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Transformation-Induced Creep and Relaxation of TiNi Shape Memory Alloy

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Abstract

If the shape memory alloy (SMA) is subjected to the subloop loading under the stress- or strain-controlled condition, transformation-induced creep or relaxation can appear based on the martensitic transformation (MT). In the design of SMA elements, these deformation properties are important since the deflection or force of SMA elements can change under constant load or constant strain. The conditions for the progress of the MT are discussed based on the kinetics of the MT for the SMA. The creep and relaxation properties are investigated experimentally for TiNi SMA. If the stress is kept constant at the upper stress plateau after loading with a high strain or stress rate up to the stress-holding start strain, the transformation-induced creep occurs due to the spread of the stress-induced martensitic transformation process. If the strain is kept constant at the upper stress plateau after loading with a high stress rate, the transformation-induced relaxation appears due to the exothermic MT until the holding strain and thereafter temperature decreases while holding the strain constant.

Keywords: shape memory alloy, superelasticity, transformation-induced creep, transformation-induced relaxation

1. Introduction

Since the shape memory alloy (SMA) exhibits superior features of an intelligent material, the application of the SMA has drawn the worldwide attention. In the case of the subloop in which strain, temperature and stress vary in the range prior to the martensitic transformation (MT) completion, the starting and finishing conditions of the MT prescribed in the full loop are not satisfied. If the condition of the MT to progress is satisfied, transformation-induced creep and relaxation occurs under constant stress and strain on the upper stress plateau.

In the paper the transformation-induced creep and relaxation in the stress-controlled superelastic subloop loading under a constant strain and constant stress are discussed by the tension test for the TiNi SMA.

2. Materials and specimens

The material used in the tests was a TiNi alloy containing Ti-50.95at%Ni. This material was produced by Furukawa Techno Material Co., Ltd. and shows SE at room temperature. The thickness and the width of the tape were uniform, equal 0.38 mm and 9.81 mm, respectively. The specimen used in the test was of gage length, 100 mm, where "gage length" (GL) means the distance between the two securing grips.

3. Transformation-induced creep deformation

Figure 1 shows the stress-strain curve obtained from the creep test under a constant stress rate of 5 MPa/s up to a strain of 2 % at the upper stress plateau, followed by a constant stress. In Fig. 1, the stress-induced martensitic transformation (SIMT) starts at a strain of 1.3 % (point S_M) in the loading process under a constant stress rate. If stress is controlled so as to remain constant at its level for 2% strain (point H_I), it initially

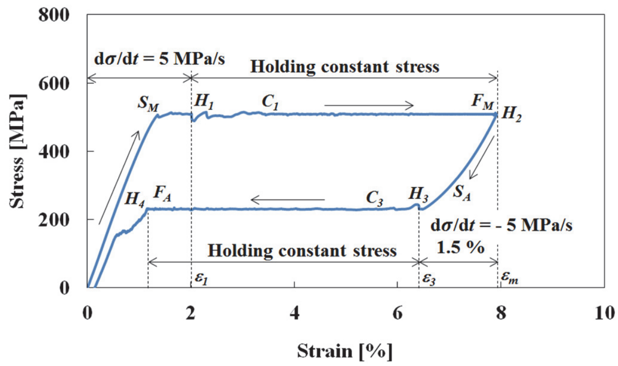

Figure 1: Stress-strain curve under a stress rate of 5 MPa/s followed by holding constant stress at 508 MPa from a strain of 2 % (point H_I) during loading

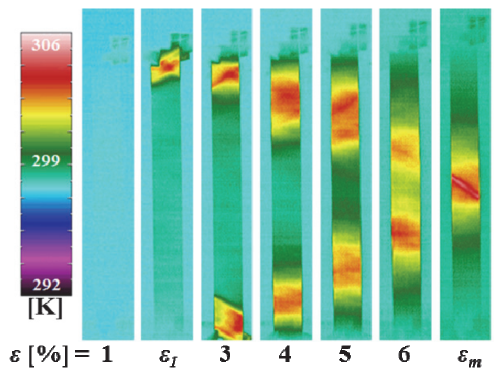

Figure 2: Thermograms of temperature distribution on the specimen surface under a stress rate of 5 MPa/s followed by holding constant stress from a strain of ε_I = 2 % during loading

fluctuates slightly before settling down to a constant 508 MPa at a strain of 3.5 % (point C_I). Next the strain is increased to about 8 % (point F_M). This phenomenon of strain increase under a constant stress is similar to the 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 2 shows thermograms of temperature distribution on the surface of a specimen. As can be seen from Fig. 2, the SIMT process due to the exothermic reaction first appears at two ends during loading at a strain level of 2 %, and then spreads towards the center where the bands combine into one, completing the SIMT. When the stress is held constant at the level reached for a 2 % strain, the SIMT bands spread due to a temperature decrease. 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 transformation- induced creep deformation.

