Scopus

Documents

Yap, S.W.[a] , Johari, N.[a] , Mazlan, S.A.[a] , Aqida Syed Ahmad, S.N.[b c] , Arifin, R.[d] , Hassan, N.A.[e] , Johari, M.A.F.[a]

Superhydrophobic zinc oxide/epoxy coating prepared by a one-step approach for corrosion protection of carbon steel

(2023) *Journal of Materials Research and Technology*, 25, pp. 5751-5766. Cited 14 times.

DOI: 10.1016/j.jmrt.2023.07.013

[a] Engineering Materials and Structures (eMast) IKohza, Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, Kuala Lumpur, 54100, Malaysia
[b] Automotive Engineering Centre, Universiti Malaysia Pahang, PekanPahang 26600, Malaysia
[c] Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang, PekanPahang 26600, Malaysia
[d] Department of Mechanical Engineering, Universitas Muhammadiyah Ponorogo, Jl. Budi Utomo No. 10 Ponorogo63471, Indonesia
[e] Department of Manufacturing and Materials Engineering, Faculty of Engineering, International Islamic University Malaysia (IIUM), Jalan Gombak, Kuala Lumpur, 53100, Malaysia

Abstract
Corrosion in carbon steel (CS) has been an existing issue and it calls attention to the need for improved corrosion protection. At present, superhydrophobic (SHB) coating technology has piqued the interest of researchers as alternative means of mitigating metal corrosion. Herein, a one-step solution deposition process was used to prepare an SHB coating based on nano-zinc oxide/epoxy (ZnO/EP) on CS and its corrosion resistance performance was analyzed by the means of electrochemical analysis and compared with that of the blank CS metal and the regular coatings (plain EP and regular ZnO/EP). Results implied the as-prepared SHB coating shows remarkable improvement in corrosion protection for the substrate. Notably, it exhibited higher in both impedance modulus (|Z|) and coating resistance (Rc) results approaching 1010 Ωcm2, than those of regular coatings by 3 orders of magnitude to that of plain EP (~107 Ω cm2), and 1 order of magnitude to regular coating (~109 Ω cm2), indicating its superior corrosion resistance performance. Besides that, the superior inhibitive effect of the SHB ZnO/EP (ZES) is also proven by the potentiodynamic polarization (PDP) results, in which the Icorr value is suppressed down to 2.08 × 10−11 A/cm2, thereby achieving an excellent corrosion rate result of 3.38 × 10−11 mm/year. The exceptional barrier protection is ascribed to the presence of a stabilized air interlayer captured within the coating/electrolyte interface thus effectively blocking the penetration of electrolyte into the coating. This facile yet effective one-step processed SHB coating offers an effective route to improve the corrosion resistance performance of the CS metal and thereafter expand its potential applications. © 2023 The Authors

Author Keywords
Carbon steel; Corrosion resistance; Durability; Superhydrophobic coating; Zinc oxide

Index Keywords
Corrosion rate, Corrosion resistance, Corrosion resistant coatings, Electrolytes, Hydrophobicity, II-VI semiconductors, Steel corrosion, Zinc coatings; Coating technologies, Deposition process, Epoxy, Epoxy coatings, Nano zinc oxide, Orders of magnitude, Performance, Solution deposition, Superhydrophobic, Superhydrophobic coatings; Zinc oxide

References

- Pandiyarajan, S., Ganesan, M., Liao, A.-H., Manickaraj, S.S.M., Huang, S.-T., Chuang, H.-C.
  Ultrasonic-assisted supercritical-CO2 electrodeposition of Zn-Co film for high-performance corrosion inhibition: a greener approach
  (2021) *Ultrason Sonochem*, p. 72 105463.
- Masmiati, N., Sarhan, A.A., Hassan, M.A.N., Hamdi, M.
  Optimization of cutting conditions for minimum residual stress, cutting force and surface roughness in end milling of S50C medium carbon steel
  (2016) *Measurement*, 86, pp. 253-265.
- Lgaz, H., Chung, I.-M., Albayati, M.R., Chaouiki, A., Salghi, R., Mohamed, S.K.
  Improved corrosion resistance of mild steel in acidic solution by hydrazone derivatives: an experimental and computational study
  (2020) *Arab J Chem*, 13 (1), pp. 2934-2954.

