High Cycle Fatigue Crack Paths in C35 Steel under Complex Loading

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ABSTRACT. *The aim of this work is to study damage mechanisms in high cycle fatigue (10^5 – 10^6 cycles) of C35 steel under complex loading (multiaxial non-proportional loading, blocks loading). Effects of out-of-phase loading on crack behaviour (initiation, propagation planes, bifurcation…) have been investigated. Results indicate that there are two principal damage modes; the diffuse damage mode is specific for the torsion loading whereas the localized damage is common for many loading cases. HCF strength is higher for out-of-phase than in-phase tension-torsion, in terms of applied stress amplitude. Stage 1 crack propagation occurs on the maximum shear stress plane in all loading cases (in-phase and out-of-phase). The role of maximum normal stress (stage 2) is less determined under out-of-phase loading. Loading sequence effect is not remarkable in C35 steel. For lifetime modelling, it should predict correctly the fatigue limit and model completely both stages of crack propagation in each loading case.*

INTRODUCTION

Fatigue crack path study is very important for structural safety. Damage mechanisms in some simple cases of proportional loading (tension, torsion, in-phase) are detailed in several works [1-4]. Under non proportional loading, there are only few significant studies addressing the damage mechanisms [3, 4]. However, the understanding is not enough to explain the role of phase shift. The problem is more complicated when we want to model a non proportional experiment where classical quantities used in proportional loading are no longer valid. The same question arises with the blocks loading where loading sequence effect is not always remarked compared with Miller's work [5].

The present study focussing on non proportional loading aims to complete the fatigue mechanisms map for C35 steel. Effects of multiaxility, of out-of-phase and of blocks loading were considered carefully. Mechanisms analyses give some discussions in relevant mechanical quantities used in modelling.

EXPERIMENTAL RESULTS

Material and experimental procedure

The material at stake is a carbon steel C35, used in many industrial applications. The main mechanical characteristics are: E = 205 GPa, $R_{p0.2}$ *monotonous* = 350 MPa, $R_{p0.2}$ *cyclic* = 280 MPa and R_m = 580 MPa. This steel shows an alternance of ferrite and pearlite bands, the average grain size is 22 μm for ferrite and 16 μm for pearlite.

All cylindrical specimens were machined from a round bar (diameter 80 mm). In order to observe the cracks at microscopic scale (5 – 10 μm), all the specimens were polished with several abrasive papers up to grade 4000. Then, all the samples were tempered at 500 °C during one hour under vacuum to remove the residual stress due to preparation stage of the specimens. HCF tests were performed on a servo-hydraulic biaxial axial – torsional machine (Instron type 1343) at room temperature and under ambient air. The cyclic loading is fully reversed (R = -1), conducted under load control at a frequency of 10 Hz. Fatigue life range is from 10^5 to 10^6 cycles, i.e. the high cycle fatigue regime. Therefore, applied normal stress amplitude σ_a and shear stress amplitude τ_a were calculated following elastic theory of strength of materials: $\sigma_a = 4F/\pi d^2$, $\tau_a = 16T/\pi d^3$ where F is the force, T is the torque and d is the minimum section diameter of specimen. Loading cases considered in this paper include: tension (k = 0), torsion ($k = \infty$), in-phase (φ = 0°) and out-of-phase (phase shift angle φ = 45° and φ = 90°) tension – torsion at different stress ratios k ($k = \tau_a/\sigma_a$) and blocks loading.

The replica technique applied on the external specimen surface was used to control crack initiation and propagation. After metallization, the replicas were observed under SEM with low acceleration voltage. The procedure of observation starts with the last replica where the principal crack can be easily identified, and comes back to the early stage of cracking. The replica is a negative image of real surface. Resolution of this technique is about 5 – 10 μm depending on the crack opening [7].

S – N curves

Damage mechanisms for simple loading cases such as tension, torsion and in-phase tension – torsion in C35 steel have been investigated by some authors [1, 2]. The present study focussing on non proportional loading aims to complete the damage mechanisms mapping of this material. The second purpose is to seek appropriate mechanical quantities allowing describing the observed mechanisms.

