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Numerical simulations of cyclic behaviors in light alloys under isothermal and thermo-mechanical fatigue loadings

G.H. Farrahi [a],*, A. Shamloo [a], M. Felfeli [a], M. Azadi [b]

[a] *School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran*
[b] *Fatigue and Wear in Materials (FWM) Workgroup, Irankhodro Powertrain Company (IPCO), Tehran, Iran*

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ABSTRACT

In this article, numerical simulations of cyclic behaviors in light alloys are conducted under isothermal and thermo-mechanical fatigue loadings. For this purpose, an aluminum alloy (A356) which is widely used in cylinder heads and a magnesium alloy (AZ91) which can be applicable in cylinder heads are considered to study their stress–strain hysteresis loops. Two plasticity approaches including the Chaboche's hardening model and the Nagode's spring-slider model are applied to simulate cyclic behaviors. To validate obtained results, strain-controlled fatigue tests are performed under low cycle and thermo-mechanical fatigue loadings. Numerical results demonstrate a good agreement with experimental data at the mid-life cycle of fatigue tests in light alloys. Calibrated material constants based on low cycle fatigue tests at various temperatures are applied to models to estimate the thermo-mechanical behavior of light alloys. The reason is to reduce costs and the testing time by performing isothermal fatigue experiments at higher strain rates.

1. Introduction

Aluminum alloys and magnesium alloys are light alloys, which have been widely used in automotive industries due to their advantages. High strength to density ratio of these light alloys is their benefits to save the cost of manufacturing. Another reason is due to their advantages including greater fuel economy and environmental conservation. In general, almost all automotive components are subjected to cyclic loadings. Several of them, used in the engine, are exposed to high temperatures. Therefore, the importance of investigating the cyclic behavior of light alloys (subjected to thermal and mechanical loadings) can be clear.

Several investigations have been done in simulating the cyclic behavior of light materials. Modeling of the high temperature stress–strain behavior in a cast aluminum alloy has been done by Smith et al. [1]. In their utilized model, material constants were determined according to the microstructure effect. This will make the model more accurate with high requirement of microstructural data. Sehitoglu et al. [2] applied a similar model for a cast 319-T6 aluminum alloy. They discussed about the relation between microstructure variables and the equivalent mechanical behavior at the macro scale. The cyclic behavior for the AZ91 alloy has been investigated by Zenner and Renner [3]. Strain-controlled tests were used for verifying the Masing behavior. Huter et al. [4] presented a simple fast routine to identify material parameters of a copper alloy in the thermo-mechanical simulation and reduce efforts of the parameter finding process.

Such these researches for steels and cast irons have been done widely in comparison to light alloys. Rezaiee Pajend and Sinaie [5] used calibration techniques for the Chaboche's model and determined material constants for the CS1026 according to the uniaxial ratcheting experiment. Shojaei et al. [6] used a numerical method to predict the behavior of CS1026 steel beam under cyclic loadings by the Chaboche's constitutive model with high performance. Hyde et al. [7] simulated the cyclic behavior of 316 stainless steel with the Chaboche's model. Material constants were attained by isothermal data. Seifert and Riedel [8] predicted the thermo-mechanical fatigue lifetime of cast iron materials based on a crack growth law. Their model observed creep, relaxation and Bushinger effects. Seifert et al. [9] compared the thermo-mechanical lifetime prediction with experimental data for three cast iron families. Szmytka et al. [10] introduced a new experimental strategy, which was able to represent a spheriodal graphite cast iron behavior on a wide range of the strain, the strain rate and the temperature.

Saad et al. [11] applied the Chaboche's constitutive model to predict the cyclic behavior of the P91 martensitic steel. The parameter determination of the Chaboche's kinematic hardening model was performed by Mahmoudi et al. [12], considering the multi-objective genetic algorithm with two objective functions of the hysteresis loop and the ratcheting prediction were applied to

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* Corresponding author. Tel.: +98 21 66165533; fax: +98 21 66000021.
E-mail address: farrahi@sharif.edu (G.H. Farrahi).

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improve the model. Numerical results of the Chaboche's model, the Skelton's model and the Nagode's model were studied by Zaletelj et al. [13] and compared to experimental results. Thermo-mechanical fatigue tests on the 9Cr2Mo alloy for different loading conditions were used and the accuracy, weaknesses and possible improvements of three models were investigated. Remy et al. [14] investigated the capability of various models under high temperature and variable temperature conditions for two body centered cubic alloys, a cast iron and a ferritic stainless steel. They improved the prediction for the cast iron with modifying flow equation estimations and improved the estimation for the stainless steel by considering the static recovery effect. Noban et al. [15] examined diverse plasticity models for 304 and 1045 steels and discussed about the structure of these models such as the multi-surface plasticity model.

Badnava et al. [16] determined material parameters of the SS304 stainless steel under the strain-controlled cyclic loading. They applied the kinematic and isotropic hardening model and optimized results by the genetic algorithm.

