Effect of Cold Working on Mechanical Damping Capacity of Al-Co Alloys[†]

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The logarithmic decrement (δ) of elastic vibration and rigidity modulus (G) were investigated for Al-Co alloys containing 0.2 to 10.0 mass% Co. δ and G were measured using an inverted torsion pendulum. In furnace-cooled and water-quenched specimens, δ is slightly increased by adding Co, but its absolute value is about 9×10^{-3} which is considerably small. The δ of furnace-cooled specimen is slightly higher than that of water-quenched one. The δ of all alloys is drastically increased by cold working after heat treatment. The value of δ in cold-worked specimens rapidly increases with the amount of Co up to about 1 mass% Co, and then the value either remains constant or decreases slightly. The alloys cold-drawn after furnace-cooled yield higher δ values than those cold-drawn after water-quenching. The difference between them is greater when the degree of working is smaller. In the furnace-cooled and water-quenched specimens, G increases as the amount of Co increases. G is decreased by cold working after heat treatment because dislocations increase. The increase in δ by cold working seems to be due to a drastic increase in the dislocation density and a decrease in the grain sizes of the α and β phases.

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I. Introduction

Vibration-absorbing alloys with high mechanical damping capacity are frequently used to solve problems caused by vibration. Various vibration-absorbing alloys based on Ni, Cu, Zn, Al and Mg as well as Fe have been developed and their damping mechanisms have been discussed⁽¹⁾⁻⁽⁷⁾. The alloys based on Al and Mg are suitable for lightening structure members, because they have a specific gravity smaller than the alloys based on Fe, Ni, Cu and Zn. The vibration-absorbing alloys except for Zn- or Al-based alloys are always heat-treated to gain a high damping capacity after being formed into its final shape. Heat treatment, however, introduces thermal stresses and warps a thin product. If a high damping capacity is given through cold working alone, it is possible to avoid distortion of thin products by thermal strain. In addition, if it is easy to carry out the rolling and drawing processes, many product shapes may be fabricated. Such processes are difficult to apply to alloys based on Mg and Cu(Cu-Al-Ni), and therefore their use is limited.

Zn-Al, Al-Si, Al-Fe, Al-Ni and Al-Ge alloys can develop a considerably high damping capacity through cold working⁽⁶⁾⁽⁸⁾⁻⁽¹¹⁾. The reason for this high damping capacity is probably the following: in the Zn-Al alloy, the cold working brings about a fine-structure composed of the hard α phase and the soft β phase, and both phases

exhibit a viscous sliding motion along the crystal grain boundaries; in the latter four alloys, cold working increases the dislocation lines that can vibrate, and also plastic motion occurs along the boundaries between the matrix phase and metallic particles.

This paper deals with a lightweight, nonferromagnetic Al-Co alloy and discusses its logarithmic decrement and rigidity modulus in the heat-treated state and in the cold-worked state.

II. Experimental

To prepare the specimens, a mother alloy of Al-20 mass% Co was melted in a high-frequency electric furnace by using Al with a purity of 99.99 mass% and Co with a purity 99.6 mass%. Then, to provide the specified composition ratios, the total amount of Al and mother alloy, 100 g, was weighed and melted in the high-frequency electric furnace to produce ingots with a 10 mm diameter. Each ingot was homogenized at 773 K for 18 ks and hot-forged into sheets and rods. Before applying cold working, the sheets and rods were heated at 773 K for 3.6 ks and then cooled in a furnace or quenched in water. Next, they underwent cold rolling or cold drawing to form 0.6 mm thick sheets and 1.1 mm diameter wires. The sheets were used to analyze the crystal structure and the wires to measure the logarithmic decrement of elastic vibration and rigidity modulus. The compositions of specimens were eight kinds of, 0, 0.2, 0.5, 1, 2, 4, 6, 8 and 10 mass% Co.

The crystal structures of the alloys were investigated with an X-ray diffractometer (Fe- K_α radiation), and the logarithmic decrement and rigidity modulus were

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measured with an inverted torsion pendulum at a frequency of 1 Hz and shear strain amplitudes of 1 to 300×10^{-6} . Since the Kster effect⁽¹²⁾ remained in the specimens immediately after cold working, all the specimens were left at room temperature for 86.4 ks (1d) after cold working and then measured.

