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Effect of Strong Magnetic Field on Strain Age Hardening of Co-based Alloy

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Changes in strain age hardening behavior of the supersaturated solid solution of the Co-based alloy with the application of the strong magnetic field have been investigated after annealing at 700, 750 and 800℃ in an applied magnetic field of 10T and 0T. At temperatures lower than 750℃ where the Suzuki effect effectively takes place, an application of magnetic field of 10T to the pre-strained samples accelerates the age hardening and enhances the maximum value of the age hardening. At 800℃, the magnetic field of a 10T retards the aging effect necessary for the maximum hardness of strain aging, indicating that the strain age hardening in the magnetic field is suppressed at this temperature region. The difference in effect of the magnetic field on the strain age hardening behavior between the two temperature regions is discussed by considering the Suzuki effect and a precipitation hardening mechanism.
Key words: Co alloy, Co-based alloy, Co-Ni-based alloy, strain age hardening, age hardening, magnetic field

1. INTRODUCTION

The alloy SPRON 510, a Co-Ni-based alloy with the crystal structure of FCC and the single-phase microstructure, has excellent mechanical properties as a promising candidate for heat-resisting spring materials. It exhibits a significantly high work hardening behavior even at elevated temperatures higher than 700℃ [1]. The structure of the dense dislocation density introduced by heavy cold working processes at room temperature remain stable during the prolonged heat treatment at temperatures higher than 700℃ [2], [3]. Thus the alloy SPRON 510, hereafter designated by the Co-based alloy, is an extremely unique alloy as a high temperature heat-resisting materials strengthened by dislocation hardening mechanism. In addition, after sever cold working, it shows a strain age hardening behavior during a heat treatment in the temperature range from 500 to 800℃. Different from the strain age hardening observed in an Fe-C system where the elastic interaction between C atoms and cores of edge dislocations is responsible for the strain age hardening, since the present Co-based alloy does not contain C, the strain age hardening is thought to be caused by a dislocation locking mechanism associated with the so-called Suzuki effect, i.e., chemical interaction between the solute atoms and stacking faults of dissociated dislocations [4]. From this viewpoint, it is likely that the strain age hardening of the present alloy, occurring by the chemical interaction, is the first revealed evidence so far reported.

In previous studies [5], [6] based on the compression tests, we demonstrated that the yield stress of the pre-strained Co-based alloy aged in the temperature range where the Suzuki effect is dominant, i.e., 670~740℃, is enhanced by the application of the magnetic field. The aim of the present study is to report results of a preliminary study on the effect of the strong magnetic field on the strain age hardening of the Co-based alloy in the temperature range from 700 to 800℃ where both the Suzuki effect and a precipitation hardening mechanism can be simultaneously operative. Thus, in the present study, the strain age hardening behavior, i.e., hardness vs. aging time, in the temperature range is extensively examined.

2. EXPERIMENTAL PROCEDURE

An ingot of 50kg in weight of Co-based alloy having the chemical composition listed in Table I was melted in a vacuum induction-melting furnace. The ingot was hot-forged into a rod of diameter 60 mm at approximately 1050℃. The rod-shaped alloy was cold-swaged and formed into a size of 4.0 mm in diameter, combined with an intermediate annealing at 1050 ℃. The obtained optical microstructure and X-ray diffraction pattern of the present alloy are reported in previous studies [1], [3] where the microstructure of the present alloy is indicated as a single phase with FCC crystal structure. The amounts of induced pre-strain at room temperature into the sample were set at an 80% and a 45% reduction in area.

Table I Chemical composition of the alloy SPRON 510.

