Damping Capacity and Magnetomechanical Properties of Ni-Co-Nb-Si Alloys[†]

Masakatsu Hinai^{††}, Showhachi Sawaya and Hakaru Masumoto^{†††}

The Research Institute for Electric and Magnetic Materials, 2-1-1, Yagiyama-Minami, Sendai 982, Japan

The effects of Nb and Si concentration on the internal friction, magnetic properties, and mechanical properties of Ni-25 mass%Co-Nb-Si alloys have been investigated, by furnace cooling or water quenching, or both. The measurements of internal friction, magnetic hysteresis and mechanical properties were carried out by an inverted torsion pendulum, an automatic recording fluxmeter and an Instron tensile testing machine, respectively. As the shear strain amplitude increased, the internal friction of these alloys first grew larger and then reached a maximum. The maximum internal friction and the shear strain amplitudes were defined as $Q_{\max}^{-1}$ and γ_c . The alloys containing no Nb showed the highest $Q_{\max}^{-1}$ value on furnace cooling for 3 mass%Si and on water quenching for 4 mass%Si. The alloys containing 1 mass%Nb showed the highest $Q_{\max}^{-1}$ value at 2 mass%Si on cooling by both methods. The strain amplitude, γ_c gradually decreased with decreasing Si concentration in these alloys. The alloys containing 3 mass%Nb had the highest $Q_{\max}^{-1}$ value and alloys with 2 mass%Si, the lowest γ_c value, on cooling by both procedures. The alloys containing 5 mass%Nb and 1 mass%Si had the highest $Q_{\max}^{-1}$ value when furnace-cooled, but for water quenching this occurred for 2 mass%Si. The lowest γ_c value was recorded when 2 mass%Si cooling by both procedures. The coercive force H_c also varied with Si concentration much like γ_c . Both H_c and γ_c were small when $Q_{\max}^{-1}$ was large. These results indicate that there is a close relationship between the damping capacity and the magnetoelastic properties of the alloys. The larger the concentration of Nb and Si, the higher becomes the tensile strength and yield strength. The elongation was found to be independent of the Si concentration.

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I. Introduction

The damping capacity in Ni-Co binary alloys is greatly increased by a quenching process which suppresses the Perminvar effect⁽¹⁾. The damping capacity is also closely related to the magnetic properties and the ΔG effect⁽²⁾. Previously it has been reported that the damping capacity Ni-Co alloy's and their mechanical properties are considerably increased by adding the element Nb, and that a high damping capacity is obtained in a state where the coercive force is low and ΔG effect is large⁽³⁾. Furthermore, it was found that these characteristics were further improved by adding Cr to Ni-Co-Nb alloys⁽⁴⁾.

This paper discusses the effect of Nb and Si on the damping capacity and the mechanical properties of Ni-25 mass%Co-Nb-Si alloys containing a specific amount of Co. The relationship between internal friction and the magnetic properties is also discussed.

II. Experimental

High-purity Ni (99.8 mass%), Nb (99.8 mass%), Co

(99.6 mass%) and Si (99.7 mass%), were used to prepare samples for this study. After adding a deoxidizer, these elements were melted in a high-frequency electric furnace while passing high-purity Ar gas. Ingots of 25 mm diameter were produced. The ingots were hot-forged into 6 mm diameter rods at 1373 K, then cold-drawn into 2.0 mm and 0.8 mm diameter wires. The wires were straightened and heated in a vacuum at 1273 K for 7.2 ks and then either cooled in a furnace or quenched in water. The 2.0 mm diameter wires were used to measure the mechanical properties and the 0.8 mm wires to measure the damping capacity (internal friction) and the magnetic properties.

To measure the internal friction, an inverted torsion pendulum was used at a frequency of 1 Hz⁽⁵⁾⁻⁽⁸⁾ to store the vibration's natural decay curve in a transient converter. A personal computer was used to analyze the waveform. An automatic recording fluxmeter was used to obtain the magnetic hysteresis loop and an Instron-type tensile testing machine was used to measure the mechanical strain.

III. Results and Discussion

The internal friction in ferromagnetic alloy is caused by the irreversibility of magnetization; therefore, it depends on the amplitude of the vibrational stress. Figure 1 shows how the internal friction Q^{-1} depends on the shear strain amplitude γ_m for the Ni-25 mass%Co-1 mass%Nb-2 mass% Si alloy cooled in a furnace after

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^{††} Present address: Ichinoseki National College of Technology, Takanashi, Hagisho, Ichinoseki 021, Japan.

^{†††} Dr. Hakaru Masumoto passed away on August 1987.

Fig. 1 Variation in internal friction $Q_{\max}^{-1}$ with shear strain amplitude γ_m for a furnace-cooled Ni-25 mass%Co-1 mass%Nb-2 mass%Si alloy.

heating at 1273 K for 7.2 ks. The internal friction linearly increases with increasing shear strain amplitude and reaches a maximum value, thereafter it gradually decreases. In this report, we have designated the maximum value as $Q_{\max}^{-1}$ and the shear strain amplitude at $Q_{\max}^{-1}$ as γ_c .

