coatings

Editorial

Structural, Mechanical, and Tribological Properties of Hard Coatings

Peihu Gao [1,2,*], Qiaoqin Guo [1,2,*], Yazhe Xing [3] and Yongchun Guo [1,2]

[1] School of Materials and Chemical Engineering, Xi'an Technological University, Xi'an 710021, China
[2] Shaanxi Province Engineering Research Centre of Aluminum/Magnesium Light Alloy and Composites, Xi'an 710021, China
[3] School of Materials Science and Engineering, Chang'an University, Xi'an 710064, China
* Correspondence: tigergaopei@163.com (P.G.); guoqiaoqin66@126.com (Q.G.)

Hard coatings have important protective effects on the surface of engineering parts due to their high hardness and decent anti-wear properties. Applications of hard coatings exist in the automobile industry, aeronautics, and astronautics, as well as engineering machinery, etc. The characteristics of hard coatings, such as mechanical and tribological properties, correlate with their chemical composition, microstructures, and surface characteristics.

This Special Issue successfully aims to exhibit the most recent studies and promote a deeper delve into the structural, mechanical, and tribological properties of hard coatings, including the synthesis of hard materials, deposition of hard coatings, analysis of microstructure, characterization of mechanical properties, and investigation of frictional behavior.

Hard coating materials are a hot research spot, including the high entropy alloy [1,2], amorphous material, ceramic, metal, or ceramic matrix composite [3–6], advanced carbon material, carbon/ceramic composite [7–9], and so on. Gao et al. [1–4] prepared CoCrFeNiMn high entropy alloy coatings and Nickel-based self-fluxing coatings on compacted graphite iron (CGI) substrates to enhance the surface wear resistance of CGI through plasma transfer arc cladding (PTA) and plasma spraying. A single phase with an FCC structure was retained from powder to coating in CoCrFeNiMn HEA coatings [1,2]. The HEA coating presented a higher friction coefficient and better wear resistance than compacted graphite iron. Chen et al. [4] prepared multiple thick iron-based claddings on CGI by PTA. A spheroidal graphite transition zone appeared, which enhanced the adhesion between the coating and substrate. Compared with CGI, the iron-based alloy claddings realized a reduction in friction and improved wear resistance simultaneously, which was attributed to the precipitated graphite's self-lubricating effect and carbides' high wear-resistance in the claddings Simultaneously, the coatings possessed a similar abrasive wear mechanism to the CGI, which was beneficial to the remanufacture and repair of CGI components. Meanwhile, Gao et al. [5] adopted a nano WC-Co strengthening cobalt binding phase to form the WC-(nano WC-Co) composite, which was used to deposit WC-(nano WC-Co) hard coatings through high-velocity oxygen-fuel spraying with an increased friction coefficient and wear resistance simultaneously. Li et al. [6] prepared Fe-based amorphous coatings through supersonic plasma spraying and laser cladding. Fe-based amorphous coatings prepared by laser cladding had a denser microstructure, less porosity and cracks, as well as a good metallurgical bond with the substrate compared to that deposited by supersonic plasma spraying so that they had better friction and wear resistance than the plasma-sprayed one.

A brake disc with a hard face is a typical friction material used in automobile, aviation, and engineering machines. Cai et al. [7] designed an interlocking surface between the grey cast iron brake disc and a non-asbestos organic (NAO) brake pad. After plasma electrolytic aluminating (PEA), the grey cast iron brake disc's surface had an increased friction coefficient and reduced wear rate when tested with the brake pad, which brought out the potential for the PEA process to enable reduced wear debris and non-exhaust emissions in perspective brake disc applications. Kim et al. [8] developed a three-dimensional

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(3D) physicochemical CVI model with the Naviere–Stokes equation and the convection–diffusion equation to simulate the dispersive behaviors of the reactive gases inside the porous preform to prepare C/C bulk composites using methane as a precursor gas and a multi-layered preform in an industry-scale reactor. The developed model had the effectiveness and utility to design CVI reactors and processing parameters and to reduce test runs greatly. Zhao et al. [9] manufactured a binary C/C brake disc through the matrix of pyrolytic carbon and resin carbon with the carbon source of modified natural gas by the isothermal chemical vapor infiltration (ICVI) with a directed flow and the pressure impregnation carbonization (PIC) process with liquid-phase furfural acetone resin. The manufactured test brake disc possessed a consistent friction coefficient with a 3.90% dispersion coefficient, which would improve the C/C brake discs' friction stability when applied in aircraft.