Co	Ni	Cr	Mo	Mn	Nb	Fe	Ti	C
Bal.	30.4	21	10.0	0.5	1.5	2.1	0.8	−

(mass%)

Aging treatments for the pre-strained samples were performed at 700, 750, and 800℃ for 1.8, 3.6, 7.2, 14.4 and 36ks under an applied magnetic field of 10T and without magnetic field. The apparatus for aging treatments with and without magnetic field are illustrated in Fig.1. The samples for aging with the magnetic field were

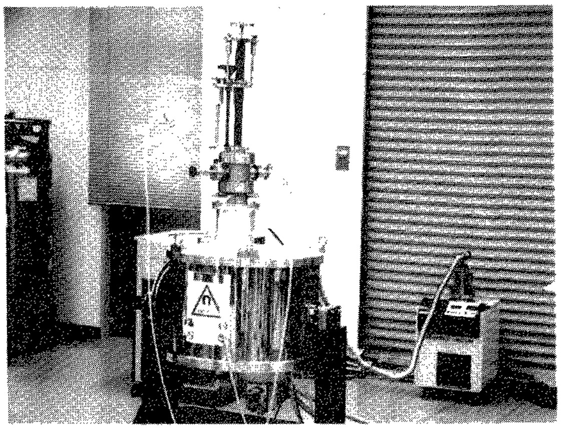


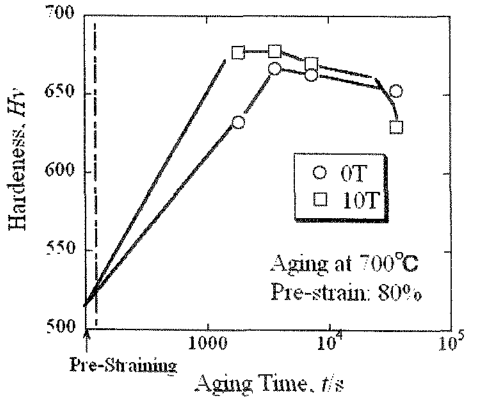
Fig.1 The superconducting magnet incorporated with a vacuum electric furnace used for annealing treatments in the magnetic field and without magnetic field.

set in the center of an electric furnace where a uniform magnetic field is applied. The evaluation of the changes in hardness of the samples during annealing in the magnetic field and without magnetic field were conducted by micro-Vickers hardness tests.

3. RESULTS

Fig.2 shows changes in hardness of 80% pre-strained samples after aging at (a) 700℃ and (b) 750℃ in a magnetic field of 10T and 0T. In Fig.2 (a), the hardness of the samples aged in 0T increases with increasing aging time and shows maximum hardness of Hv = 667 at an aging time of 3.6ks. After exhibiting the maximum, the hardness value decreases with increasing aging time. On the other hand, the hardness of the samples aged in 10T exhibits maximum of Hv = 677 at minimum aging time of 1.8ks and gradually decreases with increasing aging time. From these results, we can conclude that an application of magnetic field of 10T to the pre-strain samples accelerates the strain age hardening and enhances the maximum value of the age hardening at 700℃. The results are similarly observed in Fig.2(b) where the aged samples at 750℃ in 10T exhibit hardness slightly stronger than those in 0T.

(a)



(b)

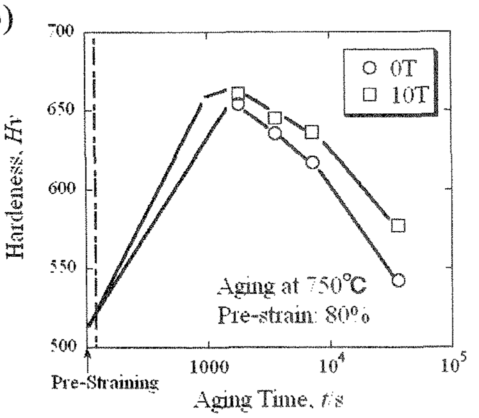


Fig.2 Hardness changes in 80 % pre-strained sample after aging at (a) 700℃ and (b) 750℃ in the magnetic field of 10T and 0T.

Fig.3 shows effect of an application of magnetic field of 10T on the strain age hardening at 800℃. Contrary to the results at 700 and 750℃, hardness of aged samples in 10T are lowered compared to those of aged samples in 0T. It should be noted in the figure that although a peak in hardness of aged samples in 0T appears at aging time of 3.6ks, the hardness gradually increase with increasing aging time, showing no peak in the present annealing time. Thus we can conclude that the strain age hardening is suppressed by the application of strong magnetic field.