III. Results and Discussion

The logarithmic decrement of Al-Co alloys changes depending on the magnitude of vibrational stress like the Al-based alloy on which the authors have reported previously. For example, Fig. 1 shows the relationship between the logarithmic decrement (δ) and the shear strain amplitude (γ_m), for Al-1.0 mass% Co alloy in three different states; as furnace-cooled after heating at 773 K for 3.6 ks, followed by additional cold drawing to 70 and 90% reductions in the sectional area. The value of the logarithmic decrement of a furnace-cooled specimen is considerably small, although it tends to increase at a small rate as the shear strain amplitude increases. On the other hand, the logarithmic decrement of the cold-drawn specimens keeps a constant value in the range of small shear strain amplitude, and then increases linearly at strain amplitudes over approximately 10 to 20×10^{-6} . The larger the areal reduction, the larger becomes the rate of increase.

Figure 2 shows the relationship between the logarithmic decrement (δ) at a shear strain amplitude of 10×10^{-6} and the Co concentration, for Al-Co alloys cold-drawn to 38, 70 and 95% reductions after furnace-cooling (FC). The reason for the selection of a shear strain amplitude of 10×10^{-6} is that the vibration amplitude of the structural members is generally on the order of 1 to 100×10^{-6} , and that the logarithmic decrement of this alloy changes in the range where the shear strain amplitude is greater, as seen in Fig. 1. As Fig. 2 shows, the logarithmic decrement of the furnace-cooled material is slightly increased by adding Co, although its

Fig. 1 Variation in logarithmic decrement (δ) with shear strain amplitude (γ_m) in an Al-1 mass% Co alloy furnace-cooled (FC) and further cold-drawn to 70 and 95% reductions in the sectional area (R).

Fig. 2 Logarithmic decrement (δ) ($\gamma_m = 10 \times 10^{-6}$) of Al-Co alloys cold-drawn to various reductions after furnace-cooling (FC).

absolute value is 9×10^{-3} which is considerably small. However, the value of the logarithmic decrement increases with increasing the degree of cold working. The value rapidly increases with the amount of Co to 1 mass%, which is the eutectic composition. Then the value either remains constant or decreases slightly.

Figure 3 shows the relationship between logarithmic decrement (δ) and the Co concentration for the Al-Co alloys water-quenched (WQ) after heating at 773 K for 3.6 ks and followed by cold drawing to 38, 70 and 95% reductions. As shown in Fig. 3, the logarithmic decrement of WQ specimen is as small as that of FC specimen, although it is greatly increased by cold working. Logarithmic decrement of specimens cold-drawn after water-quenching is slightly smaller than that of the specimens cold-drawn after furnace-cooling when the reduction is small, but the values are nearly the same when the reduction is high.

Figure 4 illustrates an equilibrium phase diagram of Al-Co alloy at the Al side according to Willey's report⁽¹³⁾. The maximum solubility of Co in Al is as small as 0.02 mass% at 930 K. This indicates that Co hardly forms a

Fig. 3 Logarithmic decrement (δ) ($\gamma_m = 10 \times 10^{-6}$) of Al-Co alloys cold-drawn to various reductions after water-quenching (WQ).

Fig. 4 Equilibrium phase diagram of Al-Co alloys after L. A. Willey.

solid solution with Al. The eutectic composition is 1.0 mass% Co and an intermetallic compound like Al_9Co_2 exists. The logarithmic decrement of such an alloy is considered to be closely related to its internal structure⁽⁸⁾. We, therefore, checked the crystal structure in the heat-treated and cold-drawn state. Figure 5 shows the X-ray diffraction patterns of the Al-4 mass% Co alloy heated at 773 K for 3.6 ks, and (a) furnace-cooled or (b) water-quenched, then cold-drawn to an areal reduction ratio of 70%. The figure shows the diffraction lines of Al solid solution (α phase) and Al_9Co_2 compound (β phase) for both cooling conditions. In this manner, most Al-Co alloys have two phases of α and β in both the heat-treated state and a strongly cold-worked state. The β phase consists of a monoclinic lattices with lattice constants $a=0.62130$, $b=0.6290$, and $c=0.85565$ nm and an axial angle of 94.760° ⁽¹⁴⁾.

