International Journal of Fatigue 61 (2014) 271–282

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Multiaxial fatigue resistance of shot peened high-strength aluminum alloys

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ARTICLE INFO

Article history:
Received 30 July 2013
Received in revised form 17 October 2013
Accepted 25 October 2013
Available online 1 November 2013

Keywords:
Multiaxial fatigue
Axial–torsion
Al-7075-T6
Shot peening
Residual stresses

ABSTRACT

This paper is aimed at investigating multiaxial fatigue of shot peened Al-7075-T6 alloy. Plain axi-symmetric specimens were subjected to combined in-phase tension and torsion loading, under nominal load ratio $R = 0.05$ and biaxiality ratio $\lambda = \tau_a/\sigma_a = 2$. The results from multi-axial tests are discussed together with those obtained under pure tension and pure torsion loading. Fatigue crack initiation sites have been investigated through scanning electron microscopy 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, several multiaxial fatigue criteria were used to account for the residual stress field. The Crossland and the Findley fatigue criteria incorporating stabilized residual stresses as mean stresses were found to predict the fatigue strength with a relative error lower than 15% within the entire fatigue life interval, for all the material variants and the loading conditions considered.

1. Introduction

Aluminum alloys are an attractive class of materials for aircraft and automotive industry because of their high specific static strength. Usually, high static mechanical properties are induced in aluminum alloys by dispersion hardening through solution and ageing heat treatments. In the last five decades, extensive studies have been conducted to understand the fatigue behavior of aluminum alloys. They showed that aluminum alloys exhibit poor plain fatigue resistance [1–3] and high notch fatigue sensitivity [4,5] with respect to steels, titanium alloys, and composites. For this reason, Al alloys are frequently subjected to surface treatments in order to improve their plain and notch fatigue strength [5–8]. Among them, shot peening is one of the most widely used. This process consists of bombarding the component with small spherical shots of a hard material at a relatively high velocity. The multiple indentation of the ductile target surface increases its surface roughness and causes localized plastic deformation, which in turn results in work-hardening and introduction of a in-plane compressive residual stress field in the surface layers. While work-hardening and related microstructural modifications (like stress induced martensitic transformation) have a significant beneficial effect on the fatigue resistance of steels [9,10], they are deemed to be marginal in the fatigue behavior of high-strength Al alloys [11], as a consequence of the exasperated hardening treatments that do not allow for further increments in their mechanical properties. Instead, it is commonly accepted that the improvement of fatigue strength is mainly induced by the introduction of compressive residual stresses in the surface region [12–15], which, if the shot peening treatment is correctly performed, overweighs the detrimental effect due to surface roughening. Clearly, the extent of the fatigue response enhancement depends strongly upon the residual stress magnitude and distribution. Any residual stress relaxation during component operation reduces the achievable improvement. Experimental investigations conducted on Al alloys indicate that residual stress relaxation occurs mostly in the first few loading cycles and a stabilized residual stress field is reached in dependence on the applied load [14,16–18].

Different approaches have been developed in order to obtain accurate assessments of fatigue life of a load-bearing structure when residual stresses are present, emphasizing either crack initiation or crack growth. The first approach, termed "safe-life" considers only the fatigue crack initiation, while the second approach, called "damage tolerance" predicts crack growth. In general, when residual stress depths are large it is usually more appropriate to use crack growth models to assess the fatigue performance, while for shallow depths of residual stresses such as in the case of shot peening, crack initiation or total life methods

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http://dx.doi.org/10.1016/j.ijfatigue.2013.10.020

Nomenclature

Symbols

D_p	mean spacing of adjacent roughness peaks
k	slope of the Wöhler curve
K_t	stress concentration factor
N_f	number of cycles to failure
p	hydrostatic pressure
R	nominal load ratio
R_t	maximum peak to valley height
$T\sigma$ ($T\tau$)	stress-based scatter index (related to the 10–90% probability of survival curves)
α, β	material parameters of a fatigue criterion
Δ	range over a fatigue cycle
ε	normal strain
γ	shear strain
λ	biaxiality ratio
σ	normal stress
σ_0, τ_0	y-intercept of the Wohler curve
$\sigma_{1\times10^6}$, $\tau_{1\times10^6}$	fatigue endurance at 1×10^6 cycles with 50% failure probability
σ_n	normal stress acting on a generic material plane
σ_{VM}	Von Mises equivalent stress
σ_Y	yield stress
τ	shear stress

