Strengthening of Aluminum Alloy Forgings for Automotive Suspension by Two-step Aging

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Abstract

In order to improve the fuel efficiency of automobiles, it is important to reduce the weight of vehicle bodies. The weight of suspensions is also being reduced, by applying Al-Mg-Si aluminum alloy forgings, for example. Further reducing the weight of suspensions will require additional strengthening of the material, and Kobe Steel has conducted a study to increase the strength by two-step aging. As a result, a two-step aging process combining pre-aging at 160℃ and high-temperature aging at 190℃ has achieved a peak proof stress of 390 MPa in a short time period of only 8 hours. Obtaining the same peak proof stress by single-step aging at 160℃ requires 56 hours. This is attributed to the fact that β″ phase, having a size of 3 to 4 nm, which is greater than the critical size for non-reversion, precipitates with a high number density during the pre-aging and grows at the high temperature to increase the strength. This technology has enabled a weight reduction of 3% over that of the conventional technology and is expected to contribute to improving fuel efficiency and reducing the carbon dioxide emissions of automobiles.

Introduction

Recently, regulations on exhaust gas have become even more stringent due to global environmental problems, and the further reduction of exhaust gas, especially carbon dioxide, has become an important issue in the automobile industry as well. The improvement of fuel efficiency through the weight reduction of vehicle bodies is a promising means that is causally linked to the emission reduction of carbon dioxide, the cause of global warming.[1] In addition, the vehicle body weight must be reduced to compensate for the weight increase due to additional safety measures, environmental measures, and equipment enhancement. Suspension materials have been studied to meet these weight reduction needs, and the application of 6000 series aluminum forgings has been expanding.[2] For further weight reduction, the strengthening of material is effective, and Kobe Steel uses 6000 series aluminum alloy forgings (KD610) with the addition of Cu.[3]

Yet further weight reduction requires additional strengthening, and an approach from the aspect of processing is also being studied. As one method, it is generally known that strengthening can be achieved by artificial aging at a low temperature for an extended period of time, in which the strengthening is attributable to fine and densely dispersed precipitates. Such a long aging time, however, causes problems of decreased productivity and an increased environmental burden. Kaneko reported that the peak proof stress of a sheet of A6061 alloy is improved by two-step aging with pre-aging at 120℃ for 24 hours.[4] This, however, poses the problem of a long pre-aging time. Moreover, such studies are being actively conducted for sheet materials that are BH-treated [Note 1), 5)] but there are few reports for structural members. Hence, Kobe Steel studied the effect of two-step aging on strengthening by applying short-period pre-aging to 6000 series aluminum forgings and considered the mechanism of such strengthening through microstructural observation. This paper introduces the outline of the study.

1. Test method

Material with the chemical composition shown in **Table 1** was used for the test. A billet of φ90 mm was cast by a horizontal continuous casting machine and shaved to φ84 mm. The shaved billet was homogenized at 500℃, air cooled, and then heated to 520℃ to be forged at a reduction rate of 70% (φ84 mm → t 25.2 mm). After solution heat treatment and subsequent water cooling, pre-aging was performed at a temperature between 120 and 180℃ for 5 hours, and the second-step aging treatment was performed at 190℃ to prepare the test material. Hereinafter, the material obtained by performing pre-aging and

Table 1 Chemical composition of specimen

(mass%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.97	0.22	0.43	0.45	0.97	0.17	<0.01	0.03	Rem.

Note 1) BH treatment is a treatment that uses the heat of paint baking to increase the strength (proof stress).

second step aging is referred to as a two-step aged material. The above heat treatment procedure is summarized in **Fig. 1**. For comparison, single-step aging curves for 160℃ and 190℃ were prepared. All the heat treatments were performed in the atmosphere.

Age hardening behaviors were evaluated by a tensile test. Each tensile test piece, a JIS No.4 subsize test piece (gauge length 25 mm), was collected parallel to the forging direction (cogging direction). Thin film specimens were prepared by electropolishing the pre-aged and two-step aged materials and were subjected to observation by transmission electron microscope (hereinafter referred to as "TEM"). The evaluation of the precipitate phase after pre-aging was performed by differential scanning calorimetry (hereinafter referred to as "DSC") measurement. These test pieces were collected from the positions shown in **Fig. 2**.

