IFT upon the resulting magnet characteristics.

After the solution treatment in a homogeneous α region, the specimens received the IFT at various temperatures of 880°~750°C for 3, 5 or 10 min, respectively. Subsequently, after the aging treatment at 600 °C for 16 hr, their magnet characteristics were measured. In Fig. 4, as an example, the coercive force is shown against the holding time of the IFT for No. 7 specimen (6.38% Ti). It is easily seen that the IFT at 840°C for 5 min leads to the highest coercive force of more than 1800 Oe. When the IFT is carried out at a temperature higher than 850°C, the coercive force obtained decreases monotonously with the treatment time. And the higher the temperature of the IFT, the lower becomes the coercive force. On the other hand, when the IFT is carried out at a temperature lower than 840°C, the situation is reversed. As the temperature of the IFT is lowered, the coercive force decreases, while the coercivity decreases monotonously with the treatment time in the same manner as in the former case. Thus, the coercive

(8) A. J. J. Koch, M. G. vd Steeg and K. J. de Vos: *Berichte der Arbeitsgemeinschaft Ferromagnetismus*, (1959), 130.

force obtained with the IFT depends upon the temperature as well as the time of the treatment, and it should be emphasized that the temperature produces a much more significant influence. A similar tendency can be observed for other specimens. With respect to the time, on the contrary, about 5 to 10 min might probably be selected for all the specimens without any serious miscarriage.

Then, the specimens with different Ti contents were subjected to the isothermal treatment for a fixed time of 5 min at various temperatures with or without a magnetic field. The coercive forces obtained after the aging at 600°C for 16 hr are shown in Fig. 5, where each curve shows a relation between the IFT temperature and the coercive force for the respective specimen. In every case,

Fig. 4 Variation in coercive force with the holding time of the isothermal treatment at various temperatures for specimen No. 7 (6.39% Ti).

Fig. 5 Effect of temperature of the isothermal treatment for 5 min with or without a magnetic field on coercive force of Ti-containing Alnico alloys, measured after aging for 16 hr at 600°C.

the coercive force is obviously shown to reach a maximum at a certain temperature of the IFT, which is to be noted as the optimum isothermal treatment temperature, T_0 . It can easily be seen that the T_0 shifts toward the higher temperature side as the Ti content increases. Moreover, the curves display the sharper and higher maxima with increasing Ti content, which, suggests that when the IFT is applied to the Alnico 8-type alloys high in Ti content, it is very significant to decide precisely the optimum temperature at which the treatment should be performed.

In Fig. 6, the magnet characteristics of B_r , BH_c and $(BH)_{max}$ are shown against the Ti content for a series of alloys subjected to the optimum IFT. As the Ti content increases, BH_c remarkably increases to a level of over 1700 Oe at about 6% Ti, and then slightly decreases. On the contrary, B_r decreases linearly with the Ti content. As a result, $(BH)_{max}$ reaches a maximum at about 5% Ti, which corresponds to the composition of Alnico 8. In other words, as long as the composition of the Alnico 8-type alloys is varied only in the Ti content, the alloy with about 5% Ti may achieve the highest value of $(BH)_{max}$, which amounts to about 5.5 MG Oe with the equiaxed cast structure.

Fig. 6 Relation between magnetic properties and Ti content in Alnico 8-type alloys under the optimal isothermal treatment.

Fig. 5 also allows a comparison between the IFT and the isothermal treatment without a magnetic field. With respect to the optimum temperature i. e. the peak temperature of the curve, a similar tendency can be recognized for all the specimens. However, the extent of the increase in coercive force due to the field application changes in accordance with the Ti content in the specimens. And the most striking effect of a magnetic field can be observed in the alloy with about 5% Ti or Alnico 8. In Fig. 7, $4\pi I_s$ and $B_r/4\pi I_s$ are plotted against the Ti content in either case of the optimum IFT or the optimum isothermal treatment without a magnetic

Fig. 7 Relation between Ti content and saturation induction as well as loop squareness factor in Alnico 8-type alloys under the optimal isothermal treatment with or without magnetic field.

field. These results would make it possible to more closely examine the efficiency of a magnetic field during the treatment. Since it is evident that $4\pi I_s$ is independent of the application of a magnetic field within the experimental error for all the specimens, the ratio of $B_r/4\pi I_s$ may be regarded as a certain measure for the efficiency of a magnetic field or the magnitude of the magnetic anisotropy induced by the field treatment.

Upon application of a magnetic field, this ratio exceeds 0.8 with the lower Ti contents, but it obviously decreases with increasing Ti content. This fact appears to imply that the addition of titanium rather deteriorates the induced magnetic anisotropy or the squareness factor of the demagnetizing curve. On the other hand, in the case without a magnetic field, the ratio is a little higher than 0.5, which might be theoretically estimated. It is to be noticed, however, that it increases above 0.6 for the alloys with higher Ti contents. This fact seems to be attributed partly to some texture which has been produced in the specimens during casting, though the ample reasons have been still unclarified.

