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METASTABLE EFFECTS ON MARTENSITIC TRANSFORMATION IN SMA
Part V. Fatigue-life and detailed hysteresis behavior in NiTi and Cu-based alloys

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The fatigue-life (traction–traction only) is experimentally studied mainly for pseudoelastic NiTi wire of 2.46 mm of diameter for eventual application in damping of structures under wind or rain. Thermal effects are highly relevant in determining the fatigue-life. The results shows that the fracture level overcomes 130000 cycles when the moving air is used for cooling. When the number of working cycles overcomes 30000, the frictional energy decreases 40% *vs.* N roughly with an exponential behavior.

Keywords: *CuAlBe, dampers, damping, fatigue-life, frictional energy, martensitic phase transformation, NiTi, SMA*

Introduction

The martensitic transformation, a first order phase transformation between metastable phases is the origin of the particular properties of the shape memory alloys (SMA): pseudoelasticity and thermoelasticity and shape memory providing the sensor and actuator characteristics. The phase transition also shows a hysteresis converting mechanical energy in thermal energy (or heat) as the classical dampers.

The target of this paper (paper 5 in a series of papers in metastable effects on SMA) describes the fatigue life mainly in NiTi and partially in CuAlBe SMA. One potential application of SMA in Civil Engineering is the damping of structures. Two different levels are considered, the damping of oscillations associated to earthquake and oscillations induced by wind and/or rain in stayed cables in bridges. In the former, the event produces around 200 oscillations associated to the quake length (i.e., one minute of oscillations) and, in the later, more than 100000 cycles per day is expected.

This paper studies the fatigue life required for application in damping for Civil Engineering applications. Some conditions to improve the number of working cycles previous to fracture are established. In addition, the evolution of the dissipated frictional energy with cycling is analyzed. The study shows some minor effects related to self-heating and subsequent cooling processes, and also associated to atomic diffusion phenomenon.

The first paper of this series was centered in the effects induced by the action of thermodynamic forces (stress and temperature) in the parent phase (paper 1) [1]. The paper 2 [2] focused in the heat treatment required for a grain growth with extremely reduced accumulative deformation effect in working cycles. The paper 3 [3] was related to diffusion effects induced by aging in NiTi and the paper 4 [4] was mainly centered on SMA dynamics (i.e., the self-heating) and SMA simulation in civil engineering structures for damping applications.

Experimental

A NiTi wire of 2.46 mm of diameter in pseudoelastic state finished in 'light oxide' furnished by Special Metals Inc. is used. Wires of CuAlBe of several diameters were produced and furnished by Trefimetaux France in the years 2003 and 2004 and by NIMESIS, France in 2006 and 2007 just after extrusion. For the cast type AH140 the reference data are: M_s=255 K; M_f=226 K; A_s=253 K; A_f=275 K with a chemical composition in mass%: Al=11.8; Be=0.5; Cu=87.7. The 'as received' wire requires (wire of 3.4 mm of diameter) appropriate homogenization (betatization) time at 1123 K, quenching and, later, lengthy aging at intermediate temperatures (i.e., 373 or 353 K).

The preliminary studies of fatigue life uses a series of homogeneous traction-traction (compression is avoided in our case) working cycles with progressive deformation as shown in Fig. 1 and detailed in Table 1. Evidently, if all the working material is subjected to the same stress state, the use of the material is optimized. This does not occur in bending or in torsion of wires. The progressive deformation is established for evaluation of SMA creep [2]. The measurements at room temperature are performed in a MTS 810 universal testing machine (servo-hydraulic) using a load cell MTS 100 kN controlled by a Multi

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Table 1 Cycle group characteristic for each deformation module corresponding to sets of measurements similar to show Fig. 1

Module	Amplitude/mm	Strain/%	Freq./Hz	Cycles#
M1	1*f*	0.79	0.5	5
M2	1.5*f*	1.18	0.5	100
M3	2*f*	1.57	0.5	100
M4	3*f*	2.36	0.5	100
M5	4*f*	3.14	0.25	50
M6	5*f*	3.93	0.25	50
M7	6*f*	4.71	0.25	50
M8	7*f*	5.50	0.25	50

