Review-Shape Memory Alloys, their Fatigue Characteristics and Applications

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Abstract

Structural and functional Fatigue is a key issue that needs to be resolved in order to promote the engineering applications of Shape Memory Alloys(SMA). In this paper, recent progresses made in theoretical and experimental analyses regarding structural fatigue features of Shape Memory alloys especially Nitinol (Nickel-Titanium Alloy) are reviewed. Further, the applications of SMAs are reviewed; finally, summary and future topics are outlined.

Keywords: Shape Memory Alloys, NiTi, Austenite, Martensite, Structural Fatigue.

1. Introduction

Shape Memory Alloy is known as an alloy that "memorizes" its original shape. They have a peculiar crystallographic structure of the alloys which assure the recovery of the original shape even after large deformations. The prominent characteristics of SMAs are based on the type of alloy and Shape Memory Effect (comprising of One-way shape memory effect and two-way shape memory effect), pseudo-elasticity. The properties of SMAs are summarised in Table 1. This well-known behaviour is due to a unique ability to exist in two different phases in three different crystal structures (i.e. twinned martensite, detwinned martensite and austenite- See Fig 1) and six transformations. The six transformations (Refer Fig. 2) are described in the work of *Sun L. and colleagues* [1] and is summarized as follows:

(1) Austenite transforms into detwinned (slipped) martensite upon loading (A to DM);

(2) Detwinned martensite undergoes reverse transformation into austenite after heating without load or with a very low load or after unloading at a high temperature or (DM to A);

(3) Detwinned Martensite in variant k (DM_k) transforms into another Detwinned Martensite in variant l (DM_l) after load is applied;

(4) Twinned Martensite transforms into detwinned martensite upon loading (TM to DM);

(5) Austenite transforms into Twinned Martensite upon cooling (A to TM);

(6) Twinned Martensite transforms into Austenite upon heating (TM to A).

These unique transforming abilities of such metal composites have drawn interest from various scientific communities. In addition, these alloys exhibit unusual fatigue and fracture responses compared to the common metals, due to their stress and/or thermally induced microstructure evolutions (see Fig. 2). NiTi (an alloy made of Nickel and Titanium) is one of the most common SMAs used but

Terminology	Definition
Shape Memory Effect	After a material has undergone deformation, it is recovered when the material is heated to cause a reverse martensitic transformation to austensite. The material does not return to its original shape upon cooling.
Two-way SME(TWSM)	A material possessing SME is thermomechanically processed, after spontaneous change in shape. Inverse shape change occurs via SME upon heating.
Rubberlike behavior	Some SMAs exhibit rubberlike flexibility. When wires or bars are bent, they restore their original shape after release of stress. This property is exhibited in the martensitic phase.
Super elasticity(SE)	This property is similar to the rubber like behavior except this occurs at the parent phase i.e. Austenite
Pseudo elasticity	This is a more generic term encompassing both super elasticity and rubberlike behavior to avoid ambiguity

Table 1 Glossary of Shape Memory terminology [2]

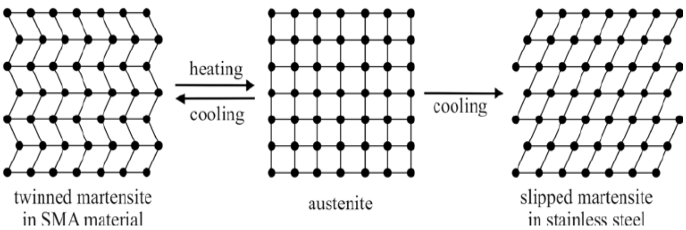

Figure 1 Three different crystal structures of SMAs [38]

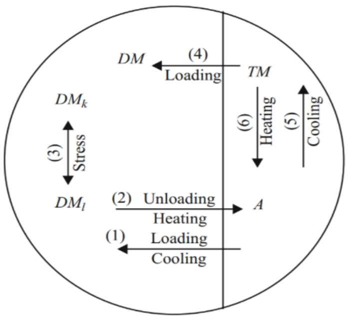

Figure 2 Three phases and six transformations: A) Austenite; TM) twinned martensite; DM) detwinned martensite; the subscripts "l" and "k" are used for the orientation variants of martensite.

is limited to high end applications such as stents, electromagnetic actuators, orthopedic, orthodontics etc. [3]. [4]. Many testing procedures were carried out by researchers in the past few years to study the fatigue properties of SMAs with the aim of using them in low end applications. In the past few decades much research was carried out to study the structural (microstructural damage that accumulates during cyclic loading and eventually leads to fatigue failure) as well as the functional fatigue (Shape Memory Effect, Pseudo-elasticity decrease with increasing cycles) of SMAs [5]. Fatigue crack growth rates were studied by *Robertson et al* [6]. who analyzed the Low Cycle and High Cycle Fatigue properties of SMAs. Fatigue properties by considering pseudoelasticity and shape memory behavior and the cyclic properties of materials of wires has been studied. In addition, rotary bending tests were also carried out to analyze the fatigue properties.

