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The influence of stress ratio on fatigue lifetime of NiTi shape memory alloy

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Abstract

The influence of stress ratio on fatigue lifetime of pseudoelastic NiTi alloy are studied. The stress-, strain- and energy-based criteria were used for analysis under on low-cycle fatigue. Increasing the stress ratio from 0 to 0.5 significantly reduces the fatigue life of the NiTi alloy when used to describe the stress range, strain range and dissipation energy density and increases when using the Odqvist's parameter. A good agreement between experimental and calculated values of predicted lifetime was obtained. The low–cycle fatigue failure criterion of pseudoelastic NiTi alloy - total elastic strain energy density that takes into account the stress ratio was proposed.

Keywords: pseudoelastic alloy; stress ratio; energy dissipation; strain raing.

1. Introduction

Shape memory alloys (SMA) are functional materials which are characterized by shape memory effect and pseudoelasticity. Due to these properties, they are widely used, particularly, in bioengineering (Morgan 2004;

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Nematollahi et al. 2019) aeronautics (Mohd Jani et al. 2014; Pecora and Dimino 2015), robotics (Zeng et al. 2020) and civil engineering (Isalgue et al. 2006).

Nomenclature

E_A	austenite modulus of elasticity
N_f	number of cycles to failure
W_t	strain energy density
W_d	dissipated energy density
W_e	elastic strain energy density
R	stress ratio
A_f	austenitic finish temperature
σ_S^{AM}	stress-induced martensitic transformation
ΣW_t	total strain energy density
ΣW_d	total dissipated energy density
ΣW_e	total elastic strain energy density
$\Delta\sigma$	stress range
$\Delta\varepsilon$	strain range
χ	Odqvist's parameter

There are known the papers, in which the effect of temperature (Iasnii et al. 2019), and type of loading (Scirè Mammano and Dragoni 2012) on fatigue lifetime of SMA were studied. Many papers deal with the influence of average stress and stress ratio on the fatigue life of pseudoelastic SMA, in particular (Mahtabi, Shamsaei, and Rutherford 2015; Matsui et al. 2006; Predki, Klönne, and Knopik 2006). The review of the influence of stress ratio and on the fatigue fracture criteria of a pseudoelastic SMA is presented, for instance, in papers (Kang and Song 2015; Robertson, Pelton, and Ritchie 2012).

The mechanical fatigue of SMA alloys taking into consideration stress ratio can be described by stress (Predki et al. 2006), strain (Robertson et al. 2012) , and energy fracture criteria. There was studied experimentally the influence of strain ratio on the strain and energy - based criteria of high-cycle fatigue of pseudoelastic $Ni_{50.8}Ti_{49.2}$ SMA (Mahtabi and Shamsaei 2016).

A modified energy-based model is proposed that takes into account the effect of mean stress and strain on the fatigue behaviour of superelastic NiTi. Therefore, the strain energy density W_t, considered as the damage parameter in this study, is the sum of dissipated energy density W_d and tensile elastic energy density W_e

There was proposed another energy-based criterion of fatigue failure – the total strain energy density (Mahtabi, Stone, and Shamsaei 2018), that is in more good agreement with high-cycle fatigue of SMA for various strain ratio and variable amplitude loading

$$\Sigma W_t = \sum_{i=1}^{N_f} (W_t)_i = \sum_{i=1}^{N_f} (W_d + W_e)_i \tag{1}$$

where W_d is the dissipated energy density per cycle; W_e is tensile elastic energy density which can be determined by the formula; N_f – is number of cycles to failure.

$$W_e = \frac{\sigma_{max}^2}{2E_A}, \tag{2}$$

where σ_{max} is the maximum stress; E_A is the austenite modulus of elasticity.

However, most studies of mean stress effect are related to high-cycle fatigue (Mahtabi et al. 2015; Matsui et al. 2006; Predki et al. 2006). The fatigue failure criterion (1) is mainly applicable for high-cycle fatigue (Mahtabi and Shamsaei 2016). Also, it is not clear whether it can be used to evaluate the durability of materials and structural elements made of SMA, taking into account the effect of stress ratio under low-cycle fatigue. There are known only some studies regarding the effect of stress ratio on the fatigue failure criteria under low-cycle fatigue.

