Effect of Heat Treatment and Cold Working on Aging in Logarithmic Decrement of Al-Zn Alloys[†]

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Aging at room-temperature in the logarithmic decrement δ and crystal structure were investigated for heat-treated and cold-drawn Al-Zn alloys. The value of δ was measured by an inverted pendulum method and the crystal structure was confirmed by using an X-ray diffractometer method.

The value δ of the Al-Zn alloys containing Zn less than 70 mass% is very low just after water quenching from a temperature of 673 K in the region of the α phase, but becomes higher over time, decreasing gradually after reaching a maximum. The nearer the eutectoid composition, the shorter the decomposition time at which the maximum of δ appears. On the other hand, in the alloys which were water-quenched from 573 K in the region of the $(\alpha + \beta)$ phase, δ shows a maximum in a short time than that from the α phase. Which the alloys contained 80 and 90 mass% Zn and were water-quenched from the region of the $(\gamma + \beta)$ phase, δ from 623 K is higher than from 573 K, and both values reach maxima just after quenching, and then decrease gradually. The variation in δ may be explained as follows. In the alloys with the α phase, δ is very low but becomes gradually higher with the increase in precipitation of the β phase due to the eutectoid decomposition reaction, it then decreases gradually with the slow growth of the grains after reaching a maximum.

The value δ upon furnace cooling is very low, whereas upon cold drawing it becomes higher because of the refinement of grains and the increasing dislocations caused by working. Further, by cold drawing after water quenching, δ is increased considerably. However, in the cold states, δ becomes lower gradually with time.

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I. Introduction

According to the Al-Zn phase diagram⁽¹⁾⁽²⁾, shown in Fig. 1, the solubility of Zn in Al is 31.6 mass% at 548 K, and is extremely small at ambient temperatures. Therefore, slow cooling from a high temperature gives the alloys a two-phase structure ($\alpha + \beta$) above the small solubility limit. Rapid cooling of single-phase alloys causes no structural changes, but the alloys gradually become two-phase structures through eutectoid decomposition even at room-temperature.

Nuttall reported that slow cooling caused the lamellar structure of the α - and β -phase grains to form an Al-78 mass% Zn alloy, and that rapid cooling produced extremely fine grains. Furthermore, after rapid cooling, the damping capacity increased with the rise in temperatures, reaching a very large maximum of 523 K, the temperature for super plasticity⁽³⁾. In one of the previous studies we showed that after either slow or rapid cooling, cold drawing raised the damping capacity of alloys in a wide range of compositions⁽⁴⁾.

Such Al-Zn alloys with a high damping capacity have low specific gravities and are nonferromagnetic. Hence,

they seem to be promising as vibrational-damping materials with a wide range of applications. As reported by Nuttall⁽⁵⁾, rapidly cooled Al-78 mass% Zn alloy changes its tensile strength as the eutectoid reaction progresses at room-temperature. Accordingly, we may well expect that the damping capacity should also change with time during the eutectoid decomposition.

In this report, with a view toward preventing an unfavorable change in the damping capacity during practical application, we examined the aging in the damping capacity and crystal structure of three types of alloys: those that were rapidly cooled, those that were cold-work-

Fig. 1 Phase diagram of Al-Zn alloys after Presnyakov *et al.*

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ed after slow cooling, and those that were cold-worked after rapid cooling.

II. Experimental

Aluminum metal of 99.99 mass% purity and zinc metal of 99.9 mass% purity were used as starting materials. A mixture of these metals was melted in an alumina crucible in an induction furnace to form an alloy ingot 10 mm in diameter. After being homogeneized at 673 K (or 623 K for 80 and 90 mass% Zn alloys) for 18 ks, each ingot was hot-forged into a 6 mm-diameter bar, then cold-drawn to wires measuring 5, 2, 1.4, and 1.22 mm in diameter. Each wire lot was heated at 673 K (or 623 K) or 573 K for 3.6 ks, then furnace-cooled or water-quenched, and 86.4 ks later cold-drawn further to a 1.1 mm diameter, from which test samples were taken. Part of the 1.1 mm-diameter wire was heated at 673 K (or 623 K) or 573 K for 3.6 ks. It was then furnace-cooled or water-quenched and served as a test sample for the sake of comparison.

