Fatigue Fracture and Residual Stress Relaxation in Shot-Peened Components

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ABSTRACT

This work is devoted to highlighting the beneficial effects of compressive residual stresses, their relaxation and the associated fatigue crack initiation and propagation in two contrasting materials. Accordingly, rotating bend fatigue tests were conducted on essentially un-notched specimens made from 7075 T7351 aluminium zinc alloy and 080M40 medium carbon steel. The tests involved assessing the life of un-peened, peened, and re-peened specimens where re-peening was applied after the exhaustion of a proportion of the specimens anticipated fatigue life. Whilst the steel demonstrated a very significant recovery of fatigue life associated with the re-peening treatment, this was not the case for the aluminium even though peening had proved highly beneficial. Residual stress measurements and fractographic examination were used to elucidate this discrepancy.

INTRODUCTION

It is now well established that residual stresses are present in nearly all engineering components and that they may profoundly influence the fatigue life of such components. The establishment of current techniques for residual stress measurement makes it possible to evaluate and hence take advantage of or allow for the influence of residual stresses. Some success has been encountered in the consideration of welding residual stresses and their influence on fatigue strength [1]. Attempts to evaluate peening in a similar way are less prevelant in the literature, but some work exists on the relaxation of peening residual stresses, [2], and on the effectiveness of periodic re-peening, in further extending the fatigue life of critical components [3], [4]. This study is concerned with establishing the way in which shot peening influences the fatigue fracture process and how peening and re-peening partially fatigued components can be best exploited.

MATERIALS AND METHODS

The selection of the materials tested reflected the desire to test alloys typical of those in current usage. This, together with their differing defect distribution, crystal structure and strengthening mechanisms prompted the current choice. The 7075 aluminium zinc alloy was in the T7351 condition, i.e., overaged for optimum stress corrosion resistance, and uniaxially stretched to control residual stresses. It possessed an essentially equiaxial grain structure with a grain size of 70µm and a significant volume fraction of strings of inter-metallic particles ranging in size from 10 - 25µm. Its yield strength was 450MPa and its ultimate was 530MPa. The 080M40 medium carbon steel, with manganese, was in a slow cooled condition, possessing a microstructure of coarse pearlite and ferrite. Its grain size was 100µm and it contained strings of rounded manganese inclusions of around 10µm.

The experimental programme was conducted using a specially built four-point rotating bend fatigue test rig which was capable of testing specimens of large diameter. It was calibrated using slip rings and a strain gauged specimen. Testing was performed at 50Hz in ambient conditions and the specimen gauge diameter was 12mm. The stress concentrator used was a 35mm radius and the overall diameter of the specimen was 34mm giving a value of stress concentration factor K_t near 1.1.

Peening was performed in a direct air pressure single nozzel system using a shot of 600 to 800µm diameter and a Hv hardness of 590-690 MPa. The peening conditions created Almen arc heights of 250µm 'A' for the aluminium and 400µm 'A' for the steel.

The fatigue testing program set out firstly to establish the life versus applied stress range relationships for the two materials in the peened and unpeened condition, and secondly to more closely examine the regime corresponding to $10^5 - 10^6$ cycles to failure. Such a regime is between the extremes of L.C.F. where rapid relaxation might be anticipated, and H.C.F., where relaxation may or may not be present. It also corresponds to a number of industrial applications, such as pressure vessels and landing gear assemblies.

RESULTS AND DISCUSSION

Figures 1(a) and 1(b) show the overall fatigue life of the aluminium and steel specimens as a function of the applied cyclic load. It may be noted that the improvements due to peening in the $10^5 - 10^6$ cycles to failure (N_f) regime is more significant in the aluminium alloy. This may be accounted for by the fact that this regime corresponds to applied stress of $\pm 0.9\sigma_y$ in the case of the steel rather than $\pm 0.5\sigma_y$ in the case of the aluminium. The improvement in the peened life of the steel at applied stresses beyond the yield stress indicates that work hardening of the exposed surface layers plays a significant role in this situation.

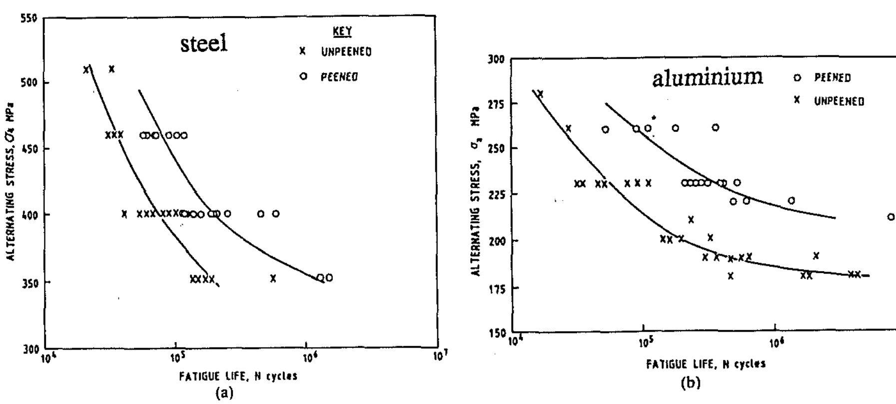

Figure 1. S-N. Curves for both materials in the un-peened and peened conditions

Figure 2 shows the response of the specimens to a re-peening treatment performed on peened specimens which had been fatigued to a known proportion of their fatigue life. It can be seen that whilst the steel specimens show essentially complete recovery of their peened life after re-peening, the aluminium ones are austensively not affected.