- Chen, S., Li, B., Xiao, R., Luo, H., Yu, S., He, J., Liao, X.
Design an epoxy coating with TiO2/GO/PANI nanocomposites for enhancing corrosion resistance of Q235 carbon steel
(2021) *Materials*, 14 (10), p. 2629.

- Liu, X., Jie, H., Liu, R., Liu, Y., Li, T., Lyu, K.
Research on the preparation and anticorrosion properties of EP/CeO2-GO nanocomposite coating
(2021) *Polymers*, 13 (2), p. 183.

- Zhang, W., Liao, D., Tang, D., Han, E., Wang, J.
Study on corrosion behavior of Ni–P/Ni–Cu–P superhydrophobic composite coatings preparation on L360 steel by two-step method
(2023) *J Mater Res Technol*, 23, pp. 3035-3047.

- Wahby, M.H., Atta, A.M., Moustafa, Y.M., Ezzat, A.O., Hashem, A.I.
Hydrophobic and superhydrophobic bio-based nano-magnetic epoxy composites as organic coating of steel
(2020) *Coatings*, 10 (12), p. 1201.

- Zhang, Z., Zhao, N., Qi, F., Zhang, B., Liao, B., Ouyang, X.
Reinforced superhydrophobic anti-corrosion epoxy resin coating by fluorine–silicon–carbide composites
(2020) *Coatings*, 10 (12), p. 1244.

- Xu, Y., Gao, D., Dong, Q., Li, M., Liu, A., Wang, X., Wang, S., Liu, Q.
Anticorrosive behavior of epoxy coating modified with hydrophobic nano-silica on phosphatized carbon steel
(2021) *Prog Org Coating*, p. 151 106051.

- Ma, Q., Wang, W., Dong, G.
Facile fabrication of biomimetic liquid-infused slippery surface on carbon steel and its self-cleaning, anti-corrosion, anti-frosting and tribological properties
(2019) *Colloids Surf A Physicochem Eng Asp*, 577, pp. 17-26.

- Ma, Q., Tong, Z., Wang, W., Dong, G.
Fabricating robust and repairable superhydrophobic surface on carbon steel by nanosecond laser texturing for corrosion protection
(2018) *Appl Surf Sci*, 455, pp. 748-757.

- Wang, H., He, M., Liu, H., Guan, Y.
One-step fabrication of robust superhydrophobic steel surfaces with mechanical durability, thermal stability, and anti-icing function
(2019) *ACS Appl Mater Interfaces*, 11 (28), pp. 25586-25594.

- Cho, E.-C., Chang-Jian, C.-W., Chen, H.-C., Chuang, K.-S., Zheng, J.-H., Hsiao, Y.-S., Lee, K.-C., Huang, J.-H.
Robust multifunctional superhydrophobic coatings with enhanced water/oil separation, self-cleaning, anti-corrosion, and anti-biological adhesion
(2017) *Chem Eng J*, 314, pp. 347-357.

- Amiriafshar, M., Rafieazad, M., Duan, X., Nasiri, A.
Fabrication and coating adhesion study of superhydrophobic stainless steel surfaces: the effect of substrate surface roughness
(2020), p. 20 100526.
Surfaces and Interfaces

- Zhou, H., Chen, R., Liu, Q., Liu, J., Yu, J., Wang, C., Zhang, M., Wang, J.
Fabrication of ZnO/epoxy resin superhydrophobic coating on AZ31 magnesium

alloy
(2019) *Chem Eng J*, 368, pp. 261-272.