In the following, we took measurements at room-temperature for all the heat-treated and cold-worked samples. These were binary Al-Zn alloys containing 30, 50, 70, 80, and 90 mass% Zn. With a frequency of about 1 Hz, the inverted torsion pendulum method⁽⁶⁾⁽⁷⁾ was used for measurement of the damping capacity. Oscillation was detected by used either a CdS photo bridge⁽⁸⁾ or a galvanometer⁽⁹⁾ methods. The logarithmic decrement was obtained from the free decay oscillation curves. The frequency was measured by an universal counter. The crystal structure was determined by an X-ray diffractometer with Cu-K α radiation.

III. Results and Discussion

It has been reported in a previous paper⁽⁴⁾ that with a eutectoid composition of 78 mass% Zn, an Al-Zn alloy has a high logarithmic decrement δ when cooled rapidly in water and a very low δ when cooled slowly in a furnace. First, the results with the water-quenched alloys are described.

Figure 2 shows the ageing curve of the logarithmic decrement of (a) a 30 mass% Zn alloy, (b) a 50 mass% Zn alloy, and (c) a 70 mass% Zn alloy after it is water-quenched at 673 K. Before they were quenched, all these alloys were of the α (or α') phase, and just after they were quenched they all had very low values. The logarithmic decrement of the alloy (a) remained low even after 20,000 ks. On the other hand, those of alloys (b) and (c) began to rise in 200 ks and 7 ks, respectively, after quenching; and then, reached a maximum and gradually decreased. Figure 3 shows the aging curve for (a) a 80 mass% Zn alloy and (b) a 90 mass% Zn alloy. Each of them showed a maximum of 0.42 to 0.72 ks after being quenched, lowered, raised again between 100 and 1000 ks, and then lowered gradually.

Figure 4 shows the aging curve of the logarithmic decrement of (a) a 50 mass% Zn alloy and (b) a 70 mass% Zn

Fig. 2 Aging curve of logarithmic decrement δ in Al-Zn alloys water-quenched at 673 K. (a) 30 mass% Zn, (b) 50 mass% Zn and (c) 70 mass% Zn.

Fig. 3 Aging curve of logarithmic decrement δ in Al-Zn alloys water-quenched at 623 K. (a) 80 mass% Zn and (b) 90 mass% Zn.

alloy after water-quenching at 573 K. Immediately after quenching, the alloy (a) had a logarithmic decrement slightly higher than that of the same composition at 673 K in Fig. 2; while alloy (b) had a much higher logarithmic decrement. In 20 ks after quenching, the logarithmic decrement of alloy (a) reached a maximum, while that of alloy (b) reached a maximum only 0.47 ks after quenching. These facts indicate that eutectoid decomposition may take place more rapidly when quenched from a two-

Fig. 4 Aging curve of logarithmic decrement δ in Al-Zn alloys water-quenched at 573 K. (a) 50 mass% Zn and (b) 70 mass% Zn.

phase ($\alpha + \gamma$) region rather than from a single-phase (α or α') region. Figure 5 shows the aging curve of the logarithmic decrement for (a) a 80 mass% Zn alloy and (b) a 90 mass% Zn alloy after water quenching at 573 K. The two alloys reached a maximum immediately after quenching, and the logarithmic decrement gradually decreased thereafter. Both δ values were smaller than those for quenching at 623 K in Fig. 3, indicating that a higher solution-treatment temperature is more suitable for the two-phase ($\alpha + \beta$) region.

