Fatigue Crack Path Evaluation on Two Different Micro-Structures HC and BCC Under Multiaxial Loading

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ABSTRACT. *Multiaxial loading effects play an important role on the crack initiation and early crack growth path. In this paper these effects are examined for two different crystallographic microstructures (bcc and hc): an high strength low-alloy 42CrMo4 steel and a magnesium alloy, respectively. For stage I, a combination of both opening and shear mechanisms are found to promote crack nucleation and growth. A series of multiaxial loading paths were carried out; the experimental fatigue life results and a fractographic analysis were considered to depict stage I behaviour regarding the different microstructures. In addition, critical plane models such as the Fatemi-Socie, SWT and Liu were applied for evaluating the initial plane orientation and to compare with the measured ones. Results show the influence of the two different micro-structures bcc and hc regarding the applied multiaxial loading conditions.*

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. Multiaxial fatigue studies in magnesium alloys are quite few nowadays; Bentachfine et al [1] 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 behaviour. Authors have 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 that way no change in loading is verified in the material along each loading cycle. The constant change in the direction of equivalent stress along the loading period due to the phase shift presence increases the anisotropy on the plastic deformation at grain level justifying, in certain cases, the decrease on fatigue life. Biaxial fatigue studies were performed by Ito and Shimamoto [2] with cruciform specimens made of a magnesium alloy. Fatigue crack propagation was analysed as well as the effect of microstructure on the material fatigue strength. The biaxial low cycle deformation led to conclude that the twinning density evolution is strictly related with crack initiation and slip band's formation on wrought magnesium alloys. Recently, Yu et al [3], also studied in-phase and out-phase behaviour under strain controlled tests on AZ61A extruded magnesium alloy using tubular specimens. The conclusions were similar to Bentachfine et al [1], the presence of the shift angle concurs to decrease the fatigue strength comparatively with in-phase cases for the same equivalent strain amplitude. At low-cycle fatigue regime was reported a kink in the strain life curve which is a typical behaviour 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. A critical plane study was performed comparing the agreement between experimental data and the theoretical one. It was used the Fatemi-Socie and SWT critical plane models. The conclusions relate a poor prediction of Fatemi-Socie model on the high cycle regime but good agreements at low cycle. Moreover, the SWT showed better results in all loading paths.

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 atomic level. This twin boundary defines a mirror image between deformed and undeformed lattice grid [4, 5].

At wrought Mg alloys the crack initiation is also associated with material inclusions but in the majority of the 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 [6, 7].

The aim of this work is to evaluate the mechanical behaviour of two different microstructures, bcc and hc, subjected to the same loading paths and point out the main differences concerning the multiaxial loading effect on the fatigue crack path.

MATERIALS AND METHODS

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 aluminium and 1% zinc. The mechanical properties of both materials are presented in Table 1. Experimental tests were performed. To evaluate the microstructure´s influence four biaxial loading paths were selected, see Figure 1. The first one is a pure uniaxial tensile test, case PT, and the second one is a pure shear loading, case PS. The PP, is a 45º proportional biaxial loading and the OP case is a 90º out of phase loading case. In Figure 2 is presented the specimen geometry and dimensions. All tests were performed at ambient temperature and ended when the specimens were totally separated. Crack initiation plane angles for each loading path were estimated by the Fatemi-Socie (FS), Smith-Watson-Topper (SWT), Liu I and Liu II multiaxial fatigue models [8].

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	211
Elongation (%)	16	14
Young´s modulus (GPa)	206	45

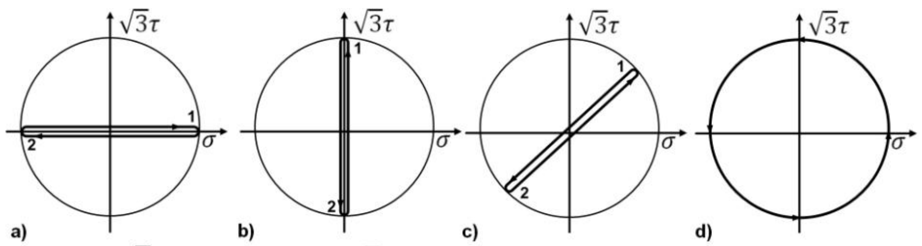

Figure 1. Loading path: a) case PT, b) case PS, c) case PP and d) case OP.

