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Effect of age-hardening conditions on high-cycle fatigue performance of mechanically surface treated Al 2024

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Abstract

The present work was aimed at evaluating the effects of shot peening on the fatigue performance of the well known age-hardening aircraft aluminium alloy Al 2024. Shot peening to full coverage was performed using spherically shot (SCCW14) with an average shot size of 0.36 mm and an Almen intensity of 0.20 mmA. After applying the various mechanical surface treatments, the changes in the surface and near-surface layer properties such as surface topography, micro-hardness and residual stress-depth profiles were determined. In addition to the mechanically surface treated specimens, electrolytically polished conditions were used to serve as reference. The fatigue results will be interpreted in terms of the process-induced changes in the resistances to crack nucleation and micro-crack growth.

Keywords: Age-hardening; Shot peening; Residual stresses; High-cycle fatigue strength

1. Introduction

Mechanical surface treatments such as shot peening and ball-burnishing are known to improve the HCF performance of structural materials such as steels and titanium alloys [1,2]. This improvement results from process-induced severe plastic deformation within the surface layer which increases the resistance to fatigue crack nucleation [3,4]. Furthermore, residual compressive stresses are generated which can drastically slow down microcrack growth from the surface to the interior [5,6]. While both modifications increase the HCF performance, the high surface roughness typically induced by shot peening has the opposite effect. Previous work on Al 2024 has demonstrated the significant effect of coverage in shot peening on fatigue performance [7]. In case of low coverage degrees shot peening was found to even deteriorate fatigue performance. The present work was aimed at evaluating the effect of shot peening at full coverage on the fatigue performance of the well known aircraft alloy Al 2024 in natural and artificial tempers. Particular emphasis was put on studying the effects of shot peening-induced residual compressive stresses on HCF strength.

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2. Experimental

The age-hardening aluminium alloy Al 2024 was received as an extrusion (Ø 63 mm, extrusion ratio ER = 15) from Otto Fuchs Metallwerke in Meinerzhagen, Germany. Specimen blanks (10 mm × 10 mm × 50 mm) were taken with the long axis parallel to the extrusion direction and were solution heat treated at 495 °C for 1 h followed by water-quenching. Part of the blanks was naturally aged for at least 5 days at room temperature (condition T4). Another part was artificially aged at 190 °C for 12 h (condition T6). In addition, the as-extruded condition was taken for comparison.

Tensile tests were performed on threaded cylindrical specimens having gage lengths and gage diameters of 25 and 5 mm, respectively.

Shot peening was done using a gravity induction system and spherically conditioned cut wire (SCCW14) having an average shot size of 0.36 mm. Peening was done at full coverage to a 0.20 mmA Almen intensity. The surface roughness was measured by a profilometer. Shot peening-induced residual stresses were evaluated with the incremental hole drilling technique using an oscillating drill with a 1.9 mm diameter driven by an air turbine with a rotational speed of about 200,000 rpm. The shot peening-induced strains in the surface layers were measured with strain gage rosettes at drilled depths of about every 20 μm. The residual stresses at each depth were then calculated

Table 1
Tensile properties of Al 2024

Condition	σ_y (MPa)	UTS (MPa)	El (%)	$\varepsilon_F = \ln A_0/A_F$
As-extruded	175	295	14.5	0.32
T4	415	595	17.0	0.23
T6	370	460	11.5	0.40

from the measured strain gage response using the macroscopic Young's modulus of $E = 74$ GPa and a Poisson's ratio of 0.30.

Fatigue tests were performed on hour-glass shaped specimens with a gage diameter of 3.6 mm in rotating beam loading ($R = -1$) in air at a frequency of 100 Hz. Before shot peening, all specimens were electropolished. Roughly 100 μm were removed from the as-machined and mechanically pre-polished surface to ensure that any machining effect that could mask the results was absent. The electrolytically polished condition (EP) was also taken as the baseline to which the shot peened conditions (SP) will be compared.

In addition, on the shot peened condition of the T6 temper a stress relief treatment at 190 °C for 1 h (SP + SR) was performed and the change in fatigue performance relative to condition SP evaluated. No such stress relief treatment was done on the T4 temper since this would have resulted in a significant change in microstructure and strength due to alterations in the degree of coherency, size and distribution of the precipitates.

