Influence of residual damage on static mechanical properties of 6082 aluminium alloy

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Abstract This investigation has been carried out in order to study the influence of the residual fatigue damage on the mechanical tensile and fracture toughness properties of a 6082-T6 aluminum alloy during high cycle fatigue. The results obtained show that, under the present experimental conditions, the tensile mechanical properties do not change with the amount of residual fatigue damage. The mechanical properties remain unchanged because in high cycle fatigue, the amplitude of plastic strain is smaller than low cycle fatigue where many works have showed that static mechanical properties change with increasing of numbers of cycle. However, the evolution of fracture toughness properties as the CODc and J_{1C} present a decreasing between 10 and 40% with fatigue damage to maximal stress applied of 275 and 200 MPa respectively. This decrease of the toughness parameters could be attributed to microcracks evolution during high cycle fatigue.

Keywords: *6082-T6 aluminum alloy, fatigue damage, tensile properties, toughness parameters, lifetime.*

1 INTRODUCTION

Fatigue damage increases with the application of load cycles in a cumulative manner. Cumulative fatigue damage takes a large place in life prediction of components and structures. Since the introduction of fatigue damage accumulation concept by Miner [1], many damage models have enlarged the Miner's approach by integrating non linear rules [2] and by taking into account the loading histories [3,4]. Fatigue damage is a process of continuous deterioration of material properties under cyclic loading [2]. The damage variable is dependent on the number of cycles and the magnitude of the stress and strain applied.

Static mechanical properties of a material, such as yield stress (Sy), ultimate strength (Su) and elastic modulus (E), as well as fracture toughness properties such as critical crack opening displacement (CODc) and critical value of J-integral (J_{1c}), are the most important and basic parameters in structural design, particularly in stress calculation and analysis of structural components and machine elements in service [5,6]. For most engineering structures and components operating under dynamic or alternating loading conditions, a common noticeable feature is that their service properties, especially mechanical properties deteriorate progressively with increasing lifetime [5,7]. This degradation in material mechanical properties due to cyclic loading, also called fatigue damage, seriously affects the service safety of structures and/or machines elements and thus is an important consideration in safe design against fatigue failure. On the other hand, remaining lifetime studies of engineering structures and/or machines elements in service generally requires the evaluation of the damage degree of fatigued materials [8]. Therefore, the investigation of the change in the static mechanical properties of engineering materials subjected to cyclic loading and the correlation of such a change with fatigue damage evolution is of utmost practical interest.

The fatigue behavior of engineering alloys, including cyclic hardening/softening properties, cyclic stress–strain, S/N and ε/N curves, etc., have been widely investigated. However, only relatively few studies have been focused on the behavior and changes in the static mechanical properties of such materials during cyclic loading and the vast majority of such studies have been conducted under low cycle fatigue (LCF) conditions [9,10].

Thus, this present investigation has been carried out in order to study the change in static mechanical properties and fracture toughness parameters (critical value of the energetic parameter J (J1c), critical value of crack opening displacement (CODc) and tearing modulus T(J)) of 6082-T6 aluminum alloy subjected to high cycle fatigue (HCF) and to obtain a better understanding of its mechanical behavior, such that it could be used in remanent life analysis. This aluminum alloy constitutes a very important engineering material widely employed in land transportation applications, for the manufacture of different parts and components, due to its high strength-to-density ratio. The variation in both the static mechanical properties and in the fracture toughness parameters of this alloy, as well as the correlation between such changes and the evolution of fatigue damage during HCF, are then discussed on the basis of the experimental results.

2 EXPERIMENTAL PROCEDURES

The present investigation was carried out with samples of a 6082-T6 aluminum alloy of the following composition (wt %): 0.6 Zn, 0.6 Mg, 0.06 Cu, 0.24 Fe, 0.70 Si, 0.90 Mn, 0.02 Cr, and Al bal. The material was supplied as sheets of 1 x 1000 x 1500 mm, from which a number of tensile and fatigue specimens were machined following the ASTM standards E8-04 and E466-96, respectively.