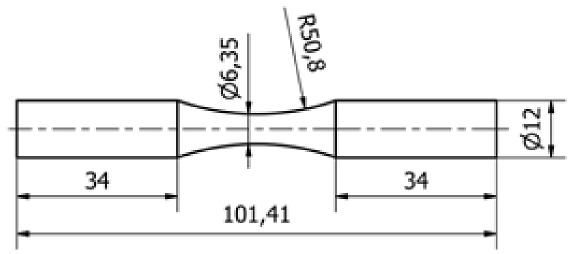

Figure 2. Specimen test geometry and dimensions (mm).

RESULTS AND DISCUSSION

Fatigue life analysis

Figure 3 presents the experimental fatigue results obtained for both materials concerning the equivalent von Mises stress. The results show that the relative damage between the loading paths considered in this study tends to have the same relative arrangement in both materials. The OP loading case remains the most severe case and PS loading case the lesser one; consequently the PT and PP SN curves are between those limits. However, concerning Mg alloy, the OP loading case seems to present a bilinear tendency. Due to the OP loading nature the strain energy involved is higher than the other loading cases on same fatigue life region, i.e., activating twinning mechanisms which leads to a different mechanical behaviour. Moreover, regarding SN curves tendencies, the damage rate between loading paths is similar for the same material excepting the loading case OP where the damage rate is more pronounced.

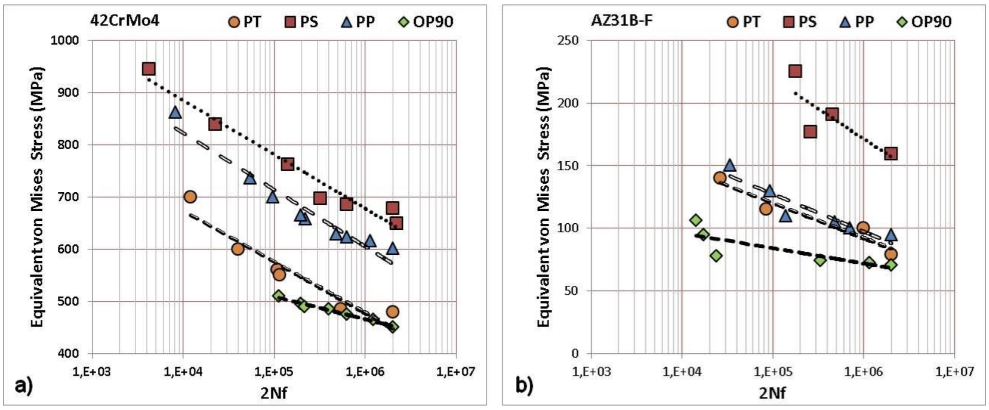

Figure 3. SN curves for: a) 42CrMo4 and b) Mg AZ31B-F.

Fractographic analysis

In Figure 4 are shown the fracture surfaces and the crack initiation measured angles for the PT loading case in each material. The 42CrMo4 specimen failed at 247953 cycles under 455 MPa and the Mg alloy failed at 13164 cycles under 140 MPa. Despite the failure occurs at different fatigue regimes in each different material the fracture surface shows a similar topology for this loading case. Both surfaces suggest a ductile fatigue failure mechanism with two different zones and roughness. A fatigue zone FZ, with smooth area and an instantaneous zone IZ, with rough area. In the smoothest part of the fatigue zone area is possible to identify the crack initiation local, as in the rough part, in the IZ, the final fracture. The roughness change in fracture surface indicates a different crack growth speed proving that the failure didn't happen suddenly. The fatigue life is spent mainly in mode I crack growth and finishes with rough and crystalline appearance. The final fracture occurs on mode II through slip mechanism on a shear fracture plane. No expressive propagation marks were observed in the high strength steel, however in Mg alloy were observed a slight river marks pointing the crack growth and the initiation spot. Initiation angles measured in both materials were zero degrees.

