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Research Paper

Multiaxial fatigue modeling for Nitinol shape memory alloys under in-phase loading

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ARTICLE INFO

Article history:
Received 27 July 2015
Received in revised form
2 October 2015
Accepted 23 October 2015
Available online 2 November 2015

Keywords:
Fatigue
Martensitic phase
Nitinol (NiTi)
Multiaxial loading
Damage mechanism
Review

ABSTRACT

The realistic loading condition for many components is multiaxial arising from multi-directional loading or geometry complexities. In this study, some multiaxial stress-based classical and critical plane fatigue models are briefly reviewed and their application for martensitic Nitinol under torsion and in-phase axial-torsion loading is evaluated. These models include von Mises equivalent stress, Tresca, Findley, McDiarmid, and a proposed stress-based Fatemi–Socie-type model. As the fatigue cracks appear to be on the maximum shear plane for the martensitic Nitinol, all the models examined here consider the shear stress as the primary damage parameter. Among all the models considered in this study, the proposed Fatemi–Socie-type model provides a better prediction for fatigue lives when compared to torsion and in-phase multiaxial fatigue experimental data from literature. Analyses indicate that critical plane approaches are more appropriate for multiaxial fatigue prediction of Nitinol alloys, at least in martensitic phase. Finally, recommendations are made to calibrate more reliable multiaxial fatigue models for Nitinol.

1. Introduction

Nitinol is a nearly equiatomic alloy of nickel and titanium and has been widely used in various industries such as aerospace, automotive, civil and bioengineering. Vibration damping devices, vehicle and airplane structural parts and engine rotors are some examples of Nitinol applications in various industries. More specifically in bioengineering, there are many applications utilizing Nitinol, including Minimally Invasive Surgery (MIS) (Song, 2010) and endodontic (Thompson, 2000), due to its excellent material properties such as superelasticity, high resistance to corrosion, non-magnetism, and biocompatibility (Mohd Jani et al., 2014). Similar stress–strain response of Nitinol to biological materials, such as bone, makes this alloy a desirable candidate for some biomedical applications. Nitinol can be also used in self-expanding stents due to its ability to recover a large amount of strain (~8%). vena cava filters, anchors to attach tendon to bone, guide wires, eyeglass frames, dental fixators and implants are some examples of biomedical applications of Nitinol. In most of the applications, the Nitinol component is under cyclic loading and, therefore, susceptible to fatigue failure.

Nitinol exhibits different mechanical behavior depending on the operational temperatures, with respect to its characteristics temperatures. Four characteristics temperatures

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http://dx.doi.org/10.1016/j.jmbbm.2015.10.022
1751-6161/

Nomenclature

$2N_f$	number of reversals to failure
A_f	austenite finish temperature – the temperature above which Nitinol is fully austenitic
A_s	austenite start temperature – the temperature at which, upon heating, martensitic Nitinol begins transforming to austenite
b	fatigue strength exponent
b_0	shear fatigue strength exponent
M_f	martensite finish temperature – the temperature below which the material is fully martensitic
M_s	martensite start temperature – the temperature at which, upon cooling, austenitic Nitinol begins to phase transform to martensite
N_f	number of cycles to failure – number of cycles that a fatigue sample experiences before failure under an applied cyclic load
Ni_XTi_Y	Nitinol of nickel (X atomic percent) and titanium (Y atomic percent)
R_σ	stress ratio – ratio of the minimum to maximum stresses ($\sigma_{min}/\sigma_{max}$) in a constant amplitude cyclic loading
R_ε	strain ratio – ratio of the minimum to maximum strains ($\varepsilon_{min}/\varepsilon_{max}$) in a constant amplitude cyclic loading
T	test temperature
$\Delta\sigma$	stress range – difference between the maximum and minimum stresses in a cyclic loading: $\Delta\sigma=\sigma_{max}-\sigma_{min}$
$\Delta\tau$	shear stress range – difference between the maximum and minimum shear stresses in a cyclic torsional loading: $\Delta\tau=\tau_{max}-\tau_{min}$
φ	the angle between the direction of the maximum shear plane and the plane of axial load
ν	Poisson's ratio
σ_a	stress amplitude – half of the difference between the maximum stress and the minimum stress in a cyclic loading: $\sigma_a=(\sigma_{max}-\sigma_{min})/2$
σ_{eq}	equivalent (von Mises) stress
σ_m	mean stress – average of the maximum and minimum stresses in a cyclic loading: $\sigma_m=(\sigma_{max}+\sigma_{min})/2$
σ_{max}	maximum stress – maximum stress in a cyclic loading
σ_{min}	minimum stress – minimum stress in a cyclic loading
$\sigma_{n,max}$	maximum normal stress on the plane of maximum shear stress
σ'_f	fatigue strength coefficient
τ_a	shear stress amplitude in a cyclic torsional loading
τ'_f	shear fatigue strength coefficient

