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SUBLOOP DEFORMATION OF SHAPE MEMORY ALLOY

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1. Introduction

Shape memory alloys (SMAs) are remarkable materials characterized by the thermomechanical properties of shape memory effect and superelasticity. Since the properties like these characteristics are highly conducive to the functions of smart materials, their applications have attracted worldwide attention. The functional properties of an SMA appear based on the martensitic transformation (MT). Research up to now in this area has been mainly concerned with a full loop (or perfect loop) of the MT completion. However, in practical applications, temperature and stress are likely to vary in various ranges. If SMA elements are subjected to loads with a subloop (or partial loop, internal loop) in which temperature or stress varies in an incomplete MT range, the conditions for the start and finish of the MT as in a full loop are not satisfied. The present paper investigates superelastic deformation behaviors of TiNi alloy in various subloop loading conditions, in particular the dependence of the subloop deformation on the loading rate, and the characteristics of transformation-induced creep in the stress plateau region under constant stress.

2. Subloop Deformation under Constant Strain Rate

The stress-strain curves obtained from the tension tests under constant strain rates of 1×10^{-4} and 5×10^{-4} s^{-1} are shown in Fig. 1. Strain is recovered in the unloading process, indicating superelasticity. At a low strain rate, an upper and a lower stress plateaus appear, due to the stress-induced martensitic transformation (SIMT) during loading and the reverse transformation during unloading. At a high strain rate, the slope of the stress-strain curve in the stress plateau region is steeper, and the starting and finishing points of the SIMT and reverse transformation are less distinct. The increase in steepness at the higher strain rate can be explained in the case of the loading process by saying that there is an increase in temperature due to the SIMT which raises stress above the level needed, at the upper plateau, for the SIMT to progress in conditions of temperature constancy. Similarly, in the unloading process at a high strain rate, the reverse transformation causes the stress to descend to a lower level than would otherwise occur at the lower stress plateau.

3. Subloop Deformation under Constant Stress Rate

The stress-strain curves obtained from the tension tests under constant stress rates of 0.5 MPa/s and 5 MPa/s are shown in Fig. 2. As before, these curves represent the hysteresis loops during loading and unloading and indicate superelasticity. Again, the slope in the stress plateau region is steeper for the higher stress rate. At the lower rate, from point A_1 in the unloading process where the strain is 8%, strain initially increases to 8.67% at point B_1 and then decreases to point C_1, which is the starting point of the reverse transformation, as a result of elastic deformation. The initial increase in strain from A_1 to B_1 is due to the fact that the conditions for the SIMT to progress are still being satisfied in this early part of the unloading process as a carry-over from the rise in temperature produced by the SIMT in the loading process up to A_1; as the unloading proceeds, the temperature then starts to come down. At the higher stress rate, for which the rate of decrease in the stress is larger during the initial stage of unloading from point A_2, any carried over increase in strain from the SIMT will be slight and balanced out by the decrease in elastic strain. As a result of these two counteracting variations in strain, stress decreases under almost constant strain down to point B_2, after which strain decreases elastically down to point C_2.

4. Transformation-Induced Creep

Figure 3 shows the stress-strain curve obtained from the creep test under a constant stress rate of 0.5 MPa/s up to a strain of 2% at the upper stress plateau, followed by a constant stress. In Fig. 3, the SIMT starts at a strain of 1.3% (point A) in the loading process, under a constant stress rate. If stress is controlled so as to remain constant at its level for a strain of 2% (point B), it initially fluctuates slightly before settling down to a constant 438 MPa at a strain of 3.5% (point C). Strain then continues to increase to about 8% (point D). This phenomenon of strain increase under constant stress is similar to what is found with normal creep deformation. The explanation in this case would be that the SIMT causes the temperature to increase during loading up to a strain of 2%, after which it decreases under a constant stress. Conditions are therefore satisfied for the SIMT to progress and strain increases.

Figure 4 shows thermograms of the temperature distributions on the surface of a specimen. As can be seen from the temperature distributions, the SIMT process due to the exothermic reaction first appears at the two ends during loading at a strain level of 2%, and then spreads toward the center where the bands combine into one, completing the SIMT. When the stress is held constant at the level reached for a strain of 2%, the SIMT bands spread due to a decrease in temperature. Transformation heat is generated at each new point of advance in the SIMT process, which leads to a chain reaction in the SIMT, resulting in creep deformation.