Fatigue crack results for the loading case pure shear PS, are presented in the Figure 5. The steel specimen was subjected to a 685 MPa von Mises equivalent stress failing at 315668 cycles. The Mg alloy specimen was subjected to 120 MPa of von Mises equivalent stress and failed at 128719 cycles. The steel specimen fracture surface shows a unique initiation source with a initiation plane oriented at 45 degrees; this is a typical result for twisting loads on ductile materials [9]. It is expected that a reduction of this angle value occurs if there are other stresses than the shear ones involved in the fatigue process i.e. mixed mode crack propagation. The FZ and IZ show a strong granulated surface in the steel specimen, however in the Mg specimen fracture surface is smoother. In generally both fracture surfaces are similar, the FZ have a fracture plane equally oriented and the instantaneous zone in both cases have a similar arrangement. At Mg specimen it is observed ratchet marks with two initiation spots growing toward the centre of the specimen, and in the instantaneous zone can be seen a material riffling like progression marks.

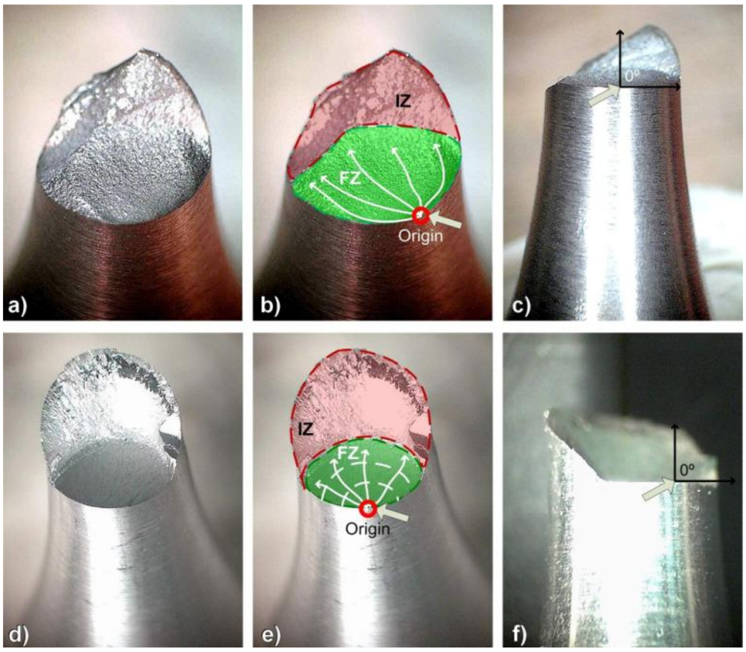

Figure 4. **Loading case PT**: fracture surface for a), b) 42CrMo4 and d) e), Mg AZ31B-F. Crack initiation angle for c) 42CrMo4 and f) Mg AZ31B-F.

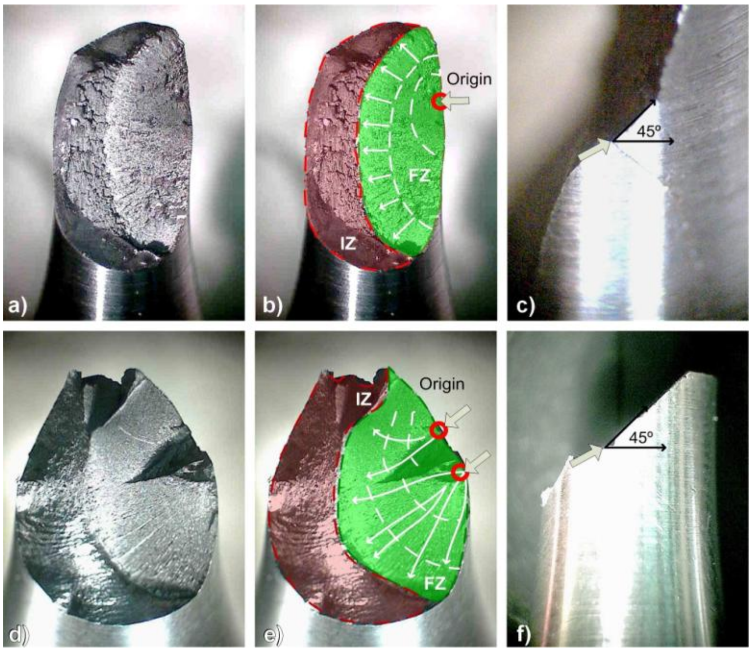

Figure 5. **Loading case PS**: fracture surface for a), b) 42CrMo4 and d) e), Mg AZ31B-F. Crack initiation angle for c) 42CrMo4 and f) Mg AZ31B-F.

