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Nanocomposite Coatings Deposited by Sol-Enhanced Electrochemical Methods

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Additional information is available at the end of the chapter

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Abstract

Nano-composite coatings have wide applications for their superior mechanical and corrosion properties. Many efforts have been devoted to the development of different types of nano-composite coatings in the last decade. Various techniques are used to modify the coating microstructure at the nano scale in order to further improve the properties of coatings. We recently developed a novel method which combines sol-gel process and electrochemical deposition process to produce nano-composite coatings. This simple method can lead to a highly dispersed distribution of oxide nano-particles in the metal coating matrix, resulting in significantly improved mechanical properties. This Chapter introduces the principle of this innovative method, the basic theory behind the deposition process, and an overview of current results. It also describes the dopant technology that is derived from this novel technique. The future development potentials and industrial applications of these coatings are also discussed.

Keywords: Nanocomposite coatings, Electrochemical deposition, Nanoparticle distribution, Dopant technology

1. Introduction

Coatings are widely used on the surface of different substrates in order to improve the durability of working parts by increasing their resistance against wear, erosion, and corrosion. Comparing with the general coatings and conventional composite coatings, the nanocomposite coatings possess much improved properties because of the “nanosize dispersion effect”. It contains nanoparticles of a wide range of materials including oxides, carbides, metals, silicates and other ceramics with a size range of 1 to 100 nm. With the development of nanotechnology, the nanocomposite coatings are not only used as a surface protection material but also for developing special functional properties. Nowadays, the nanostructured coatings

with desired properties are widely used in military, aerospace, automotive, electronics and many other industries [1-2].

Much effort has been made to improve coating properties and design new nanocomposite coatings in the past decades. One of the focuses is how to achieve better “nano-dispersion”. It was well known that the properties such as strength, hardness and wear resistance of coatings can be greatly improved by a good dispersion of the second-phase particles in the matrix. Generally, the nanocomposite coatings are synthesized by directly adding nano-size solid powders into the plating solution. The nanoparticles can be incorporated into the metal matrix during the deposition process. However, it is difficult for the second phase nanoparticles to achieve a good dispersion in the matrix because of their large surface area [3]. The nanoparticles tend to agglomerate because of their high surface energy. In order to achieve a good dispersion of the second-phase particles in the coating matrix, the powder suspension has to be maintained in the electrolyte solution by vigorous agitation, air injection, ultrasonic vibration, or adding surfactants and other types of stabilizers, etc.

However, it is always difficult for the nanoparticles to achieve a good suspension because they have very large surface area, especially when the particle size is in a nanometer level. The high surface energy leads to the agglomeration of the nano-particles even though combinations of the above methods are used to reduce the particle agglomeration. Therefore, it has been a challenge to explore new techniques to produce highly dispersive nanoparticles reinforced composite coatings, which can take the advantage of the unique properties of the nano-particles to develop nanocomposite coatings with superior mechanical and other properties [4-5].

We have developed a novel technique: sol-enhanced composite plating, to synthesize highly dispersive oxide nano-particle reinforced composite coatings. In this new method, transparent sol solution containing desirable oxide components is directly introduced into the electrolyte solution at a controlled concentration and/or speed. Nano-particles with a size of below 25 nm will be in-situ generated and then incorporated into the coating matrix. This method can lead to a highly dispersive distribution of desired nanoparticles in the coating, resulting in significantly improved mechanical properties [6-10]. In this paper, we will introduce the basic theory of this method, report the current results and discuss the strengthening mechanism. We will also describe the dopant technology that is derived from this novel technique. The potential industrial applications of these technologies are also discussed.

2. The basic theory of sol-enhanced method

2.1. Brief introduction of sol-gel process

Sol-gel processes are versatile solution processes which have been widely applied to synthesize nano-particles, nano-composites, thin films, fibers and ceramics. They have shown considerable advantages, including excellent chemical stoichiometry, compositional homogeneity and low crystallization temperature due to the mixing of liquid precursors on a molecular level [5].

The sol-gel process can be described as the creation of an oxide/chloride network by progressive condensation reactions of molecular precursors in a liquid medium.

The sols can be basically classified as inorganic sols and organic sols. The most widely used is the organic sols, which are generally fabricated by using solutions of metal or metalloid alkoxide precursors $M(OR)_n$ in organic solvents [11]. Typically, a sol-gel process comprises solution, gelation, drying and densification. The precursors are subjected to a series of hydrolysis and polycondensation reactions to form a colloidal suspension, namely sol. Further processing of the "sol" makes it possible to form materials in different shapes, such as spinning or dipping to produce coatings and films, drawing from a liquid to produce fibers, precipitating or spray pyrolysis to get ultrafine uniform powders and processing in a vessel to produce aerogels and monoliths.

2.2. The evolution of the sol solution in the electrolyte

The evolution of the sol solution in the electrolyte was analyzed from two parts: (1) the formation of nano-particles, and (2) the size evolution of nano-particles before and after adding into electrolyte [9-10]. Considering the comparability of different kinds of sol, we hereby illustrate the behavior of TiO_2 sol in electroplating bath to explain the general electrochemical process of the sol-enhanced composite plating.