As seen in Figs. 4 and 5, heat-treated Al-Co alloys are a two-phase structure, α and β , and the amount of precipitated β phase increases as the concentration of Co increases. When vibrational stress is applied to such an alloy, viscous and plastic sliding motions occur along the grain boundaries and absorb the vibration energy. This leads to an increased logarithmic decrement. The magnitude seems to be determined by the ratio of the β phase to the α one, the differences of their hardness and strength, the shapes of the crystal grains, and the total area of the boundaries between them. In addition, the increase in the logarithmic decrement due to the motion of the dislocation lines can be considered, since dislocations also exist in the alloy, even in a heat-treated state. In this case, the magnitude of the logarithmic decrement may be determined by the density of the dislocation and by the amount and distribution of impure atoms that act as fixing points (pinning)⁽¹⁵⁾. However, the logarithmic

Fig. 5 X-ray diffraction patterns of an Al-4 mass% Co alloy cold-drawn to 70% reduction after (a) furnace-cooling and (b) water-quenching.

decrement is considerably low in the heat-treated state as shown in Figs. 1-3; therefore, these two effects seem to be very small.

The logarithmic decrement of the Al-Co alloy is greatly increased by cold working after heat treatment. The reason for this seems to be related to the phenomena; the crystal grains of both the α and β phases are refined, the total area of the boundaries is increased and the dislocation density is accelerated with increasing reduction.

Figure 6 shows how the rigidity modulus (G) ($\gamma_m = 10 \times 10^{-6}$) depends on the Co concentration, for the specimens cold-drawn to 35, 70 and 95% reductions after

Fig. 6 Rigidity modulus (G) of Al-Co alloys cold-drawn to various reductions after furnace-cooling (FC).

Fig. 7 Rigidity modulus (G) of Al-Co alloys cold-drawn to various reductions after water-quenching (WQ).

furnace-cooled. Figure 7 shows the same relationship for the water-quenched materials.

As both figures show, the rigidity modulus of specimens in the heat-treated state increases with an increase in Co concentration and the rate of increase in the range of 0~1 mass% Co is drastically high. The value of the rigidity modulus is slightly higher in water-quenched specimens than in specimens furnace-cooled. Cold working after heat treatment considerably decreases the rigidity modulus, and the rate of decrease increases as the areal reduction increases. This seems to be connected to an increase in the dislocation density by cold working⁽¹⁶⁾.

Figure 8 shows the ΔG effect for the Al-Co alloy. Here we define the rigidity modulus in the heat-treated state as G_H and that in the cold-drawn state as G_R , and $\Delta G = (G_H - G_R)/G_H$ in percentage. The symbols of open circle, open triangle, and open square indicate areal reduction ratios of 35, 70 and 95% after furnace-cooled, respectively. Solid circles, solid triangles, and solid

Fig. 8 ΔG effect of Al-Co alloys cold-drawn to 38, 70 and 95% of reductions after furnace-cooling ($\circ$, $\triangle$, $\square$) and water-quenched ($\bullet$, $\blacktriangle$, $\blacksquare$).

squares indicate the areal reduction ratios of 35, 70 and 95% after water-quenching, respectively. ΔG of pure Al is very small, although it greatly increases when 1 mass% of Co is added. The value of ΔG is nearly independent of the cooling rate and increases as the reduction increases. The value of ΔG depends on the Co concentration just like the logarithmic decrement δ .

Figure 9 shows the relationship between the logarithmic decrement (δ) and the square of ΔG , for Al-Co alloy specimens in states cold-drawn to 35, 70 and 95% reductions after furnace-cooling (open-circle symbol) or water-quenching (open-triangle symbol). These relationships were obtained by means of the least square method. The results were as follows; $\delta = 24.6 \times 10^{-3} + 21.60 \times 10^{-5} \Delta G^2$ for a 35% reduction, $\delta = 38.7 \times 10^{-3} + 11.52 \times 10^{-5} \Delta G^2$ for a 70% reduction and $\delta = 70.7 \times 10^{-3} + 2.80 \times 10^{-5} \Delta G^2$ for a 95% reduction.

