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Estimation of the elastic modulus of the alumina coated AA1050 aluminum: Modeling and experiments

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ABSTRACT

This paper deals with the prediction of the elastic modulus of alumina coating deposited on an aluminum substrate. Three- and four-point bending tests were used for the mechanical characterization. Three configurations were retained: a sandwich model, a model with coating subjected to tensile and model with coating placed in the state of compression. For the prediction of the elastic modulus of anodic oxide layer, an inverse method based on a numerical/experimental comparison was used. From the main results, it was found that: Finite element (FE) simulations of three- and four-point bending tests have been successfully conducted. In particular, both numerical 2D and 3D models were considered to be compared with the experimental results. The predicted elastic modulus was found to largely depend on the coating thickness. The elastic modulus was found to be around 15 GPa for a thickness of 20–50 μm and 20 GPa for an alumina coating of 80 μm. The numerical/experimental correlation allowed to conclude that when the alumina coating was subjected to compression it was more resistant than in tensile.

1. Introduction

Today, aluminum and aluminum alloys are widely used in several fields. In particular, the anodizing of aluminum and its alloys has diverse applications in transport, abrasion-resistant coatings, decoration and dielectric and insulating films in the electronics industry [1,2]. The use of these materials in the automotive field is very important in order to lighten their structures. However, surface deterioration occurs generally as a result of mechanical problems, such as friction and deformation [3,4]. Anodization is, therefore, useful in various applications to enhance the mechanical and tribological properties such as micro-hardness, abrasion resistance and corrosion protection [5]. It is worth reminding that this treatment obtained by the electrochemical process, consists of converting aluminum into its oxide by the appropriate selection of the electrolyte and the anodizing conditions, such as current density, voltage, temperature etc.. [6,7]. Anodic oxide layers which are deposited using electrochemical process are generally characterized by very important thickness, a strong adhesion and a high hardness [8]. Nevertheless, when these oxide layers are submitted to a concentrated force, cracks and local damages appear in the coating surface [9]. The use of the tensile test to characterize the anodized aluminum can be inappropriate for some cracks that may appear in the fixtures. In the same context, Scanning Electron Microscopy (SEM) has been used by several authors to evaluate the oxide layer performances, but it could not be sufficient when it is not associated to mechanical tests [10]. Therefore, three-point bending [11–19] and four-point bending tests [20–22] have been widely used not only to evaluate the damage of the metallic coatings, but also to determine their mechanical performance.

Whatever the bending mode, there is always a contact between the punches and alumina coating, which may cause a local damage. It is well known that sandwich beams coated from both sides allow good stiffness and wear resistance when compared to an uncoated substrate [23]. It is worth noting that since there are no new added materials during the anodizing process, and as the anodic oxides are supposed to be adherent enough, research efforts have not focused much on the adhesion phenomenon. Many experimental studies have assessed the mechanical properties and failure behavior of alumina oxide coatings [24–27]. However, to our knowledge, there are few reported numerical works that were carried out to characterize such alumina coating. The results presented in this paper may provide further insight into the problem. In particular, this investigation outlines the prediction of the elastic modulus for alumina coating formed on aluminum substrate using both three and four-point bending tests. Besides, relying on some previous experimental results reported by Bargui et al. [23], a comparison between the numerical modeling and experimental approaches was conducted to extract the elastic modulus of the alumina coating.

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2. Materials and experimental details

2.1. Materials and procedures

The studied material in this work consists of an AA1050 aluminum plate with dimensions of $100 \times 20 \times 3\ mm^3$, a chemical composition (wt%): Si 0.11%, Mn 0.005%, Cu 0.005%, Ti 0.014, Zn 0.009%, Fe 0.37%, Pb 0.006%, Mg 0.005% and aluminum balance. Alumina coating was prepared by the anodic oxidation of the aluminum substrate. Before anodizing, the Al specimens were mechanically polished to P1000 grade paper followed by a chemical polishing in a 15:85 (V/V) mixture of concentrated HNO_3 and H_3PO_4 at 85 °C for 2 min, etching in 1 M NaOH solution at room temperature for 1 min and chemical pickling in 30% (V/V) HNO_3 solution at room temperature for 30 s. Water rinsing was used after each step as previously reported in the work of Bensalah et al. [28]. Afterwards, aluminum samples were anodized in a vigorously stirred sulphuric acid solution (146 g/L) maintained within ± 1 °C of the temperature set, using a cryothermostat Lab-companion RW-2025G. After the anodizing step, the samples were washed in deionised water and then dried.

2.2. Characterization methods

In order to characterize the anodic film formed on the aluminum substrate, various tests were carried out. According to the methodology described in previous works [25,27], the thickness of the anodic oxide layer was measured using ELCOMETER 355 Top thickness gauge equipped with eddy current prob. For twenty (20) measurement points on both sides, the average thickness was considered.

