Abstract

Advanced engineering steels like 17-4 PH steel and ASME SA 387 steel find their applications in critical sectors of the economy like nuclear, chemical, fertilizer, power generation, boilers, pressure vessels, etc. These steels are often used in aggressive environments like high pressure and temperature, and highly corrosive-erosive environments which lead to the premature failure of these steels. For example, 17-4 PH steel exhibits poor tribological properties and fails due to galling in extreme environments. Similarly, SA 387 steel is prone to erosive wear. The improvement in the surface and sub-surface properties of these steels is the most viable solution to prolong their usage in these extreme environmental conditions thereby reducing the material wastage and costs associated with it. Heat treatment can resolve these issues up to some extent, but the problem still persists. Surface coating is another technique to enhance the surface and subsurface properties of a component. Deposition of protective surface coatings especially thermally sprayed ceramic-based coatings has gained significant interest in the past decade due to their excellent anti-wear, anti-corrosion, and high-temperature applications. Among the thermal spray processes, the high-velocity oxy-fuel (HVOF) process has the advantage of developing anti-wear, anti-corrosive, and anti-erosive coatings at relatively low temperatures and high velocity (supersonic) that help in developing a dense coating with better adhesion with the substrate. The current research is aimed at developing hard (anti-wear), anti-corrosive, and anti-erosive ceramic-based coatings using the HVOF process. It has been divided into three modules, namely, the development of reduced graphene oxide (rGO)-doped Al_2O_3-based coating, exploring the effect of heat treatment on the coating performance, and benchmarking the performance of coated and nitrided 17-4 PH steel. For each module, several characterization techniques were used to investigate the properties of the coating and substrates in detail. For example, the hardness (Vickers and scratch) and tribological responses were recorded using a universal (CETR-UMT) tribometer. The as-coated, flame-treated, and worn surfaces were analyzed using Goniometer, scanning electron microscope (SEM), energy dispersive spectroscopy (EDS), Raman spectroscopy, and 3-D optical profilometer. Corrosive degradation was studied using potentiodynamic polarization and electrical impedance spectroscopy (EIS). Furthermore, the erosion response of the coating was recorded using an air jet erosion test rig at room temperature.

In the case of developing rGO-doped Al_2O_3-based coating on 17-4 PH steel, the addition of rGO into the Al_2O_3-0.8 wt.% CeO_2 matrix enhanced the density of the coating by promoting localized melting due to the high thermal conductivity of the rGO thereby reducing the surface roughness. The improved density in the coating led to improvement in the micro-hardness, nano-hardness, and enhanced corrosion resistance compared to the rGO-less coating. The optimum concentration of rGO was determined to be 0.2 wt.%. This Al_2O_3-0.8 wt.% CeO_2-0.2 wt.% rGO coating outperformed the other coatings and the bare steels in terms of physical, mechanical, tribological, and chemical properties. For example, the elastic modulus and nano-hardness of Al_2O_3-0.8CeO_2-0.2rGO coating were $\approx$ 101% and $\approx$ 87% higher than that of Al_2O_3-CeO_2 coating, respectively. The specific wear rate of Al_2O_3-0.8CeO_2-0.2rGO coating was reduced by $\approx$ 10 times compared to that of 17-4 PH steel at 50 N (379 MPa) load. The improved properties could be attributed to the dense microstructure of the coatings with the introduction of rGO and the participation of rGO in the tribological process. Furthermore, to study the substrate effect on the Al_2O_3-0.8CeO_2-0.2rGO coating and widen the application of this coating, the same composition coating was deposited on SA 387 steel using the HVOF thermal spray process. The properties of the developed coating were then compared with the previously developed same-composition coating on 17-4 PH steel. The results indicated that the coating on SA 387 steel was relatively softer and less corrosion-resistant than the coating on 17-4 PH steel. The reason could be attributed to the presence of diffused iron in the coating on SA 387 steel. Also, the ceramic coating performed better in terms of erosive wear resistance than the SA 387 steel owing to its higher hardness.

The work on exploring the effect of thermal treatment on Al_2O_3-0.8CeO_2-0.2 rGO coating on 17-4 PH steel was planned to access the high-temperature applicability and change in physical, mechanical, and chemical properties of the coating. The heat treatment was done using an oxy-acetylene flame. The results revealed that the thermal treatment severely deteriorated the coating properties. The specific wear rate and corrosion rate of the coating increased by $\approx$ 165 times and $\approx$ 1500 times, respectively. This deterioration in the heat-treated coating properties was attributed to the evaporation of the reinforced rGO from the as-sprayed coating making the coating highly porous. So, it is not advisable to heat treat the above-mentioned coating composition above 400 ℃.

Finally, a comparative study was carried out to evaluate the performance of the Al_2O_3-0.8CeO_2-0.2 rGO coating on 17-4 PH steel, the nitrided 17-4 PH (N17-4 PH) steel, and bare 17-4 PH steel. The results showed that nitriding improved the wear resistance of the 17-4 PH steel but reduced its corrosion resistance significantly. Further, the ceramic-based coating performed better than the other two specimens regarding mechanical, tribological, and electrochemical properties. To be specific, the coating was $\approx$ 10 times and $\approx$ 6 times more wear-resistant than 17-4 PH steel and N17-4 PH steel, respectively, at 50 N (379 MPa) load. The performance enhancement in the coating was ascribed to the coating hardness, dense microstructure, and introduction of rGO in the coatings, which participated in the tribological process. Further detailed analysis of the specimens' properties reveals that the nitriding process can be replaced with the proposed ceramic-based coating using the HVOF technique for tribological, corrosive, and other applications for 17-4 PH steel.