All the out-of-phase fatigue tests carried out are shown in Table 1. In order to reveal the role of phase difference, the out-of-phase results are interpreted in relation to the in-phase results taken from a previous work [1]. In Fig. 2, the applied normal stress amplitude σ_a is plotted as a function of the number of cycles to failure (N_f) . The Fig. 2 shows increasing of fatigue strength under out-of-phase loading with respect to in-phase loading. For the same lifetime, the specimen can resist a higher applied normal stress in case of out-of-phase loading. Study of Verreman and Guo for 1045 steel showed a similar effect of the phase shift [3]. In C35 steel, the difference is approximately 25 MPa for both stress ratios k = 0.5 et k = 1. It appears that the difference is quite similar for a loading at fatigue limit (10^6 cycles) and that in the domain of limited endurance. This is an important feature for lifetime prediction. It should start with correctly predicting the fatigue limit of each loading before modelling the limited lifetime domain.

Table 1. Out-of-phase test program

Loading case	σ_a (MPa)	τ_a (MPa)	k (τ_a / σ_a)	φ (°)	N_f (cycles)
90° out-of-phase	240	120	0.5	90	174765
	235	117	0.5	90	191974
	235	117	0.5	90	165015
	232	116	0.5	90	239053
	230	115	0.5	90	427236
	175	175	1	90	131874
	172	172	1	90	181037
	170	170	1	90	161373
	165	165	1	90	300419
45° out-of-phase	230	115	0.5	45	404162
	230	115	0.5	45	10^6 – no failure
	232	116	0.5	45	251000
	170	170	1	45	306851
	232	116	0.5	45	277179

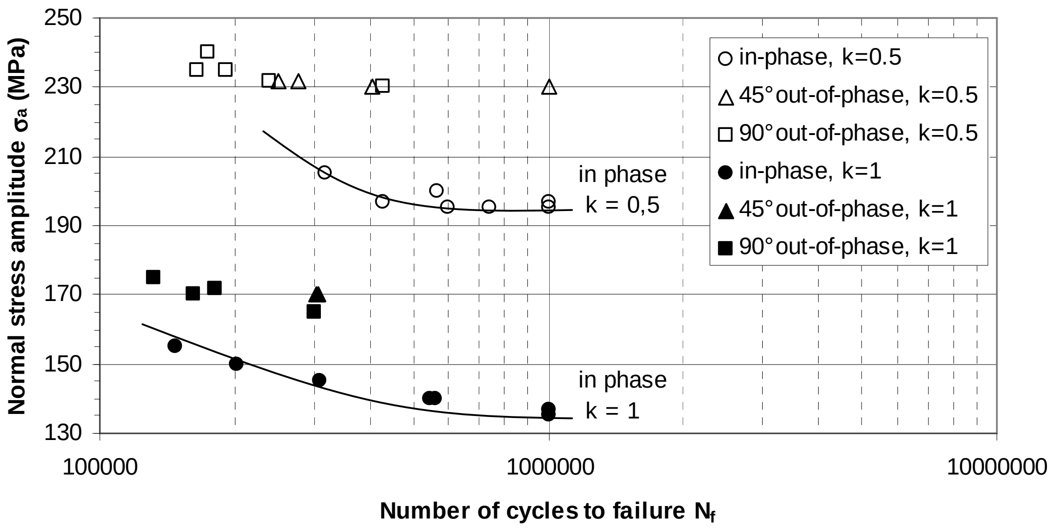


Figure 2. Multiaxial fatigue results for C35 steel

Damage mechanisms under non proportional loading

Beside the mechanical aspect, an important question arises: what is the link between the observed effect of the phase shift and damage mechanisms? In order to answer this question, crack propagation was observed on many specimens under different conditions of non proportional loading (Table 1). According to standard observation, the crack propagation includes stage 1 and stage 2. After the stage 1 occurring on the maximum shear planes (mode II – shear stress dominated), the cracks branch into planes of maximum normal stress (stage 2 – mode I – normal stress dominated). Orientation of these critical planes can be calculated by the damage accumulation method for each loading case [6]. The angle between the vector normal to the critical plane and the specimen axis is noted α. The values of α for some cases of non proportional loading are shown in Table 2.

Table 2. Calculated critical plane orientation

No.	φ (°)	k	$\alpha(\tau_{max})$ (°)	$\alpha(\sigma_{max})$ (°)
1	90	0.5	-	0
2	90	1	0 and 90	± 35
3	45	0.5	-22.5 and 67.5	20
4	45	1	-11.25 and 78.75	32

Crack propagation under proportional loading was studied by many authors [1-4]. Some common points can be remarked: the crack propagation agrees with the theoretical critical planes for both stage 1 and stage 2; a longer crack appears when the stress ratio is higher (more shear loading effect) for a given lifetime; transition of crack orientation (stage 1 – stage 2) occurs at longer crack length for higher stress ratio. For the C35 steel, two different damage modes for the reversed tension and the reversed torsion loading were analysed in some works [1, 2]. Tension is characteristic of a localized damage mode with a few marks of plastic accumulation observed on the specimen surface. Unlike tension, the specimen subjected to the torsion loading shows many activated plastic glide planes indicating a more homogeneous distribution of plasticity. Under in-phase loading, the damage mode is near to the tension mode when the stress ratio is small and near to the torsion mode in the inverse case. Analyse of damage mechanisms under out-of-phase loading will be compared with in-phase results to illustrate the role of the phase shift.

