Effect of High-Temperature Heat Treatment on the Properties of Hardperm in the Ni-Fe-Ta System*

By Hakaru Masumoto**, Yûetsu Murakami** and Masakatsu Hinai**

Considerable improvements of the magnetic properties of Ni-Fe-Ta alloys having a range of composition from 70.03 to 77.41% Ni, 9.50 to 15.96% Fe, and 9.57 to 17.80% Ta have been effected by heating in hydrogen atmosphere at high temperatures of 1050 to 1350°C, followed by cooling at rates from 100 to 8100°C/hr. The highest value of 75000 in initial permeability and of 650000 in maximum permeability can be obtained with a composition of 73.00% Ni, 11.60% Fe, and 15.40% Ta by cooling at the rate of 800°C/hr after heating at 1250°C for 30 min and 3 hr, respectively. The alloy subjected to the latter heat treatment exhibits the electrical resistivity of 70.1 $\mu\Omega$ -cm and the Vickers hardness 211. The high permeability of the Ni-Fe-Ta alloys is largely due to the effective contributions of high-temperature heat treatment in hydrogen atmosphere to the homogeneity of the alloys, removal of impurities and grain growth, associated with the low value of magnetostriction caused by the atomic arrangement in the ordered state.

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I. Introduction

In a previous paper⁽¹⁾ it has been established that Ni-Fe-Ta alloys containing 3.20~23.90% Ta exhibit a high permeability when melted in vacuum, heated in hydrogen atmosphere at 1150°C for 3 hr, and cooled at an optimum rate from a temperature above their order-disorder transformation points. In general, however, the magnetic properties of high permeability alloys depend strongly on composition and also heat treatment. The object of the present study is to clarify the magnetic properties of these alloys when subjected to homogenizing treatments in hydrogen atmosphere at different temperatures.

II. Experimental

The specimens used were 33 alloys having a range of composition from 70.03 to 77.41% Ni, 9.50 to 15.96% Fe, and 9.57 to 17.80% Ta, since they have very high permeabilities⁽¹⁾.

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** The Research Institute of Electric and Magnetic Alloys, 107, Higashi 8-bancho, Sendai 980, Japan.

The numbering system of alloys follows that in the preceding paper. The ingots of the alloys prepared in the same manner as outlined previously⁽¹⁾ were first reduced to a final thickness of 0.3 mm by forging and subsequent hot and cold rolling, from which ring-shaped plates were made by stamping. The ring-shaped plates were heated at 1050~1350°C for 30 min to 25 hr under a hydrogen atmosphere with a dew point of -70°C. After the heat treatment, the plate specimens were cooled down to room temperature at rates from 8100 to 100°C/hr from a temperature above their order-disorder transformation points. The magnetic properties of the specimens were measured by means of a ballistic galvanometer and a recording fluxmeter; the magnetic transformation points with the aid of a magnetic balance; the magnetostriction by the optical roller method; the electrical resistivities by the potentiometric method; and the hardness values by means of a micro-Vickers hardness tester.

III. Results and Discussion

The experimental data are graphically illustrated in Figs. 1~7 and tabulated in Table 1. Figures 1 and 2 illustrate the statistically drawn equi-value curves of the highest values of initial and maximum permeabilities at 20°C against composition for each of Ni-Fe-Ta

Fig. 1 Highest initial permeability μ_0 in each of Ni-Fe-Ta alloys cooled at various rates from a temperature above order-disorder transformation point after heating at several high temperatures.

Fig. 2 Highest maximum permeability μ_m of the same alloys as in Fig. 1.

alloys which were heated at 1050~1350°C for various lengths of time and cooled at different rates from a temperature above their order-disorder transformation points. Inspection of the figures shows that with increasing Ta concentration, the initial permeability μ_0 and the maximum permeability μ_m increase until maxima are reached at about 15% and then the values are gradually reduced. The highest value of 75000 in μ_0 and of 650000 in μ_m has been obtained with alloy No. 40 of 73.00 Ni, 11.60% Fe and 15.40%Ta by cooling at the rate of 800°C/hr after heating in hydrogen atmosphere at 1250°C for 30 min and 3 hr, respectively. These values are fairly larger than those of

Fig. 3 Coercive force H_c in Ni-Fe-Ta alloys heat-treated to develop the highest maximum permeability.

57300 in μ_0 and 428000 in μ_m for alloy No. 34 subjected to heating at 1150°C for 3 hr under a hydrogen atmosphere. It will be noted that improvements in μ_0 and μ_m are effected by high-temperature heat treatment under the hydrogen atmosphere.