3. Results and discussion

The microstructure of the extruded Al 2024 is shown in Fig. 1 illustrating highly elongated grains parallel to the extrusion direction (Fig. 1a). As expected from the extrusion process, these grains appear rather equiaxed perpendicular to the extrusion direction (Fig. 1b). The engineering stress–strain curves (10^{-3} s^{-1} initial strain rate) are shown in Fig. 2 comparing the as-extruded material with the age-hardened conditions T4 and T6. While both tempers clearly increase strength values compared to the as-extruded condition, naturally aging (T4) results in the highest values of yield stress, tensile strength and tensile elongation. The tensile properties of the various conditions are summarized in Table 1. The Vickers hardness (HV10) of the various conditions is shown in Table 2. The changes in surface and surface layer properties after shot peening are illustrated in Fig. 3.

Compared to the electropolished reference EP, the surface roughness strongly increases after shot peening. Fig. 3a shows an example for condition T4. No significant differences were found in surface roughness between shot peened T4 and T6. However, the changes in near-surface microhardness due to shot peening were characteristically different between conditions T4 and T6 (Fig. 3b). The much higher near-surface microhardness in T4 can be explained by the more marked strain hardening

Table 2
Hardness, HV10 of Al 2024

	Vickers hardness HV10
As-extruded	85
T4	165
T6	152

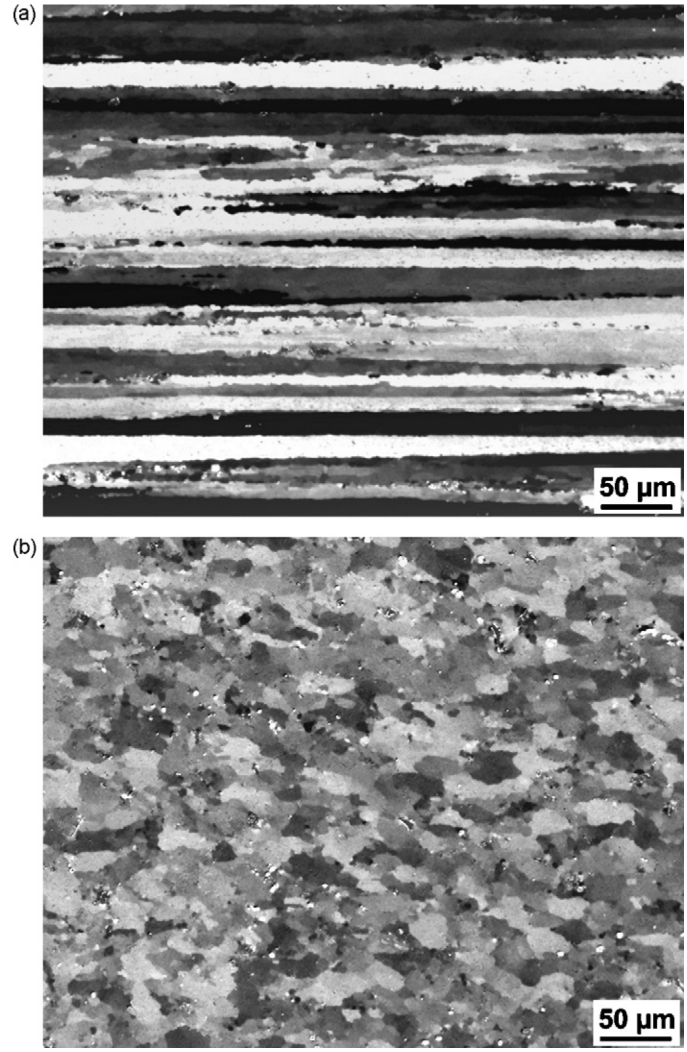

Fig. 1. Microstructure of the extruded Al 2024: (a) parallel to extrusion direction; (b) perpendicular to extrusion direction.

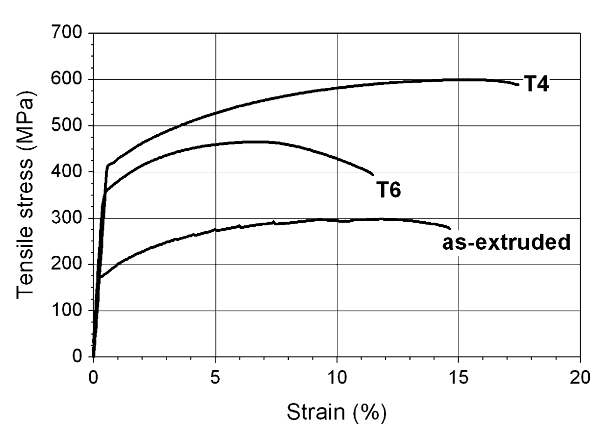

Fig. 2. Stress–strain curves in Al 2024.