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# Effects of Natural Aging and Cold Work on the Strength of 2013 Aluminum Alloy

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The effects of 20℃ natural aging and 20% cold work on the strength of the 2013 aluminum alloy (Al-1.7Cu-1.0Mg-0.8Si-0.15Cr:mass%) aged at 170℃ for 8h have been investigated. The strength of the T6 samples slightly decreased with the increasing natural aging time after solution heat treatment. Though the amount of precipitation hardening was lower than the T6 specimens, the strength was improved by the combination of natural aging and cold working, namely T8 temper. However, cold working just after the solution heat treatment resulted in a lower precipitation hardening, and thus the T8 strength was lower than that of the specimens with prolonged natural aging after the solution heat treatment. It is suggested that the lower precipitation hardening resulted from the heterogeneous distribution of the hardening precipitates formed on the microbands.

***Keywords:*** *AA2013 alloy, precipitation hardening, work hardening, T8 temper*

## 1. Introduction

For aerospace applications, the AA2024 alloy and the AA7075 alloy have been used for more than a half century because of their high strength. However, they have a low formability and corrosion resistance. In recent years, the AA2013 alloy (Al-1.7Cu-1.0Mg-0.8Si-0.15Cr: mass%) has been developed [1]. AA2013-T6 is able to be used as a substitute for AA2024-T3 because this alloy shows the same or higher strength and superior corrosion resistance than that of AA2024-T3. It should also be noted that the AA2013 alloy is able to be even more strengthened by the T8 temper.

However, the basic characteristics of the AA2013 alloy have not been sufficiently clarified because this alloy consists of a complicated Al-Cu-Mg-Si quaternary system. Though some of the 6000 series alloys, i.e., AA6111, are classified in this quaternary system, they were developed by the small addition of copper to the Al-Mg-Si alloy. The AA2013 alloy includes a higher copper content than the other Al-Cu-Mg-Si alloys, and has less reported data.

This study focused on the effects of cold work and natural aging on the strength of the AA2013-T6 from the view of the stabilization and improvement of the mechanical properties.

## 2. Experimental Procedure

In the present study, the DC cast ingot of the 2013 aluminum alloy, the composition of which is shown in Table 1, was used. The 30mm thick slices of the ingot were homogenized in air at 540℃ for 6h, and then hot-rolled and cold-rolled into 1.2mm thick plates. The plates were then solution heat treated for one hour at 540℃, quenched in water, and subsequently aged at 20℃ for 0h ~ 240h. The plate was cold rolled by 20% or not at all, then it was subjected to artificial aging at 170℃ in a silicone oil bath. These samples were divided into three types by the difference in the combination of natural aging and cold rolling as follows:

Sample N: Artificial aging without cold rolling (T6 temper)
Sample NC: Natural aging, cold rolled and artificial aging just after cold rolling (T8 temper)
Sample CN: Cold rolled just after quenching, natural aged and artificial aged (T8 temper)

As shown in Fig. 1, the heat treatments were performed at 20℃ for natural aging, and 170℃-8h for artificial aging. It was confirmed that these samples had no difference in their grain microstructures (Fig. 2).

These samples were subjected to an investigation of their mechanical properties. Aging curves at 170℃ were examined by Vickers hardness testing of the polished samples. The strength before and after the artificial aging were measured by tensile testing. For the representative conditions, examination by transmission electron microscopy (TEM) and differential scanning calorimetry (DSC) were performed. Thin foils for the TEM observation were prepared by twin-jet electro polishing in a solution of 25% $HNO_3$ and 75% $CH_3OH$ at -20℃. The TEM observation was performed at 200keV using JOEL-2010 electron microscope equipped with a double tilting stage. The DSC experiment was carried out at the heating rate of 40℃/min, and high purity aluminum (99.999%) was used as the reference material.

