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An Experimental Study on Solid Solution Softening, Age Softening and Work Softening

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Although softening is much less discussed in metals and alloys, the phenomena are seen in a number of alloys and often encountered in practical cases. The present work was intended to investigate details of the softening phenomena experimentally, and to consider the phenomena on the basis of chemical bond nature of constituent atoms. The present Vickers hardness tests revealed that Al-1.7mass%Fe alloy annealed 673K showed softening. As-cast Zn-Al alloy also showed work softening, despite that aluminum base Al-Zn posseses age-hardenability, in principle. The hardeness change in an aluminum specimen was dependent on reduction ratio and purity of the specimen in cold rolling. Both hardening and softening phenomena were observed in same alloys, due to solid solution, precipitation and cold working treatments, when the alloy composition (including purity) and heat treatment were changed. Relationships of solid-solution softening and hardneing, age(precipiitation)-softening and hardening, work-softening and hardening have also been considered.

Keywords: *metals, alloys, solid solution softening, age softening, work softening*

1. Introduction

Solid solution hardening, age-hardening (precipitation-hardening) and work hardening are well-known and typical methods to strengthen metals and alloys. On the contrary, materials softening is less investigated, although the phenomenon often occurs and reported in a number of alloys [1-4]. Conventionally, the reason of the softening phenomena has simply been attributed to recovery and recrystallization in most cases. However, the interpretation is used, *a posteriori* , for the phenomenon and unfortunately impotent to predict whether and how the softening occurs. Thus, more close examinations are needed to understand fundamental scheme of the phenomenon and relation between hardening and softening in materials. The present study aims to consider the relationship between phenomena apparently opposite to each other as “hardening” and “softening” in mechanism. According to the terminology defined by the present group, the softening is also divided and categorized into three fashions as, solution softening, age softening and work softening, similar to the hardening. The present work aimed for investigating the softening events of alloys experimentally, to consider how a newly established concept can be applied to explain them. In the present paper, experimental results are first presented separately, and subsequently the relationship of the fashions and the opposite phenomena are discussed.

2. Experimental

Commercial metals and alloys were used in this work. Specimens of 10 mm x10 mm x1 mm in size were homogenized in a furnace and quenched in water. Mechanical processing was carried out using a hammer or a mechanical roll. The Vickers microhardness measurements for the specimens were conducted using either Akashi AVK-AII or Shimadzu HMV-2000 tester.

3. Results and discussion

3-1. Solid solution softening

Pb-Sn and Fe-Ni are solid solution softening alloys. In these alloys, the melting point lowers and the strength decreases by alloying solute atoms. From the phase diagram, it is possible to anticipate that these alloys are the solid solution softening type alloys. That is, the stable intermediate phase does not appear and the melting point decreases in solid solution softening type alloys. On the other hand, the stable intermediate phase appears and the melting point increases, in a diagram of solid solution hardening type alloys.

3-2. Age softening

Zn-Al, Mg-Al and Fe-C alloys show the maximum hardness in the state quenched in water, and the hardness is decreased by subsequent aging treatment. For example, the hardness changes of a binary Al-Zn alloy during aging at room temperature are shown in Fig.1. The hardness changes clearly show that the aging treatment hardened the Al-Zn alloy, whereas the Zn-Al alloy was softened through a similar treatment. The transition can be seen from age-hardening in Al-rich alloys to age-softening in Zn-rich alloys.

When Al-1.7mass% Fe alloy is pre-annealed and rolled at a moderate temperature of 673K, this alloy is also age-softened. The hardness decreases during aging at room temperature, as is shown in Fig.2. This alloy is, of course, hardened by cold working without such prior treatments.