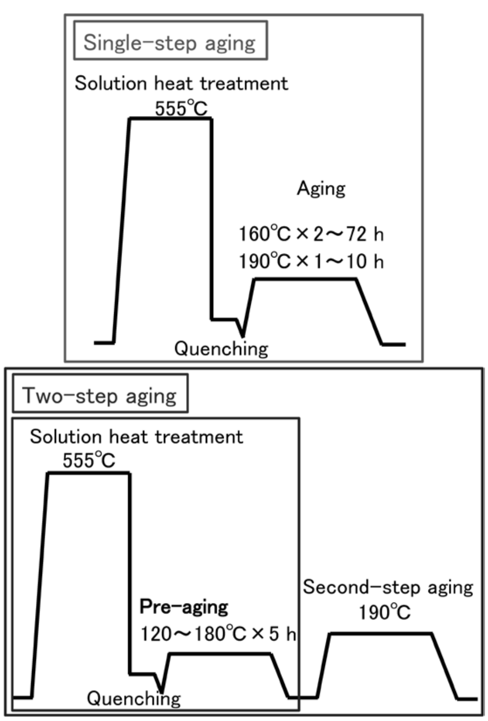

Fig. 1 Heat treatment processes of specimens

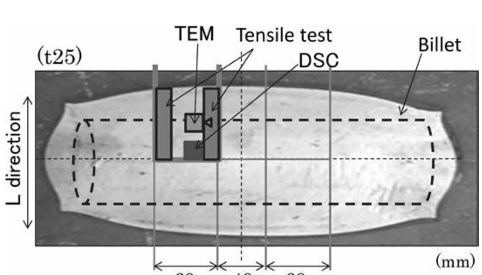

Fig. 2 Collection positions of test pieces

2. Test results and considerations

2.1 Aging curves

Fig. 3 shows single-step aging curves at 160℃ and 190℃, respectively, as well as a two-step aging curve at 190℃ after a pre-aging at 160℃ for 5 hours. The peak proof stresses were 390 MPa for the aging temperature of 160℃ and 375 MPa for the aging temperature of 190℃, the former yielding a higher strength. The aging times to the respective peaks were 56 hours and 3 hours. Meanwhile, it was found that pre-aging at 160℃ ×5 hours and subsequent aging at 190℃ can reduce the total aging time from 56 hours to 8 hours without sacrificing the peak proof stress at 160℃.

Hence the effect of the pre-aging temperature on the tensile properties of the two-step aged material was investigated to obtain the optimum pre-aging temperature. The results are shown in **Fig. 4**. The aging conditions for the second step were 190℃ ×3 hours. When the pre-aging time of the first step

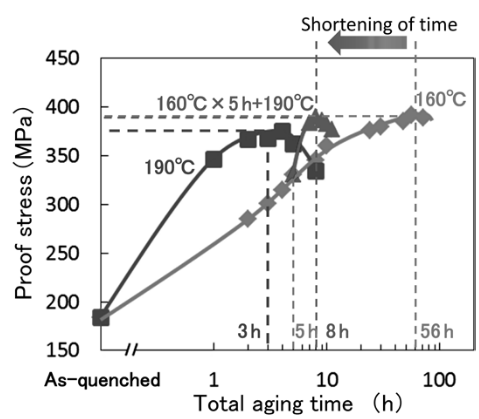

Fig. 3 Single-step aging curves at 160℃ and 190℃, and two-step aging curve at 190℃ after pre-aging at 160℃×5 h

