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High- and very high-cycle plain fatigue resistance of shot peened high-strength aluminum alloys: The role of surface morphology

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ABSTRACT

The present paper is aimed at investigating the effect of shot peening on the high and very-high cycle plain fatigue resistance of the Al-7075-T651 alloy. Pulsating bending fatigue tests ($R = 0.05$) were carried out on smooth samples exploring fatigue lives comprised between 10^5 and 10^8 cycles. Three peening treatments were considered to explore 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. Fatigue crack initiation sites were investigated through scanning electron microscopy (SEM) fractography. The surface morphology modifications induced by shot peening were evaluated using an optical profilometer. The influence of surface finishing on the fatigue resistance was quantified by eliminating the surface roughness in some peened specimens through a tribofinishing treatment. The capability of shot peening to hinder the initiation and to retard the subsequent propagation of surface cracks is discussed on the basis of a model combining a multiaxial fatigue criterion and a fracture mechanics approach.

1. Introduction

Fatigue life of metal components is spent to nucleate and propagate a dominant crack until the final failure. Usually, crack initiation involves the formation of a defect whose size is comparable with a material's characteristic slip length [1,2]. At this stage, the crack is referred to as microstructurally-small. The subsequent stage involves the growth of the crack that is, at first, physically-small, and then, long [3]. Therefore, the fatigue strength of a mechanical component can be improved if at least one of these two stages is prolonged. Resistance to crack initiation can be essentially improved through grain refinement (that controls the material's characteristic slip length) [4], work-, precipitation-, and solution-hardening (to withstand the formation of persistent slip bands) [5], surface polishing (to alleviate the stress concentration effect exerted by surface roughness) [6], mean stress effect [7]. Conversely, the crack propagation is impeded by extrinsic mechanisms such as crack closure, crack bridging, crack deflection and crack front geometry [8,9].

Shot peening is a surface treatment that is commonly used to take advantage of some of these effects to improve the fatigue resistance of metallic materials. This process consists of bombarding the component with small spherical shots of a hard material at a relatively high velocity. Clearly, the multiple indentation of the ductile target surface increases its surface roughness, but, if shot peening is correctly performed, the detrimental effect exerted on the crack nucleation resistance is overweighed by several beneficial modifications of the surface layers. Specifically, (i) the introduction of an in-plane compressive residual stress field hinders crack nucleation owing to mean stress effect [10] and retards the propagation of Physically-Small Cracks (PSC) [10–13] restoring, at least partially, crack closure that in PSC is not fully developed as in Long Cracks (LC) [14]. Obviously, the beneficial effects exerted by compressive residual stresses strongly depend upon their stability throughout the fatigue life [15]. In this regard, re-orientation and change in the magnitude of the residual strain field was found as a consequence of cyclic loading [16]. (ii) Work-hardening and the resulting increase in the near-surface dislocation density retard crack nucleation but often accelerate crack propagation due to material embrittlement [17,18]. (iii) Depending on the treatment intensity, shot peening causes more or less evident microstructural changes; among them, near-surface grain refinement (thus reducing the maximum dislocation slip length and therefore incrementing the resistance to crack initiation) [19], elongated and flattened grains near the peened surface [20], changes in the orientation of

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Nomenclature

Symbols

a	surface crack depth
c	surface crack half-width
d	material strongest microstructural barrier
D_p	mean spacing of adjacent roughness peaks
D_n	notch depth
k	factor expressing exponential crack size dependence of ΔK_{th}
K	stress intensity factor
K_r	residual stress intensity factor
K_t	notch stress concentration factor
LC	long crack
m	weight function
MSC	microstructurally small crack
N_f	number of cycles to failure
p	hydrostatic pressure
PSC	physically small crack
R	nominal load ratio
R_t	maximum peak to valley height
s	slope of the Wöhler curve
t	specimen thickness
$T\sigma$	stress-based scatter index (related to the 10–90% probability of survival curves)
x	Cartesian coordinate along the crack depth with origin on the sample surface
Y	shape factor for crack stress intensity factor
α_C, β_C	material parameters of the Crossland fatigue criterion
Δ	range over a fatigue cycle
ΔK_{dR}	smallest physically small crack threshold
ΔK_{th}	crack size dependent physically small crack threshold
ΔK_{thR}	long crack threshold stress intensity factor range
$\Delta\sigma_{eR}$	plain fatigue strength range at high number of cycles to failure
κ	driving force for fatigue crack propagation
σ	normal stress
σ^{RS}	Surface residual stress
σ_0	y-intercept of the Wöhler curve
σ_{VM}	Von Mises equivalent stress

