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Editorial

Special Issue: Multi-Functional Nanostructured Sustainable Coatings

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The applications of surface coatings have been extensively explored in various technological fields, including the aeronautic and transport, tool and die, chemical and petroleum, nuclear, electronics, and biomedical industries. Coating technology uses single or multiple thin layers of a suitable substance on the surface of the material without altering the composition of bulk material, capable of functioning in extreme environments to overcome the challenges posed by temperature, corrosion, abrasion, fatigue, friction, and erosion [1]. Over the last few decades, continued innovative research in coatings has progressively contributed to global economic growth. The composition of coating substances (such as metal, ceramics, polymers, or composites) and the coating techniques vary according to the specific application [2]. Polycrystalline and amorphous coatings have been widely used in different types of industries including chemical processing, shipbuilding, boiler and pipe manufacturing, aerospace and gas turbines, etc., since they can extend the workpieces' life span [3]. In the aerospace industry, creep-resistant coatings (Al_2O_3, Cr_2O_3, Ni-Cr-Al-Ti, etc.) are used to protect the gas turbine engine against degradation by wear, high-temperature oxidation, and corrosion or a combination of these effects. In automotive industries, the PVD coating materials, including chromium nitride (CrN and/or Cr_2N) diamond-like carbon (DLC) and nano-laminates such as Cr-N/Al-N are used for coating the cast iron and stainless-steel rings [4]. Cutting tools are coated with a thin, wear-resistant, and thermally stable protective layer (thickness < 20 μm) of TiC, CrN, ZrN, Al_2O_3, etc., to machine high-strength materials with a higher material removal rate. During service, coatings are exposed to high temperatures; thus, anisotropic coating architecture is beneficial in providing an effective thermal barrier to divert heat dissipation and protect the substrate material [5].

Nanostructured or nanocomposite coating possesses excellent physical and mechanical properties such as high hardness and wear resistance, a low frictional coefficient, superhydrophobicity, etc. [6]. The composite or more complex coatings can be prepared by adding reinforced phases such as B4C, WC, TiN, ZrO_2, Al_2O_3, etc., to gain enhanced tribological properties and higher thermal stability [5]. For example, the composite coating system of (Zr, Al)N showed stable hardness up to 1100 °C, whereas (Ti, Al)N and (Ti, Cr)N coatings are thermally stable up to about 750 °C [6,7]. Using multi-layered coating structures is another effective way to improve tribological characteristics and resistance to oxidation at higher temperatures. Harry et al. [8] explored the effect of thickness and number of elementary layers on micro-cracking in the W-C-based multi-layered coating. They found that the four-layered coating of 14 μm thickness gives the best crack resistance. The coefficient of thermal expansion of coating material and the substrate affects the coating architect, and any significant difference may cause thermal cracking and high residual stresses during coating deposition [5,9]. The use of the cold spraying deposition technique can alleviate issues such as oxidation and unfavourable compositional changes that arise during the high-temperature processing of coating materials [10]. In the cold spraying technique, micron-sized particles of a powder bond to a substrate due to high-velocity impact and the associated severe plastic deformation obtained via the expansion of pressurized gas. Cold spray coating induces compressive residual stresses in the substrate that delay the crack initiation, improving the material's fatigue strength [11].

Apart from the physical barrier, surface coatings served as a potential stock house for biomedical applications to deliver various essential therapeutic responses. Titanium (Ti) and its alloys are essential biomaterials that are commonly utilized in orthopedics and dentistry applications [12]. One serious issue associated with metallic implants is the lack of osseointegration of the implant with bone cells, which renders them prone to infection. The deposition of composite coating with osteoconductive and anti-bacterial properties over the surface of metallic material is an important strategy to improve the osteoconductivity and biocompatibility of the implant. Surface coating techniques, including chemical conversion, micro-arc oxidation, anodization, biomimetic, electrodeposition, atomic layer deposition, ion implantation, CVD and PVD, are widely reported for metallic implant applications [13]. Polymeric coating (such as chitosan) embedded with bioactive glasses, enzymes, and proteins can be deposited using the electrophoretic deposition (EPD) technique, which is effective in enabling the permanent and stable fixation of the implant with bone tissues. The mechanical and chemically stable intermediate or multi-layered coatings with high homogeneity and low thickness between metal substrate and ceramics can be obtained using the sol–gel method to deliver the required bio-functionalities [14].

Currently, magnesium (Mg) and its alloys are pioneering the field of biodegradable implants because of the breakthrough research in this field. However, the rapid degradation of Mg-alloys in the biological environment is its major downside that may lead to implant failure even before the complete recovery of the fractured bone. Coating of implants is the most suitable solution to control the degradation rate [13]; therefore, extensive research has been reported for the coating of Mg alloys such as bioactive ceramic coatings including Ca-P compounds and biodegradable polymers such as polylactic acid (PLA), poly(lactic-co-glycolic) acid (PLGA), etc. These coatings help to gain good biocompatibility and degradability within the biosafe limits. However, due to the weak adhesive strength, polymeric coatings are at a higher risk of being partially damaged. Thus, the coating system for biodegradable implants needs to be designed with self-healing or self-sealing characteristics to automatically restore the coating functions. The diversified clinical requirements for an implant can be achieved by designing the most appropriate coating architectures. Since singular coatings are insufficient to deliver multiple bio-functionalities, multi-layered composite and hybrid coating architectures can meet essential therapeutic requirements with diverse functionalities, including corrosion resistance, cell viability, osteogenesis, biocompatibility, and anti-bacterial response [15].