- Zhang, D., Qian, H., Wang, L., Li, X.
(2016) *Comparison of barrier properties for a superhydrophobic epoxy coating under different simulated corrosion environments*, 103, pp. 230-241.
Corrosion science

- Han, X., Peng, J., Jiang, S., Xiong, J., Song, Y., Gong, X.
Robust superamphiphobic coatings based on raspberry-like hollow SnO2 composites
(2020) *Langmuir*, 36 (37), pp. 11044-11053.

- Yang, Z., Wang, L., Sun, W., Li, S., Zhu, T., Liu, W., Liu, G.
Superhydrophobic epoxy coating modified by fluorographene used for anti-corrosion and self-cleaning
(2017) *Appl Surf Sci*, pp. 401 146-401 155.

- Cao, K., Yu, Z., Zhu, L., Yin, D., Chen, L., Jiang, Y., Wang, J.
Fabrication of superhydrophobic layered double hydroxide composites to enhance the corrosion-resistant performances of epoxy coatings on Mg alloy
(2021) *Surf Coating Technol*, p. 407 126763.

- Xu, S., Wang, Q., Wang, N.
Eco-friendly fabrication of superhydrophobic surface with anti-corrosion by transferring dendrite-like structures to aluminum substrate
(2020) *Colloids Surf A Physicochem Eng Asp*,

- Guo, C., Ding, H., Xie, M., Zhang, H., Hong, X., Sun, L., Ding, F.
Multifunctional superamphiphobic fluorinated silica with a core-shell structure for anti-fouling and anti-corrosion applications
(2021) *Colloids Surf A Physicochem Eng Asp*, p. 615 126155.

- Xiong, D., Liu, G., Duncan, E.S.
Robust amphiphobic coatings from bi-functional silica particles on flat substrates
(2013) *Polymer*, 54 (12), pp. 3008-3016.

- Su, C.
A simple and cost-effective method for fabricating lotus-effect composite coatings
(2012) *J Coating Technol Res*, 9 (2), pp. 135-141.

- Guo, X., Guo, R., Fang, M., Wang, N., Liu, W., Pei, H., Liu, N., Mo, Z.
A novel composite protective coating with UV and corrosion resistance: load floating and self-cleaning performance
(2022) *Ceram Int*, 48 (12), pp. 17308-17318.

- Wang, J., Pei, X., Zhang, J., Liu, S., Li, Y., Wang, C.
Reversible switch of wettability of ZnO@ stearic acid nanoarray through alternative irradiation and heat-treatment
(2021) *Ceram Int*, 47 (7), pp. 9164-9168.

- Gurav, A.B., Latthe, S.S., Vhatkar, R.S., Lee, J.-G., Kim, D.-Y., Park, J.-J., Yoon, S.S.
Superhydrophobic surface decorated with vertical ZnO nanorods modified by stearic acid
(2014) *Ceram Int*, 40 (5), pp. 7151-7160.

- Czyżowska, A., Barbasz, A.
A review: zinc oxide nanoparticles–friends or enemies?
(2022) *Int J Environ Health Res*, 32 (4), pp. 885-901.

- Faizan, M., Hayat, S., Pichtel, J.
  Effects of zinc oxide nanoparticles on crop plants: a perspective analysis
  (2020) *Sustainable Agriculture Reviews*, 41, pp. 83-99.
  Springer

- Zhang, X., Si, Y., Mo, J., Guo, Z.
  Robust micro-nanoscale flowerlike ZnO/epoxy resin superhydrophobic coating with rapid healing ability
  (2017) *Chem Eng J*, 313, pp. 1152-1159.

- Darband, G.B., Aliofkhazraei, M., Khorsand, S., Sokhanvar, S., Kaboli, A.
  Science and engineering of superhydrophobic surfaces: review of corrosion resistance, chemical and mechanical stability
  (2020) *Arab J Chem*, 13 (1), pp. 1763-1802.

- Li, M., Liu, N., Chen, J., Li, Q.
  Simple construction based on epoxy-bonded super-hydrophobic anti-corrosion coating
  (2019) *J Taiwan Inst Chem Eng*, 95, pp. 682-691.