Subscripts

a	amplitude over a fatigue cycle
appl	applied due to external loading
eff	effective
max	maximum over a fatigue cycle
min	minimum over a fatigue cycle
P	probability of failure
tot	total

precipitates [21], modification of the near-surface crystallographic texture [22], stress-induced martensitic transform [23]. The grain refinement effect has been explored in recent works in order to create nanostructured surfaces through very intense peening treatments [24].

Clearly, shot peening is a surface treatment able to modify the mechanical and microstructural characteristics of the near-surface material layers. Therefore, in many cases, especially in the high-cycle ($10^5 < N_f < 10^7$) and very-high-cycle ($N_f > 10^7$) fatigue regime, shot peening suppresses surface crack initiation and pushes the crack source beneath the hardened surface layers [17,21,25–30]. Preferential sites for subsuperficial crack initiation were found to be non-metallic inclusions [25–28,30], pores [31], the region where superimposed residual and external stresses are maximum [17] or exceed the local material's yield strength [21].

The need for fatigue strength improvement is particularly felt in Al-alloys, because their elevated specific static strength does not reflect equally high fatigue properties [4,32,33]. Their scarce fatigue resistance is imputed to (i) weak microstructural barriers to the propagation of Microstructurally-Small Cracks (MSC) [34] and (ii) a high notch sensitivity [33], making them very susceptible to the stress concentration exerted by surface roughness. Therefore, in Al-alloys the majority of fatigue cracks initiate on the surface. For these reasons, the surface modification through shot peening is an attractive method of improving fatigue performance of Al-alloys. Over the last decades, considerable research effort has been devoted to identifying the most effective peening treatments for high-strength Al-alloys [17,21,29,35–39]. It is commonly accepted that gentle treatments employing small ceramic beads induce the highest fatigue life enhancement, mainly for the following reasons: (i) the compressive residual stress peak is located close to the surface where the cracks are likely to nucleate, (ii) strain hardening is concentrated near the surface and helps maintaining stable the residual stress field in the region of crack initiation, (iii) the detrimental effect of surface roughening is reduced, (iv) geometrical details like grooves, fillets, and holes can be covered more easily [29,40]. Conversely, intense peening treatments can have even adverse effects on the fatigue performance, due to excessive surface roughness and micro-cracks created by fiercely impacting a material whose toughness is limited by the exasperated hardening treatments [38,41]. Moreover, such intense treatments tend to introduce deep in-depth residual stress- and microhardness profiles that are not optimal to prevent surface crack initiation and residual stress relaxation [15,16]. Intense peening treatments are usually applied to Al alloys when fretting rather than plain fatigue is the major concern. In this case, surface roughness increases the real contact area, thus reducing the stresses produced on the surface by the normal and tangential contact loads [42,43].

The present paper is aimed at investigating the influence of the peened surface morphology on the high- and very high-cycle fatigue behavior of the Al-7075-T651 alloy. For this purpose, pulsating bending fatigue tests ($R = 0.05$) were carried out on smooth samples exploring fatigue lives comprised between 10^5 and 10^8 cycles. Three diverse peening treatments were considered in order to explore 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. The surface morphology modifications induced by shot peening were evaluated using an optical profilometer. Particular emphasis was placed on the capability of the shot peening treatments to retard crack initiation or to arrest crack propagation on the surface. Therefore, fatigue crack initiation sites were investigated through Scanning Electron Microscopy (SEM) fractography. The influence of surface roughness on the crack nucleation was quantified by eliminating the surface roughness in some peened specimens through a tribofinishing process.

2. Materials and experimental procedures

The experimentation was performed on the aluminum alloy Al-7075-T651, widely used for aeronautical applications, supplied in the form of 4 mm thick rolled plate. Microstructure and monotonic tensile properties are reported in [29]. The fatigue

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