V. Discussions

The process through which the transformations take place in Alnico 8-type alloys is quite similar to that in Alnico 5⁽⁹⁾. A mechanism of magnetic hardening, therefore, can be explained in an analogous manner for both types of Alnico alloys by applying the theory of spinodal decomposition⁽¹⁰⁾ to the two-phase separation reaction involved in them. It is to be noted, however, that in the case of Alnico 8-type alloys the spinodal decomposition of the α phase can be made most favourably through the isothermal annealing for a short time (about 10 min) at an optimum temperature. From the theoretical standpoint of spinodal decomposition, this mode of treatment may probably be more reasonable than

the controlled cooling treatment which is generally used for Alnico 5-type alloys. It can also be expected that the average wavelength of the concentration fluctuation in the α phase, i. e. the diameter of precipitate particles, will be reduced as the annealing temperature is lowered. Moreover, if the treatment is performed in a magnetic field, the elongated fine particles of a strongly ferromagnetic α_1 phase may precipitate in the matrix of the non-magnetic α_2 phase in a regular array parallel to the field direction.

Now, it is considered that immediately after the IFT for a duration of several min, the precipitate particles have already reached almost a final height of perfection in both size and shape. In this stage, however, the matrix phase is not yet so sufficiently rich in Ni, Al and Ti as to be non-magnetic at room temperature, as described in III-3. Accordingly, its coercive force must be comparatively low at room temperature⁽⁷⁾. But, if the aging treatment is carried out at 600°C for 10~20 hr after the IFT, both constituents of α_1 and α_2 can achieve their final equilibrium compositions and consequently a favourable situation may be accomplished in which the α_1 phase is strongly ferromagnetic and the α_2 phase is non-magnetic at room temperature (cf. Fig. 3). It has been proved that its coercive force can be largely improved during the aging.

Since the aging is performed at a rather low temperature in the vicinity of 600°C, the atomic diffusion involved in the process may take place within a relatively short range which is assumed to take an order of the diameter of the precipitate particle. It follows that any appreciable change will not occur in the precipitate structure. This has been confirmed by electron microscopy of the structures. Photos. 1 (a)~(d) are the results obtained on (100) and (001) planes of a single crystal of Alnico 8, showing the precipitate structures before and after the aging, respectively. According to de Vos⁽⁶⁾, the bright area in the photographs represents the α_1 phase, and the dark area, the α_2 phase which is rich in Ni, Al and Ti. It is noteworthy that by the aging, the coercive force of this specimen has increased twice that before aging. Besides, a closer inspection of the photographs reveals the presence of very fine secondary precipitates in the matrix after the aging (cf. Photos. 1 (b) and (d)), which seem to be formed during the aging.

Now, the influence of titanium upon the isothermal field treatment will be discussed. In Fig. 8, the optimum IFT temperature (T_0), the critical temperature of the two-phase separation (T_C) and Curie points of the initial α and the final α_1 phase (θ and θ_1) are plotted against the Ti content in the specimens. The T_0 lies about 50°C below the T_C , independent of the Ti content. This suggests that the most significant factor to decide the T_0 temperature is the T_C of the alloy. Furthermore, an electron microscope study of various specimens has shown that the diameter of the precipitate particle does not depend on the Ti content but merely on the IFT temperature. It follows that the two-phase structure which is brought about by the optimum IFT grows coarser with increase in Ti content, because with increasing Ti content, the higher optimum IFT temperature is selected. Photos.

(9) C. Bronner, J.-P. Haberer, E. Planchard and J. Sauze: *Cobalt*, 40 (1968), 131.

(10) J. W. Cahn: *Act. Met.*, 9 (1961), 795.

Photo. 1 Electron micrographs of single crystalline Alnico 8, isothermally treated for 30 min at 800°C with magnetic field along the [001] axis, followed by aging for 16 hr at 600°C; (a) and (b) are before aging, and (c) and (d) after aging. (a) (100) (b) (001) (c) (100) (d) (001)

Fig. 8 Variations in critical temperature of miscibility gap reaction, optimal temperature of the isothermal treatment and Curie points of α and α_1 phases with Ti content in Alnico 8-type alloys.

larger in dimension ratio than those in Alnico 5. However, since these observations have been carried out by means of the oxide replica method for polycrystalline specimens, the above results on their diameter and dimension ratio should be regarded as rather semiquantitative ones.

