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PLASTICALLY DOMINANT / ELASTICALLY DOMINANT FATIGUE INTERACTION

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ABSTRACT

Interactions between High-Low (stress/strain) and Low-High (stress/strain) loadings have been studied extensively, yet the underlying fatigue mechanisms responsible for such interactions and thus the interaction between low cycle fatigue (LCF) and high cycle fatigue (HCF) are not clearly understood. Regimes under which High-Low and Low-High loading sequences are investigated should be specified clearly, (eg. High(LCF)-Low(HCF) where high stress/strain is in the LCF range and the subsequent low stress/strain is in the HCF range) as it can be appreciated that the mechanisms governing fatigue behaviour differ under varying regimes. Conventional classification of fatigue into LCF and HCF has been abandoned in favour of more precise terms being plastically dominant fatigue (PDF) and elastically dominant fatigue (EDF) respectively. This paper presents results on the interaction between PDF and EDF in 6061T6-aluminium alloy and highlights the significance of proper fatigue classification and specification particularly under strain controlled multilevel loading.

KEYWORDS

Plastically Dominant Fatigue (PDF), Elastically Dominant Fatigue (EDF), Low Cycle Fatigue (LCF), High Cycle Fatigue (HCF).

INTRODUCTION

Introduction of the Palmgren-Miner linear damage rule has motivated and inspired much research in multilevel loading for a vast array of materials as the problem of predicting service lives for engineering components subjected to non-uniform fatigue with any degree of accuracy has proved quite intractable. While extensive results on multilevel loading have been reported [1-7], the underlying fatigue mechanisms responsible for such interactions are not fully understood.

Historically, fatigue is classified into two main types, low cycle fatigue (LCF) and high cycle fatigue (HCF). The definition of LCF and HCF has been the subject of much ambiguity. LCF is commonly associated with fatigue lives ranging from 1 to 1000 cycles while HCF is concerned with failure corresponding to fatigue live cycles greater than 10^3. To date, the Coffin-Manson approach of determining transition life N_t, based on relative values of plastic and elastic strain, appears to be the most reliable method for defining the boundary between LCF and HCF. It is recognised that in order to avoid confusion and ambiguity with definitions involving LCF and HCF, the two regimes are more appropriately termed as plastically dominant fatigue

(PDF) and elastically dominant fatigue (EDF) respectively. Under two-level step loading, fatigue tests take the form of either High-Low or Low-High stress/strain type loading sequence. The regimes under which High-Low and Low-High (stress/strain) sequences are investigated should be specified clearly, (eg. High-Low stress/strain with both loadings in the EDF range, or a case where High stress/strain is in the PDF range and Low stress/strain is in the EDF range and vice versa) as it can be appreciated that the mechanisms governing fatigue behaviour differ under varying regimes. This paper aims to highlight the importance of specifying regimes under which multilevel loadings are conducted and present results on the interaction between PDF and EDF in 6061T6-aluminium alloy.

MATERIAL AND EXPERIMENTAL PROCEDURE

6061T6-aluminium alloy was used for fatigue testing. Hourglass shaped specimens were machined from cold rolled round bars in as-received condition having a nominal diameter of 6.35 mm and a gauge length of 31.75 mm. Mechanical polishing was carried out with No .400 and No. 1000 emery paper followed by finer grade EPA 1200 and EPA 2400 silicon carbide paper until visible machining marks were removed to give a smooth mirror-like surface finish. Tables 1 and 2 list the chemical composition and mechanical properties for 6061T6-aluminium alloy respectively.

TABLE 1

Chemical composition (% wt) of 6061T6-Aluminium alloy

Si 0.4-0.8	Fe 0.7 max	Cu 0.15-0.4	Mn 0.15 max	Mg 0.8-1.2
Cr 0.04-0.35	Zn 0.25 max	Ti 0.15	Others 0.05 max each, 0.15 max total	
Al remaining				

TABLE 2

Mechanical properties of 6061T6-Aluminium alloy obtained under a tensile strain rate of 0.001 s-1 or 6%/min

Material	Yield Strength at 0.2% offset	Ultimate Tensile Strength	Young's Modulus	Elongation
6061T6 Al	295 MPa	324 MPa	68.3 GPa	19.0 %

Specimens were first exposed to various degrees of either PDF or EDF before cycling at PDF or EDF conditions to fracture. PDF was carried out at 1.0% and 0.6% strain amplitude, while EDF was conducted at 0.4% and 0.3% and strain amplitude. All tests were performed in push-pull mode uniaxial fatigue under strain controlled zero mean strain conditions.