Figure 3 presents the crack propagation following stage 1 and stage 2 for some non proportional loading cases. On each SEM image, the maximum shear planes (mode II) are represented by dark dashed lines while the dark full lines illustrate the maximum normal stress planes (mode I). Specimen axis is shown by a white arrow.

90° out-of-phase, k = 0.5

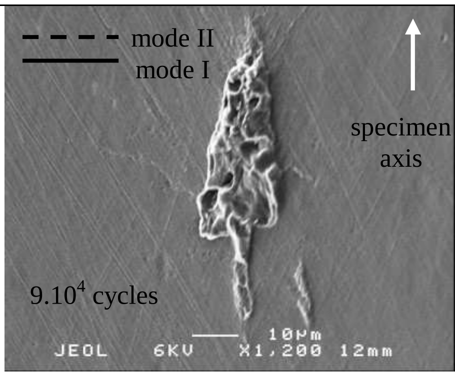
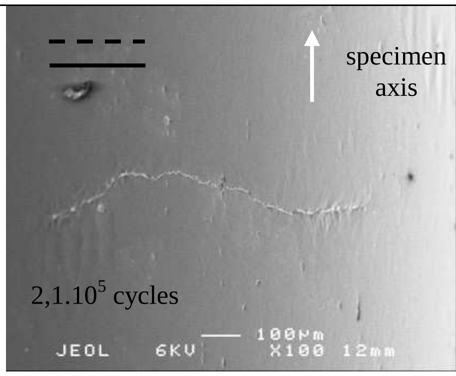
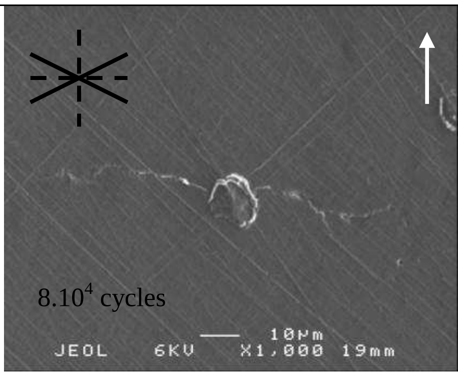
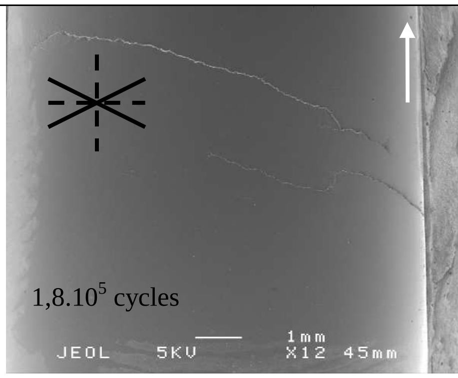
In terms of crack propagation, the 90° out-of-phase loading with k = 0.5 is a special case. There is the same maximum shear stress for all the planes designated by α. We can not determine the maximum shear stress planes. Therefore, crack initiation and crack propagation in both two stages occur on the plane where the normal stress is the highest [3]. In the present case on the Fig. 3, we observe also the initiation and the fluctuant propagation of principal crack around plane α = 0°, i.e. the plane of maximum normal stress. There is no crack bifurcation of stage 1/stage 2 in this case. Damage state is localized with only three cracks observed on specimen surface.

90° out-of-phase, k = 1

In the 90° out-of-phase loading with k = 1, difference between stage 1 and stage 2 is apparent, cracks propagation respects the critical planes of mode II and mode I. However, although torsional component is important ($\tau_a = \sigma_a$), damage mode governing crack propagation is always the localized mode with three significant cracks on specimen surface. While damage mode of in-phase loading k = 1 is near to the torsion mode, we find a damage mode near to the tension mode with the phase shift φ = 90°.