Table 1 Chemical composition of the specimens in this work (mass%)

| Cu | Mg | Si | Cr | Fe | Al |
|---|---|---|---|---|---|
| 1.7 | 1.0 | 0.8 | 0.16 | 0.15 | Bal. |

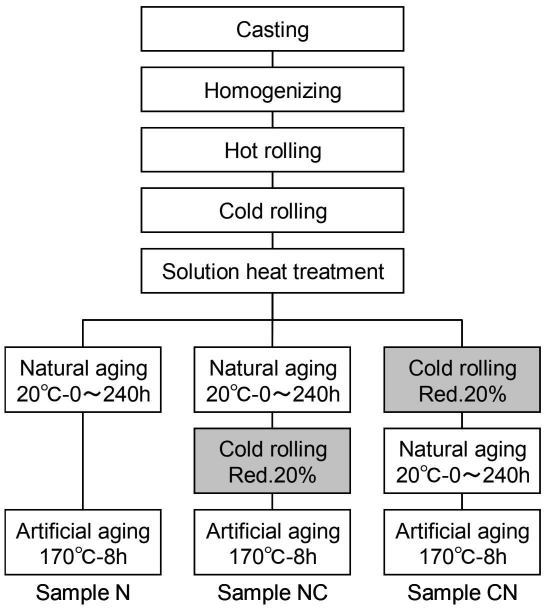


Fig. 1 Flow chart of the manufacturing process.

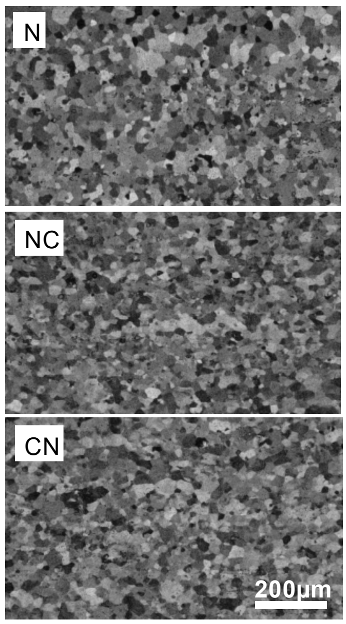


Fig. 2 Microstructure of the specimens after artificial aging.

## 3. Results and Discussion

### 3.1 Age-hardening property

Figure 3 shows the aging curves at 170℃ with natural aging at 20℃ for 240h. The hardness before the artificial aging was related to the cold rolling and the natural aging, and was in the following order: NC samples > CN samples > N samples. The time to reach the peak hardness was slightly shorter in the NC and CN samples, which were made by cold rolling, meaning that the formation of the hardening phases were promoted by the combination of cold work with artificial aging. Though it results in under-aging for the N sample and over-aging for the NC and CN samples, the basic aging condition, 170℃-8h, produces almost the peak hardness in each sample. It was confirmed that the basic aging condition is suitable for the comparison between the N, NC, and CN samples.

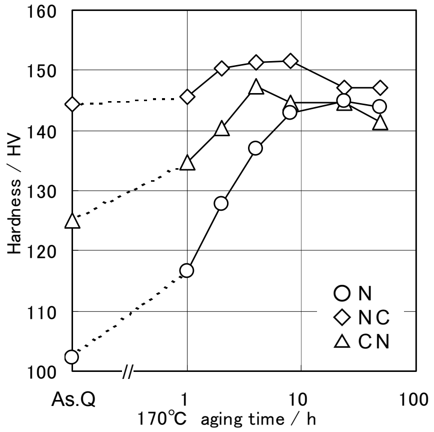


Fig. 3
Aging curves of the specimens aged at 170℃ after natural aging (20℃-240h) and cold rolling (20% Red.)

### 3-2. Effects of Natural Aging and Cold Work on the Strength

Figure 4 shows the effect of the natural aging on the strength before artificial aging. The strength of the N sample (●) increased with the natural aging. For the NC sample (◆) which is made by cold rolled after natural aging, it showed a higher strength because of the work hardening. The amount of work hardening has no dependence on the natural aging time. The similar result has been reported for the AA6111 alloy [2]. The strength of the CN sample (▲), cold rolled just after quenching and subsequently aged at 20℃, shows a lower dependence on the natural aging time.