The experimental program was conducted in the following sequence:

a) Tensile tests using virgin specimens were carried out in order to determine the initial mechanical properties (elastic modulus E_o, yield strength S_{yo} and ultimate strength S_{uo}.)

b) A number of specimens were subjected to HCF (R = 0.1) up to failure, at two different maximum alternating stresses, which allowed the determination of the number of cycles to failure, N_f.

c) The measurement of post-fatigue static mechanical properties was carried out as follows. First, specimens were previously subjected to cyclic loading. After applying a specified number of cycles, N, equivalent to a given lifetime at each stress amplitude, the specimens were tested in tension in order to evaluate their mechanical properties (E_N, S_{yN} and S_{uN}).

d) Pre-cyclic tests were performed under the same testing conditions as indicated in (3), in order to determine the fracture toughness properties. The machining of the fracture toughness samples involved the introduction of a notch, normal to the tensile axis, located in the middle section of the pre-fatigued specimens to a different degree of damage. The notch was machined by means of a diamond disc to avoid the introduction of residual stresses. In order to measure the COD and crack propagation, a fixed digital camera was employed.

Fatigue tests were conducted under axial push–pull stress-controlled conditions (R= 0.1) at a frequency of 25 Hz. The selected maximal stresses were of 200 and 275 MPa. The corresponding total number of cycles to failure was of 3 x 10^6 and 70 x 10^3, respectively. The pre-fatigue tests were interrupted after the specimens survived a predetermined fatigue damage degree, N/N_f, (between 0.25 and 0.70). All tests were conducted in air at room temperature. The tensile, fatigue and tearing tests were all conducted on a 100 kN conventional INSTRON servo-hydraulic machine. In every case, for the evaluation of the static and toughness mechanical properties, not less than 3 samples were tested, to represent each data point on the graphs. Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) examinations were performed using a Nikon Epiphot and a JEOL JSM6480 LV, respectively.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Static mechanical properties after fatigue damage

The static mechanical properties for each fatigue damage degree, N/N_f, and maximum stress applied are given in Table I. It can be observed that after fatigue damage the static mechanical properties remain almost unchanged. Such results can be interpreted in terms of the small plastic strain amplitude achieved in HCF, in comparison with those achieved in LCF. Previous investigations have shown that under the latter conditions, the static mechanical properties of the material vary with the number of cycles applied [7,9,10].

Table I. Elastic modulus, *E*; Yield stress, *Sy* and Ultimate Strength, *Su* after fatigue damage for each maximal level stresses applied.

N/Nf%	σmax (MPa)	E (GPa)	Sy (MPa)	Su (MPa)
0	200	72	300	345
25		72	297	342
50		72	300	344
75		73	298	345
0	275	72	300	345
25		70	300	346
50		71	305	342
75		72	297	341

3.2 Toughness properties after fatigue damage

The toughness parameters determined for each fractional lifetime at the corresponding maximum stress applied, after fatigue damage, are presented in Table II and the change in the parameters normalized by the values obtained with the virgin samples (N=0) are shown in Figures 1–2.

It can be observed from Figure 1 that the CODc decreases with fatigue damage in 5 and 40%, approximately when the maximum alternating applied stress decreases from 275 to 200 MPa, respectively. Figure 2, on the other hand, shows that the J-integral also decreases with fatigue damage between 20-25% for the same change in alternating stress. On the other hand, the tearing modulus T(J), which describe the crack propagation in static loading is not sensitive to the damage accumulated and to the maximum stresses applied in fatigue loading (Table II).Theses results show that fatigue damage has an influence on the toughness properties.

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Table II. Critical crack opening displacement, CODc; Critical J-integral, J_{1c} and tearing modulus, T(J) after fatigue damage for each maximal level stresses applied.

N/Nf%	σmax (MPa)	CODc (mm)	J1c (kJ/m^2)	T(J) (kJ/m^2/mm)
0	200	0.823	104	33
20		0.753	88	36
50		0.639	81	36
70		0.489	78	38
0	275	0.823	104	33
25		0.697	104	32
40		0.802	90	31
70		0.758	93	29

