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Review

Review on structural fatigue of NiTi shape memory alloys: Pure mechanical and thermo-mechanical ones

Guozheng Kang[a],*, Di Song[b]

[a] *School of Mechanics and Engineering, Southwest Jiaotong University, Chengdu 610031, China*
[b] *School of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China*

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ABSTRACT

Structural fatigue of NiTi shape memory alloys is a key issue that should be solved in order to promote their engineering applications and utilize their unique shape memory effect and super-elasticity more sufficiently. In this paper, the latest progresses made in experimental and theoretical analyses for the structural fatigue features of NiTi shape memory alloys are reviewed. First, macroscopic experimental observations to the pure mechanical and thermo-mechanical fatigue features of the alloys are summarized; then the state-of-arts in the mechanism analysis of fatigue rupture are addressed; further, advances in the construction of fatigue failure models are provided; finally, summary and future topics are outlined.

Contents

1. Introduction

Since NiTi shape memory alloys (SMAs) present unique super-elasticity and shape memory effect and good biological compatibility and wear resistance, they have been widely used in the areas of aeronautic, civil, microelectronic, and biomedical engineering as reviewed recently in Refs. [1–3] (2014, 2010). Such components and devices are often subjected to a cyclic loading, and then the cyclic deformation and fatigue failure of NiTi SMAs are key issues in assessing the fatigue life and reliability of them. For the thermo-mechanical cyclic deformation of NiTi SMAs, many experimental observations and constitutive models were performed and constructed in the last decades, respectively, as reviewed by Lagoudas [4] (2008) and Kang [5,6] (2013, 2011) and more recently in Refs. [7–14] (2008, 2009, 2011, 2012, 2013, 2014, 2015). The state-of-arts of thermo-mechanical cyclic deformation of NiTi SMAs can be referred to the reviewed papers mentioned above and the referred literature there.

As summarized by Eggeler et al. [15] (2004), the fatigue of NiTi SMAs consists of two groups, i.e., structural fatigue and functional fatigue. The structural fatigue represents the physical failure (or fracture) of NiTi SMAs with a life-time of cyclic loading; while the functional fatigue addresses the degradation of super-elasticity and shape memory effect occurred during the cyclic deformation of NiTi SMAs. When the super-elasticity and shape memory effect of

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* Corresponding author.
E-mail address: guozhengkang@126.com (G. Kang).

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NiTi SMAs are degraded to a certain degree, the SMA components and devices lose their functional capability, i.e., the functional fatigue occurs. For examples, Wagner et al. [16] (2008) set a critical residual strain as a criterion representing the functional fatigue of super-elastic NiTi SMAs occurred during the cyclic loading; Predki et al. [17] (2006), Dunand-Châtellet and Moumni [18] (2012), and Song et al. [19] (2014) took a critical dissipation energy per cycle (e.g., decreased to 4% of the value presented in the first cycle) as a criterion of functional fatigue. Since after certain cycles a stabilized state is often reached to for the degradation of super-elasticity and shape memory effect, and no fracture occurs when the functional fatigue of NiTi SMAs takes place, studies on the functional fatigue are often combined with that on the cyclic deformation of NiTi SMAs, which can be referred to the reviews done by Eggeler et al. [15] (2004) and Mahtabi et al. [20] (2015).

Therefore, in this paper, only the structural fatigue of NiTi SMAs (where, fatigue rupture is caused by a constant or cyclic mechanical loading) is addressed. Firstly, the macroscopic and microscopic observations to the structural fatigue of NiTi SMAs are summarized; secondly, advances in the mechanism of fatigue rupture and the fatigue failure models are discussed; finally, summary and future topics are outlined for the structural fatigue of NiTi SMAs.

2. Experimental observations

Since the cyclic martensite transformation of NiTi SMAs can be caused by cyclic stress (or strain) and temperature, respectively, the macroscopic experimental observations to the structural fatigue of NiTi SMAs are summarized as two parts, i.e., one for the mechanical fatigue caused by cyclic stress (or strain) and the other for the thermo-mechanical fatigue caused by cyclic temperature with a constant stress. After then, the microscopic observations to the fracture surfaces of NiTi SMAs (by scanning electron microscope (SEM)) and the formation and evolution of dislocations (by transmission electron microscope (TEM)) are addressed in order to analyze the micro-mechanism of fatigue rupture.

2.1. Macroscopic experimental observations

2.1.1. Mechanical fatigue

For the NiTi SMAs, so many researches have been done to investigate their fatigue failure caused by the stress- or strain-controlled cyclic loading, which is denoted as the mechanical fatigue of NiTi SMAs here. Since the NiTi SMAs were first used mainly in a form of wire, the early studies on the mechanical fatigue of NiTi SMAs were focused on the bending and rotating–bending fatigue failures of the NiTi SMA wires under the strain- or displacement-controlled cyclic loading conditions. The representative researches are those done by Mikuriya et al. [21] (1999), Tobushi et al. [22] (2000), Sawaguchi et al. [23] (2003), Wagner et al. [24] (2004), Matsui et al. [25] (2004), Yan et al. [26] (2007), Cheung et al. [27] (2008), Figueiredo et al. [28] (2009), Bernard et al. [29] (2011), Chan et al. [30] (2013), and Kollerov et al. [31] (2013), and so on. For examples, Tobushi et al. [22] (2000) studied the low-cycle fatigue of the NiTi SMA wires by performing the rotating–bending fatigue tests in air, water and silicon oil, respectively, and discussed the effects of fatigue-test temperature, shape memory processing temperature and ambient media on the fatigue life. Finally, they concluded that in the region of low-cycle fatigue, the corrosion caused by the water and the processing temperature hardly influence the fatigue life of the NiTi SMA wires as shown in Fig. 1, and the fatigue life obtained at an elevated temperature in air is the same as that at the identical temperature in water. Sawaguchi et al. [23] (2003) also performed the rotating–bending fatigue tests of NiTi SMA wires with different bending radii and wire diameters (i.e., 1.0 mm, 1.2 mm, and 1.4 mm), as well as at different rotational speeds, and then demonstrated that fatigue lives were related to the maximum tensile and compressive strain amplitudes (ε_a) in the surface of NiTi SMA wires. The results show that the obtained ε_a–N_f curves can be subdivided into three phases as shown in Fig. 2. In phase 1 (for $\varepsilon_a >$ 1%), fatigue rupture occurs early (i.e., with a low fatigue life N_f) and the fatigue failure characteristics depend strongly on the applied strain amplitude ε_a and rotational speed; in phase 2 (for 0.75% $< \varepsilon_a <$ 1%), fatigue lives remarkably increase and are characterized by a significant statistical scatter; in phase 3 (for $\varepsilon_a <$ 0.75%), no fatigue rupture occurs up to 10^6 cycles. More recently, Figueiredo et al. [28] (2009) analyzed the low-cycle fatigue of super-elastic NiTi SMA wires by the strain-controlled rotating–bending tests with the applied strain amplitudes from 0.6% to 12%, and found a "Z-shaped" ε_a–N_f curve as shown in Fig. 3 by the triangles, which demonstrated an increasing fatigue life with the increase in the applied strain amplitude within a specific range of strain amplitudes.