- Wang, H., Di, D., Zhao, Y., Yuan, R., Zhu, Y.
  A multifunctional polymer composite coating assisted with pore-forming agent: preparation, superhydrophobicity and corrosion resistance
  (2019) *Prog Org Coating*, 132, pp. 370-378.

- Wu, Y., Jia, S., Wang, S., Qing, Y., Yan, N., Wang, Q., Meng, T.
  A facile and novel emulsion for efficient and convenient fabrication of durable superhydrophobic materials
  (2017) *Chem Eng J*, 328, pp. 186-196.

- Nguyen, D.M., Vu, T.N., Nguyen, T.M.L., Nguyen, T.D., Thuc, C.N.H., Bui, Q.B., Colin, J., Perré, P.
  Synergistic influences of stearic acid coating and recycled PET microfibers on the enhanced properties of composite materials
  (2020) *Materials*, 13 (6), p. 1461.

- Rahmani, M., Ghasemi, F.A., Payganeh, G.
  Effect of surface modification of calcium carbonate nanoparticles on their dispersion in the polypropylene matrix using stearic acid
  (2014) *Mechanics & Industry*, 15 (1), pp. 63-67.

- Li, Y., Weng, W.
  Surface modification of hydroxyapatite by stearic acid: characterization and in vitro behaviors
  (2008) *J Mater Sci Mater Med*, 19 (1), pp. 19-25.

- Yap, S.W., Johari, N., Mazlan, S.A., Hassan, N.A.
  Mechanochemical durability and self-cleaning performance of zinc oxide-epoxy superhydrophobic coating prepared via a facile one-step approach
  (2021) *Ceram Int*, 47 (11), pp. 15825-15833.

- Standard, A.
  G61-86, Standard test method for conducting cyclic potentiodynamic polarization measurements for localized corrosion susceptibility of iron-, nickel-, or cobalt-based alloys
  (2009), ASTM standards, ASTM Philadelphia, PA, USA

- Zhao, H., Ding, J., Liu, P., Yu, H.
  Boron nitride-epoxy inverse “nacre-like” nanocomposite coatings with superior anticorrosion performance

(2021), p. 183 109333.
Corrosion Science

- Ye, Y., Zhang, D., Liu, T., Liu, Z., Liu, W., Pu, J., Chen, H., Li, X.
Improvement of anticorrosion ability of epoxy matrix in simulate marine environment by filled with superhydrophobic POSS-GO nanosheets
(2019) *J Hazard Mater*, 364, pp. 244-255.

- Seeharaj, P., Sripako, K., Promta, P., Detsri, E., Vittayakorn, N.
Facile and eco-friendly fabrication of hierarchical superhydrophobic coating from eggshell biowaste
(2019) *Int J Appl Ceram Technol*, 16 (5), pp. 1895-1903.

- Zhang, J., Wang, J., Zhang, B., Zeng, Y., Duan, J., Hou, B.
Fabrication of anodized superhydrophobic 5083 aluminum alloy surface for marine anti-corrosion and anti-biofouling
(2020) *Journal of Oceanology and Limnology*, 38 (4), pp. 1246-1255.

- Lou, C., Zhang, R., Lu, X., Zhou, C., Xin, Z.
Facile fabrication of epoxy/polybenzoxazine based superhydrophobic coating with enhanced corrosion resistance and high thermal stability
(2019) *Colloids Surf A Physicochem Eng Asp*, pp. 562 8-56215.

- Zhou, Y., Ma, Y., Sun, Y., Xiong, Z., Qi, C., Zhang, Y., Liu, Y.
Robust superhydrophobic surface based on multiple hybrid coatings for application in corrosion protection
(2019) *ACS Appl Mater Interfaces*, 11 (6), pp. 6512-6526.

