The Magnetostrictive Delay Line Characteristics in Co-Fe-Cr and Co-Fe-Cr-Ni Alloy Systems*

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The temperature coefficient of delay time, α_D , at 0 to 40°C and the maximum gradient of magnetostriction in the applied magnetic field, $(d\lambda/dH)_m$, at room temperature have been measured with the annealed alloys in the Co-Fe-Cr system, the Co-Fe-Cr-16.7% Ni system and the Co-Fe-Cr-28.6% Ni system. It has been found that in Co-31.0% Fe-9.0% Cr alloy the α_D has such a small value as -0.42×10^{-5} . The $(d\lambda/dH)_m$ is $0.36 \times 10^{-6}/\text{Oe}$ which is comparable with the absolute value of $-0.39 \times 10^{-6}/\text{Oe}$ in nickel. The α_D for Co-37.8% Fe-4.3% Cr-16.7% Ni alloy also shows a very small value of -0.07×10^{-5} , while its $(d\lambda/dH)_m$ shows a very large value of $0.80 \times 10^{-6}/\text{Oe}$ which is about two times greater than the absolute value of nickel and five times greater than that of Ni-Span C. And Co-50.0% Fe-2.4% Cr-28.6% Ni alloy has a small value of -0.21×10^{-5} for α_D and $0.19 \times 10^{-6}/\text{Oe}$ for $(d\lambda/dH)_m$ which is about half of the absolute value for nickel. Among these alloys, a Co-37.8% Fe-4.3% Cr-16.7% Ni alloy not only exhibit excellent characteristics of the magnetostrictive delay line but also can easily be cold worked. Therefore, the alloy seems to be a material suitable for the delay line.

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I. Introduction

The magnetostrictive delay line is widely used as the memory element for cyclic access memory systems such as computers, display devices and data transmission terminating apparatuses. The advantages of this memory equipment are simple and solid in construction with applicability to high frequencies and are low-priced in terms of its large memory capacity. The other advantage is that the magnetostrictive delay line has greater workability than glass- or ceramic-made delay line materials, enabling an easy adjustment of the frequency.

The most essential requirements for use of the magnetostrictive delay line materials are the properties which exhibit the low temperature dependence of the delay time and have a large value of the gradient of magnetostriction in the applied magnetic field, $d\lambda/dH$, that leads to the increased sensitivity. It is also desirable that the materials have good workability, large mechanical strength and a low value of the internal friction Q^{-1} .

Conventionally, nickel which has a large magnitude of magnetostriction has been widely used as a magnetostrictive delay line material. Although the large value of $d\lambda/dH$ is characteristic of nickel, the elements has a defect that its delay time changes with temperature because of the large temperature coefficient of the delay time α_D . Ni-Span C being used as an Elinvar-type material has nearly zero α_D and shows a very small dependence on temperature, but it is disadvantageous that in this alloy system $(d\lambda/dH)_m$ has a small value equivalent to about one-third of the absolute value for nickel.

In making an attempt at finding magnetostrictive delay line materials with a low value of α_D , experimental work has been performed with Co-elinvar (Co-Fe-Cr-Ni alloys) discovered by Masumoto and Saito⁽¹⁾⁻⁽³⁾.

II. Experimental

The analytical results of metallic Co, electrolytic Fe, metallic Cr and electrolytic Ni used in this work as the alloying materials are listed in Table 1. For the preparation of specimens, the materials weighing 100–140 g were first placed in an alumina crucible and melted in hydrogen atmosphere with a high-frequency electric induction furnace. The melt was cast into an iron mold 10 mm in inner diameter and then reduced to the shape of a rod with a diameter of 2 mm by forging and cold drawing. Specimens 10 cm in length were cut out from the rod and used for the frequency and the magnetostriction measurements. All the specimens were cooled at a rate of 200°C/hr after annealing at 1000°C for 1 hr.

The specimens used were 29 ternary Co-Fe-Cr alloys, 67 quaternary Co-Fe-Cr-Ni alloys containing 16.7%Ni and 49 quaternary Co-Fe-Cr-Ni alloys containing 28.6%Ni. All the alloys contained less than 65%Co, 20~70%Fe and less than about 18.3%Cr.

The magnetostriction at room temperature was measured in fields up to 566 Oe with the magnetostriction measurement apparatus devised by Honda, Masumoto, Shirakawa and Kobayashi⁽⁴⁾.