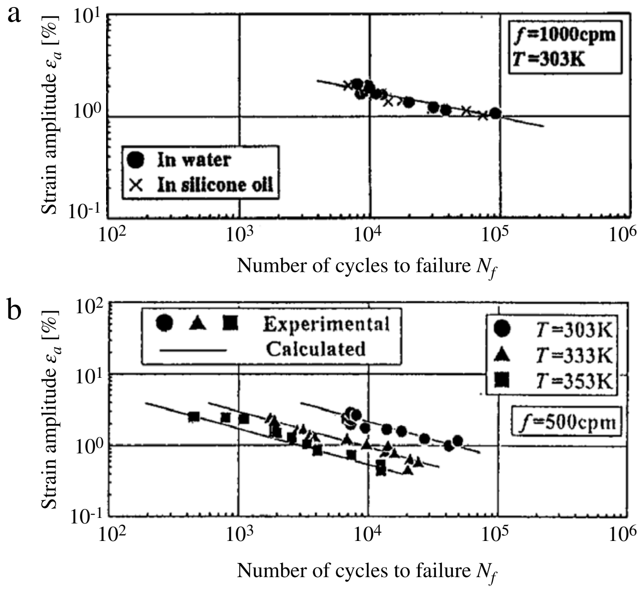


Fig. 1. Strain amplitude vs. fatigue life: (a) in water and in silicone oil; (b) at various test temperatures in water.
Source: Redrawn from Tobushi et al. [22] (2000).

Although Duerig et al. [32] (1999) showed that the experimental data of rotating–bending fatigue had a good predictive potential for other types of fatigue loading, at present, the fatigue tests of NiTi SMAs have been extended into the uniaxial and pure shear strain- (stress-) controlled cyclic loading conditions, where the solid-bar, tubular and wire specimens with relatively large size are employed, respectively, as done by Melton and Mercier [33] (1979), Moumni et al. [34] (2005), Predki et al. [17] (2006), Dunand-Châtellet and Moumni [18] (2012), Kang et al. [35] (2012), Maletta et al. [36–38] (2012, 2014), Robertson et al. [39] (2012), and Mammano and Dragoni [40] (2014), and so on. In these researches, the effects of strain (or stress) amplitude, mean strain (or stress), strain (or stress) rate and test temperature on the fatigue life of NiTi SMAs were discussed. For examples, Moumni et al. [34] (2005) investigated the uniaxial stress-controlled tensile–compressive fatigue features of super-elastic NiTi SMA at 50°C by using the dog-bone shaped specimens, and discussed the effects of stress amplitude and mean stress (i.e., with different stress ratios R) on the fatigue life, as shown in Fig. 4, which illustrates that a compressive mean stress has a beneficial effect on the fatigue behavior of the alloy because it tends to close the microfissures, whereas a traction mean stress gives the inverse effect. Kang et al. [35] (2012) also performed the stress-controlled tensile–compressive fatigue tests of super-elastic NiTi SMA bars to address the evolution of transformation ratchetting (defined by Kang

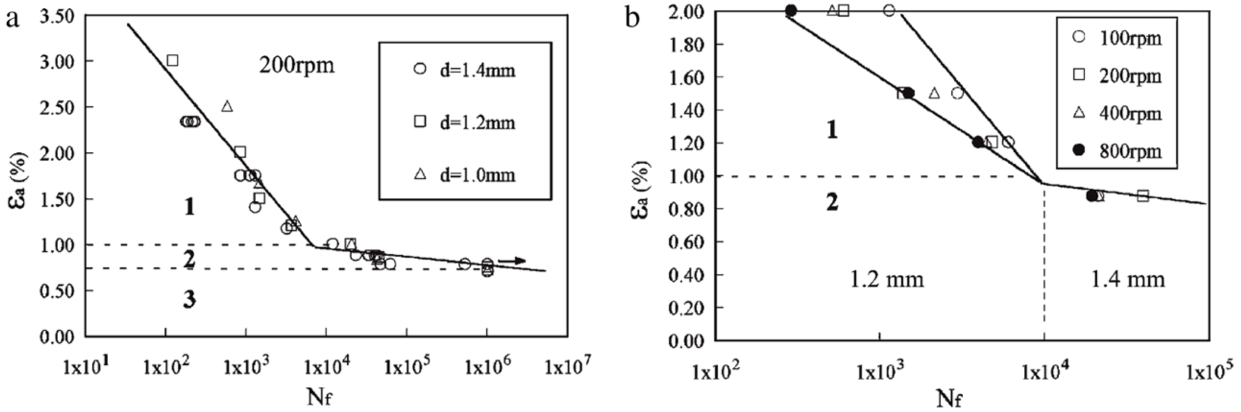


Fig. 2. Strain amplitude vs. fatigue life: (a) for three different wire diameters at a rotational speed of 200 rpm; (b) at different rotational speeds from 100 rpm to 800 rpm.
Source: Redrawn from Sawaguchi et al. [23] (2003).