Used: $f=l_u/127.3$ when l_u is the useful length of the sample (free sample between the grips) and 127.3 is a reference length, practically, the maximal available length in our measuring system

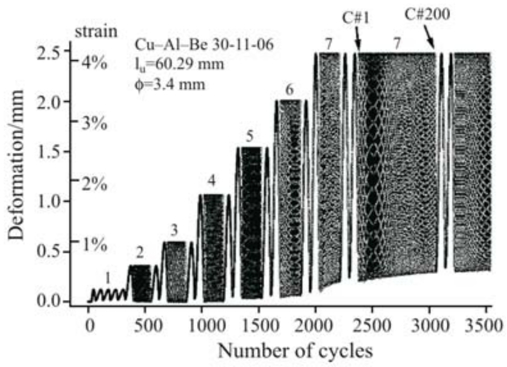

Fig. 1 Series of progressive deformation cycles (1 to 7) and fatigue cycles (form C#1 to C#200) at deformation of module 7 using CuAlBe. The set of cycles is considered of type 7-7 in Tables 2 and 3

Purpose Testware (MTS), and a Control Mode via displacement of sinusoidal cycles. In the measurements the hydraulic system cannot track the higher deformations available (i.e, in SMA deformations of several mm) at higher frequencies (higher than 0.25 Hz). In fact, the available working frequency decreases with relevant deformations.

Results and discussion

Fatigue-life

The fatigue-life is studied for two different applications, damping of earthquakes induced oscillations in family houses [4] and damping of stayed cables in bridges. The SMA interest in guaranteeing the dampers for earthquakes is relatively simple and ease, only requires some hundreds of cycles (200–400) and the fracture for CuAlBe is clearly larger than 1000 cycles at strain near 4%. Figure 5 shows an example of CuAlBe alloy with two series of 1800 cycles each. The main part of this work centers in the NiTi alloy when works in an application to damping stayed cables in bridges. In this potential application the number of cycles overcomes 10^5 cycles when several days of wind and rain are expected (the frequency for cable oscillation is situated near 0.5 Hz). The experimental analysis shows (NiTi data of Table 2) that use series of cycles always at the same amplitude produces some reduced fatigue-life.

The fatigue-life, at constant amplitude, shows (Table 2) that the mean number of oscillations remains close to 4000. This number is appropriate for damping the quakes but is clearly insufficient for use as dampers of wind or rain. Series of measurements are performed to try to improve the fracture level. Using tubes protecting the SMA wire is possible to ensure that the oscillations of the damper always remain inside a bath (water, paraffin). In water the fatigue-life (near 10000) is relatively short probably by the interaction between water and the 'unprotected' alloy atoms appearing in transformation-retransformation processes. The life increases when the fatigue series of cycles is realized after some previous sets of cycles at higher deformation (for instance Table 3). The number of cycles increases with

Table 2 Fatigue-life for constant cycling and constant amplitude (NiTi). The M*i*–M*j* indicates that the progressive deformation stops at M*i* (Fig. 1) and the amplitude of fatigue cycles relates the modulus M*j*

Measured	Free sample lenght	Strain/%	Freq./Hz	Fracture at
M4–M4	128.5	2.36	0.5	4230
M5–M5	103.9	3.14	0.25	3079
M6–M6	136	3.93	0.25	3495
M7–M7	68.56	4.71	0.25	4735
M8–M8	80.9	5.5	0.25	3012

Table 3 Improvements in fatigue-life

Measure type	Sample: free length between the grips	Strain/%	Freq./Hz	Fracture after N cycles
M6–M5	85.51	3.14	0.25	7563
M7–M6	72.27	3.93	0.25	11568
M8–M7	79.88	4.71	0.25	5290
M8–M6	66.18	3.93	0.25	11177
M7–M5	68.2	3.14	0.25	17331
M7–M4*	62.33	2.35	0.25	132668
M7–M4.2	69.2	2.46	0.25	69400

