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Reverse bending fatigue of shot peened 7075-T651 aluminium alloy: The role of residual stress relaxation

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ABSTRACT

The effect of different shot peening treatments on the reverse bending fatigue behaviour of Al-7075-T651 was studied. The fatigue improvements with respect to the unpeened condition and the influence of the peening intensity on fatigue were discussed accounting for the effects of surface modifications (roughness and strain hardening) and of residual stresses. In particular the extent of the residual stress redistribution during loading was investigated by means of X-ray diffraction (XRD) measurements. No significant residual stress relaxation was observed in samples tested to a load level corresponding to the fatigue endurance at $5 \cdot 10^6$ cycles. Residual stress relaxation was observed only when the material plastic flow stress was achieved during the compressive part of the fatigue load cycle. Accordingly, shot peened samples with deep sub-superficial compressive residual stress peak showed a fatigue endurance level corresponding to the condition of incipient plastic flow. This phenomenon was also accompanied by sub-superficial fatigue crack initiation. On the contrary, samples tested at shorter fatigue lives showed crack initiation close to the surface. The initial and the stabilized residual stress profiles were considered for discussing the improvement in the fatigue behaviour due to peening. For this purpose, a multiaxial fatigue criterion was adopted to account for the biaxial residual stress field. The fatigue life was quite accurately predicted as long as fatigue initiation occurs on the surface.

1. Introduction

High-strength aluminium alloys are widely used in aerospace applications due to a very favourable strength-to-weight ratio. Strengthened aluminium alloys, such as those of the 7xxx series, exhibit, despite high tensile strength values (greater than 500 MPa), a relatively low fatigue resistance: the fatigue endurance in the high-cycle fatigue regime (>5 millions cycle) is about 140 MPa [1]. Since the majority of fatigue cracks initiate on the surface, the conditioning of the surface to resist crack initiation and earlier crack growth is an attractive method of improving fatigue performance. For this reason, aluminium alloys are frequently subjected to surface treatments. For instance, shot peening has always received particular attention, allowing for noticeable increments in the fatigue life of mechanical components [2–6]. In the literature, the major part of this improvement has been almost unanimously attributed to the introduction of compressive residual stresses in the surface region, which very often overcompensates the worsening of surface morphology and microstructure caused by shot impacts [3–8]. Some investigations, however, pointed out that, owing to compressive surface residual stresses, the crack initiation site may move from the surface to the interior of the sample or even into the tensile residual stress region beneath the surface hardened layer, especially in the high-cycle fatigue regime [9,10].

In some cases, the shot peening treatment is responsible for beneficial microstructural transformations such as stress induced martensitic transformation of the retained austenite in carburized steels [11]. The microstructural effect of shot peening in aluminium alloys is ambiguous. On one side, work hardening is responsible for enhanced resistance to crack initiation, on the other side it causes lower crack growth resistance due to material embrittlement [12]. Taking into account the controversial effects exerted by the peening treatment on the surface layers, some indications about the process parameters have been identified in order to maximize the fatigue performance. For instance, peening of soft materials, like aluminium alloys, with steel shot, widely used for high-strength steel and titanium alloys, is known to be quite detrimental to fatigue performance. Luo et al. [13] showed that the rough peened surface of 7075-T6 aluminium specimens significantly lowered the beneficial effect on the fatigue behaviour with only a net increase of 7% in fatigue life. On the contrary, peening with lighter media such as glass or ceramic beads improves the fatigue resistance due to the decreased surface roughness [4]. In addition, aluminium alloys for aerospace

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Nomenclature

D_p	mean spacing of adjacent roughness peaks
f_{-1}	alternate fatigue strength
f_0	pulsating fatigue strength
$HV_{0.1}$	Vickers microhardness (1 N load)
k	slope of the Wöhler curve
K_t	stress concentration factor
N	number of cycles
p_m	hydrostatic pressure
R	stress ratio
R_a	average roughness
R_q	root mean square roughness
R_t	mean value of the peak-valley distance determined on a specific measurement length
$T\sigma$	scatter of fatigue results
α, β	parameters of the equation representing the Sines criterion
σ_{P50}	fatigue endurance with a failure probability of 50%
σ_{0P50}, k	parameters of the S–N curve
$\sigma_{1,2,3}$	principal stress components
$\sigma_{5\cdot 10^6}$	fatigue endurance corresponding to $5 \cdot 10^6$ cycles
σ_Y	cyclic yield stress
σ_a	stress amplitude
σ_m	mean stress
σ^{RS}	residual stress
σ_{eq}	equivalent stress

applications, such as those of the 7xxx series, are preferably shot peened using ceramic beads rather than steel shots in order to prevent the surface from ferrous contaminations that induce undesired galvanic effects.