Figure 3 shows the equi-value curves of composition vs coercive force H_c (maximum magnetic induction: 5 kG), where the H_c was obtained by the heat treatment by which the highest value of μ_m appeared in each of the alloys. With increasing Ta concentration, H_c decreases until a minimum is reached at about 15%; then the value increases rapidly. The lowest H_c value of 2.9 mOe was shown by alloy No. 40 subjected to cooling at the rate of 800°C/hr after heating at 1250°C for 3 hr. This value is much smaller than the lowest H_c of 5.2 mOe obtained in the previous paper.

Magnetic properties, electrical resistivity and hardness for the representative alloys showing specially high permeability are listed with annealing condition and cooling rate in Table 1. In the table μ_1 is the permeability in a field of 1 mOe; W_h and B_r are the hysteresis loss and the residual magnetic induction against a maximum magnetic induction of 5 kG, respectively; $4\pi I$ and λ are the magnetic induction and the magnetostriction constant in an effective field of 1 kOe, respectively; ρ is the electrical resistivity; T_c is the magnetic transformation point; and Hv is the Vickers hardness

Table 1 Magnetic properties, electrical resistivity and Vickers hardness of some high permeability Ni-Fe-Ta alloys.

Alloy No.	Composition (wt%)		Heating		Cooling rate (°C/hr)	μ_0	μ_1	μ_m	$\frac{W_h}{\text{erg/cm}^3/\text{cycle}}$	B_r (kG)	H_c (mOe)	$4\pi I$ (kG)	λ ($\times 10^{-6}$)	T_c (°C)	ρ ($\mu\Omega\text{-cm}$, 20°C)	Hv (Vickers hardness)
	Fe	Ta	Temp. (°C)	Time (hr)												
	Rest Ni															
16	14.53	10.67	1150	11	800	13	15	279	15.1	4.1	9.2	8.2	1.1	—	51.9	177
23	13.40	11.60	1250	2	1400	13	15	315	12.9	4.5	8.7	7.7	0.9	432	55.1	190
29	13.16	13.85	1250	3	1400	35	40	263	11.0	3.6	7.3	—	—	—	—	198
31	12.80	13.80	1150	6	1400	45	50	265	10.9	3.6	6.8	7.4	0.7	395	62.9	197
31	12.80	13.80	1250	2.5	600	26	33	451	7.5	4.4	5.0	7.4	0.7	—	63.7	202
34	12.05	14.95	1250	4	800	60	86	486	6.1	3.5	3.7	7.4	0.5	374	64.2	197
34	12.05	14.95	1250	5	800	54	97	594	5.1	3.6	3.3	7.4	0.5	—	64.2	204
35	11.59	14.66	1300	1	1400	48	53	141	10.6	1.6	7.0	—	—	—	—	—
39	11.88	15.90	1250	3	1400	34	42	242	9.8	3.2	6.7	6.8	0.7	—	70.7	209
40	11.60	15.40	1250	0.5	800	75	102	468	5.3	3.1	3.9	6.6	0.5	380	70.1	216
40	11.60	15.40	1250	3	800	72	116	650	3.9	3.3	2.9	6.6	0.4	—	70.1	211
47	11.10	16.50	1150	3	1400	27	33	227	10.0	3.6	8.5	6.4	0.4	340	75.1	210
48	10.57	16.61	1250	1.5	400	54	59	124	8.4	1.5	6.8	—	—	—	—	226

Fig. 4 Effect of the heating temperature and time on initial permeability μ_0 and maximum permeability μ_m for alloy No. 40 (73.00% Ni, 11.60% Fe, 15.40% Ta) cooled at the rate of 800°C/hr after heating at the cited temperatures.

under a load of 500 g. As can be seen from the table, Ni-Fe alloys with added Ta have remarkably high permeabilities, with very low values of W_h and H_c . Figure 4 shows the dependence of μ_0 and μ_m on heating temperature and time for alloy No. 40 which exhibits the highest values of μ_0 and μ_m , when the alloy was heated at several temperatures under a hydrogen atmosphere and cooled at the rate of 800°C/hr. At a relatively low heating tempera-

Fig. 5 Variations in initial permeability μ_0 and maximum permeability μ_m with cooling rate for alloy No. 40 (73.00% Ni, 11.60% Fe, 15.40% Ta) heated at 1250°C for 3 hr.

ture, μ_0 and μ_m have a maximum, respectively, and the heating time at which the maximum is revealed becomes shorter with a rise in heating temperature. The drop in permeability is produced at a heating temperature of 1300°C, the cause of which, however, remains unknown.