*little hysteresis cycle (path close to elastic zone)

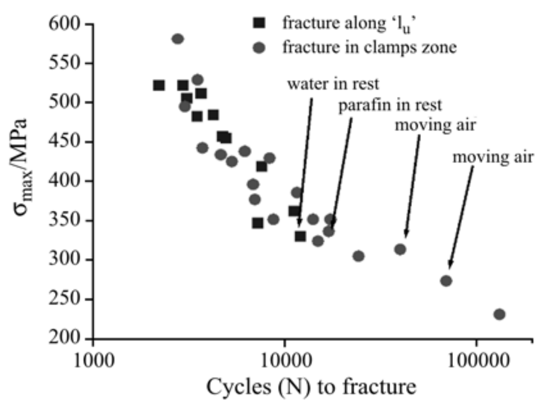

Fig. 2 Maximal stress *vs*. the number of cycles from the measurements. ● – fracture in grips, ■ – fracture between grips

increased difference between the preliminary cycles and fatigue cycles. The fatigue-life increases when the applied stress to transform decreases (Fig. 2). Also increases when the 'room temperature' of the sample decreases or remains at lower temperature. In particular, cooling the sample with a fan (maintaining the sample without self-heating effects) increases the fatigue-life.

The main problem for an increase of fatigue–life supposes a difficult maximization problem. The increase of N cycles related to: a) the decrease of deformation between preliminary cycles and fatigue, b) the sample temperature, c) the associate maximal stress and d) the martensitic transformation particularities. a, b, c and d seems the relevant parameters to be considered (for general information about SMA and martensitic transformation [8, 9]). At the present state of the art the number of cycles to fracture seems too low for the application. In practice, the minimum number of cycles in the required application is larger than 10^5 and a hysteretic path with a reasonable amount of energy dissipation is necessary. In the actual state of the art, after an improvement from 3000 to 100000, new ideas are necessary increasing the fatigue-life to 2 or $3\cdot10^5$ cycles.

Hysteresis studies

The analysis of damping possibilities requires some quantitative evaluation of frictional energy the hysteresis cycle in damping. Using the appropriate thermomechanical behavior for homogenization [2] and efficient aging, it is possible, via a thermomechanical training [2, 4], an improved reduction of SMA creep close to zero. At this conditions (Fig. 9 of [2] the low SMA creep for a relevant series of cycles) a model of hysteresis can be built inside ANSYS and structure simulations can be realized evaluating the effect of SMA dampers under the action of earthquake acceleration. Really, the main interest for simulation purposes is to obtain detailed knowledge of the rules of the eventual evolution of hysteresis (of the frictional working) against the number of working cycles N (Fig. 4). For demanding applications, for instance, the damping of wind or rain actions in stayed cables an experimental and quantitative evaluation of the fatigue-life is absolutely necessary. In the available literature [5–9] the fatigue-life is, usually, extremely focused in the required application (files, blades or drills). Figure 3 shows some experimental data extracted from [5, 6] included with our measurements. The comparison indicates that our measurements (traction-traction only) shows some improved fatigue-life. Our measurements roughly fits via one straight line using one log-log representation.

As it can be observed from Fig. 3, the fatigue-life is shorter for rotating-bending experiments than for traction–traction experiments. The complexity of strain and stress distribution due to the martensitic transformation in rotating-bending is related with this fact. Coherently, it is found a reduced life in the more complex stress states of rotating-bending plus twisting fatigue, even if some interpretations might be, at least, unclear [7].