The transparent liquid TiO_2 sol was made by using metal alkoxide tetrabutylorthotitanate ($Ti(OBu)_4$) as the precursor. This metal alkoxide is dissolved into a mixed solution of ethanol and diethanolamine (DEA). It then formed a colloidal suspension under a series of hydrolysis and polymerization reactions. The small particles in sol with the charge on the surface cannot grow up for the covered layer of solvent molecules. Different small particles can be well suspended in the solvent, subjecting to the combined effect of charge, van der Waals force and gravity [9-10, 12-13].

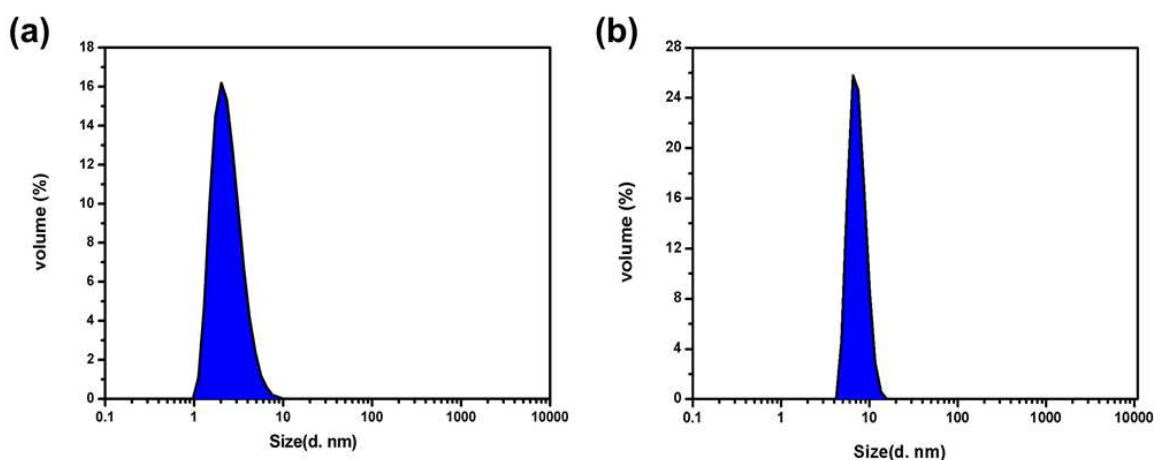


Figure 1. Size distribution of nano-particles in: (a) TiO_2 sol and (b) Ni electrolyte after adding TiO_2 sol.

The hydrolysis reaction and condensation process of TiO_2 sol has been widely investigated. Generally the stereo-hindrance and solvation effects are the main factors to make the sol

solution stable. Before TiO_2 sol is added into the electrolyte, the sol can be regarded as a stable system without solid liquid interface. Under neutral and basic conditions, the condensation process of Ti macromolecule ions started before the completion of hydrolysis; and the formation of an ordered structure was hindered.

After TiO_2 sol is added into the electrolyte, water in electrolyte aggravates the hydrolysis reaction and breaks up the dynamic balance. The sol system becomes unstable and the interface between solid and liquid emerges. Thus the amorphous TiO_2 nano-particles formed in situ [5, 9-10]. Fig. 1 presents the size distribution of nano-particles in the sol and the Ni electrolyte after adding the sol. The particle size was characterized by a laser diffraction particle analyzer (Malvern Mastersizer Hydro 2000S). The particle size of TiO_2 sol was distributed in the range of 1-10 nm, with a mean value of 2.5 nm as shown in Fig. 1a. The size distribution of sol added electrolyte keeps in a same level with the TiO_2 sol. The mean value of the particle size was increased to 7.4 nm and the particle size distribution was in the range of 3-20 nm which means no significant agglomeration occurs (Fig. 1b). The size measurement results are consistent with the HRTEM observation as shown in Fig. 2. The TiO_2 nano-particle got from electrolyte has an amorphous structure with a size of ~10 nm.

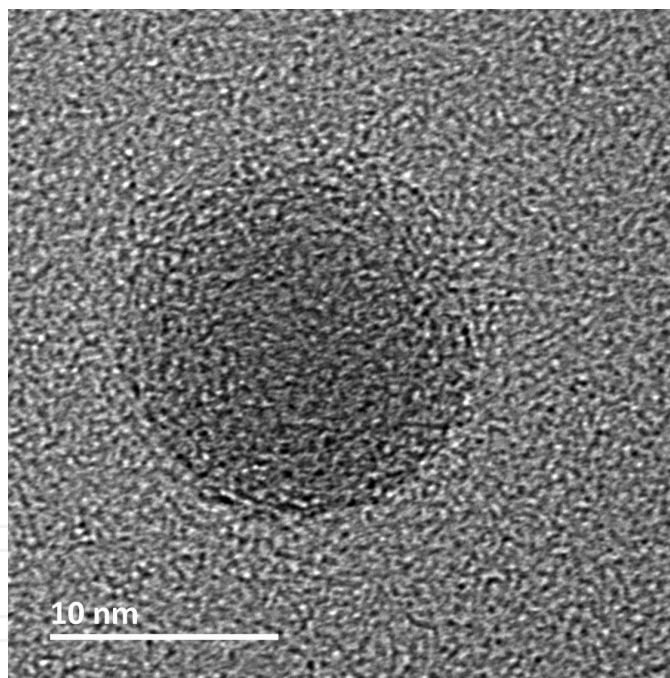


Figure 2. TEM bright field image of TiO_2 nano-particles separated from the Ni electrolyte with TiO_2 sol addition