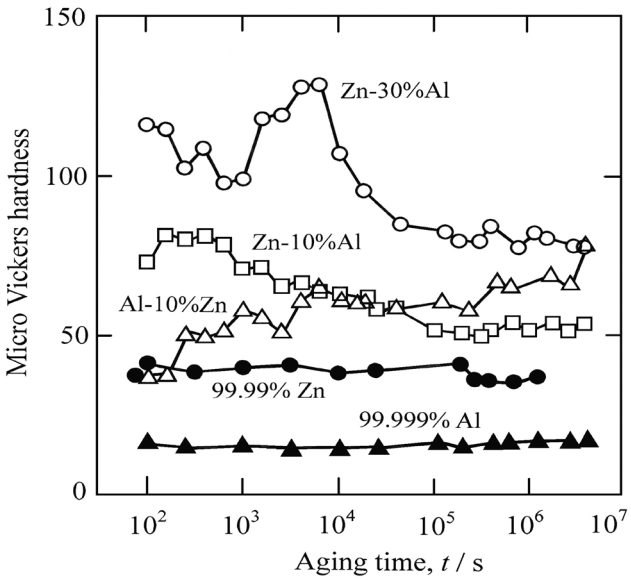

Fig.1 Age-hardening and age- softening behaviors in Al-Zn and Zn-Al binary alloys at room temperature.

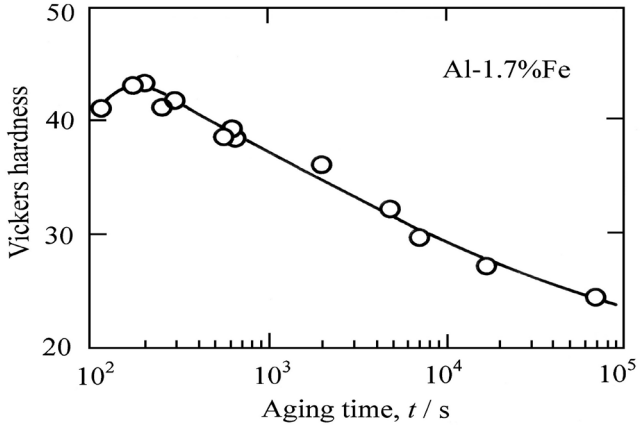

Fig.2 Age-softening of Al-1.7mass%Fe alloy at room temperature
Before aging, specimens were preliminary annealed at 673K for 3.6ks and hot-rolled at 673K to 95% reduction.

3-3. Work softening

Zn-Al and Mg-Al alloys show the maximum hardness in the as-cast state and the hardness decreases with cold working. For example, the hardness change which is introduced with cold working in Zn-Al alloys are shown in Fig.3. This figure indicates that cold working makes Zn-Al alloy softened, while Al-Zn alloy hardened.

Al-Fe alloy which is hot-rolled and annealed at the temperature of 673 K, shows work softening as shown in Fig.4. This alloy is hardened with cold working when the prior treatments are not carried out. Thus, the prior treatments are indispensable for the work softening. In the work, softening alloys, recovery and re-crystallization occur at temperatures lower than heat condition usually expected in low purity metal and alloy. If the work softened alloy receives solution-treatment, the hardness returns to the original values before the cold working. Figure 5 shows that the hardness curves depend on cold working and purity of Al specimens. The Al specimens with low 2N-5N in purity are hardened with cold working, but the high purity 5N-6N Al specimens are not hardened with a similar treatment.

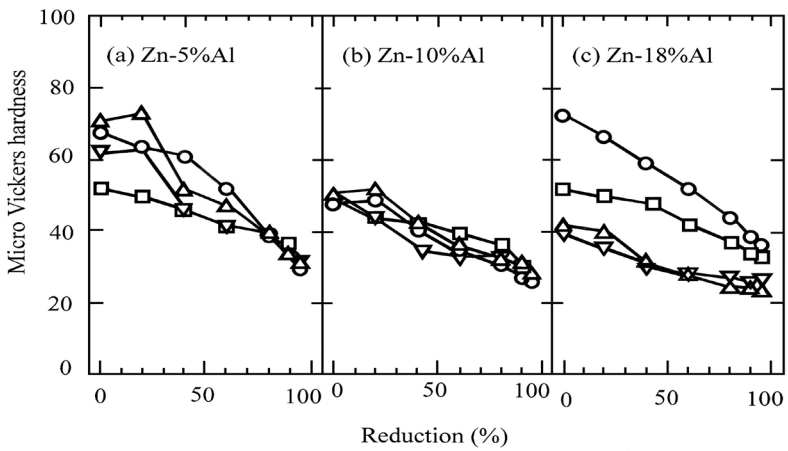

Fig.3 Changes of hardness in some Zn-Al alloys by cold working;
○: as cast, △: soaking at 573K for 86.4ks, □: hot-rolling at 573K,
▽: annealing at 573K for 3.6ks.

