Tribology of Electroless Nickel and Interlayer Coatings: A Review

A. Haniff Bharim\textsuperscript{1}, M. Zakwan Sarian\textsuperscript{1} and N. Bahiyah Baba\textsuperscript{1*}

\textsuperscript{1}Faculty of Engineering Technology, University College TATI (UC TATI), 24000 Kemaman Terengganu, Malaysia. Tel./Fax +6-09-8601000/+6-09-8635863, *Email: bahiyah@uctati.edu.my

Abstract. This review emphasizes on the development of electroless nickel composite coatings by incorporating different types of material and interlayers to improve the mechanical and tribological properties of the coatings. Electroless nickel coatings are the main focus of this review as it possesses excellent mechanical and tribological properties such as, hardness, wear and corrosion resistance. Besides, electroless nickel coating may behave as lubricating as well as wear resistance coating compared to other interlayer coatings. Tribology aspect is concern on the friction and wear phenomena which involved the moving parts that measures the overall systems’ life, efficiency, and reliability. Interlayer coatings are applied to improve the adhesion between the substrate and the outer coating materials. Various materials are used as interlayers either pure or compound metallic elements.

Keywords: Tribology, Electroless Nickel, Composite coatings, Interlayer

1. Introduction

Electroless is an in-situ chemical process where a reduction reaction of a metallic ions in the solution oxidised by itself. The process was founded by Wurtz in 1844 then Brener and Riddle developed the electroless coating in 1946 \cite{1}. Electroless process includes electroless nickel, electroless copper, electroless palladium, electroless gold \cite{2}. The most common and widely used electroless process is electroless nickel process. Electroless nickel has been used in chemical, textile, printing, electrical, food processing and automotive to aerospace industries.

Electroless nickel process can be divided into conventional and composite coating. The conventional electroless nickel is the traditional electroless process without addition of particles. On the other hand, electroless nickel composites is combination of deposition of metallic nickel with various particle together. The conventional electroless nickel usually denoted as Ni-P where the main composition of the deposits are nickel and phosphorus. Electroless Ni-P is relatively cheap, easy to control, good wear and corrosion resistance as well as high hardness and good lubrication \cite{3}. The focus subject of the review is on electroless nickel composite or sometimes called electroless nickel co-deposition.

Most of electroless nickel coating is homogeneous and uniform onto the substrate. The adhesion of the substrate and the coating are depending on the types of substrate. In order to improve the adhesion
between substrate and coating, an interlayer is introduced. There are various types of interlayer coating were investigated in the previous studies such as chromium [4], titanium nitride [5], copper [6] and others.

Electroless nickel is very well known for its high hardness, good wear and corrosion resistance which categorise them as having splendid tribological properties. The friction and wear characteristics are of the electroless nickel has been well investigated. The tribological properties of conventional electroless nickel has been enhanced by electroless nickel composites where the addition of particles either metallic, ceramics or polymers. The new variants electroless composites such as Ni–W–P, Ni–Cu–P, Ni–P–SiC, Ni–P–TiO₂ had shown improving their tribological properties [7].

2. Electroless nickel composite

Electroless nickel composite coating is a deposition of nickel together with particles either ceramics or polymers. The overview of electroless division is illustrate in Figure 1 below where the conventional electroless is a medium range phosphorus content and the composite is in low range phosphorus and the composite with metallic particles known as ternary alloys is in high range phosphorus content.

The electroless nickel composite coating is deposited simultaneously between metallic nickel and the particles onto the surface of the substrate. The particles are wrapped by the matrix material that is the nickel, which are deposited onto the substrate [8]. There are many variables involved in ensuring a successful co-deposition such as, inert nature of particles, size of particles, bath composition, suspension of particles, method of incorporation of particles in bath, bath reactivity, plating rate, stirring rate, pH, bath temperature and the compatibility of the particles with metal matrix [9].
3. Electroless nickel composite coating

Electroless nickel composite coatings in the field of tribology, can be divided into lubricating composite coatings and wear-resistant composite coatings. Electroless composite coating acts as lubricating composites since electroless coatings are known to have smoothening effect above a critical substrate roughness therefore they are in general very smooth and lubricious [10]. The surface morphology of the coating similar to a cauliflower and the smooth and lubricious properties are due to their unique nodular microstructure [11].

