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Shape deterioration and reversible shape-memory effect in Ni–Ti alloys

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The effect of constraint heating on shape-memory properties in Ni–Ti alloys is studied. Specimens which memorized linear shape showed remarkable shape deterioration under constraint conditions above 1% bending surface strain and 100° C heating temperature. A reversible shape-memory effect was obtained after constraint heating, and shape change due to this was about 1.4% bending surface strain. These effects strongly depend on ageing temperatures during shape-memory treatment.

1. Introduction

Ni–Ti shape-memory alloys are frequently used as a driving element for various actuators because of their advantages, especially in corrosion resistance and mechanical properties such as fatigue life and elongations over the other alloys with a shape-memory effect. Rozner and Wasilewski [1], Melton and Mercier [2], and Miyazaki *et al.* [3] made detailed investigations of the basic deformation behaviour of Ni–Ti shape-memory alloys, such as stress-strain curves and their temperature dependence. Melton and Mercier [4] compared the fatigue life of Ni–Ti alloys with that of Cu–Zn–Al alloys and concluded that the former have much better fatigue life than the latter. When used as a driving element in an actuator, Ni–Ti shape-memory alloys are subjected to continuous deformation at higher temperatures by an outer load and counter force coming from the bias spring, which is used for recovering the shape of the Ni–Ti element on cooling. In designing an actuator, it is necessary to know such deformation effects on the Ni–Ti element, specifically, how the deformed strain, heating temperature and time affect the shape-memory properties of the Ni–Ti element. These studies have not been reported so far.

Reversible shape-memory effect (RSM) is a phenomenon which brings about repetitive shape change of an alloy only by heating and cooling without the assistance of a bias load. RSM in Ni–Ti alloys was discovered by Wasilewski [5], where it was obtained by severe deformation in a martensitic state at low temperatures ($T < M_s$). He attributed the cause of RSM to the internal stress field induced by plastic deformation of the martensitic phase. Recently, Honma [6] found a new type of RSM, termed the all-round shape-memory effect, which displays an inversion of bending shape with heating and cooling. This effect may be introduced into nickel rich alloys by ageing at temperatures around 500° C under bending deformation. In this case, reversible shape change occurs due to the internal stress field around the $Ti_{11}Ni_{14}$ plates precipitated during constraint ageing. RSM generated by constraint heating was originally found in Cu–Zn–Al alloys by Takezawa and Sato [7]. In the present work, their method has been applied.

The purpose of the present work is to investigate the effect of constraint heating on the shape-memory properties in Ni–Ti alloys.

2. Experimental details

The specimens used were polycrystalline Ni–Ti wires with 1 mm diameter prepared by the Furukawa Electric Company, Tokyo, Japan. The alloy composition was Ti–50.2 at % Ni, and the transformation temperatures, M_s and A_f, were 35 and 50° C, respectively, measured by electrical resistivity. Specimens were put into alumina tubes, 1 mm inside diameter, and these were placed in a silica tube and aged for 1 h at temperatures between 400 and 500° C in a vacuum of 10^{-3} Pa. After ageing, specimens were cooled to room temperature in the furnace. It was then ascertained that no shape change occurred when the specimens were put into ice–water (0° C) and hot water (100° C) and the specimens had a memorized linear shape as shown in Fig. 1a. Each specimen was deformed on

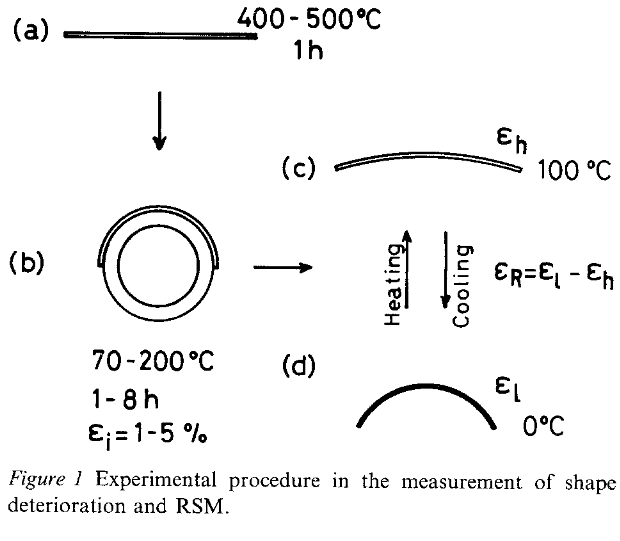

Figure 1 Experimental procedure in the measurement of shape deterioration and RSM.

