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Low-cycle fatigue of a multi-layered aluminum sheet alloy

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ABSTRACT

Low-cycle fatigue (LCF) in engineering structures is caused by a relatively low-frequency strain cycling or thermal cycling. Regardless of the fact that it is much more dangerous than high-cycle fatigue, it has not been studied enough. Coated aluminum alloys are widely used in aerospace and transportation industries, mostly because of their high toughness and strength-weight ratio and improved surface properties. The effect of one-, two- and three-layer coatings, including an inner electroless nickel layer and, additionally, electrodeposited nickel, gold and silver, on the LCF behavior of 1.6-mm-thick 6061-T6 Al alloy was studied in a strain-controlled purely bending mode at maximum plastic strain varied from 0.003 to 0.010. The lifetime of the coated alloy drastically decreases as compared to the substrate. Incipient cracks were revealed, first of all, in the electroless nickel layer and in the substrate close to its surface.

1. Introduction

It is well-known that coated Al alloys often have a relatively low resistance to cycling load, especially, in heavily-loaded parts [1–3]. For example, coating brittleness and cracks induced during anodizing are among the factors which affect fatigue strength of hard anodized components [2,3]. On the other hand, the fatigue life of a coated alloy can be significantly higher than that of the substrate, as it was reported for AA6063-T6 aluminum alloy coated with a hard alloy composite consisting of cobalt-chromium matrix and particles of tungsten carbide [4].

Electroless nickel (EN) is an engineering coating normally used because of its excellent corrosion and wear resistance. Chemical and physical properties of the deposit vary primarily with phosphorus content and subsequent heat treatment [1,5]. The results obtained for 7075-T6 [6,7] and 2618-T61 [8] aluminum alloys coated with an EN deposit show that the coating can give rise to a significant improvement in the fatigue performance of the substrate at medium and low stresses. This improvement was associated with a higher strength of the coating as compared to the substrate and with the development of compressive residual stresses in the coating during the deposition.

All abovementioned literature data demonstrating the fatigue behavior of coated alloys relate to the stress-life method, which works well if only elastic stresses and strains are present. However, most coated components may appear to have nominally cyclic elastic stresses, but various stress concentrators, such as microcracks, notches, welds, etc., present in the component may result in local cyclic plastic deformation. Under these conditions, the local strain as the governing fatigue parameter (the local strain-life method) is much more effective in predicting the fatigue life of a component. In engineering applications, relatively low-frequency strain cycling as a consequence, e.g., of start and stop operations, generates low-cycle fatigue (LCF) failure.

In the literature, there are no reported studies related to the LCF behavior of Al alloys plated with a single electroless Ni, and, especially, with multi-layered deposits. In the present investigation, the effect of a single layer and multi-layered coatings on the LCF behavior of a 6061-T6 alloy was studied.

2. Material and methods

Solutionized and artificially aged 6061-T6 aluminum alloy consists of (wt.%): 0.4–0.8 Si, ≤0.7 Fe, 0.15–0.40 Cu, ≤0.15 Mn, 0.8–1.2 Mg, 0.04–0.35 Cr, ≤0.15 Ti, ≤0.25 Zn, other elements ≤0.05% each, 0.15% total, 95.85 – 98.56 Al. Coupons of this alloy with the dimensions of 110 × 25 × 1.6 mm were coated with a single 12-μm or 26-μm-thick layer of electroless nickel (sets 2 and 3, respectively, Table 1). These layers were deposited on the alloy surface in accordance with ASTM B733 Type V, SC2/SC3. On the basis of practical experience, to increase the adhesion of nickel to the surface of the aluminum alloy, heat treatment was performed after the coupon plating process at 180 °C for one hour instead of 140–150 °C as recommended by the standard. Besides, it is known that the fatigue life of precipitation-hardened aluminum alloys increases with an increase in aging temperature from 120 °C to 180 °C, as shown, e.g., for 6063 alloy [9].Two-layered deposits include an inner 12-μm or 26-μm-thick EN and an outer 3–4- μm-thick electrodeposited Ni layer (EDN) performed in accordance with the standard SAE AMS 2424 F-2010 in a nickel sulfamate bath (sets 4 and

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Table 1
The outer deposit kind, thickness, roughness (R_a) and Vickers microhardness (VH) as compared to those of the substrate.