Therefore, the aim of this work is to study the effect of stress ratio on the low-cycle fatigue of pseudoelastic NiTi alloy under uniaxial tension.

2. Experimental techniques and material

There was studied the influence of stress ratio on fatigue of pseudoelastic $Ni_{55.8}Ti_{44.2}$ alloy. Cylindrical specimens with a diameter of 4 mm and gage length of 12.5 mm, machined from rod 8 mm in diameter, were tested under uniaxial cyclic loading at temperature 0°C at stress ratio $R = \sigma_{min} / \sigma_{max} = 0$ (here σ_{min} and σ_{max} are the minimum and maximum stresses) on the servo-hydraulic machine STM-10 with automated control and data acquisition system under sinusoidal load with a frequency of 0.5 Hz.

The longitudinal strain was measured by Bi-06-308 extensometer produced by Bangalore Integrated System Solutions (BISS). The maximum error did not exceed 0.1%. The crosshead displacement was determined by inductive Bi-02-313 sensor with an error not more than 0.1%. The tests were carried out in the chamber filled with ice and ice water (Iasnii et al. 2018). This provided the constant temperature of 0°C measured by chromel–alumel thermocouple mounted on the specimen with an error not more than 0.5°C.

Mechanical properties of $Ni_{55.8}Ti_{44.2}$ were determined according to standard (Anon 2014) in ice water at 0°C which is higher than the austenitic finish temperature (A_f = – 38.7°C). Stress-induced martensitic transformation σ_s^{AM} was equal to 447 MPa, ultimate tensile strength σ_{UTS} was equal to 869 MPa (Iasnii et al. 2018).

3. Results and discussion

Typical hysteresis loops of NiTi alloy at 0 °C for different values of maximum stress and different number of load cycles (N = 1, 10, 20 cycles) are shown in Fig. 1.

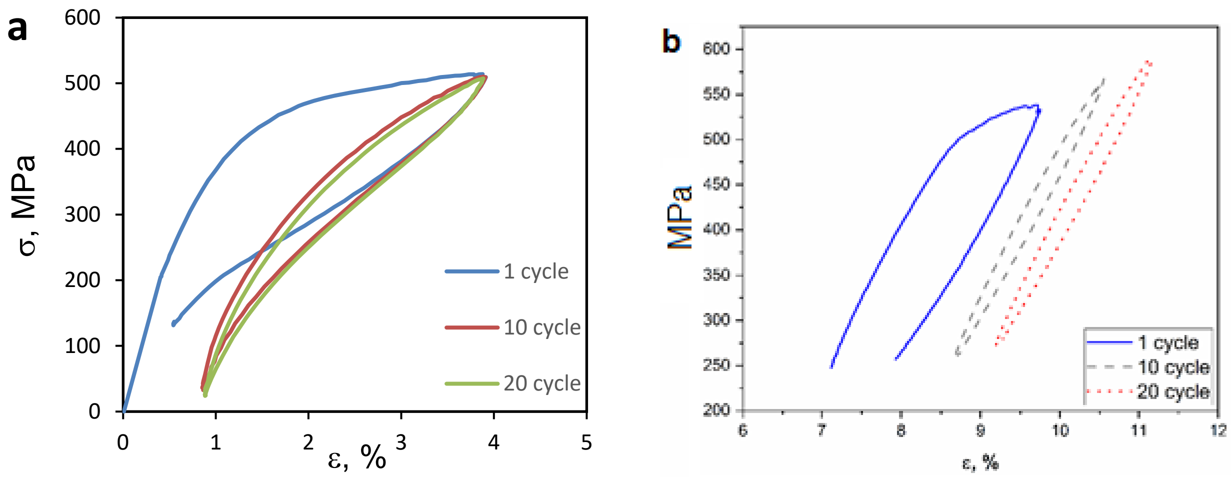

Fig. 1. Typical hysteresis loops for 1, 10 and 20 loading cycles, (a) maximum stress σ_{max}= 530 MPa and stress ratio R = 0; (b) σ_{max}= 596 MPa and stress ratio R = 0.5.