EXPERIMENTAL RESULTS AND DISCUSSION

Classification of PDF and EDF

Traditionally, the most reliable method for defining the boundary between LCF and HCF was to determine transition life N_t, from the parameters obtained by fitting strain/life trends to the Coffin-Manson relationship. Fatigue lives less than N_t were classified as LCF while fatigue lives greater than N_t were considered as HCF. The terms LCF and HCF are abandoned by the present authors in favour of more precise terms namely PDF and EDF respectively, since for fatigue lives less than N_t (i.e. PDF), plastic strain contribution to total strain is larger than elastic strain while for fatigue lives greater than N_t (i.e. EDF), elastic strain contribution to total strain is larger than plastic strain. However, it was later found, that using the Coffin-Manson approach to define PDF and EDF is inadequate since EDF close to N_t still involves considerable plastic strain; enough to induce mean stress effects during multilevel loading, a characteristic which is only supposedly inherent in

PDF. Hence, an alternative method for classifying PDF and EDF is required. It is proposed that the boundary between PDF and EDF be represented by the cyclic yield strain determined by implementing a 0.05% offset to the cyclic stress-strain curve, similar to the 0.2% strain offset method used to determine the yield point for monotonic loading. A 0.2% strain offset was not used in this case as it was discovered that it too yielded too much plastic strain for elastic conditions to prevail. Cyclic yield strain was determined to be 0.46% meaning that fatigue strain amplitudes < 0.46% are classified as EDF while any amplitudes greater are considered as PDF.

PDF/EDF interaction

Results for both High(PDF)-Low(EDF) and Low(EDF)-High(PDF) loading sequences are summarised in Table 3 while the overall fatigue life trends are illustrated in Figures 1 and 2 respectively.

TABLE 3

AVERAGE TOTAL FATIGUE LIFE CYCLES AFTER PDF-EDF AND EDF-PDF INTERACTION

Sequence type[*]	% of initial PDF life exposure						
	0	17.0	34.0	51.1	68.1	100	-
PDF (1.0%) – EDF (0.3%)	39426	14653	13028	9930	7475	176	-
	% of initial EDF life exposure						
	0	5.1	12.9	25.6	40.9	63.4	100
EDF (0.3%) – PDF (1.0%)	176	2187	5234	10298	16398	25146	39426

[*] Numbers in brackets denote strain amplitudes at which fatigue was conducted

Figure 1 shows that a High(PDF)-Low(EDF) loading sequence will result in overall fatigue lives being less than Palmgren-Miner predictions. On the other hand, a Low(EDF)-High(PDF) sequence appears to conform rather well with Palmgren-Miner predictions and doesn't seem to show much interaction effect (Figure 2). However, when results for both load sequences are plotted in a cycle ratio plot (Figure 3), the interaction effects between PDF and EDF become increasingly evident. Cycle ratio accumulation trends seen in Figure 3 conforms to typical trends observed for High-Low (stress/strain) and Low-High (stress/strain) 2-step tests in that a High(PDF)-Low(EDF) sequence yields cycle ratio summations <1 while Low(EDF)-High(PDF) a sequence results in cycle ratio summations >1.