The layer	Kind of a deposit, thickness [μm] and surface properties for sets 1–7 [a)]						
	1	2	3	4	5	6	7
1	–	12 (EN)	26 (EN)	12 (EN)	26 (EN)	12 (EN)	26 (EN)
2	–	–	–	4 (EDN)	4 (EDN)	4 (EDN)	4 (EDN)
3	–	–	–	–	–	9 (Ag)	0.2 (Au)
R_a, μm	1.98 ± 0.54	0.75 ± 0.20	0.82 ± 0.27	0.91 ± 0.42	0.82 ± 0.37	1.22 ± 0.47	0.82 ± 0.31
VH, GPa	1.05 ± 0.06	4.91 ± 0.11	5.10 ± 0.12	1.94 ± 0.07	1.94 ± 0.07	0.29 ± 0.01	–

[a)] EN and EDN denote electroless- and electrodeposited nickel coatings, respectively; Ag and Au are silver and gold coatings, e.g., the set 6 consists of three deposits on the Al alloy substrate: an inner 12-μm EN layer; an intermediate 4-μm EDN layer and an outer 9-μm silver layer.

5, respectively, Table 1). It possesses the lowest internal stress as compared to EN plating.

As presented in Table 1, three-layered coatings have an outer layer of silver (set 6) or gold (set 7) deposited in accordance with ASTM B700 Type 1 Grade A Class N (thickness class 10 μm) or ASTM B488 Type 1 Grade C Class 0.1 μm, respectively. Coatings of silver are usually employed for solderable surfaces, electrical contact characteristics, special reflectivity, etc. Electrodeposited gold coatings have high corrosion and tarnish resistance, solderability, infrared reflectivity, etc.

Specimens with the gauge width and length of 10 and 32 mm, respectively (Fig. 1), were tested on a Model IP-2 pure bending fatigue machine with the capacity of around 50 Nm in a strain-controlled loading mode at the strain ratio $R = \varepsilon_{min}/\varepsilon_{max} = 0.1$, where ε_{min} and ε_{max} are the minimum and maximum values of the total strain, respectively. A schematic diagram of purely bending fatigue is presented in Fig. 2a, where the sample 1 fixed in grips 2 and 3 was free to move in the longitudinal direction under a flexural load. The deflection amplitude *A* was measured by an indicator 4 (Fig. 2b) accuracy of ± 0.005 mm. For a simple beam, engineering bending strain of the material ε_x in the direction of the longitudinal axis X can be calculated using Eq. (1):

$$\varepsilon_x = -\frac{y}{R_n} \tag{1}$$

where the maximum strain amplitude corresponds to *y* value near the external surface amounting to a half of the beam (sample) thickness; R_n is the neutral axis radius.

