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MODEL DEVELOPMENT OF MECHANICAL STRENGTH TESTING OF PLASMA ELECTROLYTE OXIDATION COATED MG SUBSTRATE

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Abstract. Magnesium (Mg) alloys are an attractive constructive material due to their light weight and high mechanical strength. Plasma electrolyte oxidation (PEO) treatment of Mg alloys creates a thin ceramic coating with protective effects against mechanical wear and corrosion. The coating properties like its porosity and thickness can be adjusted by PEO process parameters and at the same time affects the material behaviour under tensile strength. In this work, dedicated slow-strain rate experiments of differently PEO coated Mg alloy dog-bone shaped specimen were conducted and the coating porosity, thickness and crack spacing were analyzed in order to deduce a predictive Finite Element Method (FEM) damage model. The results indicate that the thicker, more porous coatings lead to material failure at smaller strains in plastic regions. The effect can be implemented via partial differential equation into the FEM model.

1 INTRODUCTION

Mg alloys offer a broad spectrum of advantages like light specific weight and thus can be used in automotive, aerospace and biomedical application fields. However, most Mg alloys are prone to corrosion and offer low long-term durability. In order to protect the material from environmental damage, coatings can be applied to the surface. Plasma electrolyte oxidation (PEO) is an electrochemical process which includes application of a high anodic potential to the substrate in a solution which can contain additives like phosphate and aluminate salts. It results in a ceramic, mostly MgO containing coating with incorporated salts from the electrolyte. In the three-layered structure, the top layer exhibits a degree of porosity depending on the PEO process duration.[3, 2] Due to the different mechanical properties of coating and substrate, the

PEO layer cracks during elastic deformation of the Mg substrate as known from other ductile-brittle substrate-coating systems.[7] The resulting transversal cracks have a defined distance between one another which saturates above a certain strain value. In this work, PEO coated cp-Mg are subjected to tensile stress and a FEM model is constructed which captures the effects of the PEO coating on the macromechanical properties and the corresponding stress-strain curve of the material.

2 EXPERIMENTAL

Extruded cp-Mg specimen were formed into dog-bone shaped specimen. A porous PEO coating was created on the specimen in an electrolyte containing potassium hydroxide, sodium phosphate and sodium aluminate. PEO treatments were carried out using a laboratory setup, which consists of a self-made uni-polar pulse generator and a 3000 W *EA-PS 8720-15 DC* power supply. The samples were treated for 2, 5 and 20 minutes in constant current mode applying 100 mA cm^{-2} and a pulse ratio of ton : toff = 0.5 ms : 4.5 ms (200 Hz). A cooling system kept the electrolyte temperature at 20 ± 0.1 °C. The final voltages were 357 V after 2 min, 407 V after 5 min and 450 V after 20 min treatment, respectively. The specimens wee subjected to slow-strain rate (10^{-5} mm/s) at a *MTS Acumen 3* system at room temperature. The test was stopped at four different strains (0.1 %, 1 %, 2.5 % and fracture strain), respectively, and the PEO surface was analyzed via SEM.

3 RESULTS AND DISCUSSION

The porosity of PEO coatings increases with increasing treatment time. The pores are attributed to the discharge during the PEO process and corresponding sharp stress and temperature gradients. The porosity P has a direct effect on the elastic modulus of the coating.

In the SEM images in Fig. 1 it is observed that cracks transversal to the loading direction appear in the brittle PEO coating during elastic deformation of the substrate. The crack spacing is saturated above the value of 2.5 % true strain for all specimen. Larger strains only result in delamination of coating fragments from the substrate surface. Thicker PEO coatings exhibit larger steady state crack spacing values.

The stress-strain curves reveal that macroscopic failure occurs at smaller strains on PEO coated substrates compared to uncoated ones. Thicker, more porous coatings result in sooner material failure in the tensile test. A proposed explanation of this observations considering a damage evolution mechanism of microcrack formation and coalescence to macrocracks is the penetration of cracks from the brittle PEO coating into the bulk.[1]

The tensile test FEM model is based on a exponential plasticity, Lemaitre damage paradigm for macroscopical damage (variable D) and an additional PDE which incorporates the effect of PEO layer on the damage propagation due to its properties (variable θ).

Lemaitre damage reduces the effective stress in the structure according to the relation:[6]

$$\widetilde{\boldsymbol{\sigma}} = \frac{\boldsymbol{\sigma}}{1 - D} \tag{1}$$

where $\widetilde{\boldsymbol{\sigma}}$ is the reduced stress tensor that resists the load and the temporal derivative of D is defined as