This paper aims to review research papers and articles that study the Fatigue characteristics of SMAs and their applications. In addition, it also comprehends the issues associated with its application.

2. Experimental observations

Fatigue is considered to be a major factor in the application of SMAs in the medical devices industry. [7] [8] [9] [10]. Bending Rotation Fatigue (BRF) has been considered a standard test for the structural testing of shape memory wires by numerous researchers. [11] [12] [13]The structural fatigue or mechanical fatigue of NiTi SMAs is caused by cyclic stress (or strain) or by cyclic temperature under constant stress. This paper only focusses on the structural fatigue aspects.

2.1 Mechanical Fatigue

Many researchers such as *Tobushi et al.* [13] *Wagner et al.* [14], *Matsui et al.* [15], *Yan et al.* [16], *Cheung et al.* [17], *Figueiredo et al.* [18], *Bernard et al.* [19], and *Kollerov et al.* [20], have studied rotary or rotary-bending fatigue failure under displacement controlled cyclic loading conditions. One common peculiarity of these research included that these tests were carried out on NiTi SMAs mainly used in the form of wires. *Tobushi et al.* [21] concluded that in the region of low-cycle fatigue, the corrosion caused by water, hardly influence the fatigue life of the NiTi SMA wires. Wagner et al. also performed Rotary-Bending tests of NiTi SMA wires with different wire diameters (1.0 mm, 1.2 mm and 1.4 mm) and different bending radii and rotational speeds (36, 100 and 800 rpm) were carried out and it was demonstrated that fatigue life was not affected by wire diameter and rotational speeds as long as the wire temperature was kept constant.

Another research by *Robertson et al.* [22] demonstrated the relation between effect of cyclic strain amplitude on rotary bending fatigue life. The results are shown in the figure 3. Note that fatigue limit for the austenite is much higher than the martensite. This also shows that low cycle fatigue is greatly affected by temperature with an order of magnitude improvement in fatigue at 20°C. This makes NiTi SMAs a poor option for Low Cycle Fatigue (LCF) where fluctuations in temperature is associated but make it an excellent choice in High Cycle Fatigue (HCF) applications. *Hornbogen et al.* [23] conducted fatigue research on a microstructural level and

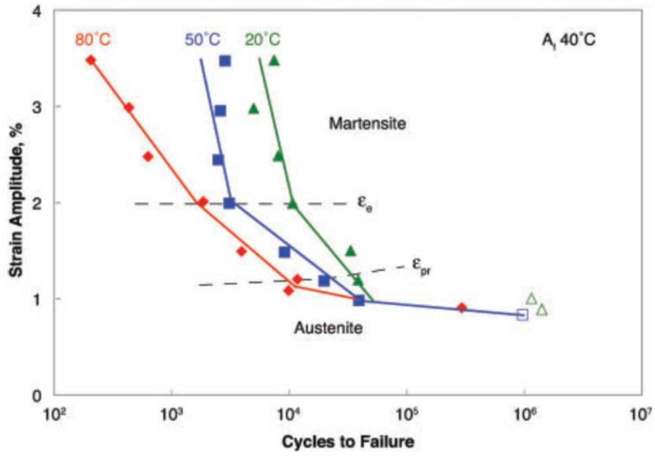

Figure 3 Effect of cyclic strain amplitude on cycles to failure at three different test temperatures