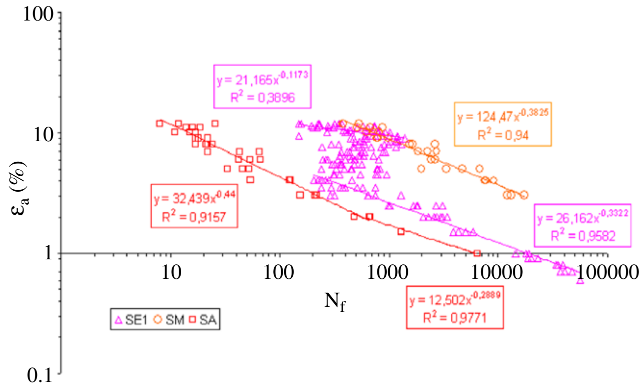


Fig. 3. Strain amplitude vs. fatigue life for three kinds of NiTi wire (the data denoted by triangles from super-elastic NiTi wires).
Source: Redrawn from Figueiredo et al. [28] (2009).

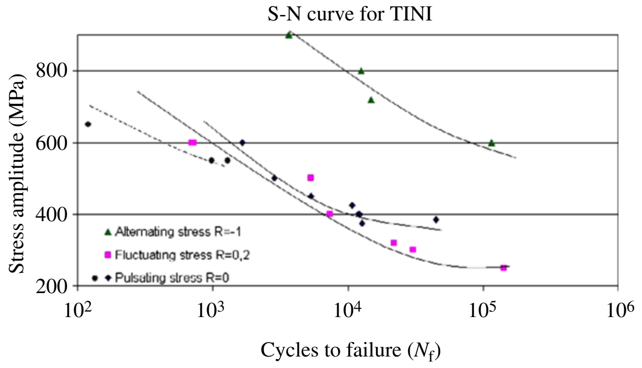


Fig. 4. Stress amplitude vs. fatigue life.
Source: Redrawn from Moumni et al. [34] (2005).

et al. [41] (2009)) during the whole fatigue life (as shown in Fig. 5) and its effect on the fatigue life. The results show that the occurrence of transformation ratchetting greatly reduces the fatigue life of super-elastic NiTi SMAs, which should be considered in the construction of fatigue failure models. Maletta et al. [36,37] (2012, 2014) conducted the strain-controlled uniaxial tensile-unloading fatigue tests of super-elastic NiTi SMA plates with different maximum axial strains ranged from 0.75% to 4.5%, and then discussed the evolution of so-called strain ratchetting and the relationship between the applied maximum strain and fatigue life, as shown in Fig. 6.

As mentioned above, the wire, plate, solid-bar, and tube specimens of NiTi SMAs with relatively large sizes are used in the fatigue tests. However, the fatigue failure of the NiTi specimens with very small geometric sizes, such as the micro-tubes used in endovascular stents, is not investigated there. Referring to the results reported by Robertson et al. [39] (2012), since the wall thickness of the NiTi micro-tubes (less than 400 μm) is smaller than the physical length of the macro-crack (1 mm) in a NiTi SMA, the macro-crack propagation does not occur in the fatigue failure of the NiTi SMA micro-tubes, which is quite different from that discussed above. Then, a non-conservative prediction will be obtained if the fatigue life of NiTi SMA micro-tubes is evaluated directly from the data obtained by the specimens with large sizes. Thus, it is necessary to investigate the fatigue failure of the NiTi microtubes and then provide more reliable fatigue data for the design of medical NiTi devices. To this end, Song et al. [42] (2015) investigated the uniaxial fatigue failure features of super-elastic NiTi SMA micro-tubes by performing a series of stress-controlled tensile–compressive fatigue tests at 37°C. They concluded that the degree of martensite transformation occurred during the cyclic deformation greatly influences the uniaxial fatigue failure of super-elastic NiTi SMA micro-tubes, and the fatigue life with more complete martensite transformation is shorter than that with incomplete one. It means that a good balance between fully utilizing the martensite transformation and improving the fatigue life of super-elastic NiTi SMAs should be achieved in the design of super-elastic NiTi SMA devices.

Besides the fatigue analysis under the cyclic tension–compression and rotating–bending tests, the torsional fatigue of NiTi SMA tubes was also investigated by Runciman et al. [43] (2011) and the effects of mean shear strain and shear strain amplitude on the torsional fatigue life was discussed and compared with the data from cyclic bending and tension tests, as shown in Fig. 7. As commented by Robertson et al. [39] (2012) and Runciman et al. [43] (2011), a complicated stress condition, e.g., multiaxial one is often encountered in the service process of implanted stents at the human's joints. Thus, it is extremely necessary to perform multiaxial tests to observe the multiaxial cyclic deformation and fatigue failure of super-elastic NiTi SMAs. Based on the studies on the multiaxial cyclic deformation of super-elastic NiTi SMAs done by Wang et al. [44] (2010) and Song et al. [45] (2014), Song et al. [46] (2015) conducted a detailed experimental observation to the stress-controlled multiaxial fatigue of the NiTi SMA micro-tubes by employing five kinds of multiaxial loading paths, i.e., square, hourglass-typed, butterfly-typed, rhombic, and octagonal ones shown in Fig. 8. It is concluded from Song et al. [46] (2015) that the multiaxial fatigue lives of the NiTi SMA micro-tubes are much shorter than the corresponding uniaxial ones due to the quicker evolution of multiaxial transformation ratchetting, and depend greatly on the multiaxial loading paths and the applied stress

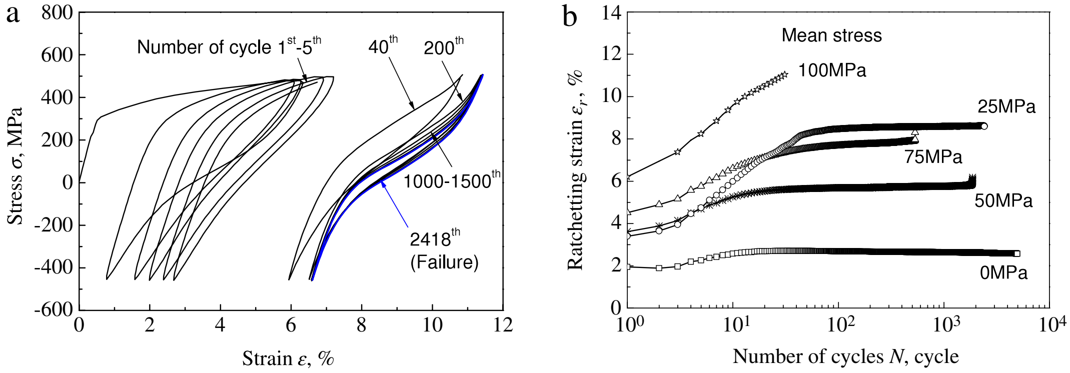


Fig. 5. Whole-life transformation ratchetting of super-elastic NiTi alloy in uniaxial tensile–compressive fatigue tests with different mean stresses and constant stress amplitude (500 MPa): (a) cyclic stress–strain curves, mean stress is 25 MPa; (b) curves of ratchetting strain ε_r vs. number of cycles N.
Source: Redrawn from Kang et al. [35] (2012).