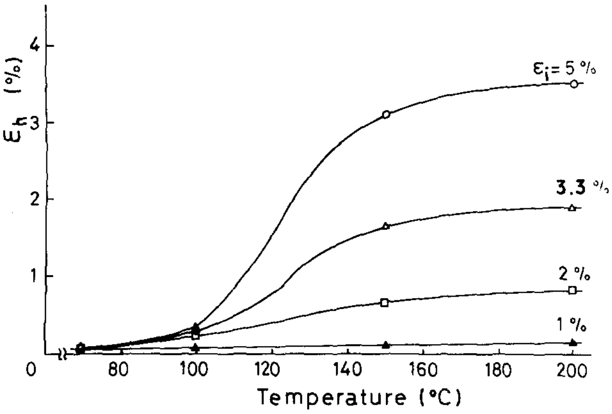

Figure 2 Temperature dependence of ε_h for each constraint strain; $T_m = 480°C$.

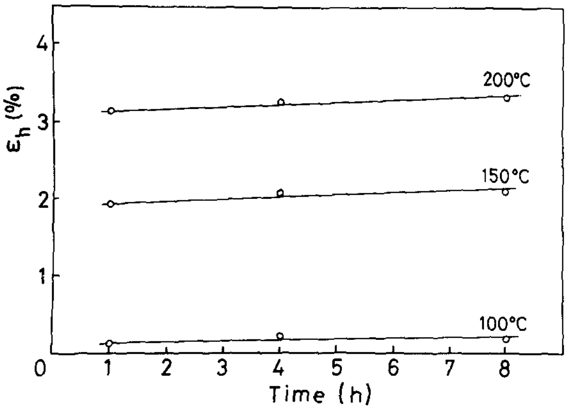

Figure 3 Time dependence of ε_h at each temperature; $T_m = 480°C$, $\varepsilon_i = 5\%$.

the side surface of a brass cylinder with the outside diameter selected by the given surface strains $\varepsilon_i = 1.05\%$ and fixed to it by a steel belt. The specimens wound on the cylinder were heated for 1 to 8 h at 70 to 200°C in an air thermostat, as shown in Fig. 1b. After these heat treatments, the constraint was removed at room temperature, and the shape of the specimen was photographed at temperatures of 100 and 0°C; the radius of curvature of each specimen was then measured. Surface strains obtained from the measured radii at 100 and 0°C are designated ε_h and ε_l, respectively, as shown in Figs 1c and d. The amount of shape change with RSM is defined by $\varepsilon_R = \varepsilon_l - \varepsilon_h$.

3. Results and discussion

3.1. Shape deterioration by constraint heating

Fig. 2 shows the dependence of ε_h on the constraint temperatures about each constraint strain, $\varepsilon_i = 1.0$, 2.0, 3.3, 5.0%. Except for $\varepsilon_i = 1.0\%$, ε_h increased abruptly between 100 and 150°C, and became saturated around 200°C. In the case of $\varepsilon_i = 1.0\%$, ε_h was very small and increased gradually with constraint temperatures. ε_h reached 3.5% at 200°C under the constraint strain $\varepsilon_i = 5\%$ and 70% of ε_i remained.

Fig. 3 shows the relationship obtained between the constraint time and ε_h for each constraint temperature under $\varepsilon_i = 5\%$. Most of the shape deterioration, ε_h, took place within an hour in the constraint heating treatment and ε_h then gradually increased with time.

Fig. 4 shows the changes of ε_h between the specimen given constraint heat treatment and that given 20 thermal cycles between 0 and 100°C. It was observed that part of ε_h was recovered by these thermal cycles. Recovery of strain, ε_h, increased in proportion to the increase of constraint strain, ε_i.

When the specimen is deformed below M_s and then heated above A_s under a constraint state, a recovery force due to shape-memory effect is generated and the internal stress increases with heating temperature. When such an internal stress surpasses critical stress for slip deformation, plastic deformation occurs and produces a shape deterioration, ε_h. ε_h increases with increasing constraint temperature, because a higher constraint temperature increases the internal stress induced by the recovery force through the shape-memory effect; but on the other hand, make the critical stress for slip deformation falls. The residual stress field induced by slip deformation produces a metastable martensitic phase. Part of this metastable martensitic phase is turned into the parent phase by thermal cycling, and part of ε_h is recovered. The amount of residual martensite increases in proportion to increasing constraint strain, ε_i, and the recovery of deterioration, ε_h, by thermal cycling also increases.