In addition to the materials in manufacturing hard coatings, preparation methods are very important, which have compatibilities according to the shape of the workpiece and its serving conditions. There are many methods to prepare hard coatings, including quenching, plating, electrodeposition, sputtering, vapor deposition, thermal spraying, cladding, implanting, and so on. There are large amounts of exceptional reviews and research work covering numerous topics in hard coatings.

Basically, quenching is the foundational and most used method to prepare hard coatings on the surface of metal or alloys. The often-used quenching fluid includes water, oil, and special quenchant. 42CrMo4 steel was quenched and hardened by three different viscosity vegetable oils. The quenched 42CrMo4 steel by Karanja oil had a hardness of 48 HRC and an impact toughness of 15 J, which had both higher hardness and impact toughness than the as-received steel in the work of Bhagyalaxmi et al. [10]. In Wang's work [11], 20CrMoH steel was treated with a combination of gas carburizing and shot peening. The microhardness of 20CrMoH steel's top surfaces with carburizing and shot peening (SP) was increased by 219% compared with the untreated one.

Plating is one of the most popular methods to form hard coatings on steel. Khani and Brennecke [12] electroplated a composite chromium coating on high-strength stainless steel with a trivalent chromium bath. The composite chromium coating had a thickness of 42 μm (±4) and a Vicker's microhardness of 860 (±10) HV, which were comparable to the coating's thickness and hardness prepared with usual baths of chromic acid. Jin et al. [13] used graphene oxide (GO) sheets to modify the electro-brush plated (EBP) iron coatings on AISI 1045 steel. Compared with EBP iron coatings, the Fe-GO composite coatings' average friction coefficient and weight loss decreased by 49.5% and 39.7% for the GO sheets' self-lubrication and reinforcement.

Micro arc oxidation and electrodeposition are often used to modify the light alloys' surface characterizations and wear properties. Zhang et al. [14] investigated the effects of $NaAlO_2$ concentration in the electrolyte on the micro-arc oxidated coatings' properties on the 7N01 aluminum alloy. The MAO coating had better wear resistance with less mass loss rates and lighter wear scar width with the increase in $NaAlO_2$ concentration. Apelfeld et al. [15] prepared to overcoat on a 5A06 aluminum alloy through group plasma electrolytic oxidation (PEO) with silicate-alkaline electrolyte. This was developed from the algorithms for the automatic correction of the PEO mode to increase the PEO coatings' stability when formed during parallel treatment in the same group.

Magnetron sputtering and multi-arc ion plating are often used to deposit hard coatings with a thin thickness on tools. Strzelecki et al. [16] used a pulsed magnetron sputtering system to synthesize multicomponent alloy coatings with mosaic targets. The improvement in the hardness of the pulsed magnetron sputtered HEA coatings was attributed to the high-frequency modulation and post-annealing. Chen et al. [17] prepared CrAlTiN coatings on compacted graphite cast iron with a multi-arc ion plating technology. The deposited CrAlTiN coatings were composed mainly of TiN, AlN, CrN, and small amounts of Al_2O_3, Cr_2O_3, Ti_2O_3, and Cr. The highest adhesion force of 61 N, the nano-hardness of 26 GPa,

the elastic modulus of 268 GPa, and the lowest friction coefficient of 0.4 guaranteed a good performance of antifriction and wear resistance.