2.3. Deposition process of sol-enhanced plating

The overall sol-enhanced deposition process can be typically divided into several steps. These steps describe the process of particles from the solution to their incorporation in the metal matrix. The first step is the in-situ generation of nano-particles after adding the sol into the electrolyte. Once the nano-particles formed in the electrolyte, some of them are immediately

physically adsorbed onto the freshly deposited surface based on the Martin-Williams model. Some of them were immediately adsorbed by hydrate metal ions due to their large surface areas based on the Whithers model [10]. Correspondingly, they were highly dispersed in the electrolyte as shown in Fig. 1b. The organic solvents probably also contribute to the dispersion of the ions-adsorbed nano-particles. Under the combination effect of migration, diffusion and convection, the coating matrix grows up with fine particles, and finally forms a highly dispersive nano-particle reinforced metal-based composite coating as shown in Fig. 3 [5, 9-10].

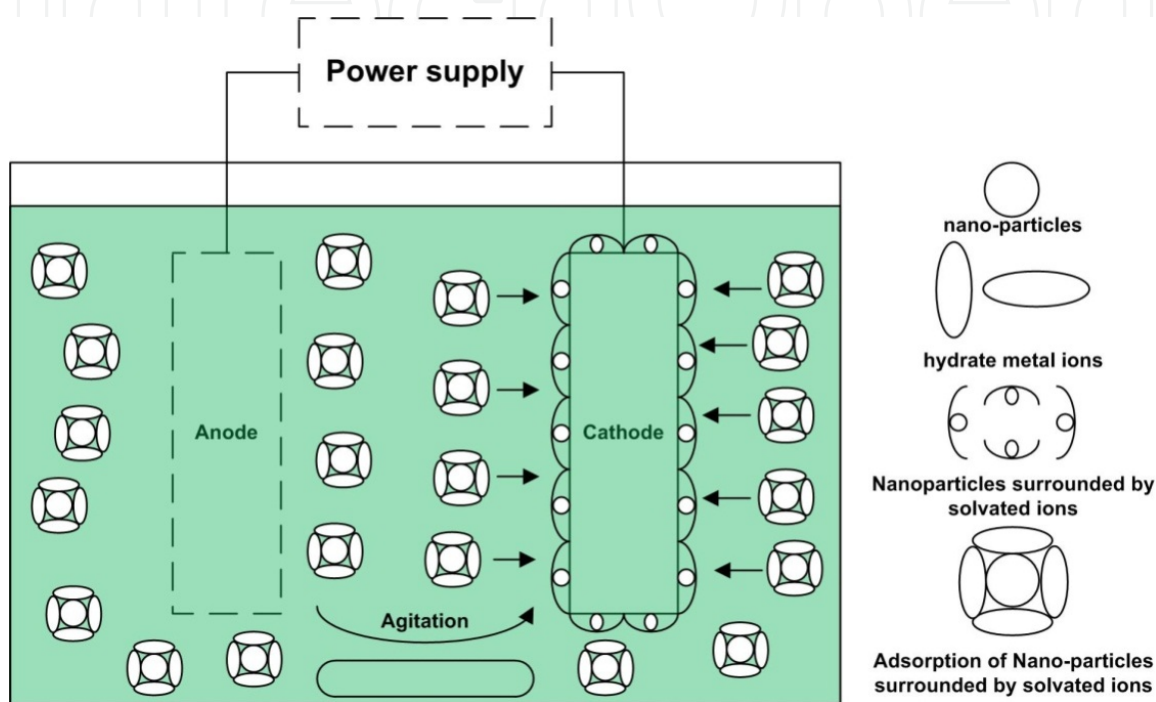


Figure 3. Sketch map of the sol-enhanced plating deposition process

3. Microstructure and property of sol-enhanced coatings

3.1. Microstructure of sol-enhanced coatings

The microstructure of sol-enhanced coatings was studied by various characterization methods. We hereby elaborate the related characterization results of cross-section, surface morphology and intrinsic microstructure of sol-enhanced coatings.

3.1.1. Cross-section images of sol-enhanced coatings

Fig. 4 shows the cross-section morphologies of Ni-P and sol-enhanced Ni-P-TiO₂ coatings. Sol-enhanced Ni-P-12.5 mL/L TiO₂ nano-composite coating has a similar cross-section image with traditional Ni-P coating. No obvious TiO₂ particles could be seen in the SEM cross-section, indicating their small size and relatively low content. However, with increasing TiO₂ addition,

the agglomerated TiO_2 particles can be clearly seen in Ni-P-50 mL/L TiO_2 composite coating. In addition, many voids were observed in the coatings [14]. When the sol concentration is relatively low (e.g., for sol-enhanced Ni-P- TiO_2 coating, the TiO_2 sol concentration is below 20 mL/L), the cross-section image of sol-enhanced coatings is similar with the traditional coating. However, when the sol concentration is relatively high (e.g., for sol-enhanced Ni-P- TiO_2 coating, the TiO_2 sol concentration is above 20 mL/L), a porous structure may form and large cluster area could be seen in the cross-section of sol-enhanced coatings due to the nano-particle agglomeration.