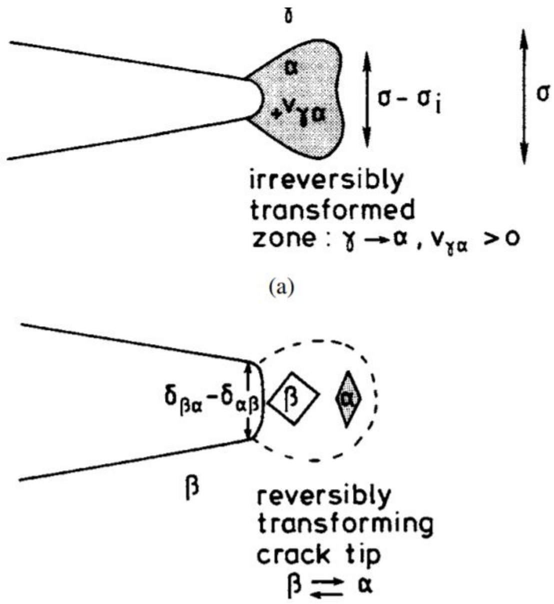

Figure 4 Crack propagation and martensitic transformation in austenitic

proposed a mechanism of crack propagation in SMAs. The transformation is reversible (martensite to austenite), or it is connected with an increase of specific volume with the growth in martensitic phase. Retardation or stoppage of crack growth is the consequence. For instance, as the number of cycles increase, there is a growth of martensitic phase near the grain boundaries. This martensitic phase is reversible but residual martensitic phase increases as the number of cycles increase. Martensite in this manner propagates through the material and with it the crack. This is shown in Figure 4 where α is

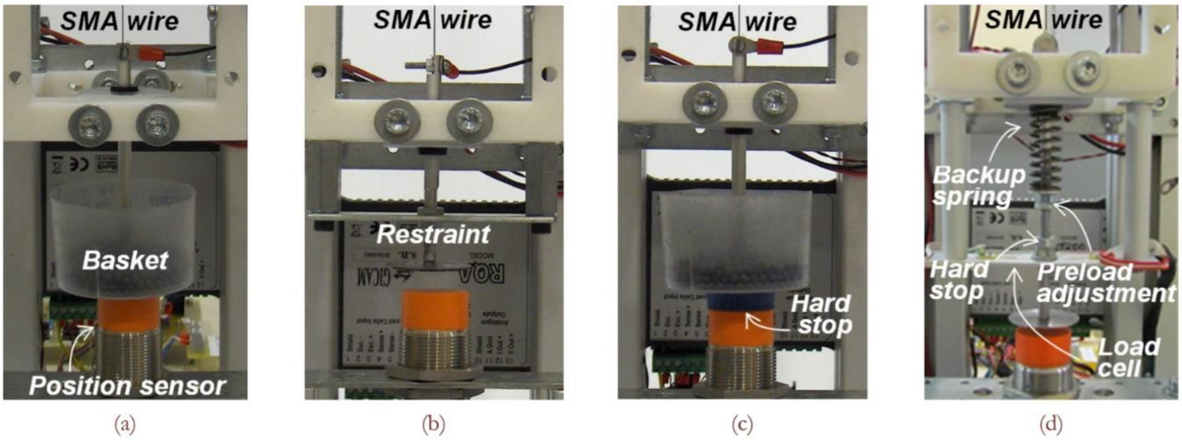

Figure 5: Details of apparatus for test conditions (a) Constant-stress; (b) constant-strain (c) constant-stress with limited maximum strain; (d) linear stress-strain cycle.

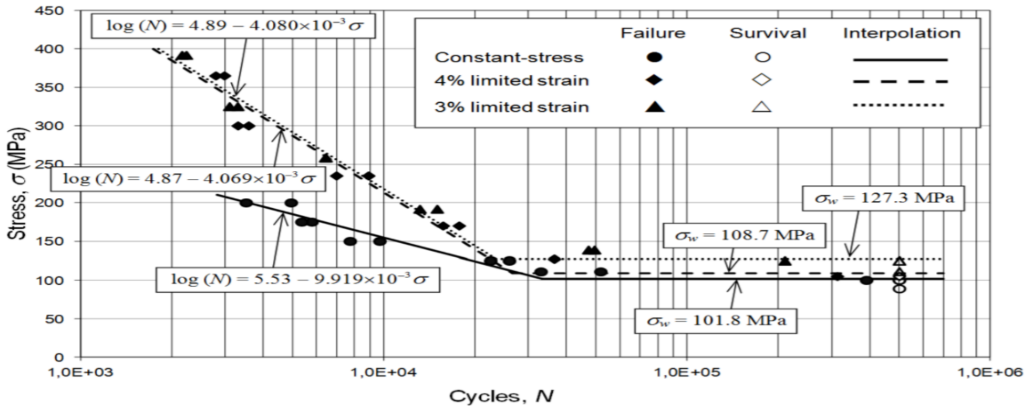

Figure 6: Woehler's diagram with fatigue results for the constant-stress tests and tests at constant stress with limited maximum strain (3% and 4%)

martensite and β is austenite. In steels the martensitic transformation is also associated with the formation of a ferromagnetic phase. This in turn may be used as a sensor, if a certain stage of crack growth has been reached.