45° out-of-phase

Two cases of 45° out-of-phase loading on Fig. 3 show some irregular features of cracks propagation. After the stage 1 on the maximum shear planes, there are no cracks respecting the theoretical maximum normal stress planes. It means that normal stress effect on stage 2 of crack growth is not very dominating in these loading cases. A similar observation were remarked by Ohkawa et al. in a S45C steel for some 90° out-of-phase loading cases [4]. It is important to note that the damage state is strongly localized for both of two loading cases.

	Propagation (stage 1 – mode II)	Propagation (stage 2 – mode I)
Out-of-phase 90° k = 0,5 N_f = 2,39.10^5 cycles		
Out-of-phase 90° k = 1 N_f = 1,81.10^5 cycles		

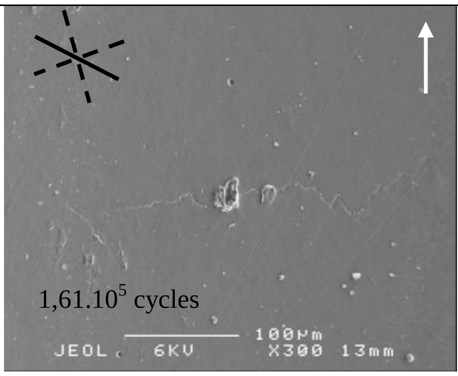
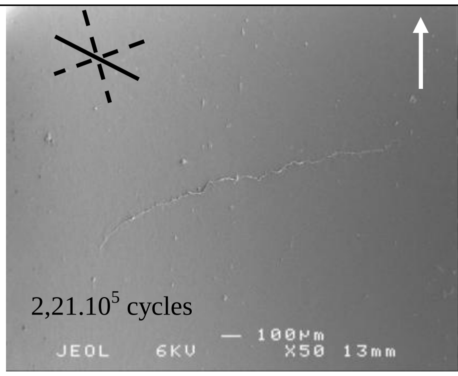
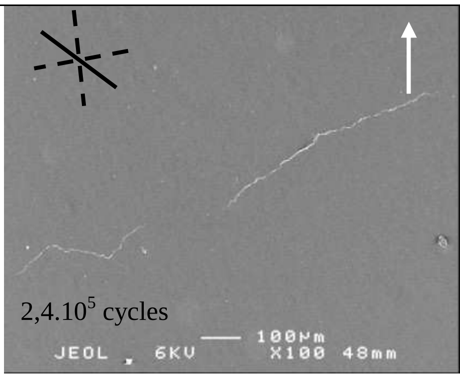
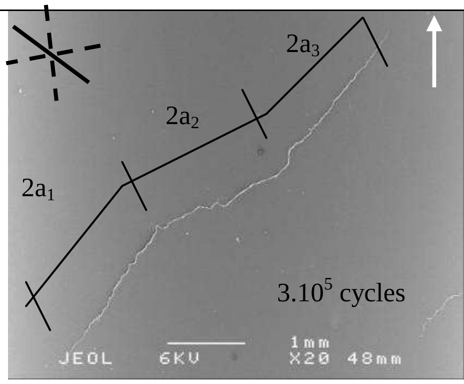
Out-of-phase 45° k = 0.5 N_f = 2,51.10^5 cycles		
Out-of-phase 45° k = 1 N_f = 3,06.10^5 cycles		

Figure 3. Crack path under out-of-phase loading

The common point of all out-of-phase loadings is that the damage mode is always localized with a few of initiated cracks on the specimen surface (2 – 4 cracks maximum). It appears that we observe very often this damage mode in many loading cases (tension, in-phase and out-of-phase). The diffuse damage mode observed in the torsion loading is really a specific case.

Surface crack length

Surface crack length is an important quantity to characterize damage state at each moment of specimen lifetime [1, 3, 4]. Measurement of total surface crack length is shown in Fig. 3 ($2a = 2a_1 + 2a_2 + 2a_3 + \ldots$). The results are plotted against the fatigue life ratio N/N_f in Fig. 4 for several loading cases in domain from 2.10^5 to 10^6 cycles. Crack length growth form is quite similar for all considered loading cases (Fig. 4). For a given fatigue life, crack length increases with the stress ratio k (more loading torsional component). Transitions of crack orientation (stage 1 – stage 2) are shown by arrows on the Fig. 4. An important remark is that growth kinetic does not vary greatly at the transition for all loading cases. Some studies report that crack length transition depends on applied normal stress [3, 4]. Our results for C35 steel confirm that the transition crack length is inversely proportional to applied normal stress under in-phase loading. However, this relation is not valid under out-of phase loading.