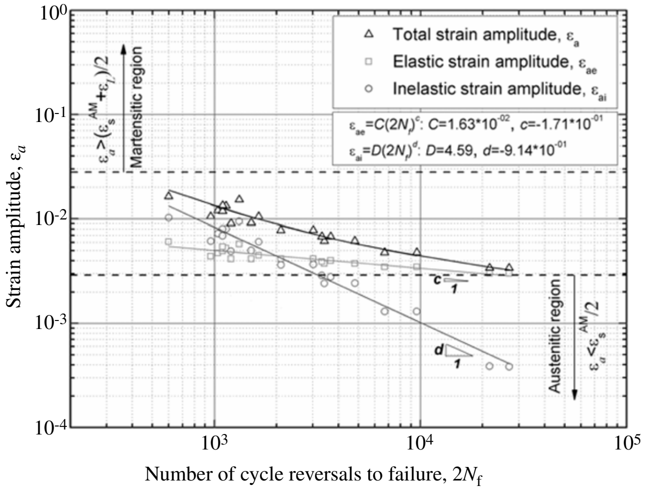


Fig. 6. Strain amplitude vs. fatigue life.
Source: Redrawn from Maletta et al. [37] (2014).

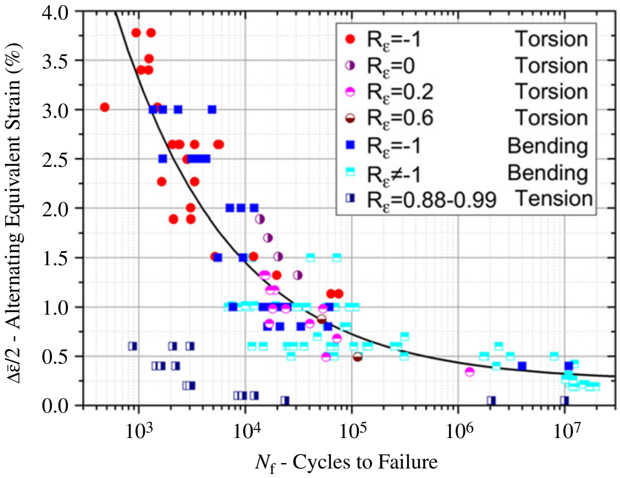


Fig. 7. Strain amplitude vs. fatigue life for cyclic torsion, bending and tension.
Source: Redrawn from Runciman et al. [43] (2011).

levels simultaneously; in general, the fatigue lives with the loading paths containing certain peak/valley stress holds are shorter than that with the paths containing no peak/valley holds; the larger the transformation ratchetting and the saturated dissipation energy, the shorter the fatigue lives are, as shown in Fig. 9.

2.1.2. *Thermo-mechanical fatigue*

Since the actuators made from NiTi SMAs often undergo a thermally activated cyclic transformation and are employed to overcome a bias force, which can be constant or variable during the operation, the degradation of shape memory effect (i.e., functional fatigue denoted by Barrera et al. [47] (2014)) and the structural fatigue rupture are also the main failure modes of NiTi SMAs in thermal cycling. Thus, it is necessary to understand the thermo-mechanical fatigue behavior of NiTi SMAs under different applied stress conditions. Bigeon and Morin [48] (1996) first conducted an experimental observation to the thermo-mechanical fatigue failure of NiTi SMA wires experienced cyclic temperature induced martensite transformation. Recently, based on the construction of thermo-mechanical fatigue experimental set-up (shown in Fig. 10(a)), Lagoudas and his co-workers [49–51] (2000, 2009), Pappas et al. [52] (2007), Demers et al. [53] (2009), and Karhu and Lindroos [54,55] (2010, 2012) performed some thermo-mechanical fatigue tests of NiTi SMA wires and plates subjected a thermal cycling with a constant axial stress or strain, and then discussed the effects of constant stress (or strain), degree of transformation during the thermal cycling, applied temperature amplitude and heat-treatment on the cyclically accumulated residual strain and fatigue life of NiTi SMAs. The results show that during the thermal cycling with a constant axial stress, the peak and valley strains gradually increase with the increasing number of thermal cycles, and become more remarkable with the increase in constant axial stress; while the start temperature of martensite transformation decreases with the increasing number of cycles, which implies that the driving force of martensite transformation will increase during the thermal cycling and the martensite transformation becomes more and more difficult. Meanwhile, the thermo-mechanical fatigue life of NiTi SMAs strongly depends on the applied constant axial stress and temperature amplitude, and monotonically decreases with the increase in axial stress as shown in Fig. 10(b) and the temperature amplitude (which determines whether a complete or partial transformation occurs during the thermal cycling).

2.2. *Microscopic mechanism analysis*

Moumni et al. [34] (2005) and Kang et al. [35] (2012) found that after the cyclic stress–strain responses are stabilized, no apparent variation could be observed for the stress–strain hysteresis loops till the rupture of the specimens suddenly took place, as shown in Fig. 5. It is different from that of ordinary ductile metals, where the hysteresis loops and unloading elastic modulus change obviously before the low-cycle fatigue rupture occurs. Thus, it is worth investigating the microscopic mechanism of fatigue failure of NiTi SMAs in detail.