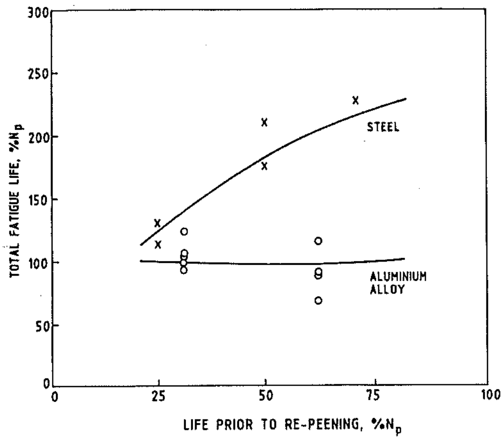

Figure 2. Total fatigue life as a function of cycles elapsed prior to re-peening

Figure 3 depicts the residual stress both at the surface and in the sub-surface regions in peened specimens subjected to cyclic loading to a known proportion of their anticipated life. Both of these results and those depicted in Figure 2 relate to applied loads of ±230 MPa for the aluminium and ±400 MPa for the steel. It can be seen that the residual stresses in the steel specimens relax more considerably than the fatigue strength improvement associated with peening. The aluminium specimens, however, did not show this trend. A consideration of the superposition of the peak compression load, and the residual compressive stress initially present in the steel also demonstrates the significance of work hardening effects.

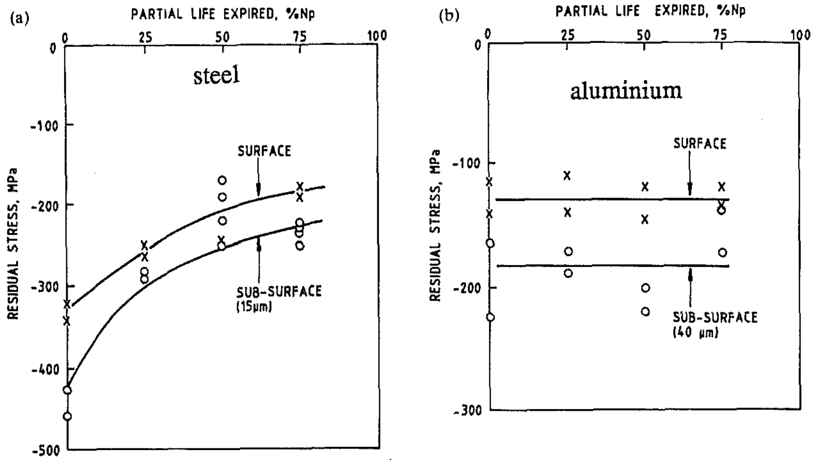

Figure 3. Relaxation of residual stress at and near the surface as a function of used life

Figure 4 depicts parts of a fracture surface typical of those encountered in the peened aluminium specimens. This sub-surface crack initiation was not observed in the un-peened specimens. This accounts for the observation that little or no residual stress relaxation was observed in the peened aluminium prior to failure.

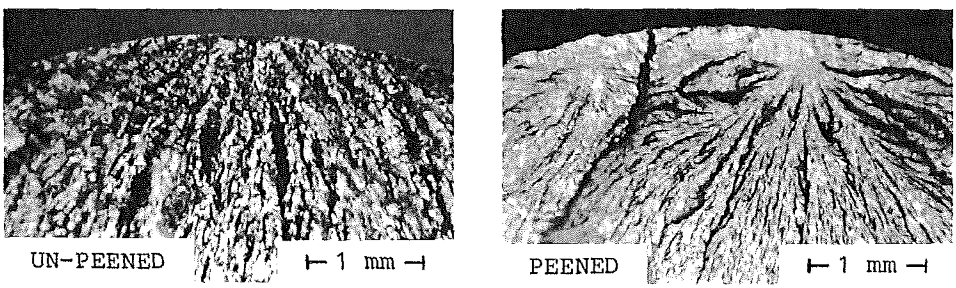

Figure 4. Fracture surfaces typical of those encountered in the aluminium in the un-peened and peened conditions

CONCLUSIONS

The present work was devoted to examining the fatigue fracture behaviour of 7075 T7351 aluminium alloy and 080M40 medium carbon steel in the presence of shot peening residual stresses. The findings may be summarized as follows:

(i) The peening treatment enhanced the fatigue life of both materials appreciably. This is due to the presence of compressive residual stresses in the vicinity of the surface, though there exists a large discrepancy between the magnitude of the residual stress and the fatigue strength improvement it yields.

(ii) The re-peening of partially fatigued specimens showed a marked effect on the steel specimens but not on the aluminium ones. This may, in part, relate to the greater degree of residual stress relaxation observed in the steel specimens prior to fracture.

(iii) The peening treatment promoted sub-surface crack initiation in the aluminium alloy. This was not observed in the steel. Clearly the development of sub-surface cracks will influence the effectiveness of the re-peening process as well as explains the lack of surface stress relaxation prior to failure in the aluminium alloy.

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