In Figure 6 is shown the fracture surfaces results for the proportional loading case, PP. The steel specimen was tested with 622 MPa as von Mises equivalent stress and reach failure at 311201 cycles. The Mg specimen was subjected to 150 MPa as von Mises equivalent stress; the fatigue life was 16800 cycles. The specimens were tested at different fatigue regimes, which can be proved by the size of IZ (instantaneous zone). For the same loading path the obtained fracture surface´s topology is quite different. On contrary to that observed in loading cases PT and PS, here the fracture surface topology is dependent on the stress level.

The steel specimen fracture surface shows one crack origin and three distinct zones: the usual FZ and IZ zones and a surface wear region. In Mg specimen fracture surface can be identified two crack origins and many river marks pointing to first crack origin. Performing the same fatigue regime in both materials will turn the fatigue fracture surface more similar. The crack initiation plane angle measured for the steel specimen was -16º, and 0º for Mg specimen, the axial load component induce a crack initiation angle between ±45º and 0º and in low cycle fatigue, it seems, Mg alloy is more sensitive to the axial component than the torsional one in low cycle fatigue regime.

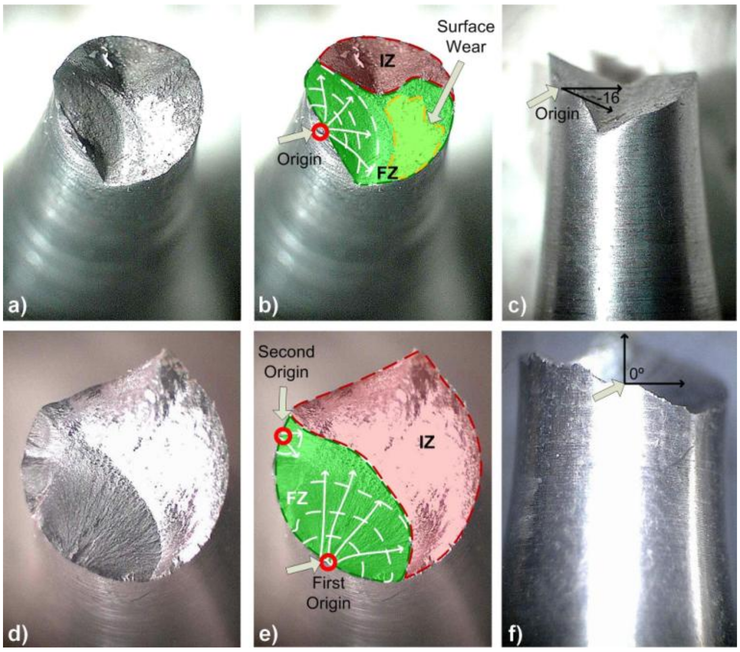

Figure 6. **Loading case PP**: fracture surface for a), b) 42CrMo4 and d) e), Mg AZ31B-F. Crack initiation angle for c) 42CrMo4 and f) Mg AZ31B-F.

The results for the loading case OP are shown in Figure 7, the steel specimen was tested with 686 MPa as von Mises equivalent stress, the fatigue life was 197548 cycles and the Mg specimen was tested with 72.5 MPa as von Mises equivalent stress performing till failure 576336 cycles. Fracture surfaces are also similar in this loading case; supporting the idea on the topology convergence in both materials in high cycle regime. At Mg specimen IZ can be seen diagonal riffles starting from the FZ throughout the end of IZ. Diagonal riffles in instantaneous zone indicate a biaxial loading at instant fracture time.