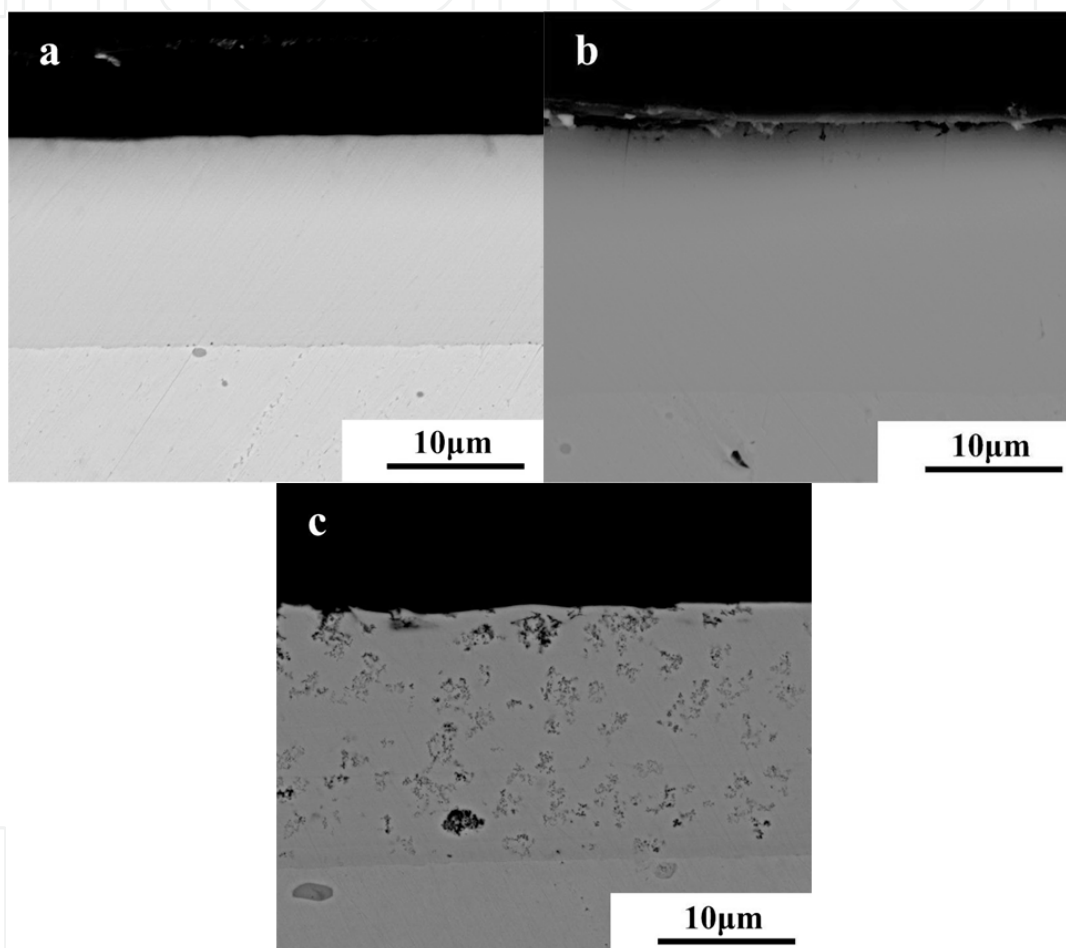


Figure 4. Cross-sectional morphologies: (a) traditional Ni-P coating, (b) sol-enhanced Ni-P-12.5 mL/L TiO_2 coating, and (c) Ni-P- TiO_2 coating with high concentration of sol (50 mL/L).

3.1.2. Surface morphology of sol-enhanced coatings

Fig. 5 shows the surface morphology of Au-Ni coating and TiO_2 sol enhanced Au-Ni- TiO_2 coatings with different TiO_2 sol concentrations. The Au-Ni coating shows typical granular morphology with the large protrusion size of ~ 400 nm. Some pores can be found on the Au-Ni coating surface, as shown by the white arrows in Fig. 4a, probably due to the formation of H_2 during the electro-deposition process. The morphology of 12.5 mL/L TiO_2 sol enhanced

composite coating shows a uniform spherically nodular structure with a size of ~ 300 nm (Fig. 5b). A great number of black dots were seen on the surface of 50 mL/L TiO_2 sol added composite coating, as shown by the white arrows in Fig. 5(c). The size of black dots ranges from ~ 50 nm to ~ 150 nm. Some of the black dots were attributed to the clusters formed by TiO_2 nano-particles, which confirmed by the EDS results. The Ti concentration in those locations was higher than other areas. As abundant TiO_2 nano-particles agglomerate into clusters, porous structure formed in the nearby area. The other black dots are the voids that may come from the H_2 release during the electro-deposition process [12-13].

