Tribology of HEAs Prepared by Spark Plasma Sintering

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High-entropy alloys (HEAs) are prospective advanced materials for the production of components that operate at high, severe friction and in high-temperature environments. This is because they possess unique properties requisite for such applications. The tribology of HEAs is described. The exploits of wear-resistant HEAs, the development techniques of wear-resistant HEAs, challenges in developing wear-resistant HEAs, and so on, are included.

Keywords: High entropy alloys, spark plasma sintering, BCC phase, FCC phase, Coefficient of friction

1. Potential Applications of High-Entropy Alloys Prepared by Spark Plasma Sintering

High-entropy alloys (HEAs) have excellent tribological properties. Consequently, they have manifold areas of prospective applications. Here, some key areas of applications are discussed.

(I) Automobile components: The wear resistance and strength without compromising the ductility of HEAs make these exceptional materials for the production of robust automobile components like engine valves, gears, brake calipers, shafts, connecting rods, engine pistons, and ball joints. Other properties displayed by HEAs that are requisites for the production of automobile components include resistance to fatigue load, as well as resistance to corrosion, wear, and impact loads. The AlCoCrFeNi HEA is light, has a high yield strength of 1263 MPa at 773 K, a high ultimate compressive strength (UCS) of 1702 MPa, and a plasticity of 19.9% up to the temperature of 773 K. This shows that it is suitable for use in structural and high-temperature applications like gears, engine pistons, and valves [1].

(II) Medical and pharmaceutical applications: Popescu et al. [2] developed TiZrNbTaFe HEA and characterized its properties for biomedical implants. This HEA was compared with the conventional implant, Ti6Al4V alloy. It was reported that corrosion heavily affects Ti64 because of the presence of α and β phases in the microstructure which initiate galvanic corrosion at their interfaces. But the novel HEA exhibited only the β phase, which is more resistant to corrosion. Moreover, the presence of Ta increased the resistance of the HEA to corrosion because it is very resistant to Cl^- by forming the Ta_2O_5 protective film. It was therefore concluded that TiZrNbTaFe HEA is more biocompatible than Ti6Al4V for biomedical applications. Two major ways by which HEAs are employed in the medical sector are in orthopedic implants (comprising hip and knee) and in dental implants. HEAs employed for hip and knee replacements usually possess high strength, low elasticity, and high biocompatibility; which are properties they share with natural human bones. CoCrFeMnNi HEA has been successfully applied in the replacement of hip and knee and has exhibited superior characteristics in clinical trials [3].

(III) Purification of water: HEAs have a high adsorption property as a result of their high surface area which provides a large area for the adsorption of contaminants. More so, the high degree of disorder in HEAs enables them to possess large binding sites for the water contaminants. The high disorder will not give the contaminants a safe haven to pile up and cause fouling in the water channel [4]; coupled with their refined microstructure. It was reported that CoCrFeMnNi HEA is a good anti-fouling agent in water purification. Furthermore, HEAs have a refined microstructure devoid of pores which does not give binding sites for water contaminants. Contaminants bond better on coarse and porous surfaces and wreck their havocs. It is equally worthy noting that HEAs have a high corrosion resistance and superhydrophobicity [5]. So, microorganisms with a high affinity to inhabiting corroded surfaces are dearth in surfaces cladded with HEAs because of the lack of corrosion ions or radicals.

(IV) Microjoining: HEAs can efficiently perform more than conventional alloys in joining small components with the application of pressure and heat [6]. This is because HEAs possess a higher strength and higher thermal properties with low weight. HEA joining is useful in the production of micro-electro-mechanical system (MEMS) devices like sensors and actuators together with repairing their small parts [7]. The high strength of HEAs is required to withstand the high stresses domiciled in a joint. The low weight is a requisite in today's need for the miniaturization innovations of components and products, hence the need for the use of HEAs. Replacing conventional alloys with HEAs for high thermal applications is imperative because refractory HEAs can withstand high temperatures without losing strength coupled with a high creep resistance. FeCrAl-XY HEA (XY = Si, C, N, B), for instance, can be applied for elevated temperature joining as they can withstand temperatures of up to 1450 °C with appreciable oxidation and corrosion resistance [8].