Low-cycle fatigue curves of NiTi alloy at 0 °C and stress ratio $R = 0$ and $R = 0.5$ are presented on Fig. 2. The stress range $\Delta\sigma$ corresponds to stabilization region at the number of half-cycles to failure. With the increase of stress ratio R from 0 to 0.5, the fatigue lifetime of NiTi alloy decreases significantly under the same stress range.

Experimental data under low-cycle fatigue shown on Fig. 2 were plotted according to the failure criterion of the specimen, and could be well-enough described by power law function.

$$\Delta\sigma \cdot N_f^{\beta_\sigma} = \alpha_\sigma . \tag{3}$$

The parameters α_σ and β_σ in equation (3), that were determined by experimental data fit (Fig. 2) are given in Table 1.

Table 1. Parameters of fatigue curves.

R_σ	α_σ	β_σ	R^2	α	β	R^2	A	B	R^2
		Eq. (3)			Eq. (4)			Eq. (6)	
0	952	0.082	0.929	8.710	0.143	0.764	0.0579	2.125	0.946
0.5	776	0.142	0.896	6.167	0.186	0.998	0.0238	9.671	0.999
R_σ	$\alpha_{\Delta W}$	γ	R^2	α_{Wt}	m	R^2	$\alpha_{\Sigma\Delta W}$	p	R^2
		Eq. (7)			Eq. (8)			Eq. (9)	
0	10.13	0.36	0.826	18.1	0.114	0.540	18.1	- 0.8856	0.9855
0.5	0.923	0.22	0.894						

Similar effect of stress ratio on fatigue lifetime was observed while using strain range $\Delta\varepsilon$ at $N = 0.5N_f$ as a failure criterion. The strain range and the number of cycles to failure under low-cycle fatigue are described by the following empirical relationship:

$$\Delta\varepsilon N_f^{\beta} = \alpha , \tag{4}$$

where α and β represent to ε_a in $N_f = 1$ and the slope of the log $\Delta\varepsilon$ - log N_f curve, respectively. The parameters (Table 1) of the equation (4) were determined by the approximation of the experimental data.

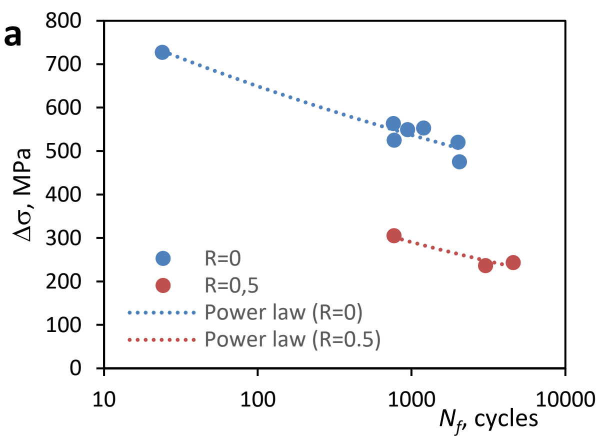

Fig. 2. Dependence of the stress range on the number of loading cycles.

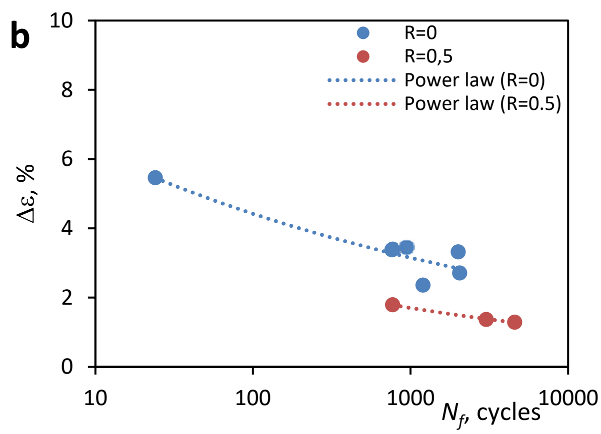

Fig. 3. Dependence of the strain range on the number of loading cycles.

The fatigue lifetime was estimated using the Odqvist's parameter, which characterizes the accumulated plastic strain $\Delta\varepsilon_p$, and under uniaxial cyclic loading is determined by formula

$$\chi = 2N \cdot \Delta\varepsilon_p, \quad (5)$$

where N is the numbers of loading cycles.

