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Fatigue crack initiation and propagation of a TiNi shape memory alloy

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In this paper, fatigue crack initiation and the propagation stages of a TiNi shape memory alloy are examined using a low cycle fatigue interrupted test. Submitted to fatigue cyclic loading, the response of the alloy presents a classical pseudoelastic response. Two potential initiation crack areas are highlighted: at the phase interfaces and at the grain boundaries. Propagation results from the coalescence of many microscopic cracks. These two stages are detectable in the last 20% of the total fatigue life.

Keywords: Low cycle fatigue; Pseudoelastic behavior; Fatigue crack initiation; Fatigue crack propagation; Dissipated energy

Shape memory alloys (SMA) are fascinating materials. Unlike the usual metallic alloys, they exhibit very specific thermo-mechanical behaviors, including shape memory effect [1,2], two-way shape memory effect [2], superelasticity [3–5] and damping [6]. Many engineering applications have been developed using these properties in various fields (medical, aeronautic, automobile, domestic or civil engineering).

Within the frame of design and reliability of systems using SMA, it is essential to have phenomenological models representing thermo-mechanical behavior as closely as possible fatigue. Understanding the physical mechanisms governing the cyclic behavior and leading to the degradation is a necessary step in making such models.

In this paper, we focus on superelasticity, also called pseudoelasticity, which describes the capacity of an SMA to support very significant recoverable deformation when a mechanical effort is applied. This deformation results from an austenite–martensite transformation under isothermal conditions, at a temperature greater than the finishing temperature of the reverse martensite–austenite transformation. The aim of this paper is to detect fatigue crack initiation and the crack propagation stages, and to link these observations with cyclic behavior.

The material investigated here is a near-equiatomic TiNi alloy. More precisely, sample analyses showed that the composition is 51.3 at.% Ti and 48.7 at.% Ni.

In order to develop pseudoelastic behavior, the following thermo-mechanical treatment was carried out:

– A first heat treatment, consisting of heating at 850 °C for 1 h followed by water quenching. At this temperature, which is above the recrystallization temperature in the austenitic field [7,8], work hardening due to machining is thus eliminated.
– A mechanical treatment, consisting of work hardening from 0 to 550 MPa at 200 °C. A high dislocation density is thus introduced. This implies an increase in the resistance for slip deformation by raising the critical stress for slip [9–11].
– Finally, a second heat treatment, consisting of heating at 400 °C for 1 h. At this temperature, which is below the recrystallization temperature, the high dislocation density is maintained [11].

The resulting microstructure is mainly made up of fine grains with an average size of 25 μm (Fig. 1a).

The transformation temperatures can be obtained by differential scanning calorimetry (DSC) measurements [12]. Figure 1b displays a DSC thermogram (heat flow vs. temperature). Initially, the material specimen was heated from approximately −40 to 60 °C (lower part of the curve). At low temperatures the material is in the martensite phase. The heat flow peak at a temperature of approximately 16 °C corresponds to the endothermic transition to the austenitic phase. The area

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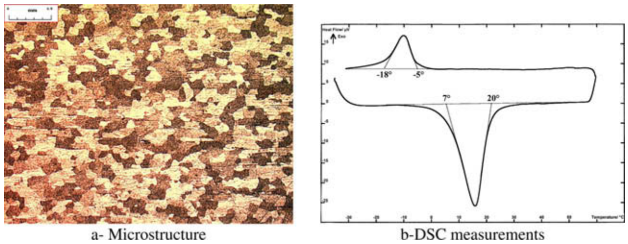

Figure 1. Properties of the TiNi alloy.

under this peak represents the latent heat of transformation and the construction lines indicate the values of the starting ($A_s = 7$ °C) and finishing ($A_f = 20$ °C) temperatures of the transition. The material was then cooled from approximately 60 to −40 °C (upper part of the curve). The heat flow peak at a temperature of approximately −10 °C corresponds to the exothermic transition to the martensite phase. The starting temperature of the transition is $M_s = -5$ °C and the finishing temperature is $M_f = -18$ °C.