Since the larger contribution of shot peening to enhance fatigue performance is given by compressive residual stresses, it is of paramount importance to understand whether the initial residual stress field remains stable throughout the service life. For this purpose, relaxation and redistribution of residual stresses occur when the summation of the residual stress and applied stress due to subsequent mechanical loading exceeds the yield condition of the material [14,15]. In addition, repeated fatigue cycling may induce residual stress relaxation, even when the mechanical load cycles do not cause macroscopic plastic deformation [16]. The extent of cyclic stress relaxation depends on applied loads as well as on the tendency of many materials to exhibit cycle-dependent softening in the surface layer because of the intense cold working introduced by the treatment. This topic has received extensive attention in the literature, especially for conventional and stainless steels as well as titanium alloys [17]. More limited is the amount of information available on relaxation of residual stresses in shot peened aluminium alloys: moderate relaxation has been reported for 2024 and 6082 aluminium alloys [6,18,19], relaxation in lesser extent was found in bending fatigue of 7075 alloys, especially at higher load levels [20,21]. Notably, most changes in the residual stress profile occurred on the first cycles, like a static effect [22]. Moreover, no discernable relaxation was found in this alloy at load levels approaching the high-cycle fatigue endurance [23].

In the present work, these aspects are considered for studying the fatigue behaviour of the Al-7075-T651 alloy, subjected to three different controlled shot peening treatments. Peening intensity was varied to have different initial residual stress profiles and surface microstructural conditions. An extensive analysis of the residual stress field was carried out by measuring with the X-ray diffraction (XRD) technique the residual stress profile before and at the end of the fatigue tests, so as to investigate the onset of a stabilized residual stress field. The dependence of the residual stress relaxation on the material's work hardening as well as on the applied cyclic load was studied. Fatigue crack initiation sites have been investigated through scanning electron microscopy (SEM) fractography and the role of surface roughness on fatigue resistance has been analyzed. The initial and the stabilized residual stress profiles were used to discuss the improvement in the fatigue response in the hypothesis of crack initiation and early crack propagation as fatigue controlling parameters. For this purpose, a multiaxial fatigue criterion was adopted to account for the residual stress field.

2. Experimental procedure

2.1. Material and mechanical testing

The experimentation was performed on the Al 7075 alloy, widely used for aeronautical applications, supplied in the form of 4 mm thick rolled plate. The material received the T651 thermo-mechanical treatment, consisting in a solution heat treatment for 30 min at 748 K, a water quenching, a stress relief by stretching to give a permanent elongation strain of 2.5% and a final aging at 394 K for 6 h. The resulting microstructure, shown in Fig. 1, consists of a fine dispersion of $Cr_2Mg_3Al_{18}$ and $(Fe,Mn)Al_6$ intermetallic precipitates, responsible for the high mechanical properties of the material. Equiaxial pancake grains were observed on the rolling plane (Fig. 1a). The grain size varies from 50 μm to 100 μm. The average grain size is approximately 70 μm. On the cross section through the plate thickness (Fig. 1b), highly elongated grains were observed as a consequence of the intense cold rolling. The average thickness of grains is approximately 10 μm.

Monotonic tensile tests (initial strain rate of $1 \cdot 10^{-3} s^{-1}$) were performed in the longitudinal (L) orientation using plane hourglass specimens (Fig. 2a). The results, summarized in Table 1, show a yield stress higher than 500 MPa, combined with a good material ductility (total elongation of 18%).

To evaluate the cyclic stress–strain behaviour, reverse strain axial testing was performed in the *L*-orientation by single-step on plane hourglass specimens similar to those used to determine the monotonic tensile properties. Specifically, the tests were performed at a strain rate of $1 \cdot 10^{-4} s^{-1}$ and at strain amplitudes ranging from 0.006 to 0.014. The tests were started in compression and carried out up to saturation of the tension and compression peak stresses (after about 15–20 cycles). The results thereof will be presented in Section 3.4.

The fatigue characterization was performed on prismatic specimens whose geometry, according to the standard ISO 3928, is illustrated in Fig. 2b. The microstructure was tested with the stress axis parallel to the *L*-direction. The fillet radius is large enough to make any notch fatigue effects negligible.

Part of the fatigue specimens was subjected to different controlled shot peening treatments. Fused ceramic beads were employed, which were found to induce a higher fatigue strength improvement as compared to steel shots without introducing undesired galvanic effects. The ceramic material composition and its mechanical properties are listed in Table 2. An air-blast machine, whose parameters are reported in Table 3, was utilized to perform three types of shot peening treatments, illustrated in Table 4. The basic idea was to apply a widely used commercial peening treatment, termed CE-Z425, employing beads of medium size