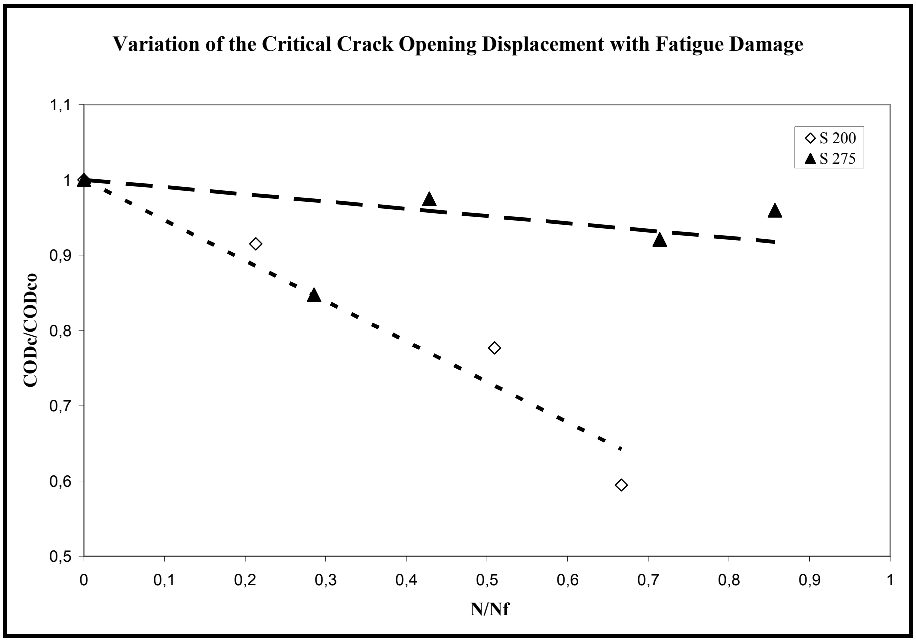

Figure 1. Variation of critical crack open displacement with fatigue damage

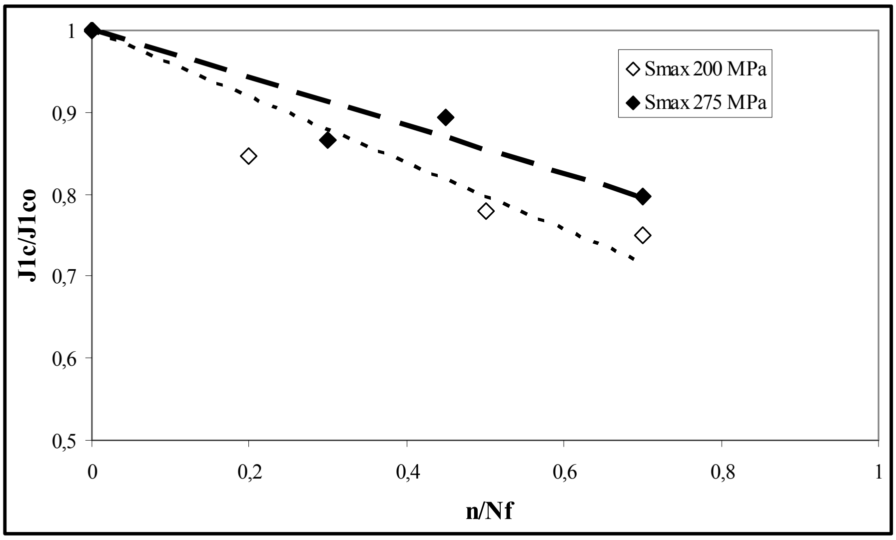

Figure 2. Variation of the critical J - integral J_{1c} with fatigue damage

3.3 Micrographic observations

3.3.1 Specimen surface observations

Figure 3a shows the smooth surface of the virgin material, where only precipitations and/or inclusions (not analyzed) are present. Figures 3b and 3c show surface of the pre-fatigued specimens at 70% of fractional lifetime for 275 and 200 MPa, respectively. Intergranular microcracks with an average size of 18 μm due to fatigue damage at higher stress applied were observed (Fig 3b). Microcracks observed for lower stress were shorter with an average size of 10 μm (Fig. 3c). It is worth to notice that they have initiated in the precipitations and propagated rather transgranulary and perpendicular to load direction.

3.3.2 Fracture surface observations

Figure 4 shows the fracture surface after tearing test at the initiation of the tearing crack propagation zone. Effect of coalescence of microcavities during tearing of virgin alloy typical for ductile fracture is shown in Fig. 4a. Figures 4b and 4c show the fracture surface after tearing test for the specimens with 70% fractional lifetime and for maximum stresses applied of 275MPa and 200MPa, respectively. Mixed brittle – ductile fractures were observed for both cases with microcracks perpendicular to load direction which are generally longer (100 μm) than fatigue microcracks observed in OM (Fig. 3b, c).