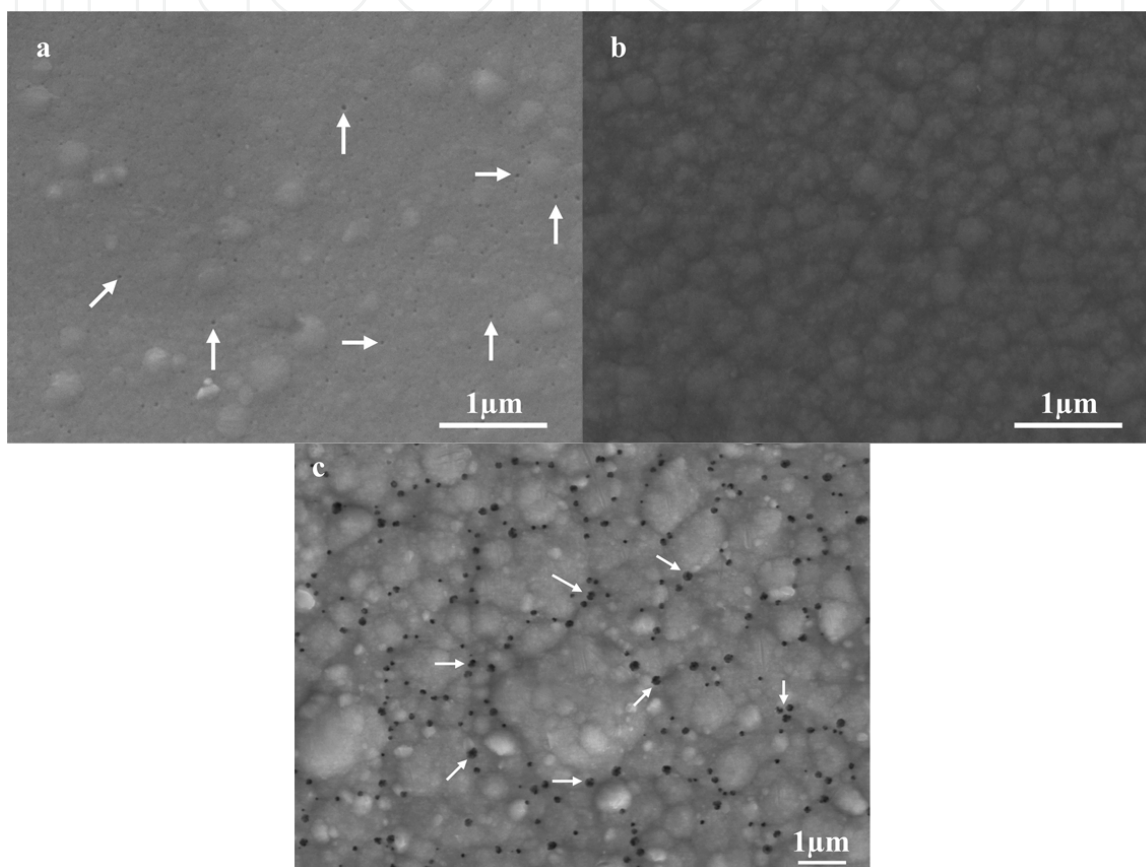


Figure 5. Surface morphology of sol-enhanced Au-Ni- TiO_2 nano-composite coatings: (a) Au-Ni as a comparison, (b) Au-Ni-12.5 mL/L TiO_2 , and (c) Au-Ni-50mL/L TiO_2

3.1.3. TEM microstructure of sol-enhanced nano-composite coatings

Fig. 6 presents the bright field image TEM and HRTEM image of sol-enhanced Ag- TiO_2 nano-composite coating. It can be seen that many white small nano-particles with a size of 10-25 nm were distributed quite uniformly in the grain boundary areas and inside the coating matrix as shown in Fig. 6a. The nanoscale probe EDX analysis indicates the white nano-particles contain Ti. HRTEM indicates that the small nano-particles have an amorphous microstructure, as shown in Fig. 6b. The grain size of the coatings can be calculated from the measured XRD patterns by using Scherrer's formula. The average grain size of sol-en-

hanced Ag-12.5 mL/LTiO₂ composite coatings shows a clear decrease from 38.5 nm of pure Ag coating to 25.7 nm [15].