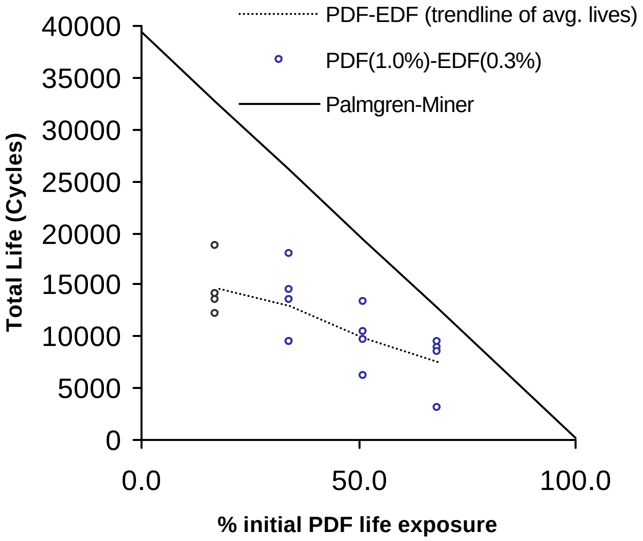

Figure 1: Fatigue life trend for High(PDF)-Low(EDF) interaction

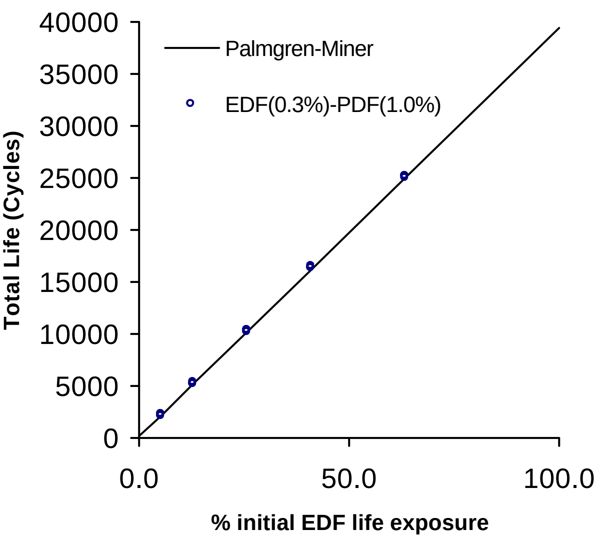

Figure 2: Fatigue life trend for Low(EDF)-High(PDF) interaction

Numerous "damage" theories have been proposed to take into account the sequence effects observed for multi-step load sequences, of which the crack growth approach first adopted by Zachariah and Miller [7] is favoured.

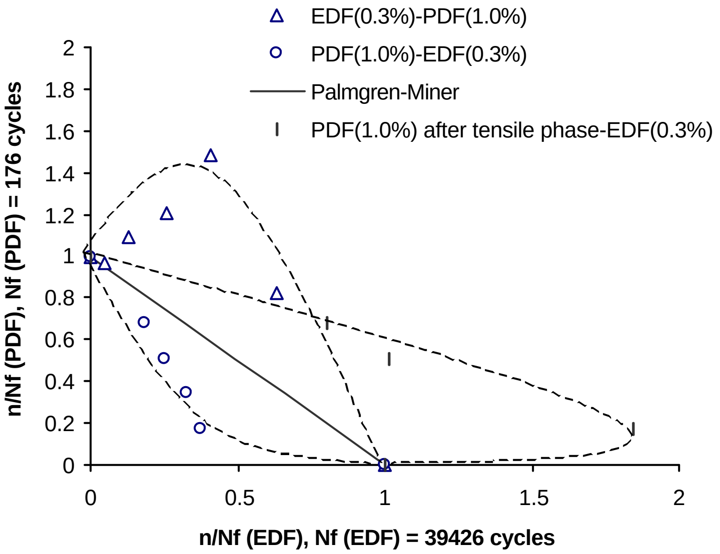

Figure 3: Cycle ratio accumulation for both PDF-EDF and EDF-PDF interaction.

Consider a fatigue crack growth behaviour for two different strain amplitudes, ${}_1$ and ${}_2$ presented in Figure 4 where a_o is the initial defect size, a_t is the transition crack size and a_f is the final crack length at complete fracture. It can be seen from Figure 4 that both a_t and the fraction of total fatigue life spent on stage II crack propagation increases with increasing strain amplitudes. As an example, in a High-Low sequence, assuming that a fraction (X_1) of fatigue life at ${}_1$ is initially applied before changing to ${}_2$, Palmgren-Miner rule predicts that the fraction of fatigue life remaining at ${}_2$ is 1-X_1. According to the fatigue crack growth curve for ${}_{1,}$ cyclic fatigue for X_1 fraction of life generates a fatigue crack of length, a_1. Assuming that the crack continues to grow from a_1 when stress amplitude is changed from ${}_1$ to ${}_{2,}$ one finds that a crack length of a_1 corresponds to a fraction life X_2 at ${}_{2,}$ which is >X_1, meaning that the actual fatigue life remaining is 1-X_2 instead of 1-X_1 and the summation of cycle ratios is <1. Conversely, in a Low-High loading sequence, if Y_2 fraction of fatigue life at ${}_2$ is applied, a crack corresponding to a length a_2 is generated. At ${}_{1,}$ a_2 corresponds to life fraction Y_1 which is < $Y_{2,}$ suggesting that the actual fatigue life remaining 1-Y_1, is > 1-Y_2 and the summation of cycle ratios is >1.