Figure 5 shows the dependence of μ_0 and μ_m on cooling rate for alloy No. 40 when heated at 1250°C for 3 hr and cooled from a temperature above its order-disorder transformation point. Both μ_0 and μ_m have a maximum depending on cooling rate, and the appearance of this maximum may be attributed to its cooling rate that

causes the alloy to have an atomic arrangement in which magnetization can most easily take place. The optimum cooling rate to reveal the maximum becomes smaller as the Ta concentration is increased. These tendencies bear a marked resemblance to the effects of additions of Cr, Mo, Cu and Nb to Ni-Fe alloys^{(2)~(4)}.

Figure 6 shows the dependence of $4\pi I$, T_c , ρ and Hv on Ta concentration for each of alloys on the dotted line ab in Fig. 2 when subjected to the heat treatment by which the highest value of μ_m was obtained. It is obvious from the figure that $4\pi I$ and T_c decrease monotonically and ρ and Hv increase linearly as the Ta concentration is increased. Figure 7 illustrates the hysteresis loop of alloy No. 40 by heating at 1250°C for 3 hr and subsequent cooling at the rate of 800°C/hr, in which H_c and W_h are very low at 2.9 mOe and 3.9 erg/cm³/cycle, respectively.

The origins of the high permeability of Ni-Fe-Ta alloys may be ascribed mainly to homogenization of the alloys, removal of impurities such as carbon, nitrogen and oxygen and grain growth by high-temperature heat treatment under hydrogen atmosphere⁽⁵⁾⁽⁶⁾, and also to the low values in magnetostriction constant (cf. Table 1) and crystal magnetic anisotropy constant due to the atomic arrangement in the ordered state⁽⁷⁾.

The hardness of Ni-Fe-Ta alloys was found to be fairly high. For example, the hardness of alloy No. 40 having the highest initial permeability in the alloy system is 216, which is remarkably high as compared with the hardness range of about 120 for conventional Permalloy and Mo-Permalloy. Since Ni-Fe-Ta alloys have not only high permeability but also exhibit a high value of hardness, the generic name Hardperm (diminutive of hard permeable alloy) has been given to these alloys.

IV. Conclusions

Thirty-three alloys having the range of composition from 70.03 to 77.41%Ni, 9.50 to 15.96%Fe and 9.57 to 17.80%Ta were melted in vacuum, forged and then rolled, from which ring-shaped plates were made by stamping. The plates were heated in the range 1050 to

Fig. 6 Highest maximum permeability μ_m for each alloy on the dotted line in Fig. 2, and intrinsic magnetic induction $4\pi I$, magnetic transformation point T_c , electrical resistivity ρ and Vickers hardness Hv when subjected to the heat-treatment to develop the highest μ_m .

Fig. 7 Hysteresis loop of alloy No. 40 (73.00% Ni, 11.60% Fe, 15.40% Ta) cooled at the rate of 800°C/hr after heating at 1250°C for 3 hr.

1350°C under a hydrogen atmosphere with a dew point of -70°C for various lengths of time. Finally cooling was done at various rates from a temperature above their order-disorder transformation points. The following conclusions are drawn from measurements of magnetic properties, electrical resistivity and hardness for the alloy specimens:

(1) Considerable improvements of the properties of Ni-Fe-Ta alloys have been effected by heating in hydrogen atmosphere at high temperature. With the increased Ta concentration, the highest values of initial permeability and maximum permeability in each alloy increase until a maximum is reached; then the values are slowly reduced. The highest value of

75000 in initial permeability and of 650000 in maximum permeability has been obtained with alloy No. 40 of 73.00%Ni, 11.60%Fe and 15.40%Ta subjected to cooling at the rate of 800°C/hr after heating at 1250°C for 30 min and 3 hr, respectively.

(2) The hysteresis loss and coercive force for a maximum magnetic induction are generally very small; their values of alloy No. 40 which underwent a heat treatment to reveal the highest value of maximum permeability are 3.9 erg/cm³/cycle and 2.9 mOe, respectively. The electrical resistivity and the Vickers hardness of the alloy are as fairly high as 70.1 $\mu\Omega$ -cm and 211, respectively.

(3) The origins of the high permeability of Ni-Fe-Ta alloys may be attributed chiefly to homogenization, removal of impurities and grain growth by high-temperature heat treatment in hydrogen atmosphere and also to the

low magnetostriction constant due to an atomic arrangement in the ordered state.

(4) Since Ni-Fe-Ta alloys are considerably higher in hardness than conventional Permalloy and Mo-Permalloy in addition to their high permeability, the generic name Hardperm has been given to these alloys.

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