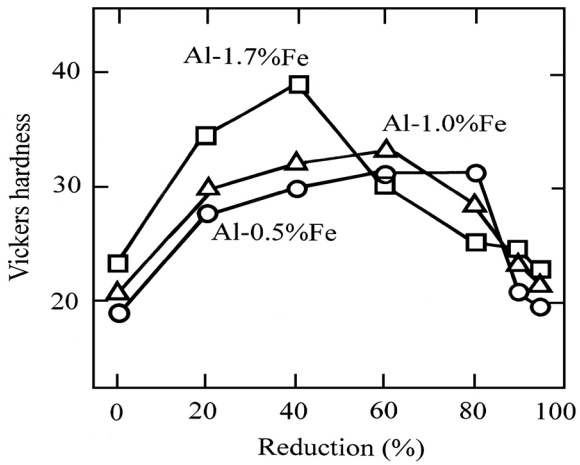

Fig.4 Work-softening in Al-Fe alloy. Specimens were hot-rolled and annealed at 673 K for 3.6ks, after soaking at 673K for 86.4ks.

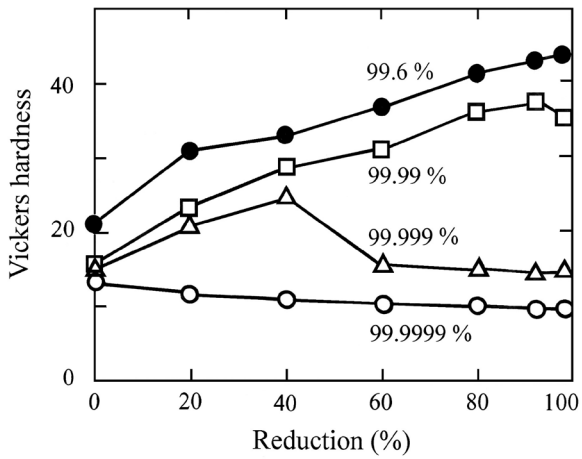

Fig.5 Purity dependence of hardness changes by cold working in pure Al. Specimens were soaked at 673K for 86.4ks and annealed at 673K for 3.6ks before cold-rolling.

Transition from work hardening in low purity Al to work softening in high purity Al can be seen in Fig.5. Although it is a striking feature that the Al-Fe alloy has two characteristics apparently opposite to each other, a similar trend was previously reported in pure gold, as a well-known fact that pure gold is not work hardened. Thus, those results leads to a conclusion that work-hardening mechanism can be exerted in a substance of which matrix is not purified.

3-4. Mutual relations among solid solution hardening, age-hardening and work hardening

It has been believed in the past that solid solution hardening and softening, age-hardening and softening, work-hardening and softening are mutually independent. However, the present study confirmed that these hardening and softening mechanisms are never independent to one another but closely related. They are mutually exclusive and suppressive to one another.

Al-Cu, Al-Zn-Mg-(Cu) and Al-Mg-Si alloys are typical age-hardening alloys. In Fig. 6, the hardness change of Al-Zn-Mg-(Cu) alloy during aging at 463K is shown together with the increase in hardness by cold working of 50% reduction at each aging time. It can be seen that an amount of the increment in hardness by cold working decreases with increasing aging time and becomes nearly zero in the final state of aging. Thus, we can conclude that age-hardening suppresses the work hardening. The hardness changes of Al-Cu, Al-Zn-Mg-(Cu) and Al-Mg-Si alloys, which have been cold worked at room temperature with 50% reduction either before aging, or after aging, are shown in Fig.7. It is evident from the comparison of Fig.6 and Fig.7 that the work hardening suppresses the age-hardening.