Thus it has been clarified that the aging in logarithmic decrement has a significant relation with changes in the crystal structure. Figure 6 shows the change with time of an X-ray diffraction pattern for 70 mass% Zn alloy which was water quenched at 673 K. In 0.61 ks after quenching, the pattern showed no phase other than α . After 82.8 ks, it included that of the β phase, which had a diffraction strength that significantly increased 2419 ks after quenching. Figure 7 shows the change with time of the X-ray diffraction pattern for a 70 mass% Zn alloy water quenched at 573 K. In 1.08 ks after quenching, the pattern already included the β phase, which had a diffraction strength that increased significantly with time. These changes in the diffraction pattern presumably correspond to those in the logarithmic decrement as shown in Figs. 2 and 4.

In the previous report⁽⁴⁾, we found that when water-quenched at 673 K, Al-base alloys containing 70 mass% or less Zn hardened so much that they were difficult to cold work. This unfavorable effect can, however, be avoided either by furnace cooling or by water quenching from the two-phase ($\alpha + \gamma$) region at 573 K. With these treatments, the alloys will be made softer and more workable. Figure 8 shows the aging curve of the logarithmic decrement of (a) a 30 mass% Zn alloy, (b) a 50 mass% Zn alloy, and (c) a 70 mass% Zn alloy after furnace cooling at 673 K and cold working, leading to 70 and 95% reductions in area. In this figure the δ values are considerably higher and more consistent than those for water quenching, shown in Fig. 2.

The alloys of 80 mass% or more Zn showed low

Fig. 5 Aging curve of logarithmic decrement δ in Al-Zn alloys water-quenched at 573 K. (a) 80 mass% Zn and (b) 90 mass% Zn.

Fig. 6 X-ray diffraction patterns after the lapse of (a) 0.61 ks, (b) 82.8 ks and (c) 2419 ks in an Al-70 mass% Zn alloy water-quenched at 673 K.

Fig. 7 X-ray diffraction patterns after the lapse of (a) 1.08 ks and (b) 2423 ks in an Al-70 mass% Zn alloy water-quenched from 573 K.

Fig. 8 Aging curve of logarithmic decrement δ in Al-Zn alloys cold-worked with reduction in area R after furnace cooling at 673 K. (a) 30 mass% Zn, (b) 50 mass% Zn and (c) 70 mass% Zn.

hardness values, regardless of the heat treatment applied. Figure 9 shows the aging curve of the logarithmic decrement of (a) a 80 mass% Zn alloy and (b) a 90 mass% Zn alloy after water quenching at 623 K and cold working, to 70 and 95% reductions in area. In this figure, the δ values appear significantly higher than those in Fig. 3, but their time dependence is smaller.

Kato *et al.* reported that an Al-78 mass% Zn alloy began hardening immediately after rapid cooling at 623 K, then began to soften quickly after the hardness reached a maximum, and gradually softened after the lapse of 60 ks⁽¹⁰⁾. These results match the results of the present study. Initially, the eutectoid decomposition promotes the hardness rise and the dislocation density increase. According to Granato and Lücke⁽¹¹⁾, such a logarithmic decrement due to the dislocations increases. Furthermore, the eutectoid decomposition causes small grains of α and β to make contact with one another. Relative viscous slipping of such grains along the grain boundaries will presumably increase the logarithmic decrement⁽¹²⁾. The magnitude of logarithmic decrement will depend on (1) the ratio of the volume of the α phase to that of the β phase, (2) the total area of the grain boundaries between the α and β phases, and (3) the differences in the mechanical strengths of the α and β phases⁽⁴⁾⁽¹²⁾. In this respect, the logarithmic decrement will be at its highest level when the volume ratio is one, or during eutectoid composition; and it will get higher, as the grains become finer and the area of the grain boundaries becomes larger.

Fig. 9 Aging curve of logarithmic decrement δ in Al-Zn alloys cold-worked with reduction in area R after water quenching at 623 K. (a) 80 mass% Zn and (b) 90 mass% Zn.