- Prontera, C.T., Sico, G., Montanino, M., De Girolamo Del Mauro, A., Tassini, P., Maglione, M.G., Minarini, C., Manini, P.
Sustainable, fluorine-free, low cost and easily processable materials for hydrophobic coatings on flexible plastic substrates
(2019) *Materials*, 12 (14), p. 2234.

- Tuong, V.M., Huyen, N.V., Kien, N.T., Dien, N.V.
Durable epoxy@ ZnO coating for improvement of hydrophobicity and color stability of wood
(2019) *Polymers*, 11 (9), p. 1388.

- de Lucas-Gil, E., Menendez, J., Pascual, L., Fernandez, J.F., Rubio-Marcos, F.
The benefits of the ZnO/clay composite formation as a promising antifungal coating for paint applications
(2020) *Appl Sci*, 10 (4), p. 1322.

- Wu, Y., Wu, X., Yang, F., Ye, J.
Preparation and characterization of waterborne UV lacquer product modified by zinc oxide with flower shape
(2020) *Polymers*, 12 (3), p. 668.

- Dou, Q., Wong, K.W., Li, Y., Ng, K.M.
Novel nanosheets of ferrite nanoparticle arrays in carbon matrix from single source precursors: an anode material for lithium-ion batteries
(2018) *J Mater Sci*, 53 (6), pp. 4456-4466.

- Seth, M., Khan, H., Bhowmik, R., Karmakar, S., Jana, S.
Facile fabrication of fluorine free zirconium zinc stearate based superhydrophobic and superoleophilic coating on cotton fabric with superior antibacterial property
(2020) *J Sol Gel Sci Technol*, 94 (1), pp. 127-140.

- Zhu, W., Wu, Y., Zhang, Y.
Fabrication and characterization of superhydrophobicity ZnO nanoparticles with

two morphologies by using stearic acid
(2019) *Mater Res Express*, 6 (11), p. 1150d1151.

- Zheng, S., Bellido-Aguilar, D.A., Huang, Y., Zeng, X., Zhang, Q., Chen, Z.
Mechanically robust hydrophobic bio-based epoxy coatings for anti-corrosion application
(2019) *Surf Coating Technol*, 363, pp. 43-50.

- Wei, H., Xia, J., Zhou, W., Zhou, L., Hussain, G., Li, Q., Ostrikov, K.K.
Adhesion and cohesion of epoxy-based industrial composite coatings
(2020) *Compos B Eng*, 193.

- Manoj, A., Ramachandran, R., Menezes, P.L.
Influence of abrasive load on wettability and corrosion inhibition of a commercial superhydrophobic coating
(2020) *Coatings*, 10 (9), p. 887.

- Wang, L., Zong, Q., Sun, W., Yang, Z., Liu, G.
(2015) *Chemical modification of hydrotalcite coating for enhanced corrosion resistance*, 93, pp. 256-266.
Corrosion Science

- Ren, T., Tang, G., Yuan, B., Yan, Z., Ma, L., Huang, X.
One-step fabrication of robust superhydrophobic coatings with corrosion resistance by a self-curing epoxy-resin-based adhesive
(2019), p. 380 125086.
Surface and Coatings Technology

- Zhang, B., Li, J., Zhao, X., Hu, X., Yang, L., Wang, N., Li, Y., Hou, B.
Biomimetic one step fabrication of manganese stearate superhydrophobic surface as an efficient barrier against marine corrosion and Chlorella vulgaris-induced biofouling
(2016) *Chem Eng J*, 306, pp. 441-451.

- Ghazali, N., Basirun, W.J., Mohammed Nor, A., Johan, M.R.
Super-amphiphobic coating system incorporating functionalized nano-Al2O3 in polyvinylidene fluoride (PVDF) with enhanced corrosion resistance
(2020) *Coatings*, 10 (4), p. 387.

- Serenario, M.E.D., Santos, B.A.F., Miranda, L.R.M.D., Bueno, A.H.S.
Evaluation of the anticorrosive behavior of epoxy-Nb2O5 paint in high temperatures submitted to the environment with sulfuric acid
(2020) *J Coating Technol Res*, 17 (5), pp. 1331-1342.