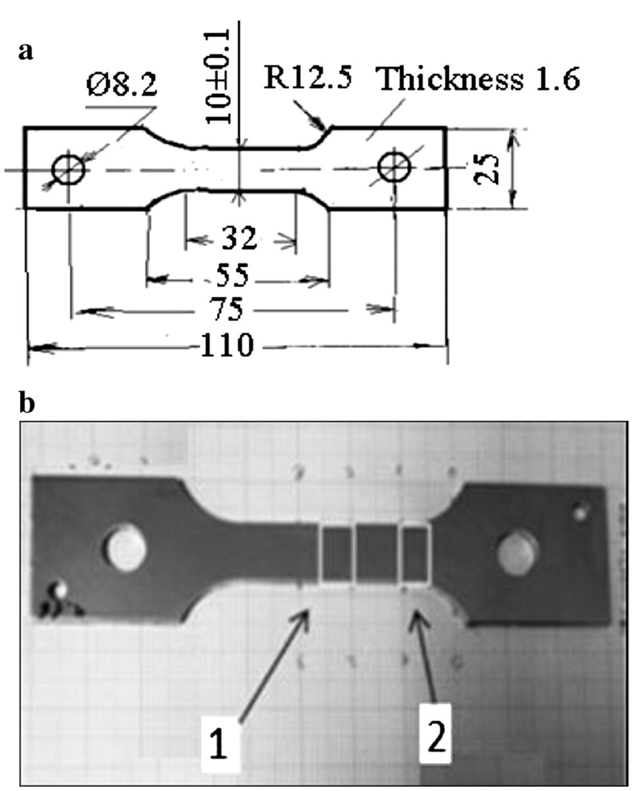

Fig. 1. Dimensions of the fatigue sample [mm] (a), and the view of the sample showing areas 1 and 2 which were cut out with an for microscopic evaluation of the crack propagation (b).

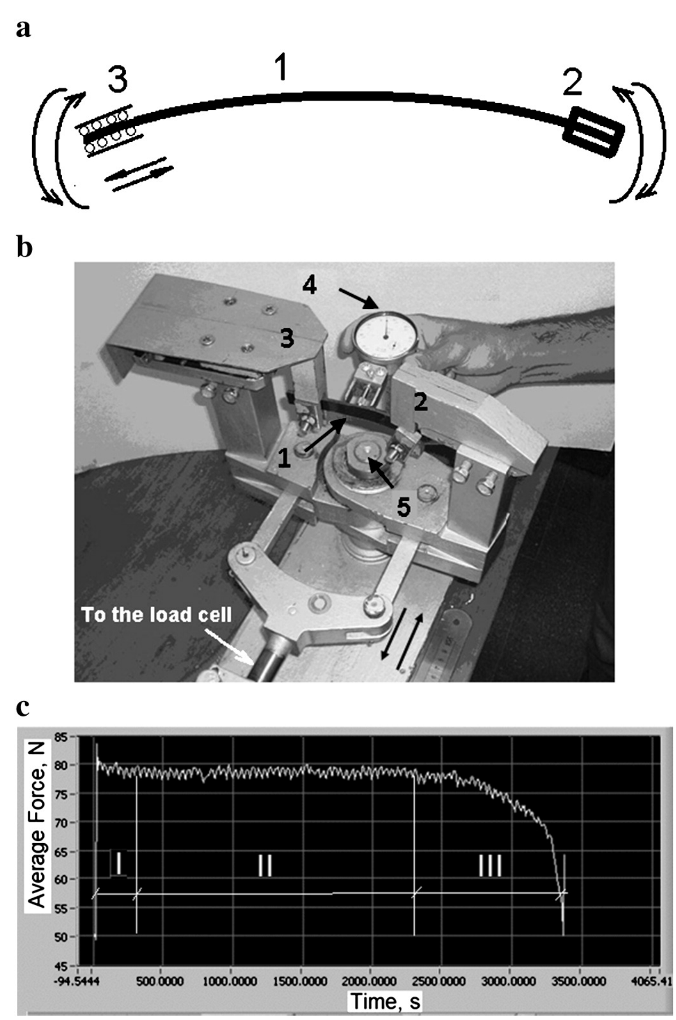

Fig. 2. The scheme of purely bending fatigue (a), view of the sample deflection measurement (b) and the system monitor demonstrating time-dependent values of ten-cycle-averaged force during a LCF test (c). 1 – sample; 2, 3 – grips (grip 3 allows additional movement of the sample in the longitudinal direction); 4 – indicator; 5 – pivot. I, II and III are strain softening, steady-state and final fatigue degradation stages, respectively.