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Short Communication

Mechanical failure of anodized aluminum under three and four-point bending tests

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ABSTRACT

In this work, three and four-point bending tests were adopted as methods for characterizing anodized aluminum beams in a sulfuric acid bath. The failure behavior of sandwich beams having aluminum oxide face sheets and aluminum core were tested. In so doing, many configurations were adopted by anodizing aluminum beams on one and both sides to investigate faces in place of tension and compression.

Bending tests showed different behaviors. When the oxide was only on the top side of the beam (working in compression) a slight sudden decrease of the load was observed. This fact was absent on beams with oxide layers working in tensile. The bending behavior of sandwich beams was similar to those with oxide on top sides but with much higher loads. The mechanical failure of the oxide was mainly caused by its failure when it is placed in compression beneath the loading rollers.

Finally, a morphological study of the aluminum oxide layers after bending tests was conducted by optical microscopy.

1. Introduction

Nowadays, aluminum and aluminum alloys are used for a wide range of applications, including transport, sport sectors and biomedical industry [1,2]. The use of these materials in the transport industry is omnipresent because of the need to lighten these structures and thus save energy [3]. Nevertheless, surface damage arises owing to certain mechanical incidents, such as friction and deflection [4–7]. Consequently, in many of these applications, anodization is practiced in order to enhance the mechanical properties of aluminum [8]. It consists on converting the substrate into its oxide by appropriate selection of the electrolyte and anodizing conditions, such as current density, voltage, and temperature [9–12]. The process running at low temperatures allows the formation of a thick and strongly adherent oxide layer with hardness close to that of high strength steel [13]. However, this coating is usually accompanied by the risk of brittle failure, especially under the surface-concentrated loads from static or cyclic contacts [5–7]. Tensile testing on the anodized aluminum can be difficult to conduct due to possible failure of the oxide layer at the two fixtures. Accordingly, three or four bending point tests can be used to study the failure of the anodic film on aluminum [14–17]. For both bending modes, there is a contact between the rollers and the oxide layer and, consequently, damages are possible. Sandwich beams comprising oxide face sheets imparts good stiffness and wear resistance. The anodizing process does not involve the addition of external material. That is the reason why anodic films are considered sufficiently adherent for the usual applications so the concept of adhesion has not been studied much.

To the author's knowledge, there are few reported results concerning the failure behavior of sandwich beams which have electrolytic oxide face sheet and aluminum core [14–17]. Further study of sandwich structures constituting an aluminum core and oxide face sheets should be carried out in order to optimize their mechanical performance.

In the present work, three and four-point bending tests on anodic oxide films formed on aluminum in a sulfuric acid bath was conducted. Many configurations were tested namely, oxides on the top side, on the back side and on both sides were formed in order to study their mechanical behavior in tension and in compression separately.

2. Experimental details

2.1. Materials and methods

Specimens of AA1050 aluminum with dimension of $100 \times 20 \times 3$ mm^3 were used as substrate. Its chemical composition is given in Table 1. Fig. 1 shows the geometrical dimensions of the anodized beams.

Prior to anodization, specimens of Al were mechanically polished to P1000 grade paper followed by (i) chemical polishing in a 15:85 (V/V) mixture of concentrated HNO_3 and H_3PO_4 at 85 °C

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Table 1
Chemical composition of the used aluminum (weight%).

Element	Si	Mn	Cu	Ti	Zn	Fe	Pb	Mg	Al
Weight (%)	0.11	<0.005	<0.005	0.014	0.009	0.37	0.006	<0.005	Balance

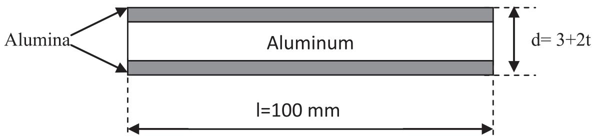

Fig. 1. Geometrical dimensions of anodized beam: *t*: thickness of one alumina face sheet, and *d*: the total thickness.

for 2 min, (ii) etching in 1 M NaOH solution at room temperature for 1 min and (iii) chemical pickling in 30% (V/V) HNO_3 solution at room temperature for 30 s. Water rinsing was used after each step.