- Cui, M., Ren, S., Chen, J., Liu, S., Zhang, G., Zhao, H., Wang, L., Xue, Q.
Anticorrosive performance of waterborne epoxy coatings containing water-dispersible hexagonal boron nitride (h-BN) nanosheets
(2017) *Appl Surf Sci*, 397, pp. 77-86.

- Situ, Y., Guo, Y., Ji, W., Liu, D., Wei, D., Huang, H.
Polyaniline encapsulated α-zirconium phosphate nanosheet for enforcing anticorrosion performance of epoxy coating
(2021) *J Coating Technol Res*, 18 (4), pp. 999-1012.

- Van Westing, E., Ferrari, G., De Wit, J.
The determination of coating performance with impedance measurements—II. Water uptake of coatings
(1994) *Corrosion Sci*, 36 (6), pp. 957-977.

- Nishikata, A., Ichihara, Y., Hayashi, Y., Tsuru, T.
Influence of electrolyte layer thickness and pH on the initial stage of the

atmospheric corrosion of iron
(1997) *J Electrochem Soc*, 144 (4), p. 1244.

- Yuan, S., Zhao, X., Jin, Z., Liu, N., Zhang, B., Wang, L., Duan, J., Hou, B.
Fabrication of an environment-friendly epoxy coating with flexible superhydrophobicity and anti-corrosion performance
(2022) *Colloids Surf A Physicochem Eng Asp*, p. 633 127545.

- Wei, R., Liu, Z., Wei, W., Wang, S., Lv, Y.-J., Han, G.-C.
Anticorrosion performance of hydrophobic acid-modified-MOFs/epoxy coatings
(2022) *Colloid and Interface Science Communications*, 46.

- Li, D.-W., Wang, H.-Y., Liu, Y., Wei, D.-S., Zhao, Z.-X.
Large-scale fabrication of durable and robust super-hydrophobic spray coatings with excellent repairable and anti-corrosion performance
(2019) *Chem Eng J*, 367, pp. 169-179.

- Tong, W., Karthik, N., Li, J., Wang, N., Xiong, D.
Superhydrophobic surface with stepwise multilayered micro-and nanostructure and an investigation of its corrosion resistance
(2019) *Langmuir*, 35 (47), pp. 15078-15085.

- Xiong, J., Sarkar, D.K., Chen, X.-G.
Superhydrophobic honeycomb-like cobalt stearate thin films on aluminum with excellent anti-corrosion properties
(2017) *Appl Surf Sci*, 407, pp. 361-370.

- Chang, C.-H., Hsu, M.-H., Weng, C.-J., Hung, W.-I., Chuang, T.-L., Chang, K.-C., Peng, C.-W., Yeh, J.-M.
3D-bioprinting approach to fabricate superhydrophobic epoxy/organophilic clay as an advanced anticorrosive coating with the synergistic effect of superhydrophobicity and gas barrier properties
(2013) *J Mater Chem*, 1 (44), pp. 13869-13877.

- Zhan, Y., Zhang, J., Wan, X., Long, Z., He, S., He, Y.
Epoxy composites coating with Fe3O4 decorated graphene oxide: modified bio-inspired surface chemistry, synergistic effect and improved anti-corrosion performance
(2018) *Appl Surf Sci*, 436, pp. 756-767.

Correspondence Address
Johari N.; Engineering Materials and Structures (eMast) IKohza, Jalan Sultan Yahya Petra, Malaysia; email: norhasnidawani@utm.my
Aqida Syed Ahmad S.N.; Automotive Engineering Centre, Pekan, Malaysia; email: rarifin@umpo.ac.id

Publisher: Elsevier Editora Ltda

ISSN: 22387854
Language of Original Document: English
Abbreviated Source Title: J. Mater. Res. Technol.
2-s2.0-85164982144
Document Type: Article
Publication Stage: Final
Source: Scopus