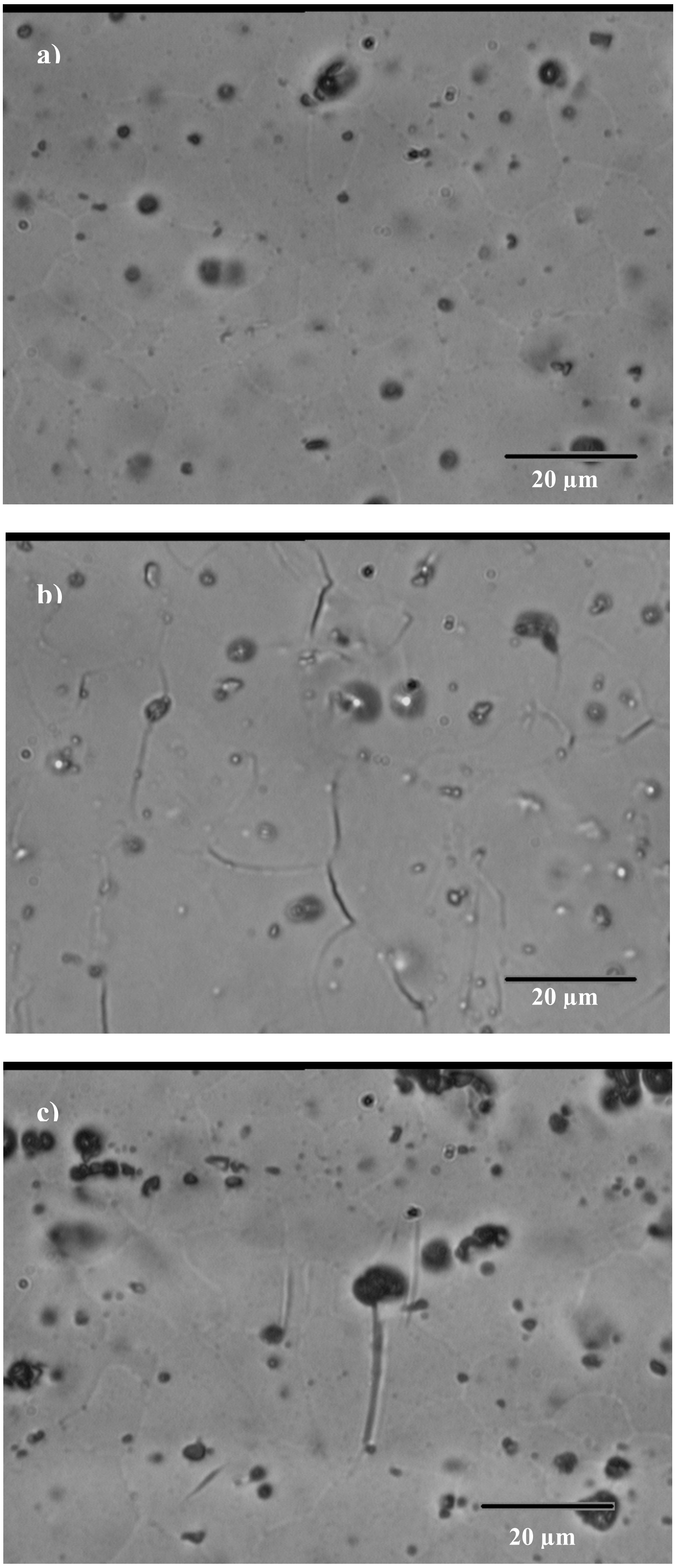

Figure 3: Electropolished surface observed in OM of specimens pre-fatigued with different fractional lifetime (n/Nf) and maximum stresses applied (Smax): a) virgin; n/Nf=0; b) n/Nf=70%; Smax=275MPa; c) n/Nf= 70%; Smax=200MPa.