Figure 2 shows how $Q_{\max}^{-1}$ and amplitude γ_c depend on the amount of Si for the Ni-25 mass%Co-0 mass%Nb-Si alloy containing 25 mass%Co and no Nb. The specimens were either (a) furnace-cooled or (b) water-quenched after heating at 1273 K for 7.2 ks. The internal friction reached a maximum value of 79×10^{-3} at 4 mass%Si for furnace-cooled specimens, and a value of 118×10^{-3} at 3 mass%Si for the water-quenched specimens. The maximum value was highest when water quenching than when furnace cooling. The value of shear strain amplitude decreased with the concentration of Si in both specimens. Figure 3 shows how $Q_{\max}^{-1}$ and amplitude γ_c depend on the addition of Si, for Ni-25 mass%Co-1 mass%Nb-Si alloy containing 1 mass%Nb, and which is heat-treated in the same way as in Fig. 2. The internal friction reached maximum values of 158×10^{-3} and 98×10^{-3} at 2 mass%Si when furnace-cooled and water-quenched, respectively. In contrast to Fig. 2 where no Nb was present, the value was higher for case (a) when furnace-cooled than for case (b) when water-quenched. The shear strain amplitude gradually decreased with the concentration of Si.

Figure 4 shows how the internal friction $Q_{\max}^{-1}$ and shear strain amplitude γ_c depend on the amount of Si for the Ni-25 mass%Co-3 mass%Nb-Si alloy which contains 3 mass%Nb. The internal friction reached its maximum values of 114×10^{-3} and 63×10^{-3} at 2 mass%Si when furnace-cooled or water-quenched, respectively. However, the value was higher for furnace cooling than water quenching. The shear strain amplitude rapidly decreased with the amount of Si and reached a minimum

Fig. 2 Internal friction $Q_{\max}^{-1}$ and shear strain amplitude γ_c for Ni-25 mass%Co-0 mass%Nb-Si alloys, (a) furnace-cooled and (b) water-quenched.

Fig. 3 Internal friction $Q_{\max}^{-1}$ and shear strain amplitude γ_c for Ni-25 mass%Co-1 mass%Nb-Si alloys, (a) furnace-cooled and (b) water-quenched.

at 2 mass%Si. Figure 5 shows the $Q_{\max}^{-1}$ and amplitude γ_c dependence on the amount of Si in the Ni-25 mass%Co-5 mass%Nb-Si alloy which contains 5 mass%Nb. The internal friction reached a maximum value of 95×10^{-3}

Fig. 4 Internal friction $Q^{-1}_{\max}$ and shear strain amplitude γ_c for Ni-25 mass%Co-3 mass%Nb-Si alloys, (a) furnace-cooled and (b) water-quenched.

at 1 mass%Si (a) for furnace-cooled specimens and 54×10^{-3} at 2 mass%Si (b) for water-quenched specimens. The value of the shear strain amplitude had a minimum value at 2 mass%Si.

Figure 6 shows how the coercive force H_c depends on the amount of Si for Ni-25 mass%Co-Nb-Si alloys containing various amounts of Nb and furnace-cooled after

Fig. 5 Internal friction $Q^{-1}_{\max}$ and shear strain amplitude γ_c for Ni-25 mass%Co-5 mass%Nb-Si alloys, (a) furnace-cooled and (b) water-quenched.

Fig. 6 Coercive force H_c for furnace-cooled, Ni-25 mass%Co-Nb-Si alloys containing (a) 0 mass%, (b) 1 mass%, (c) 3 mass% and (d) 5 mass%Nb.

heating at 1273 K for 7.2 ks. The amount of Nb is (a) 0 mass%, (b) 1 mass%, (c) 3 mass%, and (d) 5 mass%. In (a) and (b) where the Nb content is small, the coercive force decreases with increasing Si content. The coercive force shows a minimum value at 3 mass%Si for case (c) and at 2 mass%Si for case (d). As Fig. 6 shows, the variation of coercive force is very similar to the way the shear strain amplitude varies with the Si content, as shown in Figs. 2-5. These values are proportional to one another, so that when a high internal friction appears, the shear strain amplitude and coercive force are both low. This indicates that the damping capacity of these alloys is closely related to their magnetic properties. However, in these alloys the shear strain amplitude is considerably smaller than that of conventional ferromagnetic vibration-absorbing alloys. Therefore, these alloys may be of use where the vibrational amplitude are small.

Figure 7 shows the variation of the magnetic induction $4\pi I_{2.4}$ on the amount of Si in the Ni-25 mass%Co-Nb-Si alloys, in the same state as illustrated in Fig. 6. The magnetic induction nearly decreases linearly with the amount of Si and its value is lowest when the amount of Nb is maximum. An excessively low magnetic induction is not preferable because this reduces the magnetic effect which contributes to the internal friction. The Ni-Co-Nb-Si alloy used in this study exhibiting high internal friction has a magnetic induction of about 0.7T.