Continuous cycling shows a progressive reduction of the hysteresis or the dissipated energy (for instance Fig. 4). The intrinsic origin – at microscopic scale – is not clear but the analysis of the measurements shows similar reduction of the hysteresis

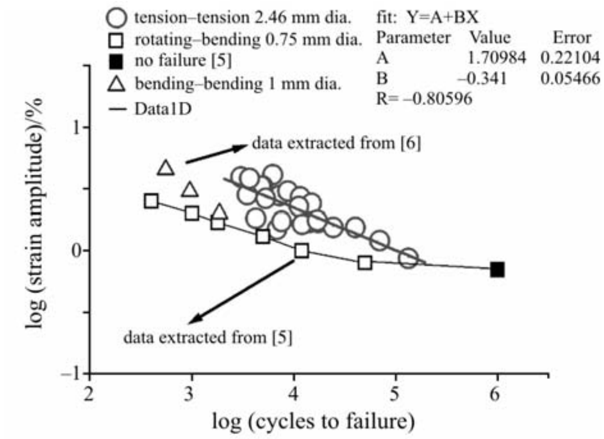

Fig. 3 Strain *vs*. fracture. ○ – this work (at 293 K), □ – data extracted from [5] (at 333 K), ■ – practically in the elastic part (associate deformation 0.75%) of [5]. △ – data extracted from [6]

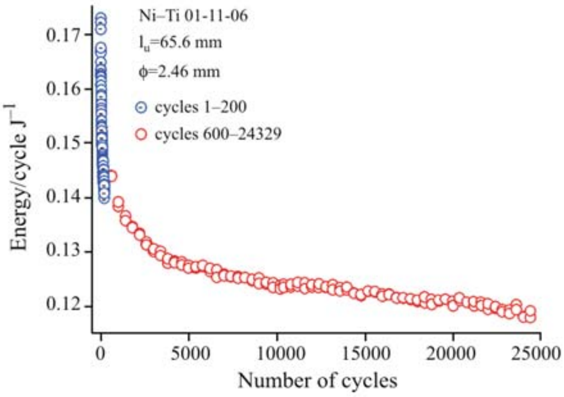

Fig. 4 Evolution of the frictional energy with cycling in a series of cycles in NiTi (wire diameter 2.46 mm, length: 65.6 mm)

width. In damping the earthquakes the energy decay is irrelevant, because the expected number of working cycles is close to 200 cycles and the decay of the energy does not overcome 2%.

In cycling some effects are concomitant, in particular the self-heating effect increase the temperature of the sample and parallel diffusion effects. When temperature increases, via the Clausius–Clapeyron coefficient, the stress also increases. Some cycling evolution can be observed mainly related with temperature diffusion effects. After stopping the cycling process, the restarting shows some increased dissipated energy. Figures 5 and 6 show the effect in CuAlBe and the NiTi, respectively. The effect cannot be associated to self-heating. In fact stopping the cycling reduces the sample temperature by a spontaneous cooling and, accordingly, the stresses are reduced. But after the stop the SMA creep seems reduced and the first cycle of the new series needs some supplementary forces and increase of effective deformations with minor increase of frictional contribution. The effects are similar in CuAlBe and in NiTi (Figs 5b and 6b the change in the hysteresis

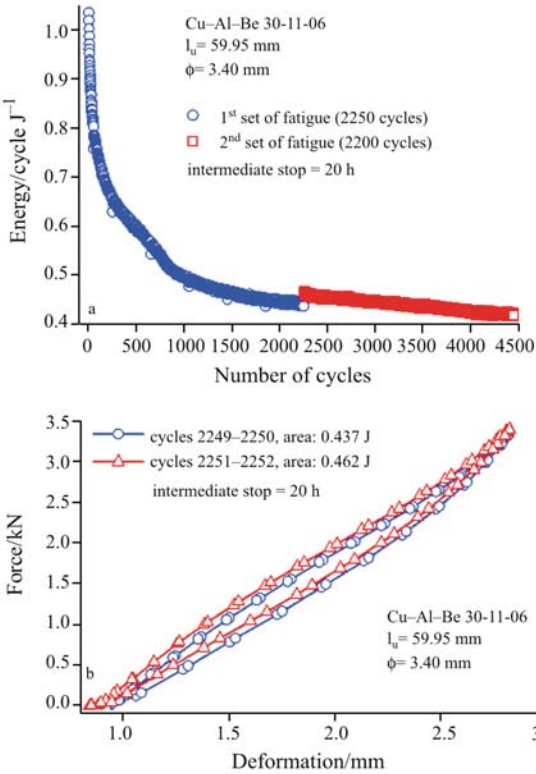

Fig. 5 Fatigue in CuAlBe alloy, sample length between the grips: 60.84 mm. Evolution in cycling of the dissipated energy. b – one cycle at each side of the intermediate stop