4. Transformation-induced relaxation

The stress-strain curve obtained by the relaxation test under a stress rate of 5 MPa/s until a point H_I at a strain ε_I = 6 % followed by holding the strain ε_I constant is shown in Fig. 3. As can be seen in Fig. 3, in the strain holding process at ε_I = 6 %, the stress decreases from σ_I to σ_2, resulting in transformation-induced relaxation $\Delta\sigma = \sigma_2 - \sigma_1$.

Figure 4 shows temperature distribution on a specimen surface at various strains during loading and at various stresses at a constant strain obtained by the thermography. Figure 5 shows the relationship of stress σ and temperature change ΔT between the average temperature on the specimen surface and the atmosphere temperature with time t during loading and holding the strain constant. As can be seen in Figs. 4 and 5, in the loading process from the MT start point S_M to the point H_I, the strain rate becomes high and little time is left for the heat generated due to the exothermic MT to transfer to the atmosphere air, resulting in a temperature increase of the specimen. In the strain holding stage from points H_I to H_2, temperature decreases by the air and the condition for the transformation to progress is satisfied, resulting in the progress of the MT. As a result, stress relaxation appears during a constant strain test.

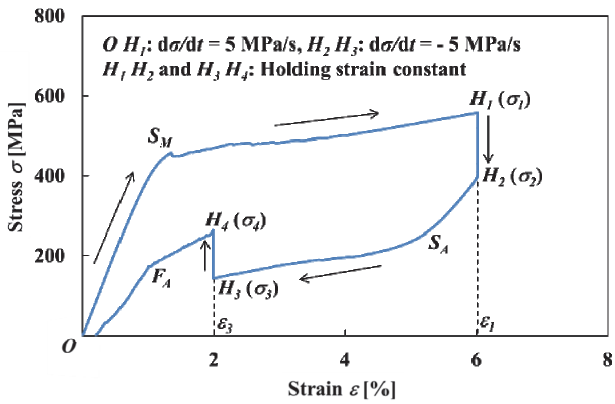

Figure 3: Stress-strain curve under a stress rate of 5 MPa/s till a point H_I at a strain ε_I = 6 % followed by holding the strain ε_I constant

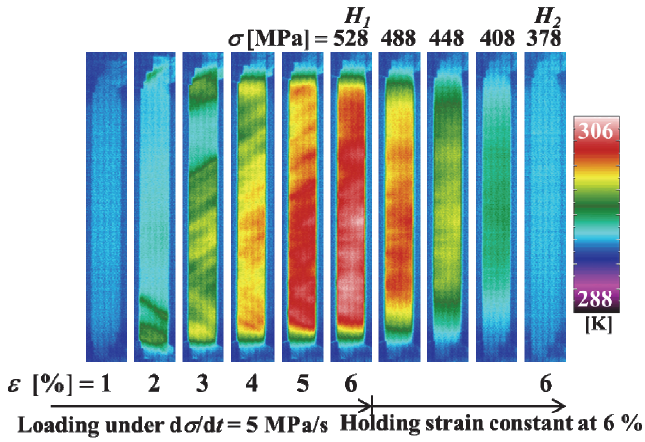

Figure 4: Thermograms of temperature distribution on the specimen surface under a stress rate of 5 MPa/s till a point H_I at a strain ε_I = 6 % followed by holding the strain ε_I constant

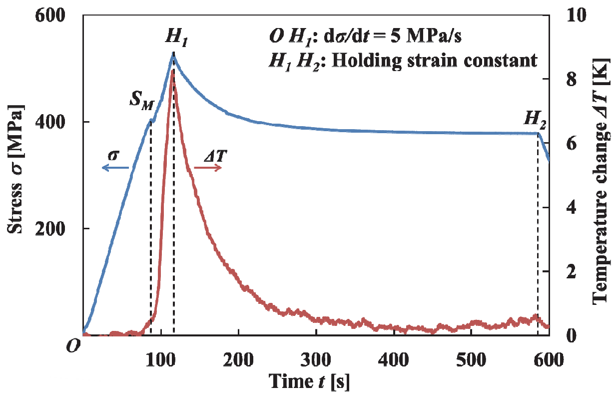

Figure 5: Variation in stress σ and average temperature change ΔT on specimen surface in the relaxation test

As can be seen in Fig. 5, temperature varies significantly in the early stage during a constant strain phase and thereafter saturates a certain value. Corresponding to this temperature change, stress relaxation appears markedly in the early stage during the constant strain test.

5. Conclusions

The transformation-induced creep and relaxation under the stress-controlled subloop loading in TiNi SMA tape were investigated based on evidence of local temperature variation as measured by infrared thermography during the creep and relaxation tests. The results obtained can be summarized as follows.

1. If the stress is kept constant at the upper stress plateau after loading up to the stress-holding start strain under a constant stress rate, the transformation-induced creep deformation occurs due to the spread of the SIMT process.
2. If the strain is kept constant at the upper stress plateau after loading with a stress rate, the transformation-induced relaxation appears due to the exothermic MT until the holding strain and thereafter temperature decreases while holding the strain constant.