(V) Space shuttle components: Aerospace components were traditionally built with superalloys and single crystal alloys. However, the narrative is changing since the discovery of HEAs. Due to their high wear resistance and strength at elevated temperatures, HEAs are being used to replace those conventional alloys employed in jet engine components like the turbine blades, compressors, and a combustor. For instance, the rotor of airplanes was hitherto built with ferritic steel. But, it has been disclosed that GE Aviation has developed NbMoTaW HEA which possesses better properties than ferritic steel [9]. Such excellent properties included being able to withstand temperatures above 800 °C, as well as possessing high strength and high corrosion resistance at elevated temperatures with sound creep resistance.

2. Tribological Challenges and Further Work on High-Entropy Alloys Prepared by Spark Plasma Sintering

It is worth clarifying that HEAs prepared by SPS are challenged by oxide inclusions during the sintering operation. The trapped oxides are most often the site for stress concentration. Once such oxides become entrapped, the area becomes the point of crack nucleation and propagation when there is even a little dislocation slip [10]. In order to offset this challenge of entrapping oxides during the SPS of HEAs, the inertness of the sintering chamber should be beefed up so as to have zero interference of O_2 and other oxidizing agents. Moreover, there is the need to introduce de-oxidizing agents into the sintering chamber or the HEA powders being sintered, which would barricade any incursion of oxide inclusion.

Again, some HEAs are sintered at a very high temperature and pressure. This may likely introduce residual or thermal stress which may negatively affect the suppression of wear by the alloy [11]. To tackle the issue of residual stress, heat treatment after fabrication is recommended. It is called “post-processing heat treatment”. Here, the sintered sample is fired to a temperature below the melting temperature of the HEA and left at that temperature for a reasonable amount of time in order to stimulate the relaxation and redistribution of the stress within the material and ameliorate the stress. Moreover, it is advised and recommended that the sintering temperature and pressure of HEAs should be as low as possible to prevent the growth of the thermal and residual stresses. Although this may induce high porosity and low densification in the alloy, the optimization of the sintering parameters using low sintering values can enhance these properties.

Furthermore, some HEAs processed through the high temperature may be affected by the high-temperature softening of the material [12]. The softened materials are prone to aggressive friction and wear. Hence, it is recommended that the sintering of HEAs should be carried out with optimized low sintering parameters, especially at a very reduced dwell time and increased heating and cooling rates.

Another tribological challenge suffered by HEAs is the evolution of a tribo-film. Even though a tribo-film is good at improving the wear suppression capacity via the reduction in the COF, sometimes, it may pose some negative influences on wear behavior. Some negative influences of the tribo-film include micro-cracks, the delamination of stressed surfaces, etc. One method of ameliorating this challenge is through surface treatments. The surface improvement of HEAs via laser surface cladding [13] or shot peening would be able to generate a more homogenous microstructure on the SPSed surface of the HEAs. This practice can eradicate the evolution of tribo-films through the removal of the potions susceptible to tribo-film formation—and can improve the metallurgical bonding of the alloys through the evolution of refined and homogenous structure [14]. The second method of ameliorating the negative influences of tribo-films is using the surface coating on HEAs prepared by SPS. Surface coatings like diamond-like carbon (DLC) [15], titanium nitride (TiN) [16], and chromium nitride (CrN) [17] can be used as a shield to prevent friction and wear on HEAs. The coatings can be applied through chemical vapor deposition (CVD) or physical vapor deposition (PVD). These coatings are hard particles which can protect the surface of the HEAs by acting as a barrier in standing against abrasive and adhesive wears.

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