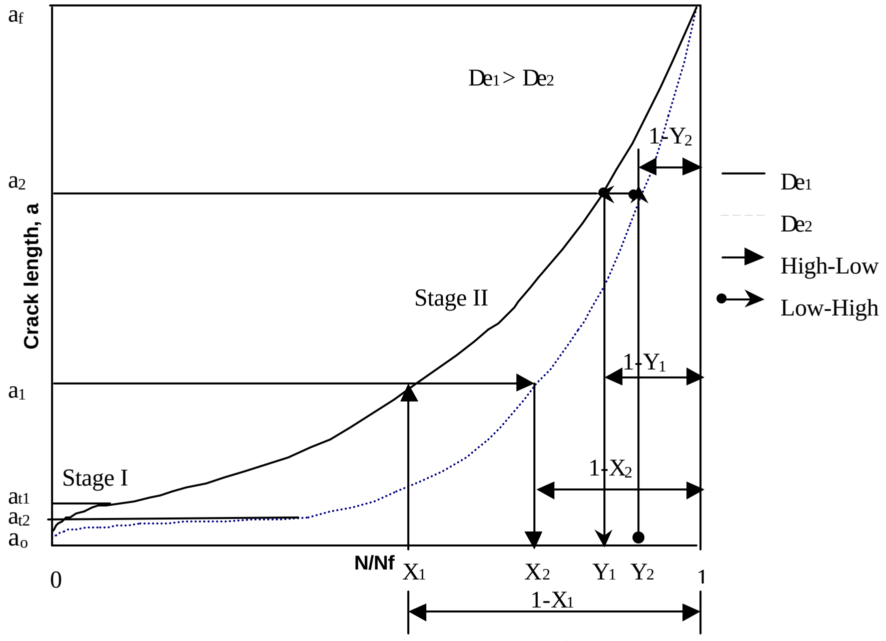

Figure 4: Fatigue crack growth behaviour at different strain amplitudes.

While the above model may help explain sequence effects and fatigue trends in most multilevel loading cases, certain limitations have to be highlighted to ensure that this model is used discriminately. Firstly, the model does not take into account important crack growth factors such as crack closure, residual stress and mean stress effects. Hence, one would be expect discrepancies between fatigue accumulation trends rationalised using the above model and trends obtained experimentally to occur, especially in cases where mean stress, residual stress and closure effects are significant.

Significance of proper PDF and EDF classification

As mentioned in the introductory note, accurate definition of PDF and EDF is important when investigating any form of multilevel loading conducted under strain control. A great majority of results presented in past literature on multilevel loading failed to recognise this importance and regimes under which multi-level fatigue was conducted were not specified. Specification of the type of fatigue (PDF or EDF) loading for the various levels of loading involved, provides a great deal of information regarding the possible mechanisms which may be responsible for the interaction effects observed.

Mean stresses induced by prior high plastic strain levels can have a prominent role in affecting overall fatigue lives. Analysis of mean stress changes during PDF(1.0%)-EDF(0.3%) interaction (Figure 5) shows that a substantial tensile mean stress is induced by prior straining at 1.0% amplitude. Mean stress relaxation during EDF is marginal and tensile mean stress persists over the remaining life of the specimen. Figure 6 shows the changes in mean stress when transition from PDF to EDF occurs after the tensile phase of initial PDF. In this case, compressive mean stress is induced on transition and again minimal mean stress relaxation occurs over EDF. As evidenced in Figure 3, 2-step fatigue conducted with similar strain amplitudes show significantly different cycle ratio accumulation trends depending on the nature in which initial PDF ends. i.e. if transition from PDF-EDF occurs after PDF compressive phase, tensile mean stress is induced and cycle ratio summations tend to be < 1. Conversely, if transition from PDF-EDF occurs after PDF tensile phase, compressive mean stress is induced and cycle ratio summations take on values > 1.