2.2 Thermomechanical fatigue

Actuators made from NiTi SMAs often undergo thermally activated cyclic transformations and are important to understand the thermomechanical fatigue properties in NiTi SMAs. Some thermomechanical fatigue tests were performed by *Lagoudas et al*. [24] *Pappas et al*. [25] *Karhu and Lindroos* [26], *G. Mammano* [27] in which NiTi SMA wires and plates were subjected to a thermal cycling with a constant axial stress or strain, or variable stress and strain. The experimental setup by *Mammano et al*. had wires and plates were subjected to a thermal cycling with a constant axial stress or strain, or variable stress and strain. The experimental setup by *Mammano et al*. is shown in the figure. The graph depicts fatigue life at Constant Stress and constant stress with limited constant strains. A staircase fatigue test was conducted and the fatigue limit for the constant-stress tests calculated from the chosen life (5x10^5 cycles) was found out to be σw=101.8MPa. For constant-stress tests with limited maximum strain, the fatigue limits are greater than for the constant-stress conditions and takes up for decreasing limit strain (108.7 and 127.3 MPa for limit strains of 4% and 3%, respectively). This can be seen in the Woehler's Diagram in Figure 6. In addition, static yield stress was found to be in the range of 400-50 MPa but loads as small as 80-100 MPa caused degradation in the fatigue life which can be seen by the increasing drift in the recovery of strain in its martensite phase.

3. Applications

Application of SMAs span over a diverse group of industries. They are used as wires and tubes in applications with hot fluids flowing through them. These materials are ideal as they can retain their shape even in a heated environment. As a result, many couplings are made from SMAs as they are able to retain contact with changes in temperature in the environment [28]. SMAs have excellent damping properties and are therefore used in civil applications for e.g. Bridge structures [29] as well as in launch vehicles and jet engines [30]. SMAs have greater ability to absorb impact energy with respect to structures made with traditional thermoplastic composites and to reduce the risk of delamination of the structures during impact. This property makes SMAs extremely useful in the field of aeronautics [33]. In certain commercials, eyeglass companies demonstrate frames that can be bent completely and retain their shape after removal of force. These frames are made from memory metals as well and exhibit super-elasticity [31]. Another possible application is in retrofitting buildings that are not designed to withstand seismic vibrations. [32] A great majority of SMA medical devices today are produced using NiTi alloys. Nowadays, dental wires are made of NiTi as they are used under constant temperature, they maintain their shape due to super elasticity [33]. But one of the most successful application is the use of stent-graft for the treatment of abdominal aortic aneurisms. The stent comprises a spiral coil or is made in cylindrical shape of a two-way shape memory alloy and has a super-elastic state. It is made of NiTi and is manufactured so that the austenite finish temperature (A_f) phase is less than the body temperature. The diameter of the stent is at least about the critical diameter or more of the stenotic vessel [34].

4. Issues

Corrosion resistance and Bio-compatibility are considered a major factor which using implants in human body. It was shown in the research that the biocompatibility and corrosion resistance of NiTi materials may be as high as of pure Ti, and much better than those of conventional implant materials [35]. But they are needed to be covered with a layer of Titanium oxide which might have a limited time period [36]. It can be said that its bio-compatibility has not been established beyond a reasonable doubt. In addition, high precision manufacturing is required which makes the process costly.

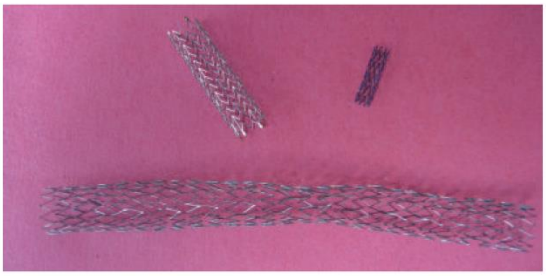

Figure 4 Example of SMA stents: (top right) coronary stent, (top left) cartoid stent, (bottom left) femoral stent.

5. Summary and Future work

The present paper provides a brief overview of structural (both mechanical and thermomechanical) of NiTi shape memory alloys. It then discusses (1) Bending–rotation fatigue rupture of NiTi wires. (2) Crack propagation during the stress induced formation of martensite. (4) Generic features of structural fatigue in NiTi shape memory alloys. 5) Summary of current applications in industry. Fatigue is a multiple parameter phenomenon. The present paper has only presented some results on fatigue of NiTi shape memory alloys. It has been shown that temperature, microstructure and surface quality affect the fatigue behaviour. In addition, the type of loading (stress or load control, tension/compression asymmetry), the strengths of austenite and martensite, the degree of order of the lattices, the volume fraction and size distributions of particles, the volume change during the transformation, how much PE plateau strain is imposed during strain-controlled testing, structural incompatibilities and others. Further investigation would be required to assess the effects of these parameters on the fatigue properties of SMAs.

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