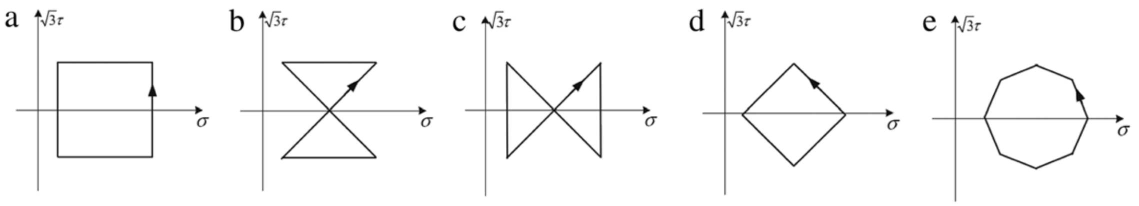


Fig. 8. Schematic diagrams of multiaxial loading paths: (a) square; (b) hourglass-typed; (c) butterfly-typed; (d) rhombus; (e) octagon.
Source: From Song et al. [46] (2015).

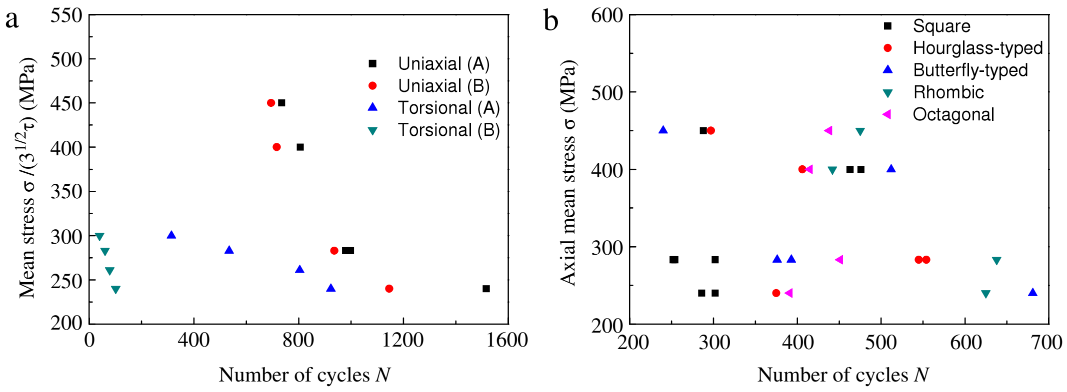


Fig. 9. Fatigue lives obtained in the uniaxial, pure torsional and multiaxial tests with the same equivalent stress amplitude of 283 MPa: (a) for uniaxial and torsional ones; (b) for multiaxial ones.
Source: Redrawn from Song et al. [46] (2015).

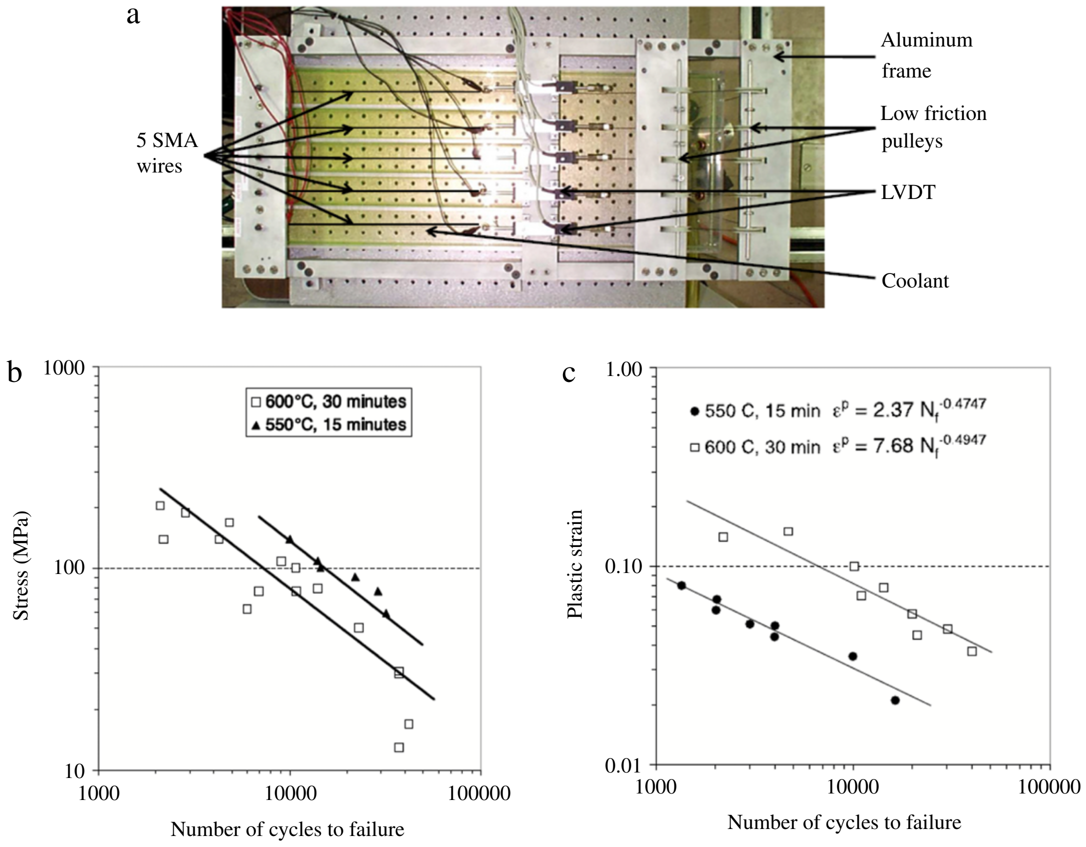


Fig. 10. Thermo-mechanical fatigue of NiTi SMAs: (a) experimental set-up, top view; (b) constant axial stress vs. fatigue life; (c) plastic strain vs. fatigue life for the case of complete transformation.
Source: From Lagoudas et al. [50] (2009).