According to Fig. 4, the Odqvist's parameter is linearly proportional to the lifetime and is described well by the dependence

$$\chi = AN_f + B. \quad (6)$$

The dependence of the dissipated energy density on the number of cycles to failure at 0 °C and stress ratio $R = 0$ and 0.5 were shown on Fig. 5. The dissipated energy density value corresponds to the stabilization region at the number of half-cycles to failure. The dissipated energy per cycle was calculated as the difference between the areas of loading and unloading lines under stress–strain curves by means of numerical integration.

The dependence of dissipation energy density on the number of cycles to failure in the case of low cycle fatigue is described by the following empirical equation:

$$W_d N_f^{\gamma} = \alpha_{Wd}. \quad (7)$$

The parameters α_{Wd} and γ, that are given in Table 1.

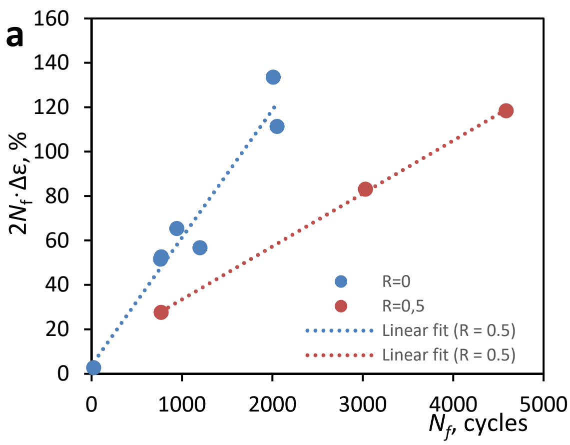

Fig. 4. Dependence of the Odqvist's parameter on the number of loading cycles at $R = 0$ and $R = 0.5$.

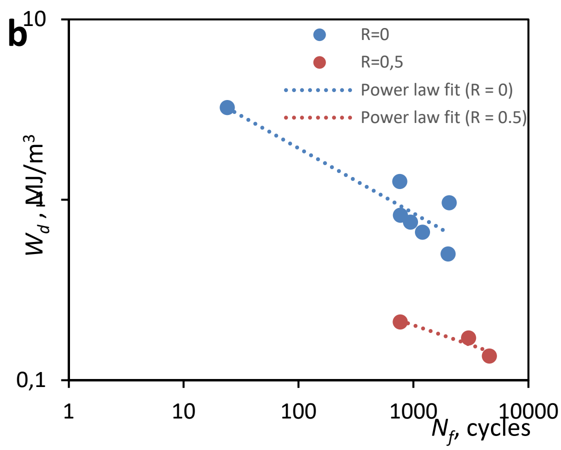

Fig. 5. Dependence of the dissipated energy density on the number of loading cycles at $R = 0$ and $R = 0.5$.

Fig. 6. shows the dependencies of the damage parameter on the number of cycles to failure the stress ratio $R = 0$ and 0.5, that were calculated by formulas (1) and (2), respectively. It should be noted, that the austenite Young's modulus E_A and maximum stress σ_{max} on the stabilization region were employed for calculating elastic strain energy density according to the formula (2).

In general, the presented results could be described by power law for various stress ratios

$$W_t \cdot N_f^m = \alpha_{Wt}. \quad (8)$$

The parameters α_{Wt} and m in equation (8) are presented in Table 1.

The calculated and experimental lifetime dependencies versus the total density energy ΣW_t at 0°C under constant loading (R = 0 and 0.5) are shown on Fig. 7.

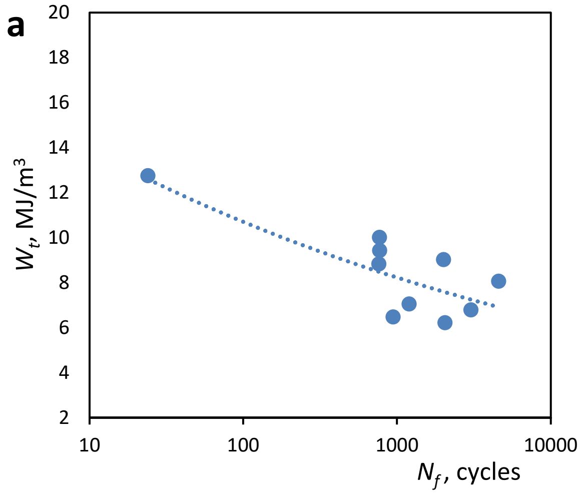

Fig. 6. Dependence of the Odqvist's parameter on the number of loading cycles at R = 0 and R =0.5.