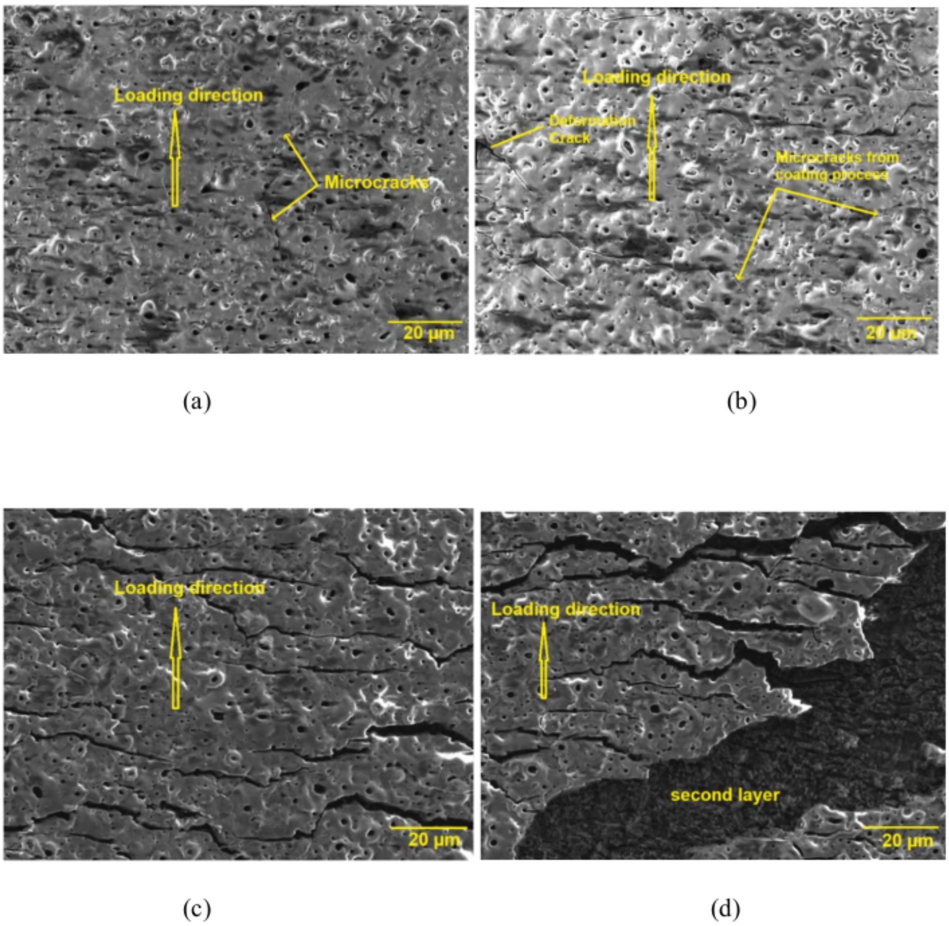


Figure 1: SEM micrograph of PEO 5 min samples surfaces deformed to (a) 0.1 % strain, (b) 1 % strain, (c) 2.5 % strain, (d) 14 % strain (fracture strain)

$$\dot{D} = -\dot{\psi}\frac{\partial F_Y}{\partial Y} = \left(\frac{-Y}{S_0}\right)^b \dot{\varepsilon}_{pl} \tag{2}$$

where $\dot{\psi}$ is a plastic multiplier, $\dot{\varepsilon}_{pl}$ is the plastic strain rate and S_0 and b are parameters.

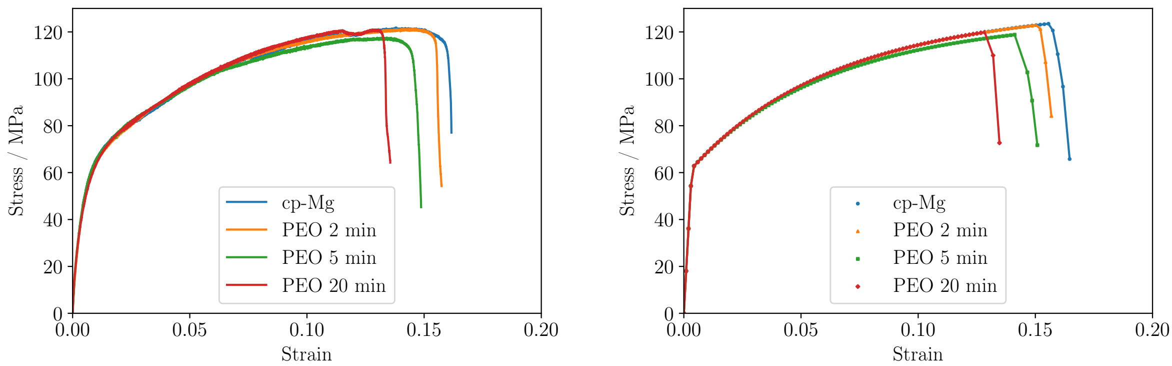
The effect of the PEO coating on the stress-strain response is introduced by the PDE:

$$\theta(\epsilon_{\mathrm{pl}=0}) = 1 \tag{3}$$

$$\frac{d\theta}{d\epsilon_{\mathrm{pl}}} = -c\frac{gl\acute{\epsilon}(t)}{\gamma\lambda} \tag{4}$$

where $\acute{\epsilon}(t)$ is the testing strain rate, λ_{ss} is the steady state crack spacing and c is a correction parameter. θ is then introduced into the plasticity equation:[5]

$$\sigma_{\mathrm{ys}} = \sigma_{\mathrm{ys0}} + \sigma_{\mathrm{sat}}(1 - \exp[-\theta\beta\epsilon_{\mathrm{pl}}]) \tag{5}$$



(a) Experimental values. (b) Simulated values.

Figure 2: Experimental and simulated stress-strain curves of bare cp-Mg and PE coated specimen.

where σ_{ys0} is the initial yield stress, σ_{sat} is the saturation flow stress, β is the saturation exponent and ϵ_{pl} is the equivalent plastic strain.

By choosing appropriate Lemaitre damage parameters and introducing the PEO porosity, crack spacing and shape factor according to equations developed by Boccaccini *et al.*[4], the stress-strain curves can be simulated as seen in Fig. 2b and 2a.

Shortcomings of the model include the fact that only the top layer properties are considered. In reality, the three-layered PEO structure affects the damage behaviour, however, for such analysis additional local methods are required.

4 CONCLUSIONS

A computational FEM damage model of cpMg coated with PEO under tensile stress was developed. It incorporates the effect of PEO coating properties (thickness, crack spacing, porosity) on the damage onset and propagation in a dog-bone specimen and enables predictive capabilities for structural applications. Further work will include the local deconvolution of the effects of single PEO layers.

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