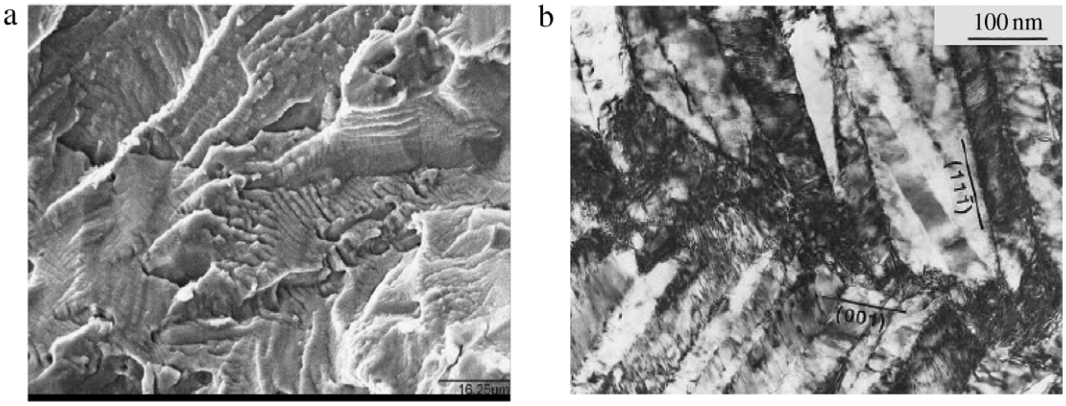


Fig. 11. Microscopic observations to the micro-morphology of NiTi SMAs: (a) SEM fractograph (from Wang et al. [59] (2014)); (b) TEM micrograph for martensite and dislocation (from Liu et al. [65] (1998)).

To this aim, many microscopic observations were conducted to analyze the fatigue rupture mechanism of NiTi SMAs. Kasuga et al. [56] (2005), Figueiredo et al. [28] (2009), Morgan et al. [57] (2004), Predki et al. [17] (2006), McKelvey and Ritchie [58] (1999), Wang et al. [59] (2014), Gall et al. [60] (2008), Robertson et al. [61] (2005), Robertson and Ritchie [62] (2007), Cocco et al. [63] (2014), and Maletta et al. [37] (2014) observed the morphology of fracture surfaces by SEM after the fatigue rupture of NiTi SMA specimens. It is seen that the fatigue fracture surfaces are almost identical for the super-elastic austenite and shape memory thermal martensite NiTi alloys, from which obvious fatigue striations, secondary cracks and river-like cleavage patterns are simultaneously observed as shown in Fig. 11(a), besides some large and shallow dimples. From the SEM observations to the fracture surfaces of NiTi SMAs, it is concluded that the fatigue rupture of NiTi SMAs consists of two stages, i.e., crack initiation and crack propagation ones, while the stable crack growth resulting from fatigue loads and the ductile overload fractures denoted by large and shallow dimples co-exist during the fatigue rupture.

Charkaluk et al. [66,67] (2000, 2002), Dunand-Châtellet and Moumni [18] (2012) and Skelton et al. [68–70] (1991, 1993, 1998) demonstrated that for most of metals and alloys including the NiTi SMAs, the moment when the stable stress–strain responses were reached to could be taken as the transition point from the dislocation-dominated micro-crack initiation stage to the micro-crack propagation one. It means that for the fatigue failure of NiTi SMAs, the number of cycles at which the transition from the micro-crack initiation stage to the micro-crack propagation one occurs can be obtained directly from the macroscopic stress–strain responses. However, the transition from the micro-crack propagation to macroscopic crack propagation cannot be determined directly from the macroscopic stress–strain responses, and then the crack initiation life and crack propagation one cannot be distinguished from the total fatigue life too. It makes the theoretical prediction of fatigue life very difficult for the NiTi SMAs. On the other hand, Stankiewicz et al. [71] (2007) found that during the cyclic deformation of NiTi SMAs, the stress induced martensite variants might accommodate themselves to the overall deformation of the alloys, which could reduce the stress-concentration caused by the unmatched inelastic deformation between the austenite and martensite phases, and then delay the crack initiation. Furthermore, Wagner et al. [72] (2010) and Olsen et al. [73] (2011) addressed that the stress induced martensite phases at the crack tip and two ends of crack wake could be taken as the inclusions in the austenite matrix, which might retard the crack propagation; Brinson et al. [74] (2004) concluded that a higher stress intensity at the crack-tip would restrain the reverse transformation from induced martensite to austenite phase, and then pin the induced martensite phase. Thus, two above-mentioned features make the NiTi SMAs possess the slowest crack propagation rate among all the alloys, as commented by McKelvey and Ritchie [75] (2001). It means that the crack propagation life of NiTi SMAs plays an important role in the total fatigue life, which makes the fatigue life of NiTi SMAs remarkably depend on the geometric size of specimens. Thus, as demonstrated by Robertson et al. [39] (2012), the fatigue life obtained from the specimens with relatively large geometric size cannot be directly used to assess the fatigue behavior of NiTi SMAs with small size, such as the NiTi SMA micro-tubes used in the endovascular stents.

To analyze the initiation mechanism of micro-cracks during the fatigue failure of NiTi SMAs, the formation and growth of microscopic defects such as dislocations were observed by TEM, as done by Hamilton et al. [76] (2004), Norfleet et al. [77] (2009), Pelton et al. [78,79] (2011, 2012), Delville et al. [80,64] (2010, 2011), Liu et al. [65] (1998), and Xie et al. [81] (1998). The obtained results show that dislocations are formed and aggregated mainly near the interfaces between austenite and induced martensite phases and the interfaces between the martensite variants with different crystallographic orientations as shown in Fig. 11(b), and around the precipitates and inclusions. However, the dislocations can be observed only in the NiTi SMAs with large grain size (e.g., larger than 300 µm), and the dislocation aggregation cannot be formed in a large scale in the NiTi SMAs with small grain size due to the retardness of grain boundary to the dislocation movement [82,83] (2013, 2014).