To withstand dynamic stresses and corrosive environments associated with service conditions, the deposited coating materials must have cohesion and adhesion strength above satisfactory limits. In the last few decades, significant progress has been achieved in coating characterization using advanced testing methods and characterization techniques [5]. For depth-resolved measurements, various analytical methods such as glow discharge optical emission spectroscopy, auger electron, X-ray photoelectron spectroscopy, and secondary electron mass spectroscopy are used, but there is a constraint of limited lateral resolution. Atomic probe tomography (APT), electron backscatter diffraction (EBSD), and the X-ray nano-diffraction technique are some advanced techniques that overcome several limitations to characterize the coatings and their in-depth analysis [16,17].

The purpose of the Special Issue "Multi-Functional Nanostructured Sustainable Coatings" is to collect and share the current research findings in the field of nanostructured functionalized surfaces and coatings. Original research papers and review articles are welcomed on topics including but not limited to multi-layered hybrid coatings for biomedical, electronics, automotive, and cutting tool applications, smart nanostructured and sustainable coatings, tribological and economical aspects of coatings, coating characterization, etc.

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References

1. Makhlouf, A. Current and advanced coating technologies for industrial applications. In *Nanocoatings and Ultra-Thin Films*; Woodhead Publishing: Sawston, UK, 2011; pp. 3–23.
2. Upadhyay, R.K.; Kumar, A. Micro-Indentation Studies of Polymers. *Polymers* **2021**, *2*, 928–937. [CrossRef]
3. Huang, B.; Zhang, C.; Zhang, G.; Liao, H. Wear and corrosion resistant performance of thermal-sprayed Fe-based amorphous coatings: A review. *Surf. Coatings Technol.* **2019**, *377*, 124896. [CrossRef]
4. Dearnley, P. Surface Engineering for Gas Turbine (GTEs). In *Introduction to Surface Engineering*; Cambridge University Press: Cambridge, UK, 2017; pp. 423–448. [CrossRef]
5. Tkadletz, M.; Schalk, N.; Daniel, R.; Keckes, J.; Czettl, C.; Mitterer, C. Advanced characterization methods for wear resistant hard coatings: A review on recent progress. *Surf. Coatings Technol.* **2016**, *285*, 31–46. [CrossRef]
6. Mohan, S.; Mohan, A. Wear, friction and prevention of tribo-surfaces by coatings/nanocoatings. In *Anti-Abrasive Nanocoatings*; Woodhead Publishing: Sawston, UK, 2015; pp. 3–22.
7. Vereschaka, A.; Aksenenko, A.; Sitnikov, N.; Migranov, M.; Shevchenko, S.; Sotova, C.; Batako, A.; Andreev, N. Effect of adhesion and tribological properties of modified composite nano-structured multi-layer nitride coatings on WC-Co tools life. *Tribol. Int.* **2018**, *128*, 313–327. [CrossRef]
8. Harry, E.; Ignat, M.; Pauleau, Y.; Rouzaud, A.; Juliet, P. Mechanical behaviour of hard PVD multilayered coatings. *Surf. Coatings Technol.* **2000**, *125*, 185–189. [CrossRef]
9. Vereschaka, A.A.; Grigoriev, S.N. Study of cracking mechanisms in multi-layered composite nano-structured coatings. *Wear* **2017**, *378-379*, 43–57. [CrossRef]
10. Assadi, H.; Kreye, H.; Gärtner, F.; Klassen, T.J. Cold spraying—A materials perspective. *Acta Materialia* **2016**, *116*, 382–407. [CrossRef]
11. Ghelichi, R.; MacDonald, D.; Bagherifard, S.; Jahed, H.; Guagliano, M.; Jodoin, B. Microstructure and fatigue behavior of cold spray coated Al5052. *Acta Mater.* **2012**, *60*, 6555–6561. [CrossRef]
12. Błoniarz, A.; Cholewa-Kowalska, K.; Gajewska, M.; Grysakowski, B.; Moskalewicz, T. Electrophoretic deposition, microstructure and selected properties of nanocrystalline SnO2/Sr enriched bioactive glass/chitosan composite coatings on titanium. *Surface and Coatings Technology* **2022**, *450*, 129004. [CrossRef]
13. Singh, N.; Batra, U.; Kumar, K.; Ahuja, N.; Mahapatro, A. Progress in bioactive surface coatings on biodegradable Mg alloys: A critical review towards clinical translation. *Bioact. Mater.* **2023**, *19*, 717–757. [CrossRef] [PubMed]
14. Chen, Q.; McEwen, G.; Zaveri, N.; Karpagavalli, R.; Zhou, A. Corrosion resistance of Ti–6Al–4V with nanostructured TiO2 coatings. In *Emerging Nanotechnologies in Dentistry*; William Andrew Publishing: Norwich, NY, USA, 2012; pp. 165–179.
15. Singh, N.; Batra, U.; Kumar, K.; Mahapatro, A. Investigating TiO2–HA–PCL hybrid coating as an efficient corrosion resistant barrier of ZM21 Mg alloy. *J. Magnes. Alloy.* **2020**, *9*, 627–646. [CrossRef]
16. Riekel, C.; Burghammer, M.; Davies, R. Progress in micro- and nano-diffraction at the ESRF ID13 beamline. *IOP Conf. Ser. Mater. Sci. Eng.* **2010**, *14*, 012013. [CrossRef]
17. Keckes, J.; Bartosik, M.; Daniel, R.; Mitterer, C.; Maier, G.; Ecker, W.; Vila-Comamala, J.; David, C.; Schoeder, S.; Burghammer, M. X-ray nanodiffraction reveals strain and microstructure evolution in nanocrystalline thin films. *Scr. Mater.* **2012**, *67*, 748–751. [CrossRef]