3.2. Reversible shape-memory effect

RSM was observed after constraint heating. Fig. 5 shows ε_h, ε_l and the reversible shape change ε_R $(=\varepsilon_l - \varepsilon_h)$ as a function of constraint temperatures. In this case, the constraint strain, ε_i, was 5.0% and the constraint heating time was 1 h. The specimens in Figs 5a and b memorized the linear shape on ageing for 1 h at 400 and 500°C, respectively. It can be seen that the shape deterioration, ε_h, is larger in the specimen aged at the higher temperature. On cooling the specimen from 100 to 0°C, all the specimens deformed in the bending direction, and the surface strain changed from ε_h to ε_l $(\varepsilon_l > \varepsilon_h)$. This shape change was recovered on heating the specimen to 100°C, and a reversible shape change was observed with thermal cycling between 100 and 0°C. Reversible shape change, ε_R, was small in specimens aged at 400°C as shown in Fig. 5a. However, specimens aged at 500°C indicated a peak value of ε_R with constraint temperature, of

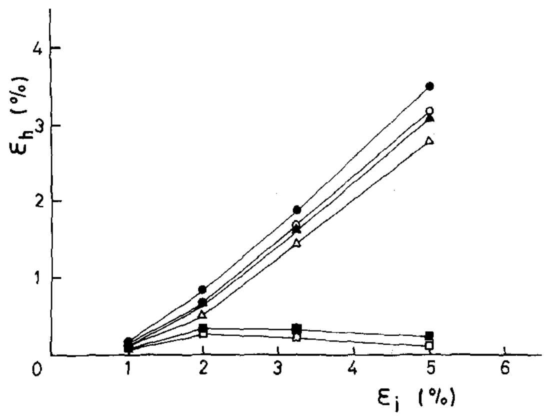

Figure 4 Recovery of ε_h with the thermal cycling, at $T_m = 480°C$. (○, ●) 200°C, (△, ▲) 150°C, (□, ■) 100°C, (●, ▲, ■) before, (○, △, □) after thermal cycling.

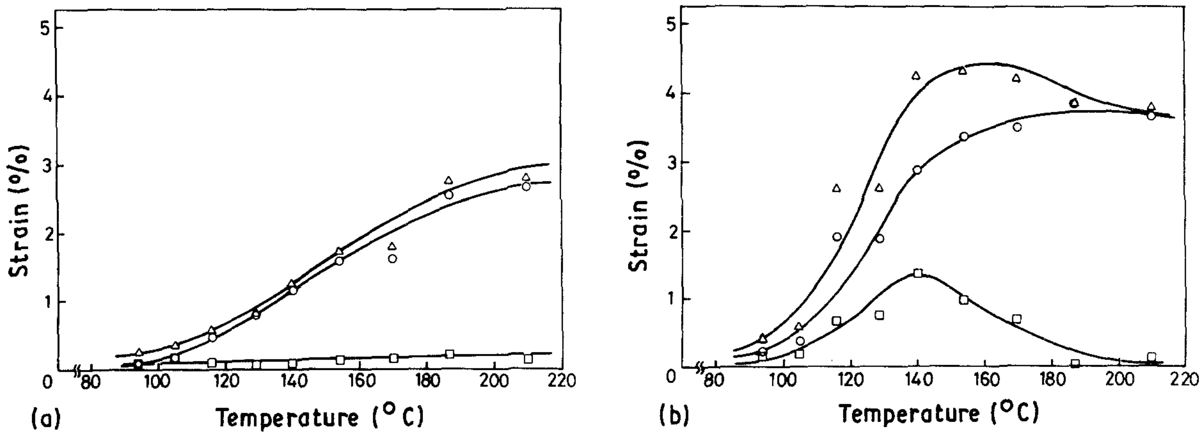

Figure 5 Constraint temperature dependence of (○) ε_h, (△) ε_l, (□) ε_R: (a) aged at 400° C, (b) aged at 500° C.

about 1.4% around the constraint temperature of 140° C.

The reason why this peak value exists is thought to be as follows. RSM obtained is generated by the residual stress field produced by plastic deformation under constraint heating. This stress increases on heating, because the recovery force due to the shape-memory effect increases. However, above 140° C stress relaxation occurs and the stress field generating RSM decreases on heating. It is thought that the specimen memorized the bending shape again around 200° C. Shape deterioration, ε_h, and reversible shape change, ε_R, heavily depend on ageing temperature during the shape-memory treatment, due to the specimens used in this work having a high dislocation density because they were used as-received after wire drawing. Because specimens aged at higher temperature have a low dislocation density, slip deformation under constraint heating occurred easily and the stress field generating RSM increases. The reversible shape change, ε_R, obtained in this work is almost the same as those obtained by Wasilewski [5] and Honma [6].

4. Conclusion

A remarkable shape deterioration occurs under constraint conditions above 1% constraint strain and 100° C constraint temperature. The causes of the shape deterioration will be plastic deformation, stress relaxation, and retained martensites. Reversible shape change shows a peak profile with constraint temperatures. The reversible shape change, ε_R, reached 1.4%, and this value is almost the same as those obtained by other methods [5, 6] in Ni–Ti alloys.

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