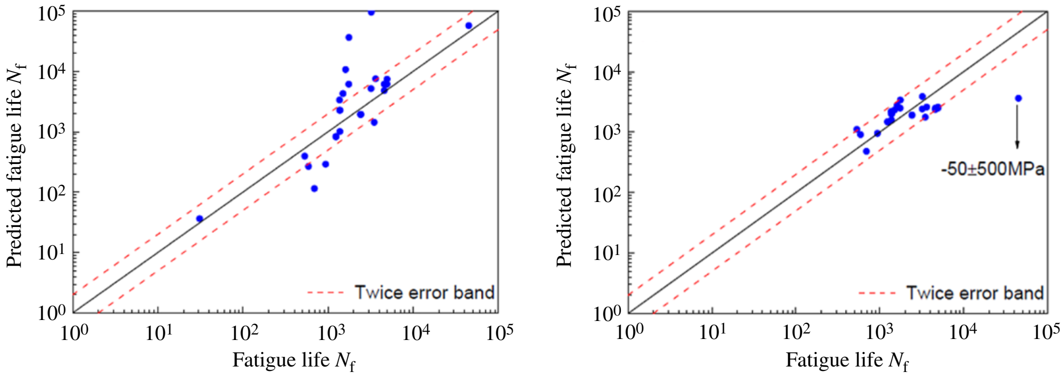
2.3. Fatigue failure model

Based on the experimental observations to the fatigue failure of NiTi SMAs, some fatigue failure models have been established to predict the fatigue life, as done by Tobushi et al. [22] (2000), Lagoudas et al. [50] (2009), Runciman et al. [43] (2011), Maletta et al. [36,37] (2012, 2014), Moumni et al. [34] (2005), Kan et al. [84] (2012), and Song et al. [85] (2015).

From the low-cycle fatigue data of NiTi SMA wires obtained in the rotating–bending tests in air, water and silicon oil, Tobushi et al. [22] (2000) calibrated them by using an equation similar to the Manson–Coffin relationship for normal metals in low-cycle fatigue, i.e., the equation listed as follows:

$$\varepsilon_a \cdot N_f^{\beta} = \alpha, \tag{1}$$

where ε_a is the strain amplitude, N_f is the number of cycles to fatigue failure, and α, β are the parameters representing ε_a with $N_f = 1$ and the slope of the lg ε_a–lg N_f curve, respectively. To



(a) Moumni's model.

(b) Kan's model.

Fig. 12. Comparison of experimental fatigue lives and predicted ones by two energy-based models.
Source: From Kan et al. [84] (2012).

consider the dependence of fatigue life on the test temperature, the parameter α is further set as:

$$\alpha = 8.56 \times 10^{-0.012(T-M_s)}, \tag{2}$$

where T is the test temperature and M_s is the start temperature of martensite transformation. Setting $\beta = 0.5$, the calculated results are shown in Fig. 1(b), from which a good consistence is observed.

As commented by Maletta et al. [36,37] (2012, 2014), the fatigue failure model such as Eq. (1) cannot take into account the unique martensite transformation features of super-elastic SMAs. To overcome such shortcomings, Maletta et al. [36,37] (2012, 2014) proposed a modified Manson–Coffin model to predict the fatigue life of NiTi SMAs under the stress-controlled cyclic loading conditions, which takes into account the different strain mechanisms involved during the stress-induced transformation in super-elastic NiTi SMAs, and is listed as follows:

$$\varepsilon_a = \varepsilon_{ae} + \varepsilon_{ai} = C(2N_f)^c + D(2N_f)^d, \tag{3}$$

where ε_a, ε_{ae} and ε_{ai} are the total, elastic and inelastic strain amplitudes, respectively. The inelastic strain amplitude, ε_{ai}, can be regarded as the super-elastic strain, i.e., it can be attributed to the reversible stress-induced phase transformation, and can be obtained from the measured total strain amplitude, ε_a, and the elastic strain amplitude, ε_{ae}, calculated from a specific procedure proposed by Maletta et al. [36,37] (2012, 2014). The coefficients C and D and the exponents c and d can be obtained from the experimental data. The predictions of the proposed model can be referred to Fig. 6.

For the thermo-mechanical fatigue failure of NiTiCu SMAs, Lagoudas et al. [50] (2009) proposed another kind of modified Manson–Coffin relationship between the number of cycles to failure (N_f) and the accumulated plastic strain (ε^p) as follows:

$$\varepsilon^p = \alpha \cdot N_f^{\beta}. \tag{4}$$

The parameters α and β are called the fatigue ductility coefficient and the fatigue ductility exponent, respectively. These material parameters are derived by fitting the fatigue test data of NiTiCu SMAs as shown in Fig. 10(c). Furthermore, Runciman et al. [43] (2011) extended the modified Manson–Coffin model to predict the torsional fatigue life of NiTi SMAs by using the equivalent strain amplitude instead of the accumulated plastic strain in Eq. (4), as shown in Fig. 7. It should be noted that the basic variables used in the modified Manson–Coffin models are the strain amplitude and equivalent strain amplitude, which are taken from the stable cyclic stress–strain hysteresis loops of NiTi SMAs.

On the other hand, some fatigue failure models are established by taking the dissipation energy at the stabilized cycle as the basic variable. Using the saturated dissipation energy, Moumni et al. [34] (2005) proposed an empirical energy-based fatigue failure model (Eq. (5)) to predict the fatigue life of super-elastic NiTi SMAs. After then, Kan et al. [84] (2012) modified the Moumni's model by replacing the power-law equation by a logarithmic one (i.e., Eq. (6)), and confirmed the improvement of prediction capability in the modified model by comparing the predicted lives with the experimental ones from Kang et al. [35] (2012), as shown in Fig. 12.

$$D = \alpha \cdot N_f^{\beta}, \tag{5}$$

where D is the dissipated energy at the stabilized cycle, N_f is the number of cycles at failure, and α and β are material parameters.