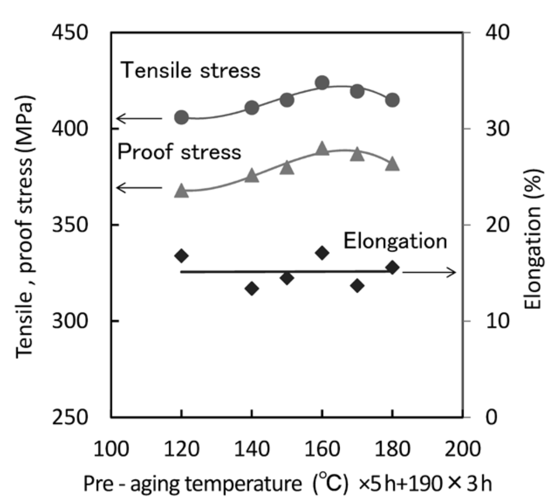

Fig. 4 Effect on tensile properties of pre-aging temperature

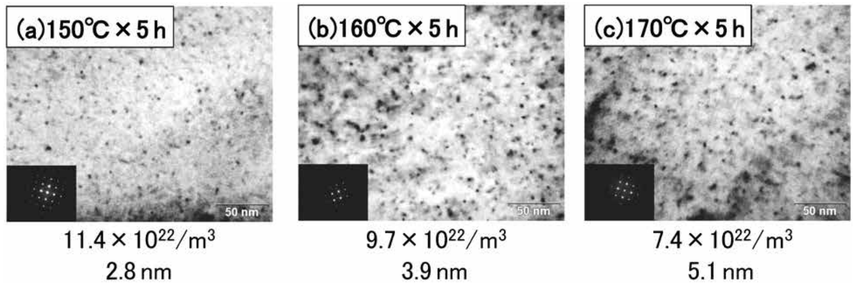

Fig. 5 TEM micrographs after pre-aging (upper values: number density of precipitates, lower values: size of precipitates)

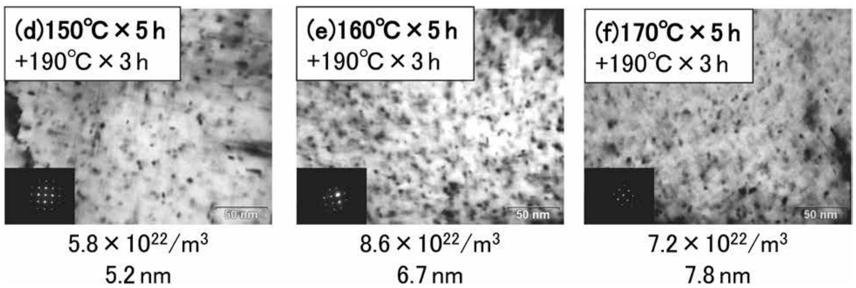

Fig. 6 TEM micrographs after two-step aging (upper values: number density of precipitates, lower values: size of precipitates)

was fixed at 5 hours to vary the aging temperature, the highest strength was found to be reached at 160℃. Here, a decision was made to investigate this mechanism in detail by microstructure observation.

2.2 Microstructural observation

Fig. 5 shows TEM micrographs after 5 hours of pre-aging at 150℃, 160℃ and 170℃. Precipitates are observed by the TEM for all the aging conditions, and these precipitates are considered to be β'' phase.[6] The precipitates become finer and more densely populated due to having been aged at lower temperatures.

Fig. 6 shows the TEM micrographs of the pre-aged materials in Fig. 5 subsequently aged at 190℃ ×3 hours in the second step. Regardless of the pre-aging conditions, the size of the precipitates is increased by the second-step aging. For the material pre-aged at 150℃, the number density of precipitates is found to be significantly decreased by the second-step aging. The relationship between the precipitate size and the number density is summarized in **Fig. 7**. It should be noted that the number density of precipitates has been calculated by measuring the number of black dots precipitated in the vertical direction of each photograph and multiplying the number by a factor of three. The pre-aging at a low temperature makes precipitates finer and more densely populated, while the second step aging increases the precipitate size. However, some portion of the material pre-aged at 150℃ has been found to have undergone reversion. From this,

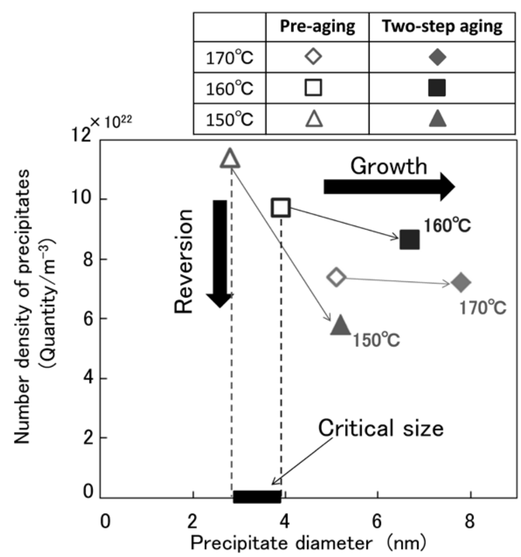

Fig. 7 Relationship between size and number density of precipitates after pre-aging and two-step aging

it is estimated that a critical size of precipitates that undergo reversion at 190℃ exists between 3 and 4 nm.

2.3 DSC

In order to confirm the microstructural change during heat treatment, DSC was performed while combining the aging and heating rate of the second step (**Fig. 8**). The results show an exothermic peak 1, considered to be attributable to β'', and an exothermic peak 2, considered to be attributable to β'.[7] The pre-aging temperature of 150℃ or lower results in a high β''peak and the pre-aging temperature of 160℃ or higher results in a smaller peak. This seems to indicate that the precipitation of β'' is completed at 160℃ and higher.