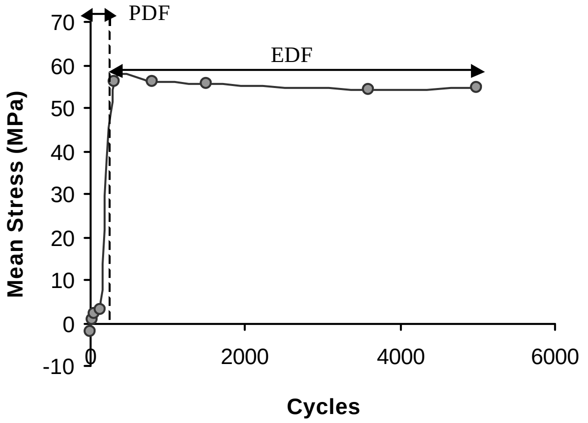

Figure 5: Mean stress changes for PDF(1.0%)-EDF(0.3%) interaction

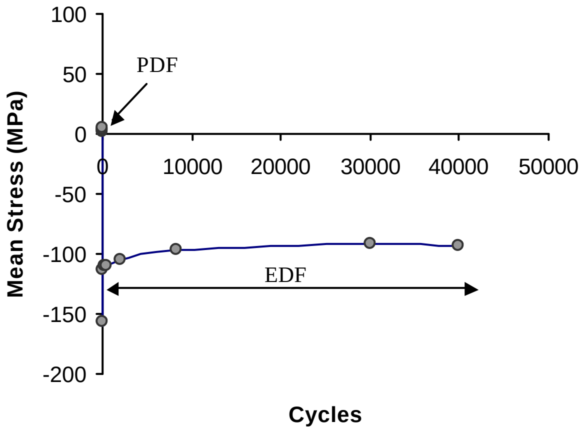

Figure 6: Mean stress changes for PDF(1.0%) after tensile phase-EDF(0.3%) interaction

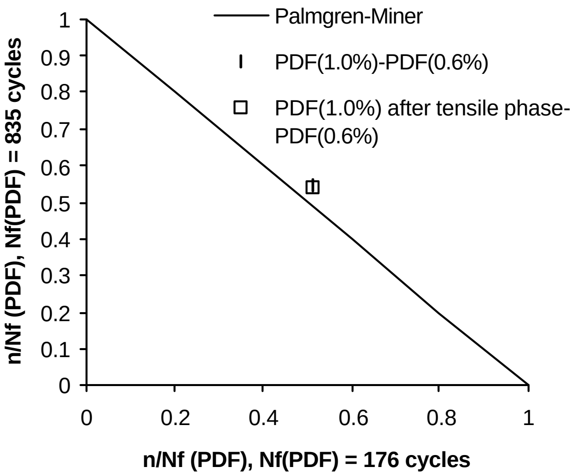

Figure 7: Cycle ratio accumulation for PDF(1.0%)-PDF(0.6%) interaction

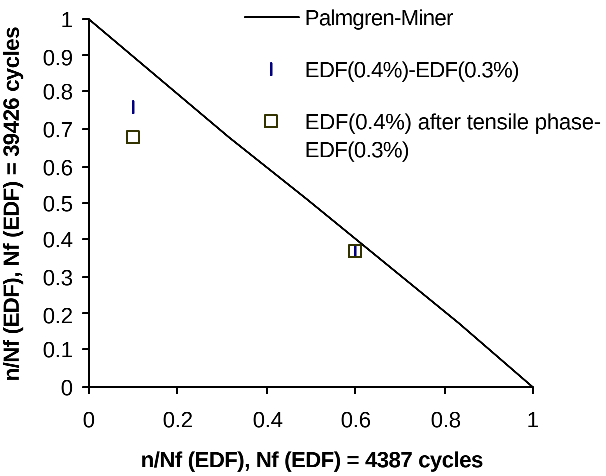

Figure 8: Cycle ratio accumulation for EDF(0.4%)-EDF(0.3%) interaction

Similar High-Low loading programs were implemented for PDF(1.0%)-PDF(0.6%) and EDF(0.4%)-EDF(0.3%) interactions. Figures 7 and 8 indicate that overall fatigue lives remain relatively unaffected regardless if initial strain level ended after a compressive or tensile phase. Zero mean stress is observed in the second stage of loading for all cases studied (Figures 9-12), further emphasising that mean stress plays no part in the interaction effects observed for PDF-PDF or EDF-EDF loading. Note that the negative mean stresses are observed in Figures 9-12 are the result of reduced crack opening tensile stress as rapid crack growth ensues on approach to fracture.