$$N_f = \alpha \ln\left(\frac{W_{sat}}{\beta}\right), \tag{6}$$

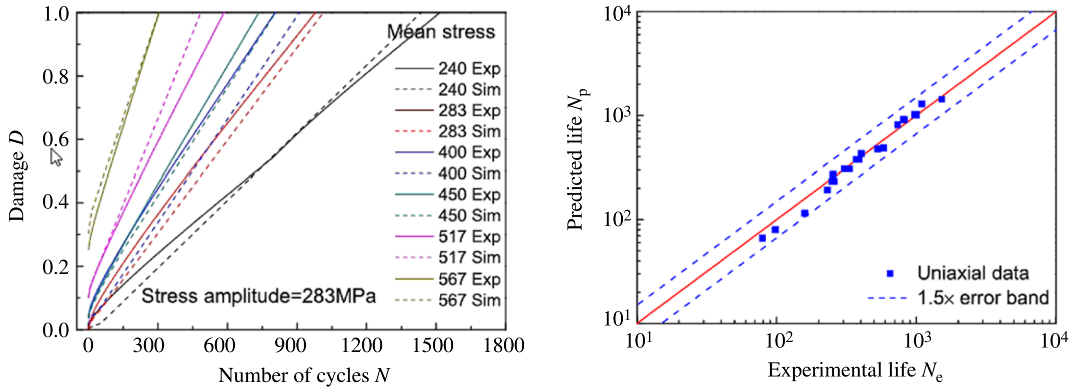
where W_{sat} is the dissipated energy at the stabilized cycle and N_f is the number of cycles at failure, and α and β are material parameters.

It should be noted that the fatigue failure models discussed above were established directly from the experimental data of fatigue life, no physical nature of fatigue rupture was involved there, and the different contributions of crack initiation and propagation lives to the total fatigue life were not touched yet. Recently, based on the experimental investigations to the uniaxial whole-life transformation ratchetting and fatigue failure of NiTi SMA micro-tubes, Song et al. [85] (2015) proposed a new damage-based fatigue failure model by dividing the total damage sources into three parts, i.e., micro-crack initiation, micro-crack propagation and martensite transformation induced damage. Song et al. [85] (2015) defined the damage variable as the ratio of the accumulated dissipation energy after a prescribed number of cycles N to that obtained at the failure life N_f, i.e.,

$$D = \frac{\sum_{i=1}^{N} W_i}{\sum_{i=1}^{N_f} W_i}. \tag{7}$$

Such definition of damage variable takes the effect of cyclic deformation on the fatigue life of the alloys before the stabilized cycle is reached to. Based on the experimentally obtained evolution curves of damage variable D vs. the number of cycles as shown in Fig. 13(a), the damage-based fatigue failure model is proposed as

$$N_f = N_{sat} + 1 + \frac{1 - \left[g_1 + g_3 \int_0^{N_{sat}} W_N \mathrm{d}N\right]}{g_2 + W_{sat}\, g_3}, \tag{8}$$



(a) Damage evolution.

(b) Fatigue life.

Fig. 13. Predicted results of damage-based fatigue failure model.
Source: From Song et al. [85] (2015).

where N_{sat} is the number of cycles at which the stabilized cycle is reached to, W_{sat} is the dissipation energy at the stabilized cycle, and W_N is the dissipation energy at the N-th cycle. g_1, g_2, and g_3 are constants which can be obtained from the experimental data. It is seen from Fig. 13(b) that all the points are located with the 1.5-times error-bands, and the model predicts the uniaxial stress-controlled fatigue life of super-elastic NiTi SMA micro-tubes very well.

3. Summary and future topics

The state-of-arts of macroscopic experimental observations to the fatigue failure of the NiTi SMAs can be summarized as follows: (1) the observations are mainly focused on the mechanical fatigue of NiTi SMAs, where the cyclic transformation is induced by stress- or strain-controlled cyclic loading, but the thermo-mechanical fatigue failures caused by the thermal cycling are investigated insufficiently, only the one undergoing the thermal cycling with a constant axial stress or strain is conducted as reviewed above; (2) most fatigue tests are performed under the cyclic uniaxial, bending and torsional loading conditions, much effort should be paid to the non-proportionally multiaxial fatigue of NiTi SMAs; (3) existing researches only address the fatigue of NiTi SMAs with constant stress or strain amplitude and at constant temperature and loading rate, the studies with varied stress or strain amplitude and at varied temperature and loading rate are insufficient; (4) although some existing researches have discussed the effect of the extent of martensite transformation on the thermo-mechanical fatigue of NiTi SMAs, more systematic experimental observations are necessary to reveal the interaction of fatigue damage and martensite transformation in NiTi SMAs; (5) most of fatigue tests are conducted under the strain-controlled cyclic loading conditions, the interaction of fatigue damage and transformation ratchetting occurred in the NiTi SMAs under the stress-controlled cyclic loading conditions has not been investigated thoroughly.

The micro-mechanism of fatigue failure of NiTi SMAs has been studied tentatively by some researchers; however, much effort should be paid for this topic in the future due to the complexity caused by the interaction of fatigue damage and martensite transformation. The future studies should at least include the following issues:

(1) The fatigue failure of NiTi SMAs with small geometric size such as the micro-tubes used in the endovascular stents. The existing results for the NiTi SMAs with relatively large geometric sizes demonstrated the important role of crack propagation life in the total fatigue life; however, the physical size of macro-cracks observed there is larger than the thickness of micro-tubes. So, the process of fatigue rupture occurred in the NiTi SMAs with small size should be different from that with large size and should be investigated further.

(2) The mechanism of multiaxial fatigue failure. Since the evolutions of microstructure and fatigue damage during the fatigue loading have not been observed in situ, the effect of multiaxial loading path on the crack initiation and propagation is not reasonably investigated. Much more detailed microscopic observations by SEM and TEM are necessary in the future to summarize the micro-mechanism of mechanical and thermo-mechanical fatigue of NiTi SMAs.

For the fatigue failure models of NiTi SMAs, most of them belong to phenomenological and semi-empirical ones, which do not consider sufficient physical natures of fatigue damage and failure, especially for the multiaxial one. Although some in-situ measures can be used to observe microscopically and straightforwardly the microstructure evolution during the cyclic deformation of ordinary metals, such observations are very difficult for the NiTi SMAs due to their unique stress (or strain) and temperature induced martensite transformation. Therefore, to reveal the micro-mechanisms of fatigue damage and construct the mechanism-based failure models, some numerical simulation methods in the microscopic scale, such as molecular dynamic simulation (Kastner et al. [86] (2011), Zhang et al. [87] (2013)), phase-field method (Jin et al. [88] (2001), Zhong and Zhu [89] (2014)), and phase-field-based finite element analysis (Grandi et al. [90] (2012)) should be used in the future studies.

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