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Crack path evaluation on HC and BCC microstructures under multiaxial cyclic loading

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ABSTRACT

In this paper the multiaxial loading path effect on the fatigue crack initiation, fatigue life and fracture surface topology are evaluated for two different crystallographic microstructures (bcc and hc): high strength low-alloy 42CrMo4 steel and the extruded Mg alloy AZ31B-F, respectively.

A series of multiaxial loading paths were carried out in load control, smooth specimens were used. Experimental fatigue life and fractographic results were analyzed to depict the mechanical behavior regarding the different microstructures.

A theoretical analysis was performed with various critical plane models such as the Fatemi–Socie, SWT and Liu in order to correlate the theoretical estimations with the experimental data. A new approach based on maximum stress concentration factors is proposed to estimate the crack initiation plane, estimations from this new approach were compared with the measured ones with acceptable results. To implement this new approach a virtual micro-notch was considered using FEM. Moreover, the multiaxial loading path effect on stress concentration factors is also studied. The obtained results clearly show the effect of the applied load conditions on local microstructures response.

1. Introduction

Structural failure is often caused by fatigue cracks which frequently initiate and propagate in the critical regions, generally due to complex geometrical shapes and/or multiaxial loading conditions. Fatigue crack initiation and crack growth orientation have been paid growing research attentions, since it is a crucial issue for an accurate assessment of fatigue crack propagation lives and for the final fracture modes of cracked components and structures [1–3]. Although there are a lot of publications regarding multiaxial fatigue behavior of steels, there are very few studies regarding multiaxial fatigue of magnesium alloys; Bentachfine et al. [4] studied a lithium–magnesium alloy under proportional and non-proportional loading paths under low-cycle and high cycle fatigue regime observing the deformation mode evolution and plasticity behavior. It was stated that the phase shift angle in the non-proportional loading paths decreases the material fatigue strength. The comparative parameter used to correlate experimental data was the von Mises equivalent stress/strain. However with this approach the material under non-proportional loadings keeps a constant equivalent stress and in this way no change in the material occurs along each loading cycle. However, the constant change in the direction of principal stress during the loading period due to the phase shift increases the anisotropy on the plastic deformation at grain level and causes, in certain cases, the decrease on fatigue life [5]. Biaxial fatigue studies were performed by Ito and Shimamoto [6] with cruciform specimens made of a magnesium alloy. It was analyzed the fatigue crack propagation as well as the effect of microstructure on the material fatigue strength. From the biaxial low cycle fatigue tests, it was concluded that the twinning density evolution is strictly related with crack initiation and slip band's formation on wrought magnesium alloys. Recently, Yu et al. [7], have also studied in-phase and out-phase behavior under strain controlled tests on AZ61A extruded magnesium alloy using tubular specimens. The conclusions were similar to Bentachfine et al. [4], the presence of the phase shift angle leads to decrease the fatigue strength compared with in-phase cases for the same equivalent strain amplitude. At low-cycle fatigue regime, it was reported a kink in the strain life curve which is a typical behavior for uniaxial fatigue regime in magnesium alloys. Furthermore, the effect of compressive mean stress was evaluated, concluding that a compressive mean stress enhances fatigue life [8].

There are mainly three types of shear transformations beyond slip mechanisms namely deformation twinning, stress induced at martensitic transformations and kinking. The twinning deformation occurs in hc metals deformed at ambient temperature and at bcc metals when they are deformed at lower temperatures. Twinning mechanism occurs when is created a boundary on the material lattice defining a symmetric region due to shear strain at

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atomic level. This twin boundary defines a mirror image between deformed and undeformed lattice grid [9,10].

At wrought Mg alloys the crack initiation is also associated with material inclusions but in most cases the twinning deformation and slip bands inherent to the twinning density flow are the main cause for the crack initiation. Crack propagation follows in general along the deformation twin's fields [11–13].

The goal of this paper is to evaluate the mechanical behavior of two different microstructures, bcc and hc, subjected to the same multiaxial loading paths and point out the main differences concerning the multiaxial loading effect on the fatigue crack initial path, fatigue life and fracture surface topology. In this work a critical plane study was performed comparing the agreement between experimental data and the theoretical one. Critical plane models such as Fatemi–Socie, SWT, Liu1 and Liu2 were applied and a new approach based on the highest stress concentration factor to determine the critical plane direction was performed.

Regarding the two different microstructures the applicability of the studied models and the corresponding obtained results are discussed.

2. Materials and methodology

In this work two materials were studied, one is the low-alloy steel DIN 42CrMo4 (AISI 4140), the other one is the extruded Mg alloy AZ31B-F with 3% of aluminum and 1% zinc. The mechanical properties of both materials were determined by the authors following the standard procedures, namely following ASTM E8 and ASTM E606 standards, and are presented in Table 1.