The temperature coefficient of the delay time, α_D , was evaluated in the following way. At first, the delay time D and the resonance frequency f are given by

$$D = L/V = L/\sqrt{E/\rho}$$

and

$$f = C d/L^2 \cdot \sqrt{E/\rho}.$$

Here V is the velocity of an elastic wave, L is the length, E is the Young's modulus, ρ is the density, d is the diameter of the delay line and C is a constant containing the degree of oscillation and the acceleration of

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Table 1 Results of chemical analysis of metals used.

Metals	Co (%)	Fe (%)	Ni (%)	Mn (%)	Cu (%)	Al (%)	Pb (%)	Si (%)	C (%)	P (%)	S (%)
mt. Co	—	0.150	0.140	0.012	—	—	—	0.025	0.007	—	0.004
el. Fe	—	—	—	0.005	0.004	—	—	0.005	0.005	0.004	0.005
mt. Cr	—	0.21	—	—	—	0.06	—	0.07	0.03	0.01	0.02
el. Ni	0.18	0.0007	—	0.0000	0.0005	—	0.0000	0.0004	—	—	0.0002

gravity. By eliminating $\sqrt{E/\rho}$ from the above equations, we obtain

$$D = C \cdot d/fL.$$

Partial differentiation of both terms by the temperature T leads to

$$\alpha_D = \partial D / D \partial T = -\partial f / f \partial T.$$

Consequently, using the experimental data on the temperature dependence of resonance frequency in the delay line, we can derive α_D . For its measurements reported in this work, the vibrator-controlled oscillator system devised by Shirakawa and Oguma⁽⁵⁾ was used.

III. Results and Discussion

1. Temperature coefficient of the delay time

The composition dependencies of α_D for ternary Co-Fe-Cr alloys and quaternary Co-Fe-Cr-Ni alloys containing 16.7 and 28.6%Ni in the furnace-cooled state are shown in Figs. 1, 2 and 3, respectively. In these figures the compositions of the measured specimens are marked with closed circles.

As shown in Fig. 1, α_D in Co-Fe-Cr alloys decreases rapidly with increasing Co concentration beyond about 48% and reaches zero value, after which the value changes from the positive to the negative sign and shows a negative maximum at about 53%Co and 10%Cr. With a further increase in Co concentration, α_D goes to zero from its negative value and then increases in the positive sign gradually. The dependence of the Cr or Fe concentration on α_D is very remarkable compared to the dependence of the Co concentration on α_D . The alloy composition of 53% Co, 37%Fe and 10%Cr having the greatest negative value of α_D is nearly consistent with a composition of Stainless-Inver⁽⁶⁾ with the smallest thermal expansion coefficient and also with a composition of Co-elinvar⁽⁷⁾ with the greatest temperature coefficient of rigidity in the same alloy system.

Figure 2 shows the measured values of α_D to illustrate the effect of alloying addition of 16.7%Ni to Co-Fe-Cr alloys. As can be seen in the figure, the curve $\alpha_D=0$ extends over a wide composition range up to about 42%Co and about 36%(Cr+16.7%Ni) and the variation in α_D with increasing Co or Cr concentration is very small. The composition where the maximum value of α_D in negative sign appears is shifted remarkably to lower Co and Cr concentrations as compared with the Co-Fe-Cr alloy system.

For the cases with the addition of 28.6%Ni, the composition range for the curve $\alpha_D=0$ is considerably broad and α_D shows a small composition dependence.

Fig. 1 Temperature coefficient of the delay time, α_D at 0–40°C for Co-Fe-Cr alloys in the annealed state.

Fig. 2 Temperature coefficient of the delay time, α_D at 0–40°C for Co-Fe-Cr-Ni alloys containing 16.7%Ni in the annealed state.

Fig. 3 Temperature coefficient of the delay time, α_D at 0–40°C for Co-Fe-Cr-Ni alloys containing 28.6%Ni in the annealed state.

2. The maximum gradient of magnetostriction as a function of magnetic field

Figures 4, 5 and 6 represent the composition dependencies on the maximum magnetostriction gradient in the applied magnetic field for Co-Fe-Cr alloys and Co-Fe-Cr-Ni alloys containing 16.7 and 28.6%Ni.