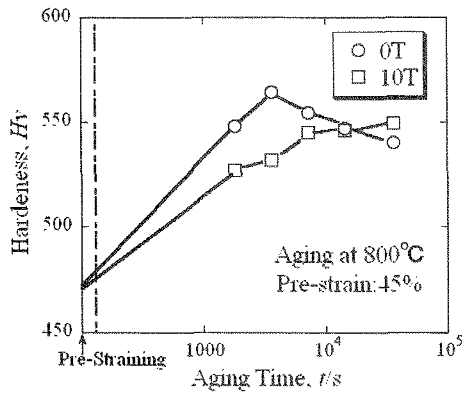


Fig. 3 Hardness changes in 45 % pre-strained sample after annealing at 800℃ in the magnetic field of 10T and 0T.

4. DISCUSSION

It was reported in a previous work [1] that in the Co-based alloy, dynamic strain aging originating from the Suzuki effect occurs in the temperature range from 500 to approximately 750℃. Thus it is assumed that the strain age hardening observed at 700 and 750℃ with and without magnetic field of 10T as shown in Fig.2 is associated with occurrence of the Suzuki effect[4]. That is, in the present samples, dense dislocations are introduced by the pre-straining and locked by the solute segregations to the stacking faults bounded by the partial dislocations during aging treatments, resulting in age hardening (strain age hardening). As pointed out in previous works [5], [6], the stacking faults formed in the paramagnetic FCC matrix are thought to have ferromagnetic properties because the stacking faults are considered to be two layers of ferromagnetic HCP Co phase. If this is the case, a magnetic field enhances the stability of stacking faults and thereby the dislocation dissociation can be facilitated even if the density of the induced dislocations by pre-straining is high. Thus it can be concluded that the age hardening after pre-straining is enhanced by the application of strong magnetic field in the temperature range where the Suzuki effect effectively takes place, i.e., ~700℃, as actually observed in the present study (see Fig. 2).

On the other hand, at temperatures higher than 750℃ where the Suzuki effect vanishes [3], since the present alloy is the supersaturated solid solution [3], a dominant mechanism of the strain age hardening can be replaced by a precipitation hardening similar to the case of Al-Cu alloy system. Although no precipitation was observed in the well-annealed sample by the furnace cooling from e.g., 1050℃ or prolonged annealing at e.g., 800℃ [7], the severely deformed sample readily precipitates the stable Co_7Mo_6 phase by annealing at 800℃ [8], resulting from the pipe diffusion along the dislocation cores. As shown in Fig.3, the application of magnetic field of 10T lowers the strain age hardening. This trend can be described by considering the effect of magnetic field on the precipitation behavior of transitional phases such as the G.P. zone or Co_3Mo, and stable phases such as Co_7Mo_6 from the matrix (see the calculated phase diagram of the present Co-based alloy in reference [3]). If the precipitation of these transitional and stable phases is suppressed during the aging treatment in the magnetic field, the amount of the age hardening is lowered as observed in Fig.3. Since the nucleation and the growth rate of the precipitates are controlled by the long-range diffusion process of the solute atoms, e.g., the Mo atoms, we can conclude that the application of strong magnetic field to the Co-based alloy decreases the diffusivity of solute atoms.

5. CONCLUSIONS

The effect of the strong magnetic field on the strain age hardening behavior of the Co-based alloy has been investigated. The obtained results are summarized as follows:

1. At temperatures lower than 750℃ where the Suzuki effect effectively takes place, the strain age hardening is enhanced by an application of the magnetic field of a 10T.
2. At temperatures higher than 800℃, an application of the magnetic field of a 10T retards the aging effect necessary for the maximum hardness of strain aging.
3. Because the present Co-based alloy is a supersaturated solid solution, a precipitation hardening mechanism can be operative in the severely deformed sample where the diffusivity of the solutes is enhanced by the pipe diffusion along the dislocation cores. Thus a dominant mechanism of the strain age hardening, caused by the Suzuki effect, can be replaced by a precipitation hardening at temperatures higher than 750℃.
4. An application of the magnetic field of a 10T promotes the Suzuki effect and retards inversely the diffusivity of the solute atoms in the present Co-based alloy.

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