The effect of the natural aging on the strength after artificial aging at 170℃ for 8h is shown in Fig. 5. The strength of the N sample (○) slightly decreased with the natural aging time. Both the NC (◇) and CN samples (△) showed a higher strength than that of the N sample. The T8 strength increased with the natural aging in the NC sample, however, that of the CN sample decreased. These results indicated that natural aging between quenching and cold rolling is required above 10h at 20℃ to stabilize the T8 strength. The NC sample with natural aging for 240h resulted in the highest strength in this study, which was 20MPa higher in tensile strength, 77MPa higher in yield strength than that of the T6 temper.

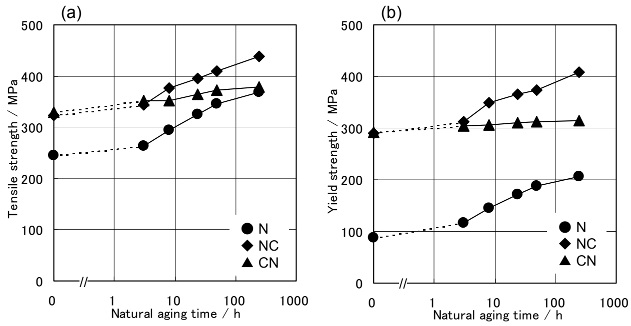


Fig. 4 Effect of natural aging on (a) tensile strength and (b) yield strength of the specimens before artificial aging.

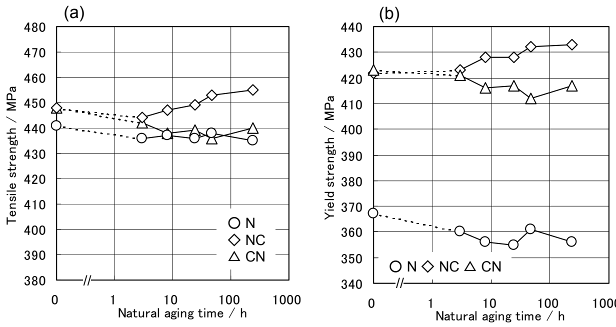


Fig. 5 Effect of natural aging on (a) tensile strength and (b) yield strength of the specimens after artificial aging at 170℃ for 8h.

### 3.3 Deformation Microstructure

Figure 6 shows the stress-strain curve of the N sample just after quenching and after natural aging for 240h. The stress-strain curve of the as-quenched sample was serrated, indicating the natural aging effects on the formation of the deformation microstructure. Figure 7 shows the TEM micrographs of the N sample stretched by 20% after quenching with or without natural aging for 240h. The microbands observed in the sample stretched just after quenching, on the other hand, it uniformly deformed in the sample with sufficient natural aging. It is suggested that in the as-quenched sample, rich solution atoms prevent the migration of dislocations and leads to the concentration of dislocation migration on specific slip planes.

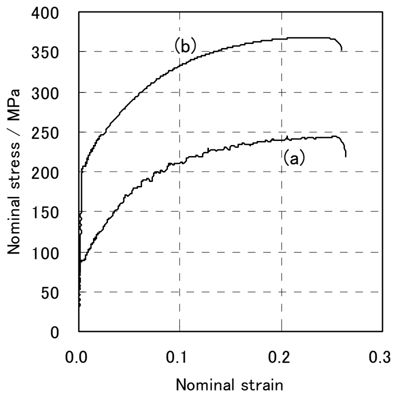


Fig.6 Stress-Strain curve of the specimens after solution heat treatment (a) without natural aging and (b) with natural aging at 20℃ for 240h.

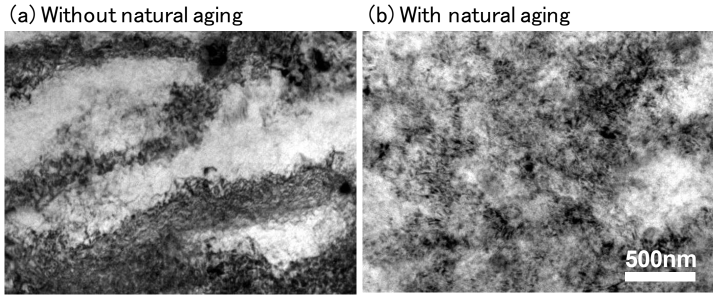


Fig. 7 TEM micrographs of the specimens strained by 20% after solution heat treatment (a) without natural aging and (b) with natural aging at 20℃ for 240h.