Three and four-point bending tests were performed on an universal machine LLOYD instrument LR 50 kN at a loading speed of $2\ mm\ min^{-1}$. The distance between the fixed indenters is $l = 60$ mm for the two bending modes with a diameter $d = 5$ mm, while the calibrated distance between the loading ones in the four-point bending was $S = 30$ mm with a diameter $D = 10$ mm. A displacement of 8 mm was applied on these punches (Fig. 1a–d). For both three-point and four-point bending tests, thirty (30) measurements were made and the average value was considered. Fig. 1a–d shows all the possible configurations in the case of three and four-point bending tests. The anodic oxide layer to be formed on aluminum substrate will be subjected to tensile or compression or both tensile and compression.

3. Numerical analysis

In this work, the numerical analysis was carried out using the commercial nonlinear FE code ABAQUS. The alumina oxide layer was assumed to be perfectly bonded to the core, eliminating the delamination failure mode. The core was completely constrained by the oxide layer. Moreover, the thickness of the tested sheets can be neglected when compared to the sheet surface, thus a plane-

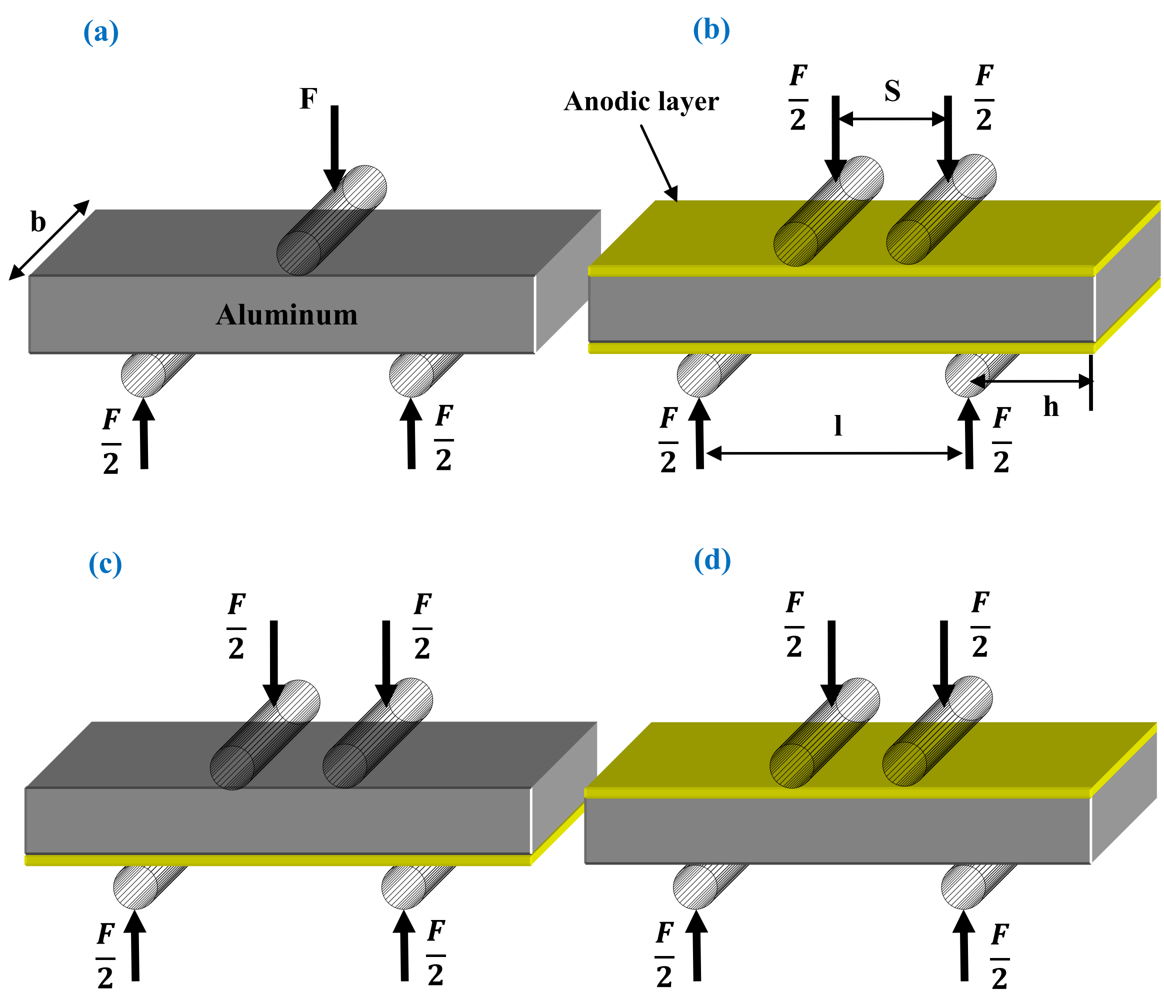

Fig. 1. Schematic of the geometry of the sandwich beam and the loading rollers: (a) threepoint bending, (b) four-point bending: sandwich model, (c) four-point bending: oxide layer placed in state of tensile, and (d) four-point bending: oxide layer placed in state of compression.