ABSTRACT

Magnesium (Mg) alloys are attractive lightweight structural materials due to their low density, high specific stiffness, and good impact resistance. Their high chemical reactivity, however, results in poor corrosion performance and limits long-term use in aggressive environments. Electroless surface coatings have been widely reported as an effective route for enhancing the corrosion resistance of Mg alloys.

In the first major phase of this work, a quaternary electroless Ni-Zn-Cu-P coating was synthesized on Mg AZ31 alloy. The study focused on optimizing the coating parameters, specifically the concentrations of Nickel sulfate hexahydrate ($NiSO_4 \cdot 6\,H_2O$), Zinc sulphate heptahydrate ($ZnSO_4 \cdot 7\,H_2O$), and Sodium hypophosphite ($NaH_2PO_2H_2O$), using the Taguchi Design of Experiment (DOE) (L27 orthogonal array). The resulting coatings exhibited substantial improvements in microhardness, increasing from 87 $HV_{0.01}$ for the substrate to values as high as 650 $HV_{0.01}$ with a plating time of 10 min. To accurately predict microhardness based on input parameters, Artificial neural network (ANN) with feed-forward backpropagation algorithms were employed. The best-performing model (ANN 3-7-1) yielded a high regression coefficient ($R^2 = 0.982$), validating the effectiveness of machine learning in surface property prediction. Microstructural analysis confirmed the formation of amorphous, nodular coatings with fine elemental distribution and good adhesion to the substrate. It is identified that the coating fails beyond 10 min of plating time.

The second phase of this research investigated the underlying causes of coating failure and aimed to mitigate the environmental and safety concerns associated with conventional pretreatment methods that uses hazardous chemicals such as Hydrofluric acid (HF) and Chromic anhydride (CrO_3). To achieve this, an eco-friendly, single-step pretreatment route based on aqueous Iron (II) sulfate heptahydrate ($FeSO_4 \cdot 7\,H_2O$) was employed to enable the deposition of Ni–W–P coatings. It was identified that the coating fails because of rapid evolution of hydrogen during plating as a result of high rate of deposition. The addition of Ammonia (NH_3) in the plating bath (T1) promoted higher deposition kinetics, whereas the NH_3-free bath (T2) produced thicker, crack-free coatings. The defect-free T2 coatings exhibited superior mechanical performance and significantly improved corrosion resistance compared to both the substrate and T1

coatings. Nanoindentation tests revealed that the T2 coatings achieved a hardness of 7.73 GPa, with better elastic recovery and a higher H/Er ratio, indicating superior wear resistance. Electrochemical impedance spectroscopy and Tafel analysis further confirmed the enhanced corrosion protection offered by the T2 coatings, supported by greater charge transfer resistance and lower corrosion current density.

Since conventional electroless coatings do not inherently exhibit superhydrophobicity, their applicability remains limited for functional surface technologies such as self-cleaning, anti-icing, and anti-fogging. To address this limitation, in the third part of this work, a Superhydrophobic surface (SHS) is developed on AZ31 magnesium alloy using environmentally benign chemical method. The fabricated surfaces display a Cassie–Baxter wetting state with an apparent static contact angle (CA) of approximately $155°$.

While droplet impact dynamics on SHS have been widely investigated at low-to-moderate Weber numbers, the low-We regime remains comparatively less understood. Here, we examine the impact behavior of water droplets on SHS in the low Weber number range ($We < 17$). Existing theoretical descriptions for the maximum spreading factor ($\beta_{\max}$) typically rely on scaling arguments and empirical correlations. In this study, an improved theoretical formulation for $\beta_{\max}$ is proposed by incorporating a geometric approximation of the droplet profile at maximum spread. The developed model shows good agreement with the present experiments and with existing models reported in the literature.

Detailed analysis of droplet morphology reveals the formation of short-lived toroidal configurations and the presence of two distinct minima in the height evolution, highlighting previously unreported features of inertial–capillary coupling at low impact energies. Additionally, a holding time (t_h) is introduced, defined as the duration for which the droplet remains at its maximum spread. The holding time is observed to decrease with increasing Weber number and is empirically described by $t_h = 5.2 - 2.84, We^{0.2}$. These results provide improved physical understanding of droplet spreading and recoil in the low-We regime and offer useful design guidelines for superhydrophobic coatings intended for low-energy liquid–surface interactions, including self-cleaning interfaces and microfluidic applications.