The internal friction is expressed as $\Delta E/2\pi E$, where, E is the vibration energy and ΔE the energy consumed per cycle. When the vibrational stress is acting, the vibration energy is proportion to the square of the amplitude, and the consumed energy corresponds to the hysteresis loss caused by the irreversibility. A process where magnetic

Fig. 7 Magnetic induction, $4\pi I_{2,4}$, for furnace-cooled Ni-25 mass% Co-Nb-Si alloys containing (a) 0 mass%, (b) 1 mass%, (c) 3 mass% and 5 mass% Nb.

Fig. 8 Tensile strength σ_B , yield strength σ_y , and δ for furnace-cooled Ni-25 mass% Co-Nb-Si alloys containing (a) 0 mass%, (b) 1 mass%, (c) 3 mass% and (d) 5 mass% Nb.

rearrangement, such as the movement of the domain walls, occurs due to the reverse effect of magnetostriction.

As previous described, the internal friction of Ni-25 mass% Co-Nb-Si alloys increases with the addition of Si, and it reaches its maximum value in the range 0 to 5

mass% Nb before Si reaches 5 mass%. As the Nb amount increases, the maximum value of the internal friction shifts towards the composition containing a small amount of Si. If Nb is not present in these Ni-25 mass% Co-Nb-Si alloys, the internal friction will show a value as high as 100×10^{-3} or more when rapidly cooled (water quenching). Moreover, if 1 mass% Nb or more is contained in the alloy, the internal friction will further increase when gradually cooled (furnace cooling). This effect is related to the case where no Nb is present and the sample is gradually cooled, a Perminvar effect appears to increase the coercive force. While, when Nb is added and gradually cooled, a Perminvar effect is suppressed, thereby decreasing the coercive force. The increase in coercive force makes it difficult for magnetization to occur⁽²⁾, and increases the shear strain amplitude. This increases the vibration energy and reduces internal friction. Meanwhile, if the coercive force is small, a small shear strain amplitude can change the magnetization, which will lead to a high internal friction.

Figure 8 shows the tensile strength σ_B , yield strength σ_y , and elongation δ and how they depend on the amount of Si in the Ni-25 mass% Co-Nb-Si alloys. The tensile strength and yield strength increase with the content of Nb except for 5 mass% Nb. Then, they gradually increase with the amount of Si. Note that the tensile strength and yield strength rapidly increase at 5 mass% Si in (b), at 4 mass% Si in (c), and at 3 mass% Si in (d). The reason for this seems to be the precipitation of the intermetallic compound, which will be detailed in the next report. The elongation is hardly affected by the amount of Si, but is considerably small at 3 mass% Si in 5 mass% Nb (d).

IV. Conclusion

The effect of Nb and Si content on the internal friction, magnetic properties, and mechanical properties of the Ni-Co-Nb-Si alloys containing 25 mass% Co and 0, 1, 3, and 5 mass% Nb was investigated. The samples were furnace-cooled or water-quenched after heating at 1273 K for 7.2 ks. The following results were obtained:

(1) The internal friction increases linearly with the shear strain amplitude, until it reaches its maximum value $Q_{\max}^{-1}$, and thereafter it gradually decreases. We expressed the shear strain amplitude at $Q_{\max}^{-1}$ as γ_c . The $Q_{\max}^{-1}$ of Ni-25 mass% Co-0 mass% Nb-Si alloy reached its maximum value at 3 mass% Si after being furnace-cooled, and at 4 mass% Si after being water-quenched. The maximum value was higher when water-quenched than when furnace-cooled. The $Q_{\max}^{-1}$ of the Ni-25 mass% Co-1 mass% Nb-Si alloy reached a maximum value at 2 mass% Si independent of furnace-cooled or water-quenched. In contrast to the case in which no Nb is present, $Q_{\max}^{-1}$ was higher when furnace cooled than when water-quenched. The γ_c of the above 0 mass% Nb and 1 mass% Nb alloys gradually decreased with the amount of Si.

(2) The $Q_{\max}^{-1}$ value for the Ni-25 mass% Co-3 mass% Nb-Si alloy reached a maximum at 2 mass% Si,

whether it was furnace-cooled or water-quenched. The γ_c value also fell to a minimum at 2 mass%Si. The Ni-25 mass%Co-5 mass%Nb-Si alloy reached its maximum value in $Q_{\max}^{-1}$ at 1 mass%Si when furnace-cooled, and at 2 mass%Si when water-quenched. The γ_c reached its minimum at 2 mass%Si. In this way, the $Q_{\max}^{-1}$ value of these alloys was greatly increased by the addition of Si, independent of the Nb amount present.

(3) The change in coercive force H_c with the Si amount was very similar to the change for γ_c , when a high $Q_{\max}^{-1}$ appeared, γ_c and H_c were both low. This indicates that the damping capacity is closely related to the magnetoelastic properties.

(4) The higher the content of Nb and Si, the higher the tensile and yield strength. The elongation was hardly affected by a change in the Si content.

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