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Experimental investigation and fatigue life prediction for 7475-T7351 aluminum alloy with and without shot peening-induced residual stresses

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Abstract

The effect of shot peening on small crack growth and on the fatigue life of 7475-T7351 aluminum alloy has been investigated. The experimental results show that cracks initiate at second phase particles in the alloy and that fatigue crack growth rates are greatly reduced after shot peening treatment. Stress intensity factors for small cracks subjected both to external loads and to shot peening-induced residual stresses have been determined using weight function methods. Small crack growth rates and fatigue lives of naturally occurring small cracks in shot peened and unpeened specimens were calculated using small crack theory and a crack closure model. The predicted results agree well with the experimental data. The study demonstrates that fatigue life extension by shot peening can be attributed to beneficial compressive residual stresses in the surface layer, that the principle of superposition is applicable to fracture mechanics, and that the effect of residual stress on crack growth can be quantitatively analyzed using weight function methods. It is shown that the total fatigue lives for materials/structures containing residual stresses can be predicted by the crack closure-based small crack theory, provided that residual stresses are properly taken into account.

Keywords: Small crack growth; Shot peening; Residual stresses; Fatigue life prediction; Weight function method

1. Introduction

Fatigue fracture is one of the main causes of failure for aircraft materials and structures. High strength aluminum alloys are widely used to manufacture aircraft structural components and extensive experimental investigations on the fatigue of aluminum alloys have shown that small crack growth from initial material defects to about 1 mm in length often occupies over 80% of the total fatigue life. For many structural engineering components the fatigue life is therefore dominated by the small crack growth stage. It is thus of great practical importance to be able to predict fatigue lives based on small crack growth analysis.

Various surface strengthening methods, such as shot peening [1], laser shock peening [2] and hole cold expansion [3], are utilized in the aircraft industry to increase component fatigue lives. Among these surface enhancement processes, shot peening is widely used due to its ease of operation, the high production rate achievable, and the good surface integrity obtained. The effects of shot peening on fatigue strength/limits have been studied quantitatively and reported in the literature [4]. However, only a few investigations have considered the effects of residual stress fields induced by shot peening on fatigue small crack growth. Because fatigue lives are dominated by the small crack stage it is important to quantify the effect of surface strengthening processes on small crack growth.

Early studies on various aircraft materials have made successful fatigue life predictions using small crack theory [5–9]. However, none of these studies have considered the

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effect of residual stresses caused by shot peening. There are two key questions to be solved in predicting fatigue lives using small crack theory for cracks in residual stress fields. One is how to accurately determine the residual stress distribution caused by shot peening, the other is how to calculate stress intensity factors (SIFs) for cracks in residual stress fields with steep gradients in the material surface layer. For the first problem advanced X-ray diffraction methods can be used to determine residual stresses. Recently developed non-destructive techniques, such as neutron scattering and synchrotron radiation techniques, can also be used to measure subsurface residual stresses. For the second problem the weight function method can be employed. This method is powerful and can be used to accurately determine SIFs, and is especially suited for complex residual stress fields involving steep gradients. The powerfulness of the weight function method stems from the fact that a weight function is solely a property of the crack geometry and, once derived, can be used for the same geometry to determine SIFs for any loading through simple quadrature. Weight functions for various two-dimensional (2-D) and three-dimensional (3-D) crack problems are given in detail for many load cases in Wu and Carlsson [10], Zhao et al. [11], and Fett and Munz [12].

The main objectives of the present study are to investigate the effect of shot peening on small crack growth behavior, to develop methods for quantifying the effects of shot peening-induced residual stresses on small cracks, and also to explore the possibility of applying a total fatigue life prediction methodology based on small crack theory to problems where residual stresses are involved.

2. Material and experimental procedure

2.1. Material

The widely used high strength aluminum alloy 7475-T7351 was chosen for the present investigation. This alloy has a fine grain size and an optimized precipitate dispersion, and so has a good combination of high strength and good toughness. A plate of 20 mm thickness was cold rolled to 10 mm and all fatigue samples were cut along the rolling direction. The specimens were heat treated at 743 K (470 °C), then water quenched, and then stretched to 2%. Following this the samples were given a first aging at 394 K (121 °C) for 24 h and then a second aging at 436 K (163 °C) for 24 h. The chemical composition of the plate is listed in Table 1 and the relevant mechanical properties are presented in Table 2. A typical microstructure of a heat-treated specimen after the second aging treatment is shown in Fig. 1.

2.2. Experimental procedure

A single edge notch tensile specimen (SENT), shown in Fig. 2, was used to produce naturally initiated cracks. The notch is semicircular with a radius (r) of 3.2 mm, specimen width (w) of 50 mm, thickness ($B = 2t$) of 5 mm and distance between grip lines of 200 mm. The semicircular geometry provides easy access to the notch surfaces to allow monitoring of the cracks by replicas. Shot peening was conducted on a pneumatic machine at an intensity of 0.20 mm (Almen strip A) and surface coverage of 100%, using S110 steel shot under an air pressure of 0.25 MPa. Residual stresses were determined using an X-ray diffraction stress analyzer (X-3000) combined with layer by layer electropolishing [13]. A Cr Kα X-ray source was used at a voltage of 20 kV and current of 8 mA. Prior to fatigue testing the specimens were electropolished for 4 min in a solution of 80% ethanol and 20% perchloric acid to obtain a good surface finish and to reduce any surface residual stresses induced by the machining process. This process may, however, remove a thin layer (to a depth of 20 μm) of

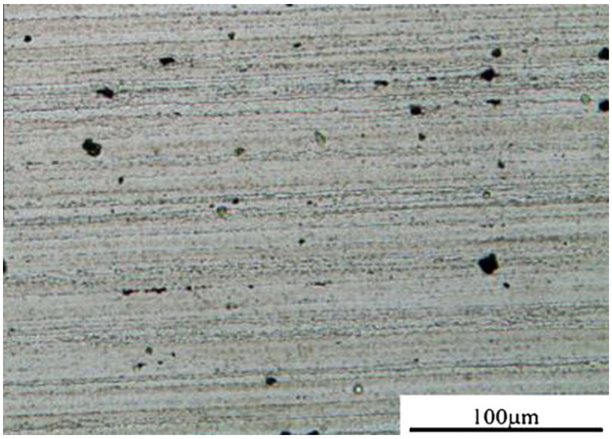

Fig. 1. Microstructure of the 7475-T7351 aluminum alloy.

Table 1
Chemical composition of the 7475-T7351 aluminum alloy (wt.%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.01	0.053	1.43	0.0016	2.42	0.22	5.70	0.013	Balance

Table 2
Mechanical properties of the 7475-T7351 aluminum alloy.

Material	$R_{p0.2}$ (MPa)	R_m (MPa)	Elongation (%)	Reduction in area (%)
7475-T7351	450	528	13.3	44