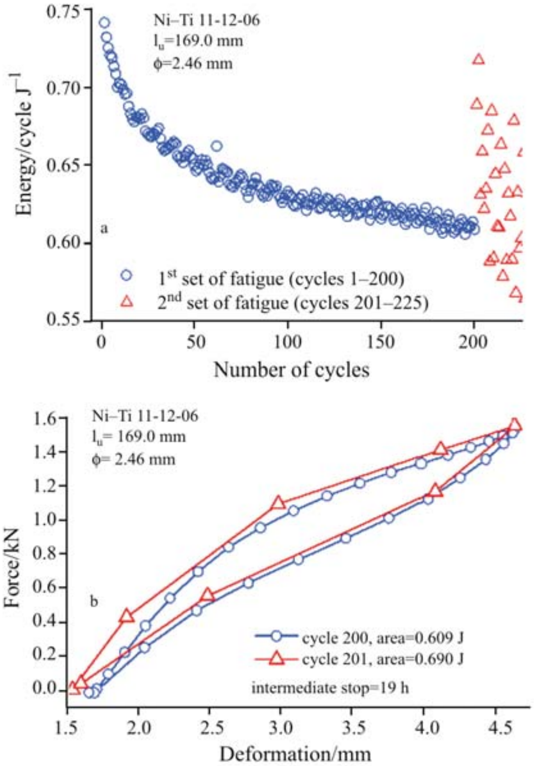

Fig. 6 Fatigue in NiTi alloy. Sample length between the grips 69.2 mm. a – Evolution in cycling of the dissipated energy. b – One cycle at each side of 19 h of the intermediate stop

cycle at the two sides of the stop). The area is increased by 7 and 15% in CuAlBe and NiTi respectively (Figs 5b and 6b). In these effects the action of minor atomic diffusion effects probably is mixed with self-heating and spontaneous cooling effects. Their quantification requires more careful and slow measurements. The roughly analysis of Fig. 8 in paper [4] relates cycles realized at 0.1 Hz for CuAlBe wires of squared section of 1.2×1.2 mm^2 suggest changes of behaviour of the wire with cycling frequency (from 0.25 to 0.1 Hz), the dominant effect is self-heating at 0.25 Hz but other effects, related to atomic diffusion, are 'dominant' at 0.1 Hz, as maximum force increases with cycling at 0.25 Hz but decreases with cycling at 0.1 Hz [10, 11]. The high dispersion of the right points in Fig. 6a is produced by too reduced number of data points in the hysteresis cycle (8 points in Fig. 6b).

Conclusions

In the bibliography some analysis of NiTi wires are available for healthy applications [5, 6]. The fatigue-life is higher in our study (wire diameter 2.46 mm) only related to tension-tension stress-strain cycles without any bending or flexion or compression. Usually in the references, the transformation is associated to more complex process and, obviously, lower fatigue-life. The fatigue study in NiTi is, for instance, performed in wires (0.75 mm) for drilling [5] using rotating bending test that produces sequential traction-compression cycles. In this case, the fatigue-life approaches 1500 cycles at maximal deformation close 2% (rotating speed 500 r.p.m.) [5]. In wires for files (diameter 1 mm) with deformation near 3% the fatigue-life is close 1000 cycles (at 350 r.p.m.) [6]. The ref. [5] indicates fracture-life over 10^6 for strain amplitude close to 0.8% also in rotating bending fatigue. At this deformation level the behavior of SMA is practically equivalent to an elastic material without hysteretic cycle without interest for damping.

In the actual state of the art the fatigue-life (near 120000) is appropriated for preliminary tests of damping in stayed cables when new improvements in fatigue life are expected. Obviously the SMA are appropriated for dampers in family houses. The required number of cycles is reduced (close to 200) in comparison with the experimental level of fracture (several thousand).

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