Conclusively, it can be seen from Fig. 8 that for the specimens with higher Ti contents, $\theta < T_0 < \theta_1$. Therefore, when a specimen is quenched from a homogeneous α region down to the T_0 temperature where the two-phase separation may set in, it will be paramagnetic in the earliest stage. Consequently, it is likely that the decomposition would take place rather in an isotropic mode at least in the earlier stage, though its duration might be so short. As the decomposition advances in some extent, the precipitates of the α_1 phase is enriched in Fe and Co enough to be ferromagnetic even at the T_0 temperature. Then, in virtue of an interaction between the ferromagnetic moments and the applied field, the structure will be altered to an anisotropic structure with particles

Photo. 2 Electron micrographs of Alnico 8-type alloys containing various Ti content, after the optimal isothermal treatment followed by aging. (a) No. 3 (3.10% Ti) (b) No. 5 (4.36% Ti) (c) No. 7 (6.39% Ti) (d) No. 8 (7.52% Ti)

2 (a)~(d) show the structures obtained by the optimum treatment for some of the specimens with various Ti contents. Since the field cooling treatment of the specimen with 3.10% Ti gives a coercive force higher than by the IFT, the structure brought about by the field cooling treatment with a rate of about 1°C/sec is shown in the photograph. From these photographs it is clear that as the Ti content increases from 3.10 to 7.52%, the particles grow larger from 200 to 500 Å in average diameter. Thus it is shown that the precipitate particles in the high titanium Alnico are much larger in average diameter than those in Alnico 5 (about 150 Å). It is also noted that the particles in the high titanium Alnico are by far

elongated in the field direction⁽¹¹⁾. Since in the high titanium Alnico T_c and T_0 are much higher than θ , it seems likely that the earlier isotropic decomposition is sufficiently advanced and consequently disturbs the subsequent anisotropic alteration effect due to the applied field.

Recently high titanium Alnico magnet alloys have become the object of increasing attention on a global level. The present work is concerned with a series of Alnico 8-type alloys in which only the Ti content is varied. Further attempts will be made to solve the high titanium Alnico problems in order to contribute to the development of a higher quality of magnet alloys.

(11) J. W. Cahn : J. Appl. Phys., 34(1963), 3581.

VI. Summary

In the present work, a series of Alnico 8-type alloys have been investigated in which only the titanium content was changed and the other chemical compositions were kept in the same proportion as in the commercial magnet alloy, Alnico 8. Micro-examination of the structures, thermomagnetic analyses and measurements of resistivity at elevated temperatures and magnet characteristics were carried out to investigate the relationships between the transformations such as the magnetic transition and the titanium content and also to clarify the mechanism of magnetic hardening in the Alnico 8-type alloys. Furthermore, factors involved in the isothermal field treatment were investigated for these alloys, and particularly influences of the temperature and the time of the treatment upon magnetic characteristics were closely examined with various titanium contents. The results obtained in the present work are summarized in the following:

(1) On the whole, behaviours of transformations and the mechanism of magnetic hardening in Alnico 8-type alloys are very similar to those in Alnico 5, as have been so far clarified.

(2) With increasing titanium content, the $\alpha \rightarrow \gamma$ transition temperature gradually falls so that the precipitation of the γ phase is limited to a narrow temperature range.

(3) The critical temperature for the two-phase separation transformation rises with the titanium content.

(4) For these alloys with more than 2% Ti, the Curie point of the homogeneous α phase lies below the critical temperature of the two-phase separation transformation. And the Curie point of the α_1 phase is probably situated above 890°C independent of the titanium content. On the other hand, the Curie point of the α_2 phase markedly falls as the annealing temperature is lowered. Also, with increasing titanium content, the Curie point of the α_2

phase falls. This seems to imply that the titanium content is dissolved preferentially into α_2 phase in the same manner as aluminum and nickel.

(5) The optimum time of isothermal magnetic treatment is 5~10 min, but the coercive force achieved does not depend largely upon the time of the treatment. On the contrary, the coercivity depends profoundly upon the temperature of the treatment, and especially the alloys with over 5% Ti are so sensitive that the treatment should be performed at the optimum temperature within an error of $\pm 10^\circ\text{C}$.

(6) The optimum temperature of the treatment appears to lie about 50°C below its own critical temperature of the two-phase separation transformation, and it rises gradually with increasing titanium content.

(7) Among the magnetic characteristics achieved with the optimum treatment, the coercive force remarkably increases as the titanium content increases up to about 5%, while the saturation induction and the remanence decrease linearly with the titanium content. It follows that a maximum energy product reaches a maximum at about 5% Ti, which corresponds to the titanium content in Alnico 8.

(8) From an electron microscopic examination on the precipitate structures obtained with the optimum treatment, it has been found that the precipitate particles become larger in diameter and in dimension ratio with increasing titanium content.

(9) Magnetic anisotropy induced by the applied field during the treatment appears to be rather reduced with increasing titanium content.

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