### 3.4 Precipitation Behavior during Artificial Aging

To investigate the effects of natural aging and cold rolling on the precipitation behavior, the DSC measurement was carried out under the conditions shown in Fig. 8a . These results are shown in Fig. 8b. First, the exothermic peaks X appeared at around 100℃ only in the samples made without natural aging (conditions A and C). Thus the X peaks correspond to the formation of the G.P. zones during the natural aging. For the comparison of conditions A and C, the intensity of peak X was lower for condition C. This indicates that the G.P. zones are difficult to form in the deformation microstructure. For the sample that was cold rolled just after quenching, as in condition C, the quenched-in vacancies may vanish into dislocations. The same tendency is able to be confirmed in Fig. 3. In addition, for the condition without cold rolling (conditions A and B), the exothermic peaks Y caused by the hardening phase, $\beta$ '' phase and Q' phase [3][4], were observed at around 275℃. The peaks Y observed at a slightly lower temperature, around 255℃, for the condition with cold rolling (conditions C, D and E). As shown in the TEM micrograph of the NC sample after artificial aging, heterogeneous precipitation of the hardening phases on the dislocations was observed (Fig. 9). Accordingly, as generally known for other age-hardenable alloys, the stimulation of precipitation is due to the existence of dislocations in for the AA2013 alloy. Similar results have been confirmed in other aluminum alloys. For example, Matsuda et al. [5] reported that the 1% pre-strain before artificial aging produces a finer distribution in the hardening phase and higher precipitation strengthening in the Al-Mg-Si alloy. However, they also referred to the improvement in precipitation hardening by pre-strain becomes smaller for the higher strain. On the contrary, Sugamata et al. [6] reported that the precipitation hardening improved by 30% pre-strain before artificial aging for the high Mg/Cu ratio in Al-Cu-Mg alloys. These experimental results indicate that the effect of strengthening by the T8 process was significantly affected by the strain and alloy composition. In this study, the precipitation hardening becomes smaller by 20% cold working before artificial aging. Therefore, the AA2013 alloy is not suitable to improve the precipitation hardening in combination with cold working, namely the T8 temper. Nevertheless, it is expected that work hardening produces a higher strength by the T8 temper than that of the T6 temper.

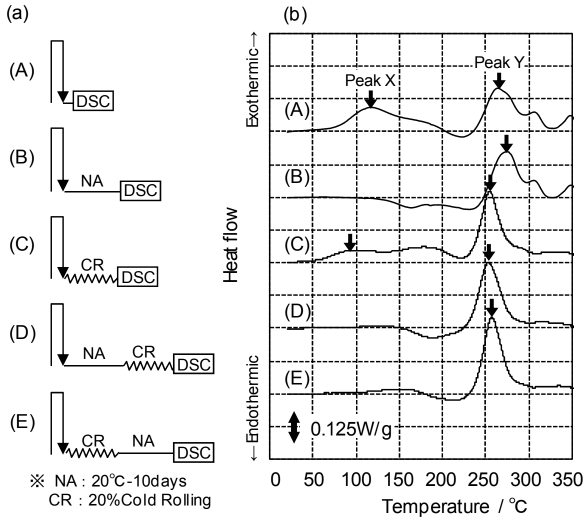


Fig. 8 (a) Schematic diagram of thermomechanical treatments and (b) DSC curves of the specimens subjected to the thermomechanical treatments.

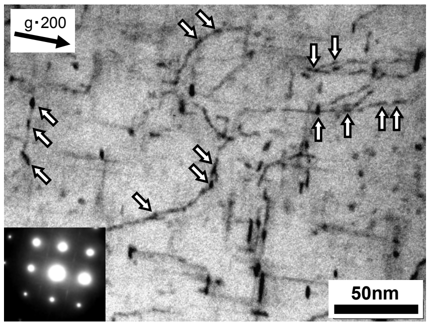


Fig. 9 TEM micrograph of the T8 specimen. The arrows indicate heterogeneous precipitates on the dislocations.