typically associated with a Nitinol alloy are; M_f, M_s, A_s, A_f. The martensite finish temperature, M_f, is the temperature below which the material is fully martensitic. The martensite start temperature, M_s, is the temperature that, upon cooling, austenitic Nitinol alloy starts transforming to martensitic phase. The temperature at which, upon heating, martensitic Nitinol tends to transform to the austenitic phase is called austenite start temperature, A_s. Finally, the austenite finish temperature, A_f, is the temperature above which Nitinol preserves the austenitic phase in an unstrained condition. Therefore, depending on the operating temperature, the material can be superelastic (for working temperatures above A_f) or fully martensitic (also known as shape memory) for temperatures below M_f. The stress–strain response of Nitinol at different temperatures is schematically shown in Fig. 1. As presented in this figure, Nitinol exhibits superelastic behavior at temperatures above A_f, in which a hysteresis loop forms through straining and unstraining. The formation of this hysteresis loop enables the material to dissipate a large amount of energy. For temperatures below martensite finish temperature, although the stress–strain response of the material is similar to other metals, the shape memory Nitinol can still tolerate a large amount of plastic strain (i.e. ~8–12%) that is recoverable by heating up to a temperature above A_f.

Even under uniaxial loads, Nitinol has a complicated fatigue behavior due to its unique mechanical properties. In the last two decades, several researchers have studied the fatigue behavior of Nitinol and mostly focused on the strain-controlled uniaxial tests (Kim and Miyazaki, 1997; Pelton et al., 2013, 2008; Tobushi et al., 1997). Mahtabi et al. (Mahtabi et al., 2015) recently reviewed various aspects of fatigue of Nitinol and discussed the challenges in current state of knowledge. Under uniaxial loads, the fatigue behavior of Nitinol is greatly affected by the test temperature. The general trend in the change of the fatigue resistance of Nitinol with respect to operating temperature is also dependent on the fatigue analysis approach (i.e. stress-based or strain-based fatigue approach) (Mahtabi et al., 2015). With increasing temperature, fatigue resistance of Nitinol typically increases in the stress-based fatigue analysis (stress-life data), whereas a decrease in fatigue resistance is typically observed in the strain-based fatigue analysis (strain-life data). Some other review articles on the fatigue behavior of Nitinol alloys can be found in

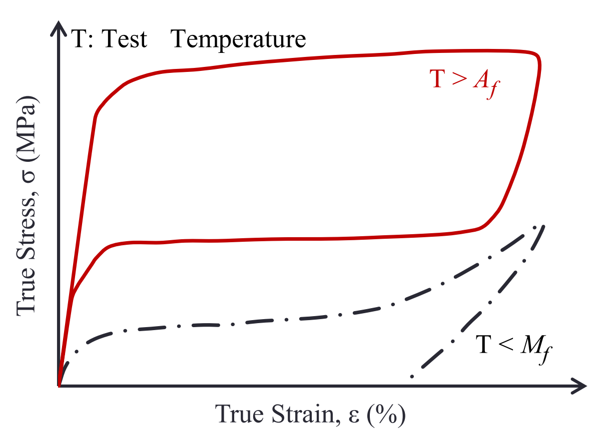

Fig. 1 – Schematic monotonic stress–strain behavior of Nitinol at different test temperatures, *T*.