Subscripts

a	amplitude over a fatigue cycle
C	Crossland fatigue criterion
F	findley fatigue criterion
FS	Fatemi–Socie fatigue criterion
m	mean over a fatigue cycle
max	maximum over a fatigue cycle
maxθ	maximum over the inclination angle of the material plane
$mSWT$	modified SWT fatigue criterion
P	probability of failure
S	Sines fatigue criterion

are usually used to assess influence on fatigue life [19]. Most total life methods rely on establishing multiaxial fatigue criteria to account for the presence of residual stresses. Residual stresses are dealt with in the same way as mean stresses superimposed to the oscillating stresses caused by the external loads [20]. To this regard, Flavenot and Skalli [21] compared several multiaxial fatigue criteria incorporating residual stress effects by predicting the fatigue strength of induction-hardened components and ground samples. They concluded that Crossland [22] , Sines [23], and Dang Van [24] criteria provide a better correlation to experimental results. Bertini and Fontanari [25] included residual stresses, evaluated by means of a numerical–experimental technique at the notch root of induction-hardened notched components, into the Sines criterion, obtaining a satisfactory agreement with experimental observations. Fathallah et al. [26] modified the Crossland and the Dang Van multiaxial criteria to account for strain hardening profiles and surface damage to predict the fatigue resistance of a shot-peened steel SAE 3415. Benedetti et al. [14,27] used the Sines criterion incorporating stabilized residual stresses and the stress concentration factor due to surface roughness to model the plain and notch fatigue behavior of variously shot peened Al alloys. Liu and Pang [15] proposed an analytical model to predict the fatigue life of shot-peened materials by integrating residual stresses into the Findley multiaxial fatigue criterion [28]. Palin-Luc et al. [29] simulated the fatigue strength of induction-hardened smooth samples using Crossland and Dang Van criteria. Prasannavenkatesan et al. [30] interpreted the fatigue behavior of shot peened gear steels using the Fatemi–Socie critical plane approach [31].

So far, the majority of investigations have been focused on uniaxial loading, whereas the effect of residual stresses, and of shot peening in particular, under multiaxial fatigue loading is poorly explored. This topic is however of great interest, mainly for two reasons: (i) surface treatments, like shot peening, and manufacturing processes, like welding [32], often introduce a multiaxial residual stress field, (ii) structural parts made of high-strength Al alloys for aerospace applications (e.g., aircraft fittings, gears and shafts) are frequently subjected in service to multiaxial loading (axial, torsion, bending); therefore, it is interesting to quantify the beneficial effect of shot peening in the presence of such external multiaxial stress field and to identify the most suitable multiaxial fatigue criteria that can simulate the fatigue response of high-strength Al alloys.

To this regard, Zhao and Jiang [33] pointed out a lacking knowledge of the multiaxial fatigue of Al alloys and tried to shed more light on this topic by conducting a systematic experimental investigation on the fatigue behavior of 7075-T651 Al alloy under tension, torsion, and tension–torsion loading as well as different mean stresses. They concluded that a modified version of the Smith–Watson–Topper (SWT) criterion [34] proposed by Chu [35] gives accurate predictions of the fatigue life and cracking behavior.

This paper is aimed at investigating multiaxial fatigue of shot peened Al-7075-T6 alloy. Plain axisymmetric specimens were subjected to combined in-phase tension and torsion loading, under nominal load ratio $R = 0.05$ and biaxiality ratio $\lambda = \tau_a/\sigma_a = 2$. The results from multi-axial tests are discussed together with those obtained under pure tension and pure torsion loading. Fatigue crack initiation sites were investigated through Scanning Electron Microscopy (SEM) fractography and the role of surface roughness on fatigue resistance was 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, several multiaxial fatigue criteria incorporating the residual stress field and the stress concentration factor due to surface roughness were used to predict the fatigue life of the specimens.

2. Materials and experimental procedures

The experimentation has been performed on the aluminum alloy Al-7075-T6, widely used for aeronautical applications, supplied in the form of extruded bars with 15 mm diameter. The bulk material properties have been determined on five standard monotonic tensile tests (initial strain rate of $1\times10^{-3}\ s^{-1}$) performed in the longitudinal orientation. The results, summarized in Table 1, show

Table 1
Monotonic tensile properties of the Al-7075-T651 alloy.

E (GPa)	$\sigma_{Y0.2}$ (MPa)	UTS (MPa)	σ_F (MPa)	TE (%)	RA (%)
72 (±1)	515 (±5)	575 (±5)	760 (±10)	15 (±2)	20 (±2)

E: elastic modulus; $\sigma_{Y0.2}$: 0.2% yield stress; UTS: ultimate tensile strength; σ_F: true fracture stress; TE: total elongation; and RA: reduction in area.