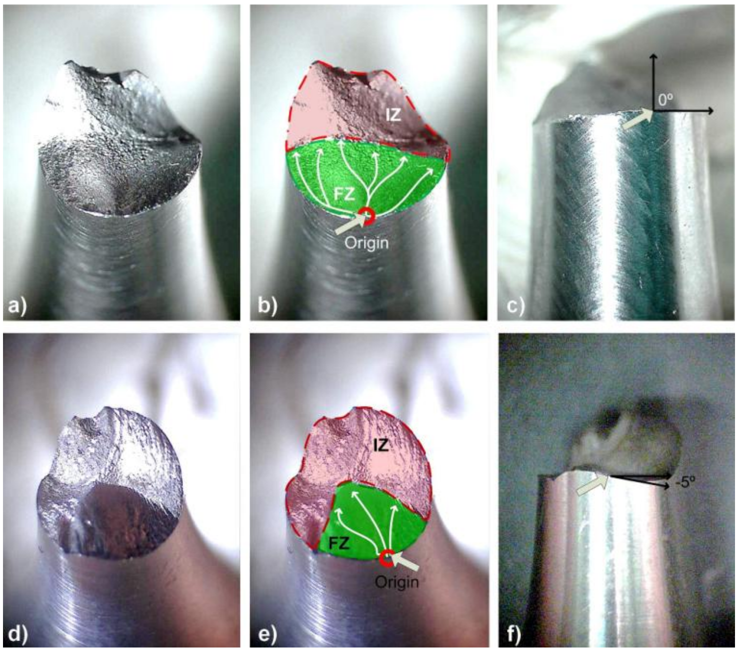

Figure 7. **Loading case OP**: fracture surface for a), b) 42CrMo4 and d) e), Mg AZ31B-F. Crack initiation angle for c) 42CrMo4 and f) Mg AZ31B-F.

Critical Plane analysis

Table 2 presents the measured crack initiation angles and also the critical planes estimations by the FS, SWT, Liu I and Liu II models for the studied loading paths. The SWT and Liu I models estimate well the crack initiation plane in both materials for the loading cases PT and PS. The first principal strain have a key role on this results, however, the FS and Liu II models have poor results for this two loading cases. For the PP loading case, the results are satisfactory in the 42CrMo4, in contrast, for the Mg alloy, the theoretical results strongly differ from the experimental data. In the OP loading case the estimated critical plane angle agree well with the experimental results.

Table 2. Critical planes measured and estimated for 42CrMo4 and AZ31B-F.

	Case PT		**Case PS**		**Case PP**		**Case OP**	
	AZ31	**42CrMo4**	**AZ31**	**42CrMo4**	**AZ31**	**42CrMo4**	**AZ31**	**42CrMo4**
Measured	**0**	**0**	**45**	**45**	**0**	**-16**	**-5**	**0**
FS	±43	±43	±3; ±87	±3; ±87	-18	-18	0	0
SWT	0	0	±45	±45	25	25	0	0
Liu I	0	0	±45	±45	25	25	0	0
Liu II	±45	±45	±90; 0	±90; 0	-20; 70	-20; 70	±90; 0	±90; 0

CONCLUSIONS

From the experimental and theoretical work carried out with two materials, a low-alloy steel and a Mg alloy, some remarks can be drawn:

-Regarding fatigue life analysis the relative damage between the applied loading paths tends to have the same relative arrangement in both materials. The damage rate between loading paths is similar for the same material excepting the loading case OP where the damage rate is more pronounced.

-Concerning fractographic analysis in loading cases PT and PS the fracture surface topology in both 42CrMo4 and Az31B-F specimens are similar and independent on the equivalent stress level. Under multiaxial loading regime the loading path and equivalent stress level have a huge influence on the AZ31B-F surface topology. In high cycle fatigue regime the fracture surface is strongly dependent on the loading path nature, for the same loading path the 42CrMo4 and AZ31B-F fracture surface tend to be similar.

-Regarding critical plane analysis the crack initiation angle in pure axial and pure torsional loading cases doesn't change with the equivalent stress level. Moreover, at uniaxial loading cases the initiation angles don't vary for the studied materials, however in multiaxial loadings that it is not true.

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