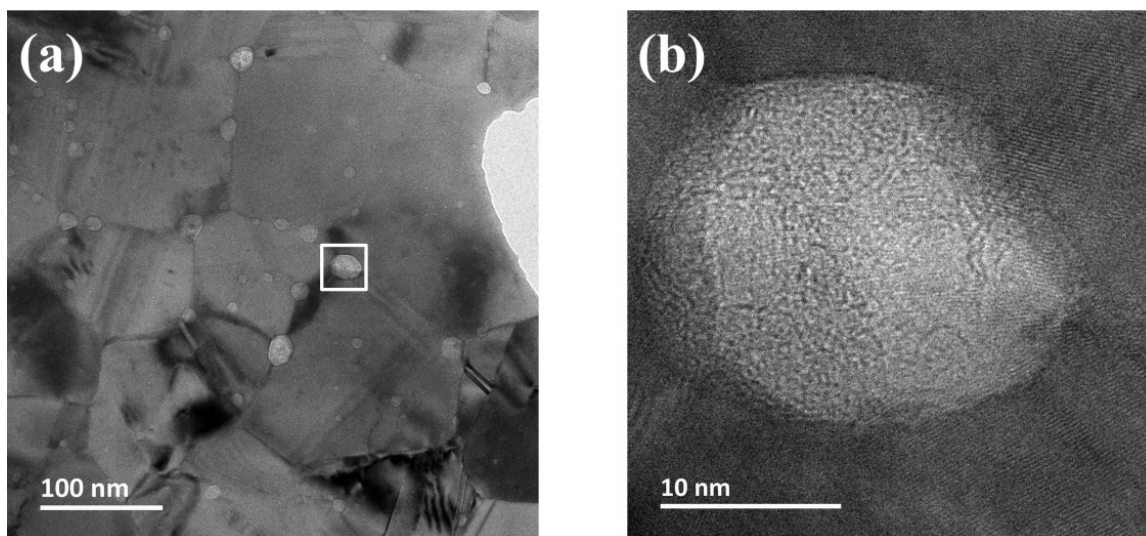


Figure 6. Bright field image and HRTEM image of sol-enhanced Ag-TiO₂ coating

Based on the results described above, we can conclude that when proper sol was added into the electrolyte, small nano-particles will be formed in-situ and co-deposited with the metal ions onto the substrate. These small amorphous nano-particles were distributed uniformly in the grain boundaries and inside the coating grains. Due to their small size, it is hard to detect them by using conventional microscopic tools such as optical microscope and scanning electron microscope.

These nano-particles incorporated into the coating matrix can increase the number of nucleation sites, while the other nano-particles distributed in the grain boundary can act as the obstacles that restrict the grain growth. The increasing nucleation center and obstacles for grain growth finally lead to an obvious grain refinement. However, when excessive sol was added into electrolyte, the nanoparticles start to agglomerate and tend to form voids in the coating matrix, finally causing a porous structure and deteriorating the property of coatings.

3.2. Mechanical property of sol-enhanced coatings

Several different kind of sol-enhanced coatings including Ni [8-10, 16-17], Ni-P [7, 14, 18], Ni-B [19-21], Ag [15] and Au-Ni [12-13, 22-24] nano-composite coatings were developed. Their mechanical property and microstructure were systematically studied. The mechanical properties of these sol-enhanced coatings are summarized in Table 1.

Based on the experimental results of mechanical properties and related microstructure of coatings, the corresponding strengthening mechanisms were suggested. A clear model of particle nano-dispersion, grain size and mechanical properties was established. We select sol-enhanced Au-Ni-TiO₂ nano-composite coating as an example to demonstrate the strengthening mechanism as below.

Type of coatings	Microhardness or Nano-hardness (optimum value)
Ni electroplating (on mild steel)	~320 HV _{0.1}
Sol-enhanced Ni-TiO ₂ electroplating (on mild steel)	~430 HV _{0.1}
Sol-enhanced Ni-TiO ₂ pulse electroplating (on mild steel)	~503 HV _{0.1}
Ni-P electroplating (on copper)	~520 HV _{0.1}
Sol-enhanced Ni-P-TiO ₂ electroplating (on copper)	~710 HV _{0.1}
Ni-B electroplating (on mild steel)	~677 HV _{0.2}
Sol-enhanced Ni-B electroplating (on mild steel)	~1061 HV _{0.2}
Ni-P electroless plating (on AZ31 Mg alloy)	~590 HV _{0.2}
Sol-enhanced Ni-P-TiO ₂ electroless plating (on AZ31 Mg alloy)	~1025 HV _{0.2}
Sol-enhanced Ni-P-ZrO ₂ electroless plating (on AZ31 Mg alloy)	~1045 HV _{0.2}
Au-Ni electroplating (on Ni coated brass)	2.55±0.13 GPa
Sol-enhanced Au-Ni-TiO ₂ electroplating (on Ni coated brass)	3.20±0.15 GPa
Sol-enhanced Au-Ni-TiO ₂ pulse electroplating (on Ni coated brass)	3.48±0.07 GPa
Sol-enhanced Au-Ni-ZrO ₂ electroplating (on Ni coated brass)	2.89±0.07 GPa
Sol-enhanced Au-Ni-ZrO ₂ pulse electroplating (on Ni coated brass)	3.31±0.11 GPa
Ag electroplating (on Ni coated brass)	1.33±0.05 GPa
Sol-enhanced Ag-TiO ₂ electroplating (on Ni coated brass)	1.64±0.05 GPa