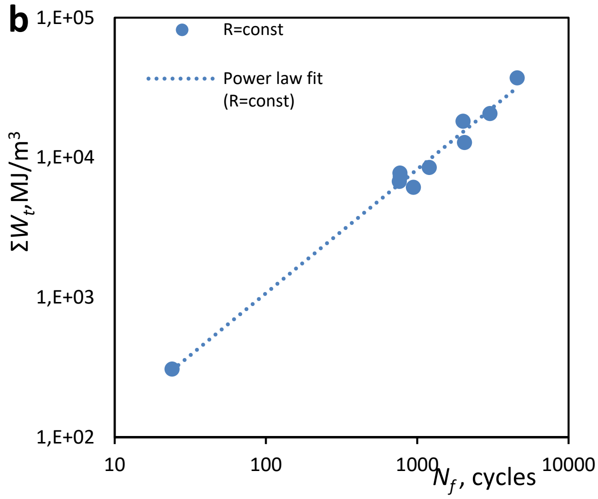

Fig. 7. Dependence of the dissipated energy density on the number of loading cycles at R = 0 and R =0.5.

As it can be seen from Fig. 7, the total strain energy ΣW_t can be described by power law function that depends on N_f at various stress ratios

$$\Sigma W_t \cdot N_f^p = \alpha_{\Sigma W_t} \tag{9}$$

The parameters $\alpha_{\Sigma W_t}$ and p (Table 1) in equation (8) were determined by fitting of experimental data.

The error between experimental ($N_{f,e}$) and calculated ($N_{f,p}$) lifetime of SMA by the criterion ΣW_t does not exceed 25% (Table 2). From the obtained results, that are given in Table 2, the total dissipation energy ΣW_d at R = 0 and 0.5 for all tested specimens varies in range (0.017 - 0.155) ΣW_t. Only for specimen No. 12 (N_f = 24 cycles) total dissipation energy ΣW_{dis} is equal to 0.25 ΣW_t.

Table 2. Experimental ($N_{f,e}$) and calculated ($N_{f,p}$) lifetime of SMA according to ΣW_t criterion.

Specimen No	R_σ	$N_{f,e}$, cycle	ΣW_d,MJ/m³	ΣW_e, MJ/m³	ΣW_t, MJ/m³	$\Sigma W_d / \Sigma W_t$	$N_{f,p}(\Sigma W_t)$, cycle	$N_{f,p}$ (ΣW_e), cycle
10	0	2010	1005	17105	18110	0,055	2438	2446
12	0	24	78	228	306	0,255	24	24
13	0	773	634	6648	7282	0,087	872	889
14	0	763	962	5768	6730	0,143	797	764
15	0	1201	793	7662	8455	0,094	1032	1035
16	0	2053	1971	10778	12749	0,155	1640	1492
17	0	944	708	5390	6098	0,116	713	711
18	0.5	4587	624	36301	36925	0,017	5449	5475
19	0.5	770	162	7538	7700	0,021	928	1017
20	0.5	3031	518	20032	20550	0,025	2812	2897

In general, with the increase of cycles to failure number the relative portion of dissipation energy in the total strain energy density decreases.

The comparative dependencies of the total strain energy density ΣW_t, the total elastic strain energy ΣW_e and the total dissipation energy ΣW_{dis} of NiTi alloy upon the experimental lifetime at $R = 0$ and 0.5 at temperature 0 °C are presented on Fig. 8. In general, with the increase in the number of loading cycles the relative contribution of dissipation energy to the total strain energy density decrease.
In addition, the variation of the experimentally determined total dissipation energy ΣW_d far exceeds the variation of the total elastic strain energy ΣW_e. It should be also noted that the dependencies of the total strain energy density ΣW_t and the total elastic strain energy density ΣW_e almost coincide. From the mentioned above fact, it can be concluded that the fatigue failure is controlled by the total elastic strain energy density of ΣW_e and to a lesser extent by the energy dissipated density ΣW_d.