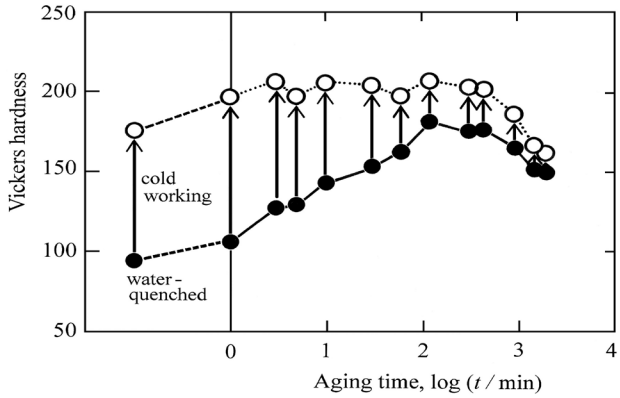

Fig.6 Hardness change during aging at 463K and the increase in hardness by cold working (50% reduction) at various aging times. The chemical composition of the alloy was Al-5.53%Zn-2.54%Mg-1.52% Cu (in mass%) which was solution treated at 758K for 1.8ks before water-quenching.

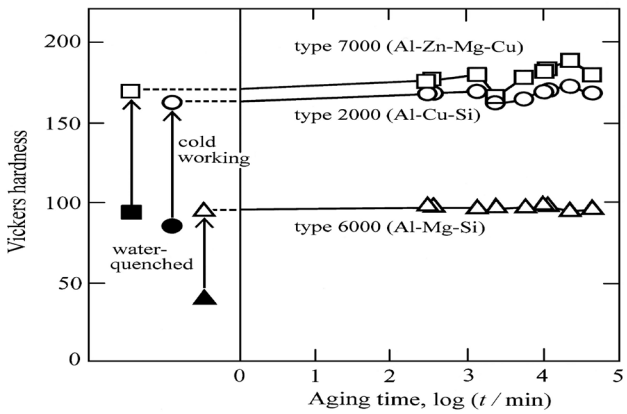

Fig.7 Influences of cold working on age-hardening behaviors in Al-4.11%Cu-0.80%Si alloy (2000), Al-5.53%Zn-2.54%Mg-1.52%Cu alloy (7000) and Al-0.46%Mg- 0.92 %Si alloy (6000). These specimens were solution-treated at 773K for 1.8ks before water-quenching.

Figure 8 shows the HV hardness of specimens at several stages of the secondary aging after receiving the prior cold working of 50% in reduction. The alloy composition of the specimens is Al-5.53%Zn-2.54%Mg-1.52%Cu (in mass%), and both specimens were solution treated at 758K for 30 min and then water-quenched. The hardness does not increase but decrease rapidly during the secondary aging after 50% reduction at each annealing stage. This result also reflects that the work hardening suppresses the age-hardening.

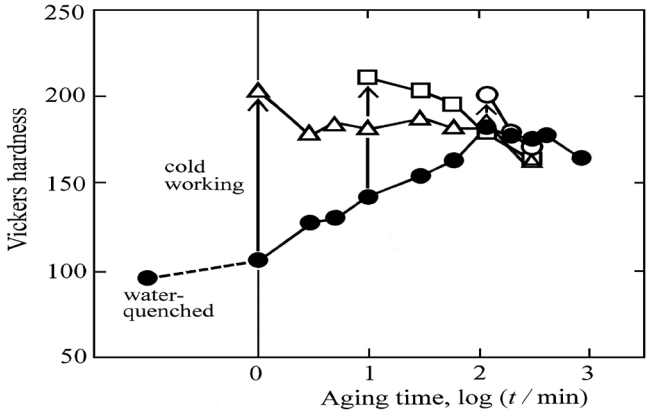

Fig.8 The change in hardness during the re-aging after cold working of 50% reduction at each aging time; just after water-quenched, 0.6ks and 7.2ks. The closed circles denote the results for only aging without cold-working.

4. Conclusions

The changes in hardness of Al metal, Al alloys and Zn alloys were experimentally examined through aging processing and/or working processing in this work.
The following conclusions were obtained from the experimental results;
(1) In Al and Zn alloys, not only age- and work-hardenings but also age- and work softenings were experimentally observed.
(2) A low purity Al is hardened by cold working but high purity Al did not show any work hardening.
(3) The present study confirmed that the age-hardening suppresses the work hardening and inversely the work hardening suppresses the age-hardening in Al alloys.

References

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