Often, vapor deposition is used to deposit dense hard coatings, including physical vapor deposition and chemical vapor deposition. Koshuro et al. [18] used induction physical vapor deposition to prepare superhard Ta–O–N coatings on titanium. The Ta–O–N coating is composed mainly of Ta_2O_5, Ta_2O, TaON, TaN, TiO_2, TiO, α-Ta, and α-Ti. A superhard hardness, ranging from 46.18 to 89.88 GPa, was obtained on the surfaces of titanium.

Thermal spray is commonly used to prepare, repair, or remanufacture engineering parts with hard-face coatings, including electric arc spray, plasma spray, high-velocity oxygen-fuel spray (HVOF), and cold spray. Tian et al. [19] prepared a FeNiCrAl coating through high-velocity arc spraying with mixed α- and γ-Fe, Ni-Al, and Fe-Al intermetallic compounds, $Cr_{0.19}Fe_{0.1}Ni_{0.11}Al_{0.17}$ solid solution, and Fe_2B, FeO, and $(Fe, Cr)_3C$. The presence of multiphase compounds and high-density dislocation tangles enhanced the coating's cohesive strength and hardness. Islam et al. [20] prepared MoS_2 coatings reinforced with 2–4 wt% CNTs through plasma spraying over steel substrates. The MoS_2 coating's hardness and elastic modulus increased by 2–3 folds. Zhu et al. [21] prepared a CoCrFeNi high entropy alloys (HEAs) coating with fully dense microstructure on AZ91 alloy through the cold spray, depending mainly on the deformation of the feedstocks. The deposited HEA coating had a microhardness five times higher than Mg alloys. The cold-sprayed HEA coating had a weight loss two orders of magnitude lower than Mg alloys.

Cladding is often applied in strengthening and repairing engineering parts, for example, shaft and roller parts, including laser cladding, plasma cladding, plasma transfer arc cladding as well as ion beam cladding, etc. Sun et al. [22] prepared $Fe_{48}Cr_{15}Mo_{14}C_{12}B_3Si_6Y_2$ coatings through laser cladding. The coating had the highest hardness and smallest wear rate upon remelting twice. Wang et al. [23] prepared non-equiatomic FeCrNiCoMoW medium-entropy alloy coatings with (0–30 wt%) amounts of WC-10Co on 304 parts of stainless steel by electron beam cladding. There was a face-centered cubic (FCC) solid solution, $M_{23}C_6$ (M = Fe, Cr, Mo, or W), and WC particles in the composite coatings. When the added WC-10Co into the FeCrNiCoMoW was 30 wt%, the composite coating exhibited the preferred hardness and wear resistance with hardness around four times and wear resistance about two times that of the substrate.

Ion implanting is always used for surface modification when adjusting the surface's frictional and wear properties. Dou et al. [24] used low-energy nitrogen ion implantation on YG8 cemented carbide tools with TiC coatings. There was an amorphous TiC, TiN, as well as sp^2C–C phase in the implanted Ti-C-N coating. After ion implantation, the coating's hardness decreased first and then increased in the form of the TiN phase with the increase in ion implantation dose. Meanwhile, the top coating's surface roughness increased and then decreased with the increase in the nitrogen ion implantation dose. Nitrogen ion implantation could reduce the TiC coating's friction coefficient and improve its wear resistance. When the nitrogen implant dose was 1×10^{18} ions/cm^2, the modified Ti-C-N coating had the best wear resistance.

In conclusion, based on the hard-facing materials and these preparation methods, hard coating properties and their performance can be adjusted and regulated according to serving conditions. Hard coatings play a crucial role in realizing the reliable operation of workpieces, prolonging their use and lifespan, and reducing production costs. This Special Issue of *Coatings* aims to collect original research articles and review papers. The contributions focus on the materials, preparation processing, and structural, mechanical, and tribological properties of hard coatings. The potential of the covered subject in the hard coating is emphasized when serving in different conditions. The development of hard-facing materials, new preparation methods, processing optimization, microstructural design, as well as post-treatment is essential and greatly expanded in the application of hard coatings in engineering.

Conflicts of Interest: The authors declare no conflict of interest.

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