According to Granato-Lücke model⁽¹⁵⁾, the part Δ_1 of the logarithmic decrement independent of the shear strain amplitude is due to the damping resonance of the dislocation lines. The Δ_1 is proportional to L^4 (L : the average length of the dislocation loops), while ΔG is proportional to L^2 . This leads to the conclusion that Δ_1 is proportional to ΔG^2 . This relationship was verified by Thompson *et al.* using a single Cu crystal irradiated with neutrons⁽¹⁷⁾. Figure 9 gave the linear relationship between the logarithmic decrement and ΔG^2 . This relationship indicates that the intercept values at which ΔG^2 is 0 are 24.6×10^{-3} , 38.7×10^{-3} , and 70.7×10^{-3} . Note that these values increase with the reduction. The probable reason for this is the plastic sliding motion between the α phase and the Al_3Co_2 compound particles. The coefficients of ΔG^2 are 21.60×10^{-5} , 11.52×10^{-5} , and 2.80×10^{-5} , which decrease with the reduction. This seems to indicate that, in the range where the shear strain amplitude is as small as about 10×10^{-6} , the dislocation's contribution is small at a high reduction.

Fig. 9 Relation between ΔG^2 and δ of Al-Co alloys cold-drawn to reductions after furnace-cooled ($\circ$) and water-quenching ($\triangle$).

Fig. 10 Granato-Lücke plot for an Al-1 mass% Co alloy furnace-cooled and subsequently cold-drawn to a 70% reduction.

To check whether the dislocation affects the logarithmic decrement, it is generally sufficient to observe whether the linear relationship holds between $\text{Ln}(\Delta_H \cdot \gamma_m)$ and γ_m^{-1} where Δ_H is assumed to be the part that depends on the shear strain amplitude (γ_m). Figure 10 shows the Granato-Lücke plot for the Al-1 mass% Co alloy furnace-cooled and subsequently cold-drawn to a 70% reduction. In the figure, the linear relationship holds in the range where the shear strain amplitude is high, indicating that the dislocation contributes to the logarithmic decrement within this range.

As described so far, the logarithmic decrement of an Al-Co alloy is considerably increased by cold working after heat treatment. For example, a logarithmic decrement of 73×10^{-3} is given to Al-2 mass% Co alloy furnace-cooled and then cold-drawn to a 95% reduction. This value exceeds the highest value of 63×10^{-3} that we obtained for Al-4 mass% Ni alloy in a previous study. Besides, very low specific gravity of the Al-Co alloys can lighten devices and components. Also, this Al-Co alloys is nonferromagnetic and thus does not have any undesirable magnetic effects on other parts surrounding it. Thus, it is a promising vibration-absorbing alloy.

IV. Conclusion

The crystal structure, logarithmic decrement (δ), and rigidity modulus (G) of Al-Co alloys containing 0.2 to 10.0 mass% Co were investigated in different states, such as a furnace-cooled state and a water-quenched state after heating at 773 K for 3.6 ks, and in states resulting after additional cold working. The results were as follows:

(1) For furnace-cooled and water-quenched specimens, δ is slightly increased by adding Co, but its value is about 9×10^{-3} which is considerably small (at a shear strain amplitude of 10×10^{-6}). The value of δ is slightly higher in the furnace-cooled specimens than in the water-quenched specimens.

(2) The δ of all alloys became considerably high by cold working after heat treatment. The value of δ in cold-worked specimens rapidly increases with the amount of Co to 1 mass%, then the value either remains constant or slightly decreases. The value of δ for the specimens cold-drawn after furnace-cooling is higher than that for those cold-drawn after water-quenching. The difference between them is greater when the degree of working is smaller. The maximum δ of 73×10^{-3} was obtained with the Al-2 mass% Co alloy by cold drawn to a 95 % reduction after furnace cooling.

(3) In the furnace-cooled and water-quenched specimens, the shear modulus G increases with increasing Co concentration. In the specimens cold-drawn after heat treatment, G decreases with increasing reduction. The ΔG effect depends on the Co concentration just like δ depends on the Co concentration.

(4) The increase in δ by cold working after heat treatment seems to be due to the effect of cold working that drastically increases the dislocation density and decreases the grain sizes of the α and β phases.

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