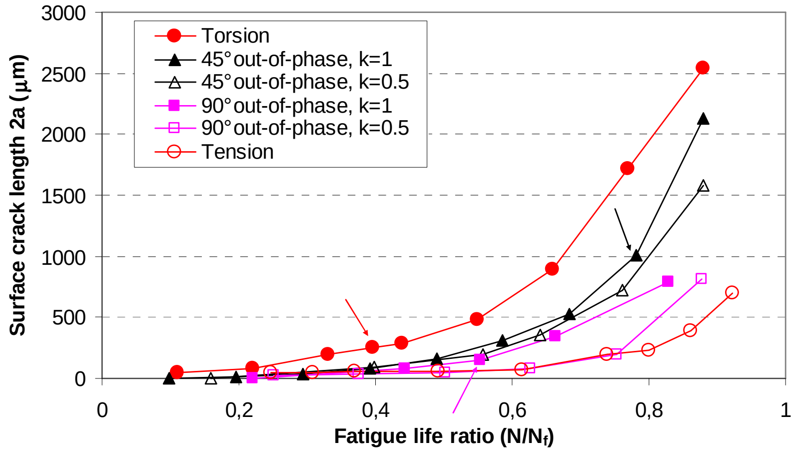


Figure 4. Surface crack length as function of fatigue life ratio

Blocks loading

We have studied the damage mechanisms of several loading modes under constant amplitude. This paragraph aims to understand material behaviour when the specimen is subjected to two blocks of different nature (reversed tension and reversed torsion). A series of experiments were carried out with two loading sequences: tension followed by torsion and torsion followed by tension. Applied stress amplitudes are of 250 MPa in tension and of 185 MPa in torsion. When each mode was applied separately at amplitude levels chosen, they would give the same fatigue life of $3{,}2.10^5$ cycles. The results of blocks loading are presented in Fig. 5, as plot of fatigue life fraction spent during each loading mode (N_{Ta}/N_f for the tension and N_{To}/N_f for the torsion).

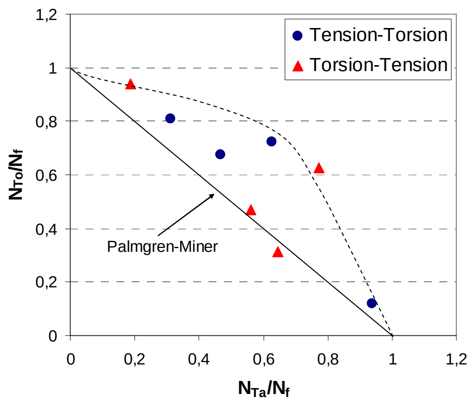


Figure 5. Experimental results of blocks loading in C35 steel

It appears that loading sequence effect is not very remarkable in C35 steel. It can be explained that the significant difference between tension damage mode and torsion damage mode prevents from a strong interaction between two modes. Independent cracks systems created in each block are often observed in this steel.

Discussion

Both analyses from mechanical and mechanisms viewpoint allow concluding on the high cycle fatigue damage mechanisms of the C35 steel under constant amplitude. The stage 1 of crack propagation respects the maximum shear stress plane in all loading cases (in-phase and out-of-phase loading). The stage 2 is governed by maximum normal stress under in-phase loading whereas the role of this later stress is less determining under out-of-phase loading. We note that under out-of-phase loading, initiation and stage 1 of propagation represents an important part of total life (50 – 80 %). Stage 1 under in-phase loading is shorter (30 – 50 %). It means that the role of maximum shear stress is more important under out-of-phase loading not only in the stage 1 but also in the stage 2. It is the reason why the cracks branch into an irregular plane in the stage 2.

The loading sequence effect has its origin in the interaction between different stages (stage 1 – stage 2) of each loading block [5]. In order to predict correctly the fatigue lifetime and describe the loading sequence effect, it is advised to model completely both stages of crack propagation.

CONCLUSIONS

Fatigue mechanisms map for C35 steel under complex loading (constant amplitude) has been presented. There are two principal damage modes; the diffuse damage mode is specific for the torsion loading whereas the localized damage is common for many loading cases including the tension, the in-phase and the out-of-phase. Concerning the role of phase shift, HCF strength is higher for out-of-phase than in-phase tension-torsion, in terms of the applied stress amplitude. Stage 1 crack propagation occurs on the maximum shear stress plane in all loading cases (in-phase and out-of-phase). Effect of maximum normal stress (stage 2) is less determined under out-of-phase loading. Loading sequence effect is not remarkable in C35 steel. For lifetime modelling, it should predict correctly the fatigue limit and model completely both stages of crack propagation in each loading case.

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