High wear-resistant coating can be enhanced by incorporated of high hardness particles and different surface treatment lead to change in conventional microstructure of coating that modified friction behaviour. The incorporation of particle in electroless nickel composite is highly depend on the dispersion of co-deposited particle in the coating where the stability of particle dispersion with high surface energy and activity in the plating bath control the segregation and agglomeration of the particles [12]. The particle dispersion in the bath can be conveniently realized by capping the particles with appropriate surface-modifying agents [13]. Besides incorporation of inert particles, the wear properties of a coating are affected by numerous other parameters such the applied stress and the surface morphology the wear resistance of electroless nickel deposits depends on both phosphorus content and the type of post heat treatment applied.

The purpose of tribological based application of electroless coating is to impart both smoothness and hardness onto the surface as to reduce friction and wear [14]. Surface treatment such as heat treatment able to reduce the friction coefficient of various electroless coatings and minimization of the friction of the coating is a necessary [15]. Previous studies found that heat treatments of the coatings able to decrease the average and maximal roughness [16-17].

Heat treatment increases hardness and wear resistance however at higher temperature, the grain coarsening gives negative impact to the wear resistance [18]. Surface treatment such as laser irradiated onto the coatings induced low wear than that of as-deposited amorphous alloy and furnace annealed coatings [19].

Poor adhesion between substrate and coating do not provide good protection, because the adhesion evaluation of electroless nickel are still unsolved [20]. The existence of a stronger metal-to-metal bonding makes the electroless nickel coatings having better adhesion compared to the nickel electrodeposition.

4. Interlayer coating

Interlayers are coating introduced between substrate and the outer coating layer. It acts as intermediate to enhance the adhesion of interfacial bonding between the substrate and the outer coating. Other than electroless nickel coating as interlayers, there are many other intermetallic coatings that had been investigated. Other interlayers can be divided into copper-based, and titanium-based.

Copper (Cu)-based interlayer is used either in its pure composition or intermetallic. A self lubricating coating of Cu/Cu-MoS₂ was investigated where Cu is the interlayer [6]. It was found that Cu interlayer on high speed steel give better wear resistance than the uncoated ones. Another study used copper in term of transient liquid phase (TLP) bonded joints with nickel at 580°C which is comparatively low temperatures and it showed that the shear strength of joints increase with holding time [21].
Titanium (Ti)-based interlayers has widely used such as Ti, TiN, TiC, TiAlN and others. A study done on Ti deposition onto 316L stainless steel substrate with thickness 200 nm by magnetron sputtering in a closed field arrangement showed that the adhesion increased with increase in the interlayer thickness due to crystalline tribology superelastic property [22]. Interlayers of TiC and TiC/Ti(C,N)/TiN were investigated as an effective interlayer for diamond film onto high speed steel substrate [5]. This is because coated diamond directly onto high speed via chemical vapour deposition induced high diffusion carbon into steel, thus by adding TiC interlayer the adhesion was improved and no delamination was found.

Chromium (Cr)-based interlayers are another type of interlayers used to enhanced adhesion bonding between coating and substrate. CrZrN was coated onto AISI H13, high speed steel and tungsten carbide substrate with Cr interlayer in between using unbalanced magnetron sputtering [4]. The adhesion strength is proportional to the interlayer thickness as similar trend found for TiC interlayer [22]. It is shown that maximum value at 300 nm thickness of the interlayer, and then the adhesion strength showed decrement as the interlayer increased further to 450 nm. In another study, CrZrN coated on H13 steel substrate using DC magnetron PVD method used Cr as interlayer due to its close lattice parameter and cubic crystal structure to H13 substrate [23]. The suitability of the interlayers should consider the crystal structure that will give better adhesion in between. Bouzakis et. al used Cr/CrN-nanointerlayer onto carbide cutting insert via high power pulse magnetron sputtering (HPPMS) showed the adhesion bond is strongly depends on the substrate surface integrity and on the interlayer thickness [24]. It concludes that if interlayer thickness is adapted to the substrate roughness, the interlayer adhesion and cutting performance can be appreciably improved.

5. Conclusions

Tribological aspect of the conventional electroless nickel, electroless nickel composite and several interlayers were reviewed. The focus was given to materials, mechanical properties, deposition method, and friction and wear characteristics of these types of coatings. The extensive literature evaluated on the electroless nickel coating either with and without incorporated inert particles. The speciality of electroless nickle coatings are their ability to act as lubricating as well as wear resistance coatings. Whereas other types of interlayer coatings mostly act as wear resistance coating. Moreover, either electroless nickel or other interlayers coatings, show the thickness of the coating plays an important criteria for good adhesion between substrate and outer coating. Surface integrity and treatment affected the tribology friction, corrosion behaviour, and wear resistance in which improve the properties.

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