Fig. 9 shows the results of TEM observation, in which the material pre-aged at 160℃ ×5 hours has been quenched at the exothermic peak 1 temperature of 220℃. A comparison with post pre-aging (Fig. 5(b)) shows that the density of precipitates has decreased. From this, it is estimated that some of the β'' precipitates have undergone reversion, while the rest has coarsened.

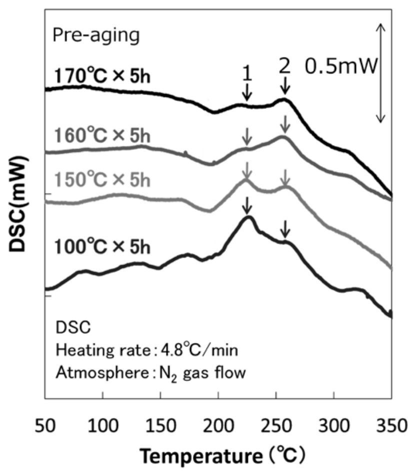

Fig. 8 DSC results after pre-aging

2.4 Mechanism of two-step aging in appropriate conditions

A model of the precipitation process is shown in **Fig.10**. The model assumes that β'' phase precipitates during the pre-aging, and then the β'' phase grows during the second-step aging and contributes to strengthening. Compared with the pre-aging at 160℃ (Fig.10 (b)), pre-aging above 170℃ (**Fig.10** (a)) results in β'' precipitating at a lower density during the pre-aging. In the subsequent second-step aging, the β'' phase grows and contributes to strengthening. On the other hand, when pre-aging is performed at 150℃ or below (Fig.10 (c)), finer β''

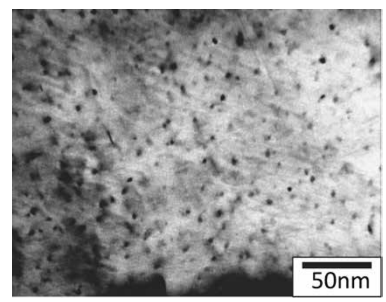

Fig. 9 TEM micrograph of specimen pre-aged at 160℃× 5 h and quenched at temperature of DSC peak 1 (Number density of precipitates: $5.2\times10^{22}/m^3$, size of precipitates: 6.7 nm)