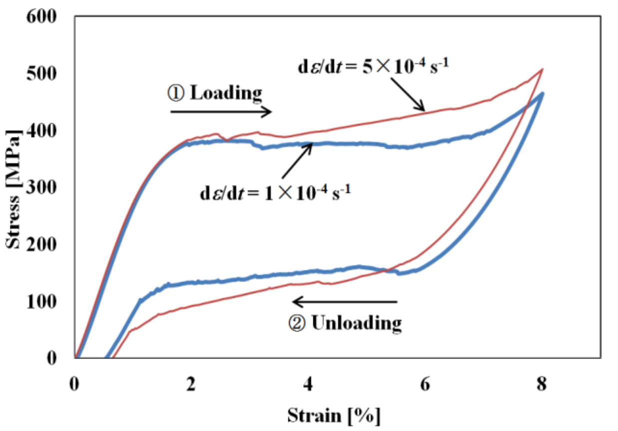

Fig. 1 Stress-strain curves under strain rates of $d\varepsilon/dt = 1 \times 10^{-4}$ and $5 \times 10^{-4}\ s^{-1}$

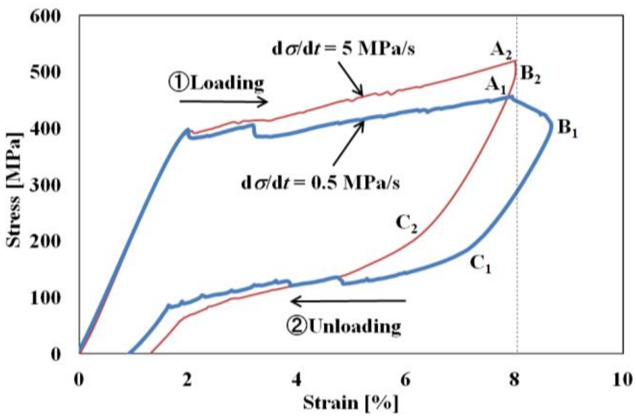

Fig. 2 Stress-strain curves under stress rates of $d\sigma/dt = 0.5$ and 5 MPa/s

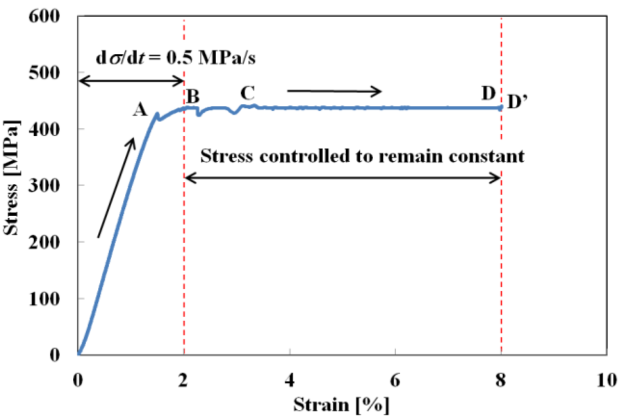

Fig. 3 Stress-strain curve under stress rate of $d\sigma/dt = 0.5$ MPa/s till strain of 2% followed by stress controlled to remain constant

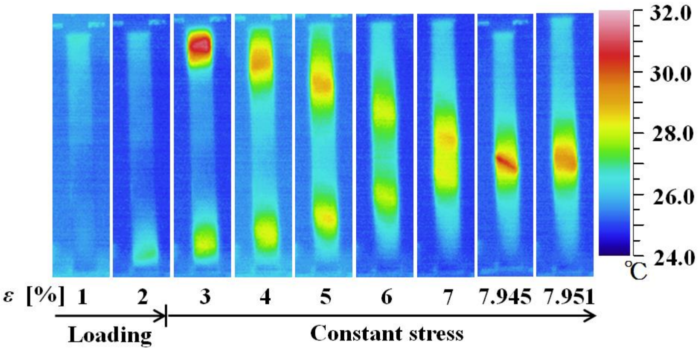

Fig. 4 Thermograms of temperature distribution on the specimen surface under $d\sigma/dt = 0.5$ MPa/s up to a strain ε of 2% followed by constant stress.