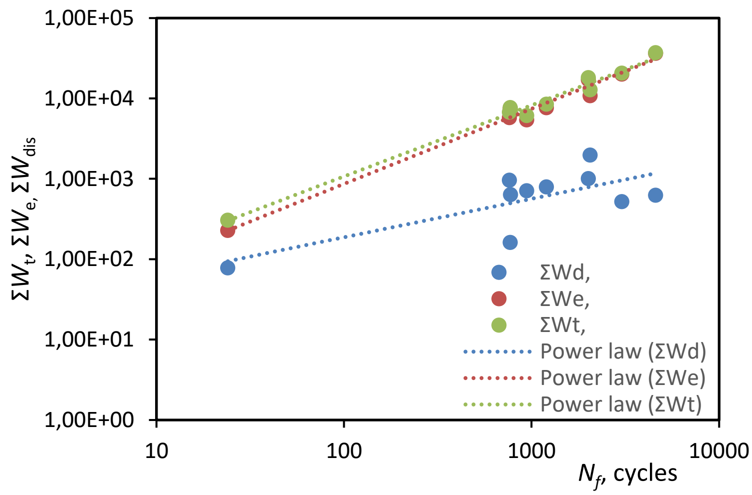

Fig. 8. Dependence of the dissipated energy density on the number of loading cycles at $R = 0$ and $R = 0.5$.

As it can be seen from Fig. 8, the total elastic deformation energy ΣW_e can be described by power law function that depends on N_f at various stress ratios

$$\Sigma W_e \cdot N_f^q = \alpha_{\Sigma W_e} \tag{10}$$

The parameters $\alpha_{\Sigma W_e}$ and q of equation (10): $q = -\,0.9341$; $\alpha_{\Sigma W_e} = 11.693$.

The influence of cyclic loading and strain range on the austenite Young's modulus is mentioned in the papers (Nayan et al. 2008; Phillips, Wheeler, and Lagoudas 2018; Predki et al. 2006). In particular, with the increase of maximum tangential stress at fully reverse torsion of hollow rod made of NiTi with 50.8% of Ni, austenite Young's modulus is decreasing at the comparative number of loading cycles (Predki et al. 2006). There was obtained the similar regularity of the stress range effect ($\Delta\sigma$ = 257; 315; 405 and 450 MPa) on the cross–section austenite Young's modulus at uniaxial tension for the NiTi alloy of 55.88%Ni at test temperature 22°C (A_f =21.4 °C) (Nayan et al. 2008). The variation of mechanical properties, particularly austenite Young's modulus, determined on the different specimens can be explained by the differences of texture, transformation temperature and precipitations that can be the result of insignificant changes of chemical composition or/and the thermal treatment technology (Mahtabi et al. 2018). Therefore, the change of austenite Young's modulus will reflect also on the total elastic strain energy density, that controls the fatigue behaviour of SMA. That is, the ΣW_e criterion, to the larger extent, takes into account the individual mechanical properties of specimens

The number of cycles to failure, that were calculated by the criterion of the total elastic strain energy density, are presented in Table 2. The error between the calculated ($N_{f,p}$) lifetime of NiTi shape memory alloy by the total elastic strain energy density ΣW_e and total strain energy density ΣW_t criterions does not exceed 10%.

4. Conclusions

The stress-, strain- and energy-based criteria were used to analysis the influence of stress ratio on low-cycle fatigue of pseudoelastic NiTi shape memory alloy. Increasing the stress ratio from 0 to 0.5 significantly reduces the fatigue life of the NiTi alloy when used to describe the stress range, strain range and dissipation energy density and increases when using the Odqvist's parameter.

A weak correlation of the fatigue life of the NiTi alloy at different stress ratio with the damage parameter in the form of the sum of the dissipation energy density and the elastic energy density was revealed.

The low–cycle fatigue failure criterion of pseudoelastic NiTi alloy - total elastic strain energy density that takes into account the stress ratio was proposed.

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