In the case of rapid cooling, the logarithmic decrement increases as the time needed to reach the maximum value decreases. The δ values are tied to the rise of the Zn concentration between 30 and 90 mass%, except that the δ (and the time) at the 80 mass% is higher (and shorter) than that at 90 mass%. Before the maximum value is reached, the aging of the δ largely differs between the alloys heat-treated at 673 K (or 623 K) and 573 K. Beyond the maximum, the δ of the alloy water-quenched at 573 K decreases more slowly than that of the alloy (of the same composition) water-quenched at 673 K. Therefore, the logarithmic decrement decreases gradually after completion of the eutectoid decomposition, possibly because the α and β grains increase in size and soften.

On the other hand, when furnace-cooled or water-quenched and then cold-worked, the alloys show finer α and β grains, as the reduction in area increases more. In this case, the logarithmic decrement did not show a maximum because the eutectoid reaction was completed. As we reported in the previous paper⁽⁴⁾, the alloys with higher Zn concentrations soften as do the alloys with a hexagonal structure⁽¹³⁾. In addition, when cold-worked, they develop dislocations. Ball's observations of dislocations⁽¹⁴⁾ suggest that the alloys of small Zn concentrations will have more dislocations if they are less work-softened.

According to Nuttall's observations, after cold working, subgrains appear, recrystallization takes place around them, and the alloy regains its initial crystal state after a long time of, for example, 5200 ks⁽⁵⁾; Al-Zn alloys have low melting points and hence their crystal grains

grow even at ambient temperature, possibly causing a rearrangement and union-extinction of grains, just as in heated high-temperature alloys that have dislocations that migrate and combine with one another⁽¹²⁾. These structural changes seem to account for the faster change in the logarithmic decrement of the cold-worked alloys than in the water-quenched alloys.

In the present study, a drop in the damping capacity is inevitable in binary Al-Zn alloys that have been heat-treated or cold-worked, even after eutectoid decomposition is completed. This is a major drawback in its application as a practical vibration-damping material. Nevertheless, the alloy system is attractive in view of its high damping capacity, low specific gravity, and nonferromagnetic properties. Therefore, in order to establish suitable stabilization measures to prevent a drop in the damping capacity, further studies are in progress now.

IV. Conclusions

The room-temperature aging of the logarithmic decrement and crystal structure with heat-treated and cold-worked Al-Zn binary alloys containing 30, 50, 70, 80, and 90 mass% Zn were studied. The results are as follows:

(1) The alloys of 70 mass% or less Zn had a very low logarithmic decrement immediately after water quenching at 673 K at which the alloy was in an α (or α') phase. The logarithmic decrement increased with time and decreased gradually after reaching a maximum. The nearer the eutectoid composition, the shorter became the decomposition time at which the maximum of δ appears. When water-quenched at 573 K at which the alloy was in the two-phase (α and γ) region, it showed a maximum in a shorter time.

(2) The 80 and 90 mass% Zn alloys showed a maximum in logarithmic decrement immediately after water quenching at 573 and 623 K at which they were in a two-phase (α and γ) region. Afterwards, the logarithmic decrement decreased gradually. The logarithmic decrement of the alloys quenched at 623 K was always higher than that of the alloys quenched at 573 K.

(3) When the water-quenched alloy had a single α phase, its logarithmic decrement was initially very low, but began to rise as the β -phase grains precipitated, eventually reaching a maximum. When it reached the maximum point depended on its chemical composition. After reaching the maximum, the logarithmic decrement decreased, presumably because the crystal grains grew gradually.

(4) When heat-treated and cold-worked, the alloys attained a very high logarithmic decrement, not only because the crystal grains were very fine but also because the dislocations were very dense. In this case, as time passed, the logarithmic decrement dropped gradually. One plausible reason for this is that subgrains appeared and recrystallized, eventually leading to the recovery of the original crystal structure.

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