2.1. Material cyclic behavior

Structural materials have different properties regarding cyclic and monotonic regimes, for instance the cyclic yield stress can be quite different from monotonic one, depending on the material behavior. Some materials can soften or harden or even maintain similar to monotonic properties under a cyclic regime [14,15]. Another category is point out by Lopez and Fatemi, where cyclic softening at low strain amplitudes is followed by cyclic hardening at higher strain amplitudes [16].

When a cyclic softening occurs the cyclic yield stress is lower than the monotonic one, in this case, usually, the cyclic curve is under the monotonic curve for all strains. Material hardening occurs when the cyclic regime induce material plasticity in such way that the cyclic yield stress appears above the monotonic yield stress, as well as the cyclic curve appears above the monotonic curve.

Magnesium alloys tends to have a cyclic hardening behavior being highly dependent on the grain refinement, purity, lattice intrinsic behavior like twinning or foundry transformation processes [7,8,15–18]. On the other hand 42CrMo4 material tends to cyclically softening.

Table 1
Mechanical properties of the materials studied, 42CrMo4 and AZ31B-F.

	42CrMo4	AZ31B-F
Microstructure type	bcc	hc
Poisson's ratio	0.3	0.35
Density (Kg/m^3)	7830	1770
Hardness (HV)	362	86
Tensile strength (MPa)	1100	290
Yield strength (MPa)	980	203
Elongation (%)	16	14
Young's modulus (GPa)	206	45
σ'_f Fatigue strength coefficient (MPa)	1154	450
b Fatigue strength coefficient	−0.061	−0.12
ε'_f Fatigue ductility coefficient	0.180	0.26
c Fatigue ductility exponent	−0.53	−0.71

Identifying the cyclic material behavior is of prime importance to accurately interpret the material local stress states. The softening behavior leads to have a local stress lower than the one estimated with the monotonic curve, however, if the monotonic curve is used as reference to fatigue experiments then the cyclic total strains will be greater than the monotonic ones. At cyclic hardening the opposite occurs, the local stresses are greater than the monotonic ones for the same total strain value. Under these assumptions it can be concluded that fatigue models used in order to estimate crack initiation planes and fatigue life estimations must be implemented taking in to account the cyclic behavior of the material once they are based on stress and strain amplitudes [5,18,19].

Material cyclic curve can be used as a reference to fatigue loadings in order to implement elastic–plastic numeric simulations, however the fatigue crack nucleation process induces micro-notches which in turn induces stress risers, with great probability of local plasticity. Besides, the fatigue crack opening occurrence involves plasticity in the fatigue process which leads to conclude that the plasticity effect on the stress and strains states cannot be neglected on the determination of the crack initiation plane [12,20,21]. In this

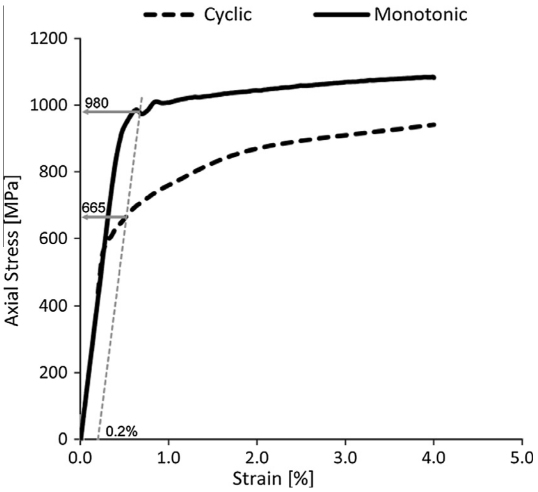

Fig. 1. 42CrMo4 monotonic and cyclic behavior.

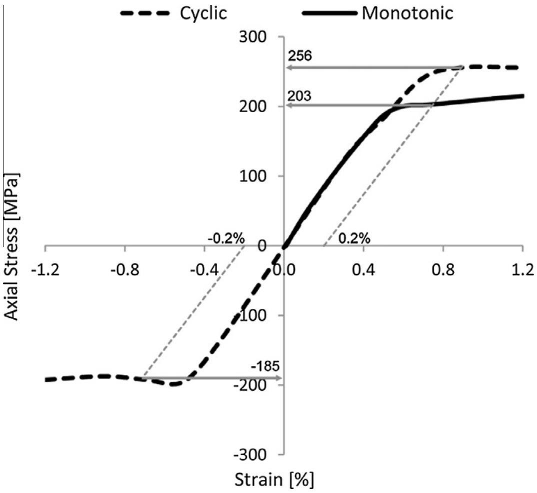

Fig. 2. AZ31 alloy monotonic and cyclic behavior.