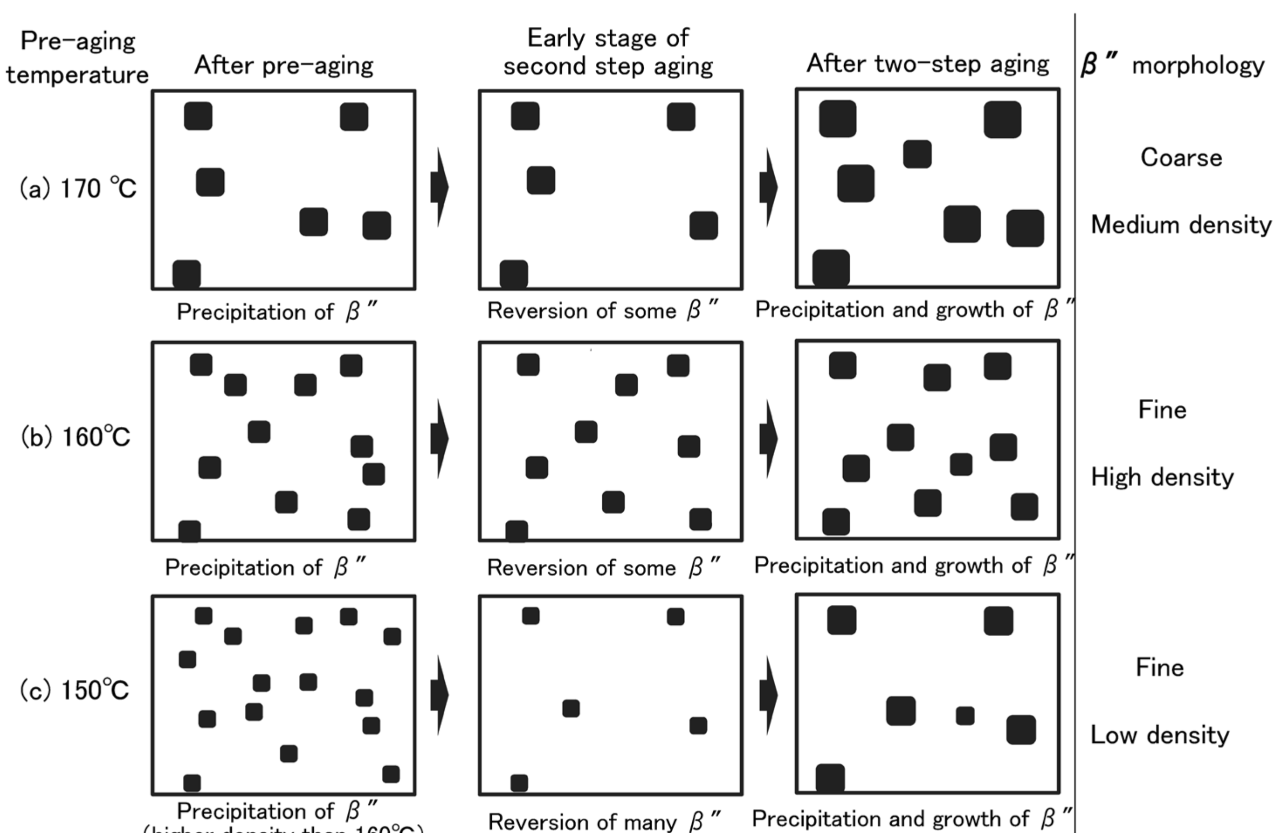

Fig.10 Schematic models of precipitation processes for two-step aging

phase is precipitated at a higher density compared with the pre-aging at 160℃. However, since the precipitate size is small, most of the precipitates undergo reversion during the second-step aging. This is considered to have caused the precipitate density after the second-step aging to become lower than that for the pre-aging at 160℃. In other words, 160℃ is considered to be the temperature at which the β'' phase that has precipitated during 5 hours of pre-aging remains at the highest density during the second step aging without undergoing reversion.

3. Weight reduction effect of strengthening by two-step aging

The relationship between the proof strength and weight reduction rate of aluminum alloys is shown in **Fig.11**.[8] Kobe Steel is already mass-producing KS651 and KD610, each having a strength higher than that of A6061. It has been found that further strengthening of the material can be realized by the newly developed two-step aging. This new approach is expected to achieve a weight reduction of approximately 3% compared with the conventional KD610, while minimizing the decrease in productivity.

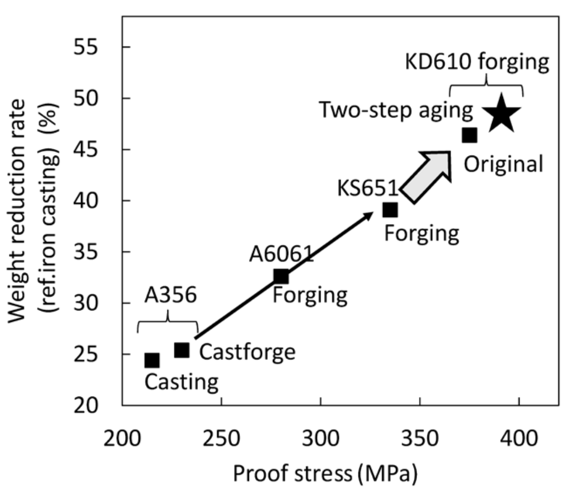

Fig.11 Relationship between proof strength and weight reduction rate of aluminum alloy[8]

Conclusions

The effect of pre-aging on the aging behavior of Al-Mg-Si-Cu alloy has been studied. As a result, the peak proof stress has been found to be increased by changing the aging temperature from 190℃ to 160℃, which, however, requires a long heat treatment time of 56 hours.

Meanwhile, short-time strengthening conditions utilizing two-step aging have been investigated, and the following has been found:

- Two-step aging: By applying first-step aging (160℃ ×5 hours) followed by second-step aging (190℃ ×3 hours), the peak proof stress obtained at low temperature after an extended period of time was achieved in 8 hours.

The strengthening mechanism under these conditions is considered to be as follows:

- It has been found that precipitating β'' phase greater than a critical size of 3 to 4 nm at a high density during pre-aging results in growth without reversion during the second step aging.
- A high pre-aging temperature results in a sparse distribution of precipitates, and a low pre-aging temperature also results in a sparse distribution of precipitates due to reversion during the second-step aging. In neither case could high peak proof stress be achieved.

Automotive materials are required to be even lighter to improve fuel efficiency. Kobe Steel will respond to these weight reduction needs and realize the strengthening of material for further expanding the use of aluminum forged suspensions.

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