Barrett et al. [17] presented an improved unified cyclic visco-plastic material model for the high temperature fatigue behavior of the P91 steel. They proposed a novel method for the identification of the cyclic visco-plastic parameters. They utilized the strain-rate independent parameter to increase the precise of the model at a wide strain-rate range. Christ and Bauer [18] adapted a multi-component model for the cyclic stress–strain behavior under thermo-mechanical fatigue conditions. They investigated an austenitic stainless steel behavior within the temperature range of the thermo-mechanical loading which these alloys display a ductile–brittle transition. Hyde et al. [19] simulated in-phase and out-of-phase thermo-mechanical tests for the P91 power plant steel and employed the optimization procedure to raise the accuracy. They discussed about the relation among the cyclic softening, the evolution of the microstructure and the propagation of the micro-cracks.

In this article, cyclic behaviors of an aluminum alloy and a magnesium alloy are studied under isothermal and thermo-mechanical fatigue loadings. According to this objective, two material behavior models are used including the Chaboche's hardening model and the Nagode's spring-slider model. Then, material constants of light alloys are calibrated based on experimental data.

2. Materials types

Two light alloys are considered in this article to investigate their cyclic behaviors: the A356 alloy with the element composition of 7.06% Si, 0.37% Mg, 0.15% Fe, 0.01% Cu, 0.02% Mn, 0.13% Ti and remainder Al [20]; and the AZ91 alloy with the element composition of 9.00% Al, 1.05% Zn, 0.06% Mn, 0.04% Si, 0.68% RE and remainder Mg [21]. In addition, a typical heat treatment is applied to the AZ91 alloy. The production method of light alloys is the gravity casting in permanent molds. More details about the microstructure, material processes and etc. are reported in literature [20,21]. These light alloys have applications in engine components. The A356 alloy has been widely used in diesel engine cylinder heads and the AZ91 alloy is an inventive feature for cylinder heads and blocks.

As reported in literature [20,21], the cyclic hardening occurs in the AZ91 alloy under isothermal and thermo-mechanical loadings, both at low and high temperatures. This magnesium alloy has a brittle behavior due to the observation of cleavage marks on the fracture surface of specimens [22]. However, in the A356 alloy, the cyclic hardening occurs at low temperatures and the cyclic softening behavior occurs at high temperatures. This aluminum alloy has a ductile behavior due to the observation of dimple marks on the fracture surface of samples [23]. Thus, a proper material model should be used with the capability of predicting both cyclic softening and hardening behaviors.

3. Material models

In this section, two types of governing equations including Chaboche [24] and Nagode and Fajdiga [25] constitutive models are discussed. The first unified model is based on the total strain decomposition into elastic and visco-plastic parts. The second non-unified one uses elasto-plastic and visco-plastic strains [25]. The Chaboche's model is based on the combined nonlinear isotropic/kinematic hardening. The Nagode's model considered spring-slider elements for the material behavior.

The Chaboche's model (the unified visco-plasticity) in the small strain framework has been chosen as a first model to represent the uniaxial cyclic behavior of light alloys [24]. In this model, Eq. (1) represents the strain decomposition into the elastic strain (ε_e) and the plastic strain (ε_p). Eq. (2) displays the Hook's law and the Von-Mises elastic domain (f) has been given in Eq. (3).

$$\varepsilon = \varepsilon_e + \varepsilon_p \tag{1}$$

$$\sigma = E(\varepsilon - \varepsilon_p) \tag{2}$$

$$f = |\sigma - X| - R - k \leqslant 0 \tag{3}$$

In which, σ is the stress, ε is the total strain and E is the elastic modulus of the material. In Eq. (3), X is the kinematic hardening variable, R is the isotropic hardening variable and k is the initial yield surface.

In case of the visco-plastic behavior, the relation between the yield function (f) and the accumulated plastic strain rate ($\dot{p}$) can be written according to Eq. (4), as the following equation:

$$\dot{p} = \left\langle \frac{f}{D} \right\rangle^n \tag{4}$$

where D is the drag stress and n is a material constant. The bracket $\langle\rangle$ is the Macaulay bracket, which is used to cancel out the plastic strain rate when inside the bracket, is equal or less than zero.

Substituting Eq. (3) into Eq. (4) leads to Eq. (5).

$$\sigma = X + (R + k + \sigma_v)\mathrm{sgn}(\sigma - X) \tag{5}$$

where σ_v is called the overstress which can be defined as Eq. (6).

$$\sigma_v = \dot{p}^{1/n} D \tag{6}$$

Isotropic hardening (R) and kinematic hardening (X) evolutions are as following equations:

$$\dot{R} = b(Q - R)\dot{p} \tag{7}$$

$$\dot{X}^i = C^i(T)\dot{\varepsilon}^p - \gamma X^i \dot{p} + \frac{1}{C^i(T)}\frac{\partial C^i}{\partial T} X^i \dot{T} \tag{8}$$

$$X = X^1 + X^2 + X^3 \tag{9}$$

where b and Q are isotropic material constants, and C and γ are kinematic material constants. In Eq. (8), C is a function of the temperature. These material parameters can be determined by experimental isothermal data. It should be mentioned that under the isothermal condition, the third term in Eq. (8) is omitted, since the temperature is constant during cycles. By substituting Eq. (2) into Eq. (5) and applying isotropic and kinematic hardening evolutions, we are able to simulate the cyclic behavior.

The Nagode's model (the non-unified visco-plasticity) in the small strain framework has been also chosen as the second model to represent the uniaxial cyclic behavior of light alloys [25].