As shown in Fig. 4, the highest value of $(d\lambda/dH)_m$ appears in the vicinity of the composition of 70%Co and 5%Cr and the peak containing the highest value extends over the composition near 60%Co. The curve

Fig. 4 Maximum gradient of magnetostriction in the applied field, $(d\lambda/dH)_m$ at room temperature for Co-Fe-Cr alloys in the annealed state.

Fig. 5 Maximum gradient of magnetostriction in the applied field, $(d\lambda/dH)_m$ at room temperature for Co-Fe-Cr-Ni alloys containing 16.7% Ni in the annealed state.

Fig. 6 Maximum gradient of magnetostriction in the applied field, $(d\lambda/dH)_m$ at room temperature for Co-Fe-Cr-Ni alloys containing 28.6% Ni in the annealed state.

$\alpha_D=0$ is in contact with the curve $(d\lambda/dH)_m=0.4 \times 10^{-6}/\text{Oe}$ in the vicinity of the composition of 59.8%Co and 8.7%Cr. Thus, for Co-Fe-Cr alloys, there appear only a slight variation of the delay time with temperature and the delay line having the maximum magnetostriction gradient of $0.4 \times 10^{-6}/\text{Oe}$ can be obtained.

For quaternary Co-Fe-Cr-Ni alloys containing 16.7%Ni, $(d\lambda/dH)_m$ shows a large value in excess of $1.0 \times 10^{-6}/\text{Oe}$ at the composition of 20% (Cr+16.7% Ni) and 40%Co as shown in Fig. 5 but decreases gradually with the deviation from this composition. The curve $\alpha_D=0$ is in contact with the curve $(d\lambda/dH)_m=0.8 \times 10^{-6}/\text{Oe}$ at the composition of 41.2%Co and 21.0% (Cr+16.7%Ni). This implies that for Co-Fe-Cr-Ni alloys containing 16.7%Ni the delay line showing a negligibly small temperature dependence of delay time and the maximum magnetostriction gradient of $0.8 \times 10^{-6}/\text{Oe}$ is obtained.

For quaternary Co-Fe-Cr-Ni alloys containing 28.6%Ni, $(d\lambda/dH)_m$ has two maximum values as shown in Fig. 6. However, the highest value of $(d\lambda/dH)_m$ which shows $\alpha_D=0$ is as small as the order of $0.21 \times 10^{-6}/\text{Oe}$.

The values of $(d\lambda/dH)_m$ for the alloys of very low α_D values in the ternary Co-Fe-Cr system and the quaternary Co-Fe-Cr-Ni system (16.7 and 28.6%Ni), nickel and Ni-Span C are tabulated in Table 2. The field dependencies of magnetostriction for these alloys, nickel and Ni-Span C are plotted in Fig. 7.

Fig. 7 Magnetostriction-magnetic field curves at room temperature for the typical alloys in the Co-Fe-Cr and Co-Fe-Cr-Ni systems, nickel and Ni-Span C.

Table 2 Temperature coefficient of the delay time α_D at 0–40°C and the maximum gradient of magnetostriction, $(d\lambda/dH)_m$ at room temperature for Co-Fe-Cr alloy, Co-Fe-Cr-Ni alloys, nickel and Ni-Span C in the annealed state.

Composition (%)					α_D ($\times 10^{-5}$)	$(d\lambda/dH)_m$ ($\times 10^{-6}/\text{Oe}^{-1}$)	H (Oe)
Co	Fe	Cr	Ni	Ti			
60.0	31.0	9.0	—	—	— 0.42	+0.36	3
41.2	37.8	4.3	16.7	—	— 0.07	+0.80	12~15
19.0	50.0	2.4	28.6	—	+ 0.21	+0.19	12
—	bal.	5.3	42.3	2.5	~ 0	+0.15	2
—	—	—	100	—	+41.33	—0.39	5

IV. Conclusion

Measurements of the mean temperature coefficient of the delay time at $0\sim 40^{\circ}\text{C}$ and the magnetostriction at room temperature have been carried out for Co-Fe-Cr alloys and Co-Fe-Cr-Ni alloys containing 16.7 and 28.6%Ni in the annealed state. It has been made clear that a Co-37.8%Fe-4.3%Cr-16.7%Ni alloy has the outstanding features of not only having a considerably higher value of $(d\lambda/dH)_m$ than the absolute value for nickel but also a very low value of α_D . Besides the above features, the alloy exhibits good workability. The alloy, therefore, appears suitable for use as a material of the magnetostrictive delay line element.

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