The test specimen used was cylindrical, with a gauge section 8 mm in diameter and 20 mm in length, and with a total length of 120 mm. The gauge length was polished mechanically with silicon carbon paper in order to minimize the effects of any surface irregularities, like work hardening due to machining or oxide layers developed at 850 °C. The final surface preparation was then achieved by an electrolytic polishing.

A low cycle fatigue test was conducted on a servo-hydraulic machine (MTS 810) under controlled force (from 0 to 23.4 kN) at 1 Hz. In order to work on the austenitic phase, the test was performed at 50 °C. The signal was sinusoidal in shape, with a null stress ratio.

The strain amplitude was measured using an EPSILON extensometer with a root of 10 mm, placed on the gauge of the test specimen.

The aim was to observe the initiation of cracks (size between 5 and 10 μm) and to follow their growth. The test was stopped at various stages of cycling and disconnected from the servo-hydraulic machine. At each stop, observations of the specimen surface were carried out in a JEOL scanning electron microscope (JSM 5910 LV). The observations reported here were noticed in a homogeneous way on the test specimen surface.

In this paper, the results of the cyclic behavior are presented in two ways:

- As hysteresis loops (Fig. 2a and b), which describe the stress–strain behavior.
- As dissipated energy vs. number of cycles (Fig. 2c), the dissipated energy being equal to the surface of the hysteresis loop in the stress–strain curve.

During its fatigue life, the material investigated here showed two different behaviors:

- From cycles 1 to 1259 (Fig. 2a), a classical pseudoelastic response can be observed. Although the test is stopped, the cyclic behavior looks like those described by Moumni et al. [4] and by Miyazaki et al. [11] on non-stopped tests. Namely, the stress–strain response is characterized by hysteresis loops which evolve during cycling, changing their form and become smaller. Nevertheless, this change tends to stabilize with increasing number of cycles. As many authors [6,11,13,14] have shown, this stabilization effect occurs around the 100th cycle. Contrary to Moumni et al. [4] and Paradis et al. [13], no residual strain is noticed after the first unloading. Residual strain starts to appear at the end of the second unloading, increases during cycling and tends to saturate with a value of 0.4%. Note that in order to observe the surface of the specimen the test is stopped and the specimen is disconnected from the machine. However, following this pause, at the resumption of cycling, the form of the hysteresis loop remains unchanged. This behavior,

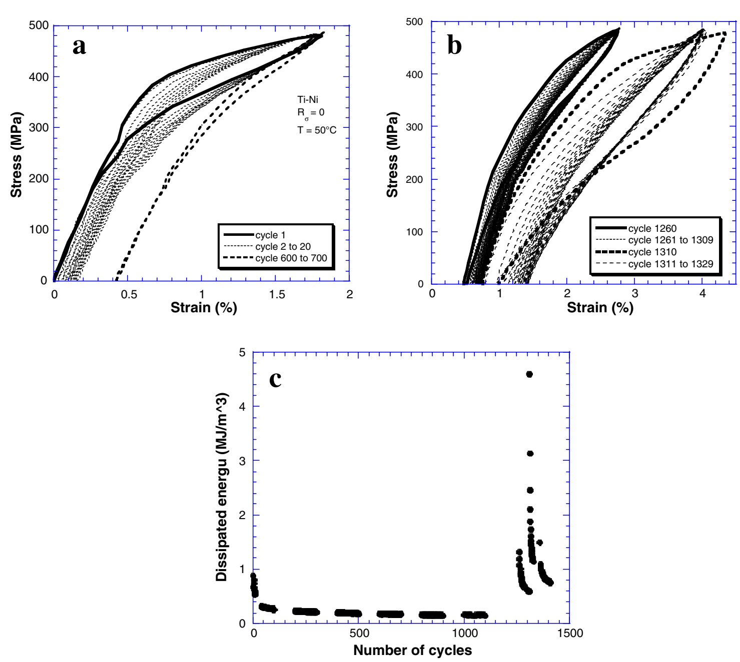

Figure 2. Cyclic behavior. (a) Pseudoelastic behavior, cycles 1–1250; (b) pseudoelastic behavior, cycles 1260–1329; (c) dissipated energy vs. number of cycles.