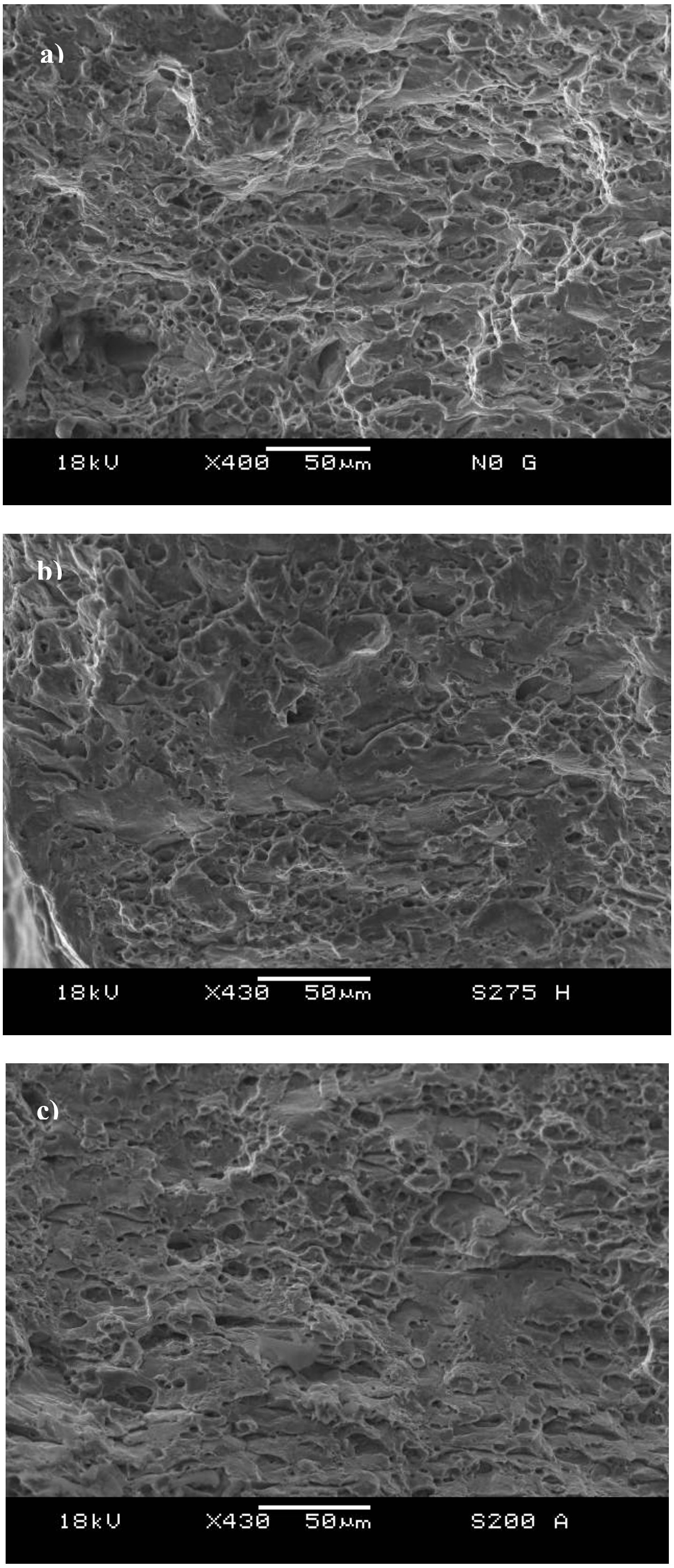

Figure 4: Fracture surfaces of specimens after tearing test for different fractional lifetime (n/Nf) and maximum stresses applied (Smax) located at the initiation of crack propagation zone: a)virgin; n/Nf=0; b) and c) n/Nf=70%; Smax=275MPa and Smax= 200MPa.

4 CONCLUSIONS

The static mechanical properties evaluated by means of tensile tests conducted after fatigue damage (E, Sy, Su, K and n) were weakly affected by the fractional lifetime n/N_f, whereas the global (J_{1c}) and local (CODc) parameters were quite sensitive to the residual damage induced by HCF. On the other hand the tearing modulus T(J) was not affected by fatigue damage in the HCF. These results are full of promise, they deserve to continue in this way to identify correlations between the static and toughness properties with the fatigue damage in HCF. In order to understand better the mechanisms that govern the evolution of theses parameters during cyclic loading under HCF conditions, further work is being carried out, particularly addressed to the analysis of aluminum alloy by means of transmission electron microscopy and X-ray diffraction analysis.

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