### 3.5 Formation of Deformation and Precipitation Microstructure in T8 temper

All these factors previously mentioned for the process of forming the microstructure in the T8 temper are summarized schematically in Fig. 10. First, in the NC sample, cold rolled after natural aging, fine G. P. zones are formed in the matrix during natural aging. These form a homogeneous deformation microstructure formed by cold rolling. During the subsequent artificial aging, though heterogeneous precipitation on the dislocations produces smaller precipitation hardening than that in the T6 temper, the T8 strength become higher than that of the T6 temper because of work hardening. In addition, in the CN sample, the microbands are formed by cold rolling just after quenching. Moreover, the quenched-in vacancies vanish into dislocations, thus the G.P. zones formed in the subsequent natural aging also decrease. The nonuniformity of the dislocations promotes the heterogeneous distribution of the hardening phase. As already mentioned, to effectively gain the effect of strengthening by the T8 temper, it is necessary to maintain room temperature for a sufficient time between quenching and cold working.

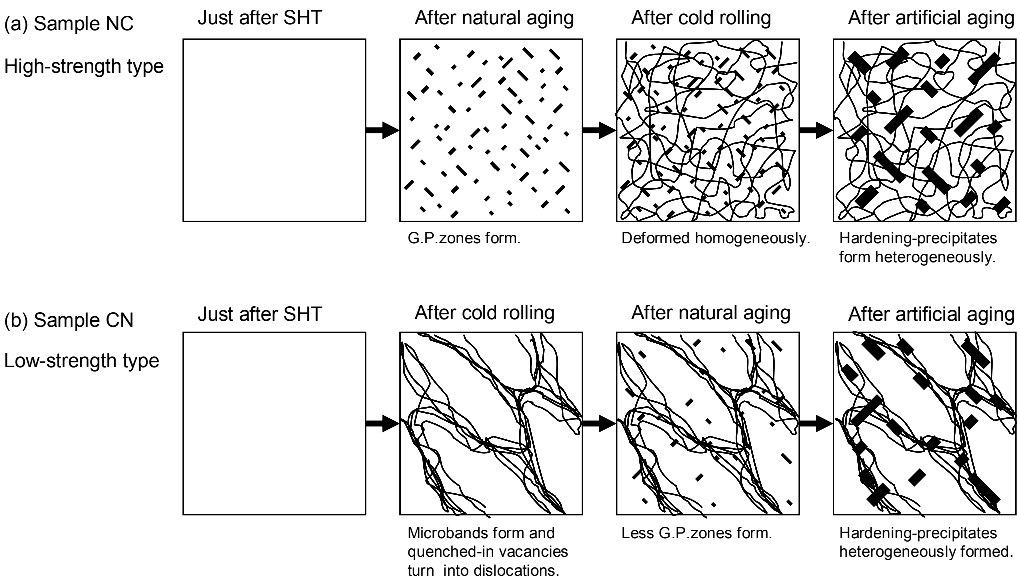


Fig. 10 Schematic diagram of the microstructure in the matrix during the manufacturing processes

## 4. Summary

The study of the effects of natural aging and cold work on the strength of the T6 temper and the T8 temper of the AA2013 alloy (Al-1.7Cu-1.0Mg-0.8Si-0.15Cr) had the following conclusions:

(1) The T6 strength becomes slightly lower with the increasing natural aging time.
(2) In the T8 process, a homogeneous deformation structure forms by cold rolling with sufficient natural aging after quenching. This condition is suitable to obtain a higher T8 strength. However, the precipitation strengthening is lower than that of the T6 temper.
(3) The T8 strength become lower when the natural aging between the quenching and cold work was insufficient. It is suggested that the nonuniform dislocations produces a heterogeneous distribution of the hardening phase formed during the artificial aging.

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