Table 1. The mechanical properties of sol-enhanced coatings

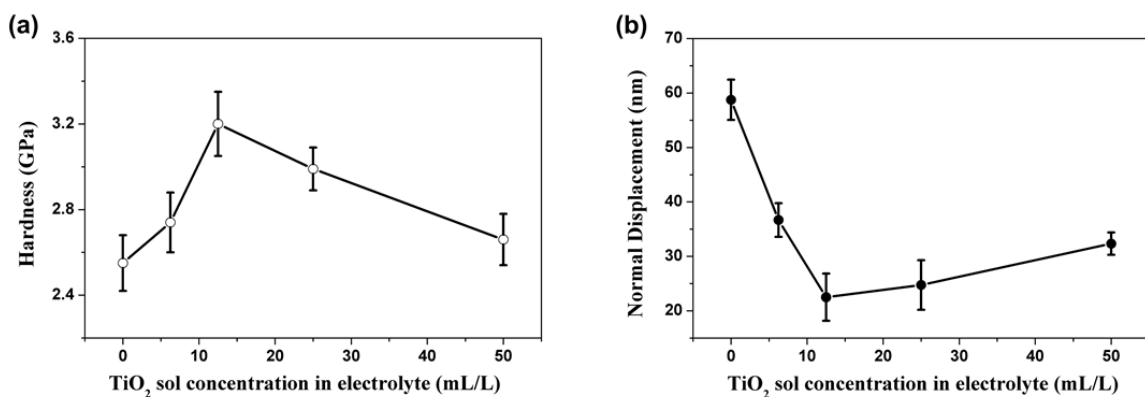


Figure 7. Nano-hardness and nano-scratch displacement results of sol-enhanced Au-Ni-TiO₂ nano-composite coatings

Fig. 7 shows the nano-hardness and scratch displacement of Au-Ni-TiO₂ coatings with different sol additions. The nano-indentation hardness and scratch tests were conducted on a Nanoindenter (Hyston, USA). Nano-scratch resistance tests were performed by using a conical tip with a 1000 μ N constant load to 10 μ m distance. The deeper of the scratch dis-

placement, the better wear resistance of coating. The nano-hardness and scratch displacement of Au-Ni coating was 2.55 ± 0.13 GPa and 58.8 ± 3.7 nm, respectively. At a low sol concentration, nano-hardness increases and scratch displacement decreases gradually with increasing TiO_2 content. 12.5 mL/L TiO_2 sol enhanced composite coating to the highest nano-hardness of 3.20 ± 0.15 GPa (26% increase) and the lowest scratch displacement of 22.5 ± 4.3 nm (reduced to 38%). However, further increasing the concentration of TiO_2 to 50 mL/L led to a decrease of nano-hardness to 2.66 ± 0.12 GPa, although it was still higher than that of the un-doped Au-Ni coatings. Meanwhile, the scratch displacement increases to 32.3 ± 2.1 nm.