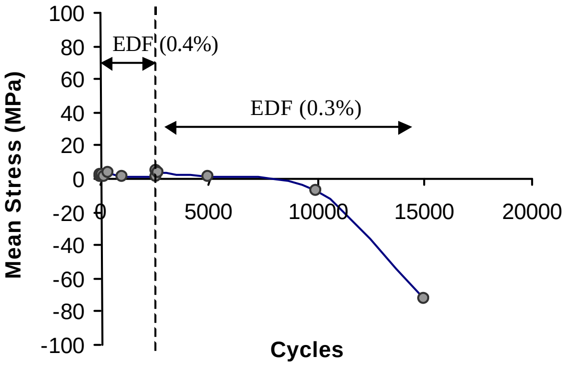

Figure 9: Mean stress changes for EDF(0.4%)-EDF(0.3%) interaction

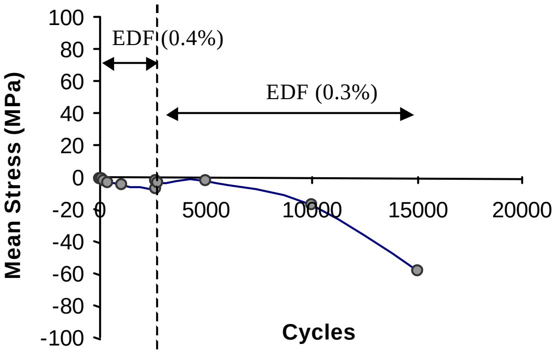

Figure 10: Mean stress changes for EDF(0.4%) after tensile phase-EDF(0.3%) interaction

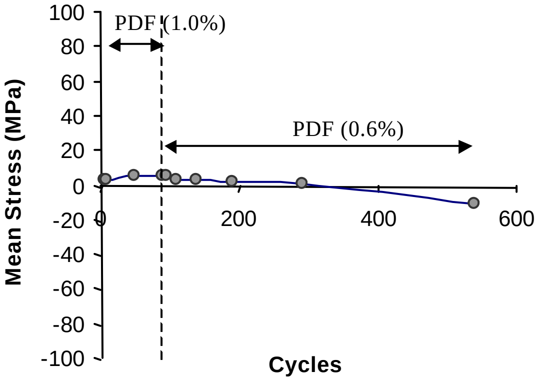

Figure 11: Mean stress changes for PDF(1.0%)-PDF(0.6%) interaction

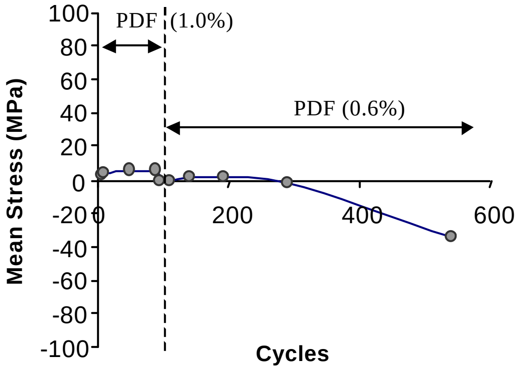

Figure 12: Mean stress changes for PDF(1.0%) after tensile phase-PDF(0.6%) interaction

CONCLUSION

1) High-Low sequences yield cycle ratio summations of <1 while Low-High sequences result in cycle ratio summations >1.
2) Mean stress effects are heavily involved in PDF-EDF interactions. Means stress induced (positive or negative) depends on the nature in which PDF ends (i.e. after compressive or tensile phase).
3) Mean stress plays no part in the interaction effects observed for PDF-PDF and EDF-EDF loading.
4) Proper definition and specification of the type of fatigue used in multilevel loading is important.

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