Afterwards, samples were anodized in vigorously stirred sulfuric acid solution maintained within ±1 °C of the set temperature. The anodizing conditions were 5 °C, 2 A/dm^2, 146 g/l for temperature, current density and sulfuric acid concentration, respectively. The anodization duration was adjusted so that to obtain oxide layer thicknesses of 40 μm according to the second order model of the oxide layer growth rate developed elsewhere using Doehlert design [18]:

$$\widehat{Y_1} = 0.527 - 0.064X_1 + 0.279X_2 + 0.013X_1^2 - 0.004X_2^2 + 0.022X_3^2 - 0.006X_1X_2 + 0.014X_1X_3 + 0.001X_2X_3 \quad (1)$$

where X_1, X_2, and X_3 are the coded variables of the anodizing temperature (°C), the current density (A dm^{-2}) and the sulfuric acid concentration (g L^{-1}), respectively.

Fig. 2 shows the used experimental apparatus. It should be noted that the used cathodes were also aluminum sheets. After anodization, samples were first washed with deionised water and then dried.

2.2. Testing methods

In order to characterize the anodic oxide film formed on aluminum the following tests were carried out.

2.2.1. Thickness measurement

The thickness of the anodic oxide layer was measured using ELCOMETER 355 Top thickness gauge equipped with eddy current probe. The average thickness of 20 measuring points was taken.

2.2.2. Vickers microhardness

The Vickers microhardness of the oxide layers was conducted using digital microhardness tester HVS 1000 by applying 200 g load for 15 s. The results represent the average of 20 measurements for each sample.

2.2.3. Bending test

Three and four-point bending tests were performed on a universal machine Lloyd instruments LR 50 kN at a loading speed of 2 mm min^{-1}. The total length of the beam and the distance between the fixed rollers are $l = 100$ and $L = 60$ mm, respectively for both bending modes. The calibrated distance between the loading ones in the four-point bending was $h = 30$ mm (Fig. 3). $b = 20$ mm is the width and d is the total thickness of the specimen (Fig. 3). Having a large ratio of support span, L, to depth, d ($\geqslant 16$) suggests having tensile-compression stress dominant to shear stress ASTM: D6272. The inner span is set to be $L/2$ because this set-up is easy to handle and less sensitive to positioning errors. For the ratio of support span, L, to load span depth, h, it is set to 2.

Fig. 3 shows the retained configurations in the case of three and four-point bending of the anodic oxide layer formed on aluminum. These configurations aim to study tensile, compression and both tensile/compression behavior of the anodized beams.

The load–deflection response was recorded using NEXYGEN software program.

2.2.4. Surface morphology of the oxide

A morphological investigation has been performed by optical microscopy using a LEICA optical microscope equipped with a digital camera type CANON and a binocular loupe type TM630/T. For observations of the back side, working in tensile, the topside, working in compression, and their cross-sections, anodized specimens were embedded in epoxy resin in molds made of PMMA after bending tests. After that, samples were polished up to P1000 grade

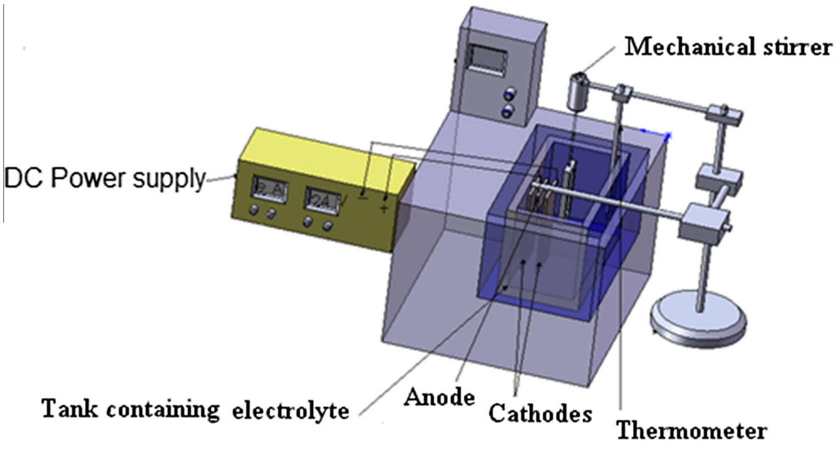

Fig. 2. Experimental apparatus used for anodization.