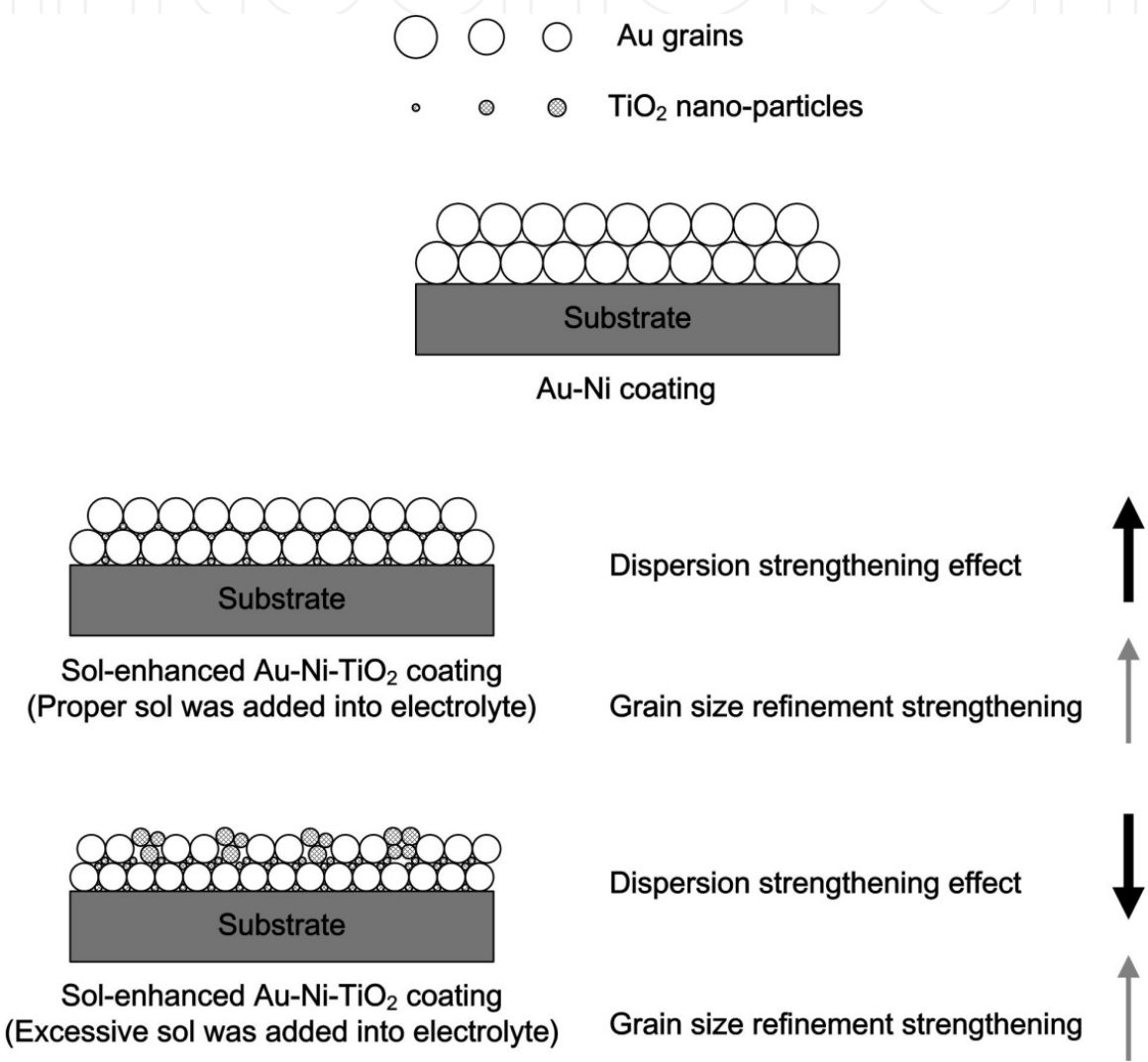


Figure 8. Schematic drawings of the enhancement mechanism of TiO_2 sol in the composite coating

The enhancement mechanism of TiO_2 sol on the composite coating can be elaborated in Fig. 8. The improved nano-hardness of sol-enhanced Au-Ni- TiO_2 coating could be attributed to the combined effects of grain refinement and dispersion strengthening. The highly dispersed reinforced phase should play a more important role as the grain size change is rather small. When proper TiO_2 sol was added into electrolyte, a good dispersion strengthening and grain

refinement can be achieved, resulting in a significant improvement of mechanical property for the coating. However, when excessive TiO_2 sol was added into electrolyte, TiO_2 nanoparticles start to agglomerate and tend to cause porous structure in the grain boundaries, which reduced the effect of dispersion strengthening; finally lead to a deterioration of the mechanical property although the grain size was continuously decreased [12-13].

3.3. Corrosion property of sol-enhanced coatings

Corrosion resistance is another important property for many coating applications. It was generally understood that materials with two phase microstructure may promote galvanic corrosion in corrosive environments therefore reducing their corrosion resistance. However, the nano-dispersion of a second phase can largely avoid galvanic corrosion and does not reduce the corrosion resistance of the composite coatings.

Fig. 9 shows the surface morphologies of Ni-B and sol-enhanced Ni-B- TiO_2 composite coatings after salt spray test for 120 h. The traditional Ni-B coating presented a corroded surface and the rust area can be clearly seen in Fig. 9a. The sol-enhanced Ni-B-12.5 mL/L TiO_2 coating displays an improved corrosion resistance as only two small corrosion pits can be seen by the white arrows in Fig. 9b. However, the sol-enhanced Ni-B-50 mL/L TiO_2 coating surface exhibited a corroded surface, similar to the un-doped Ni-B coating. A large area of coating surface was covered by rusts as shown in Fig. 9c.

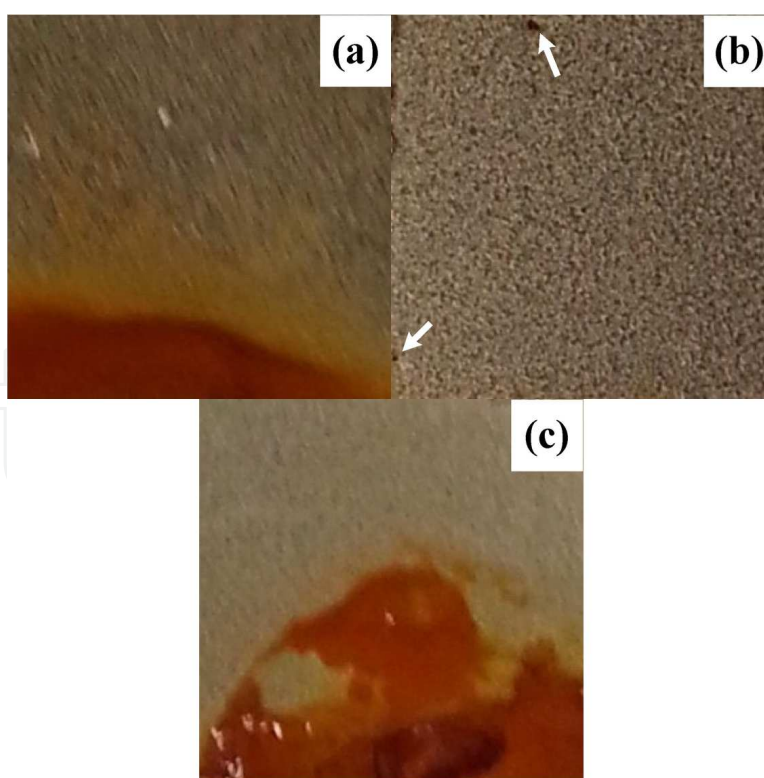


Figure 9. Surface morphologies of coatings after salt spray test in 5 wt. % NaCl solution for 120 h without removing the corrosion products: (a) Ni-B, (b) Ni-B-12.5 mL/L TiO_2 coating, and (c) Ni-B-50 mL/L TiO_2 coating.

The corrosion behaviors of coatings have a close relationship with the sol content due to its influence on the coatings microstructure. As it is well known that the corrosion resistance of a coating largely affected by its compactness, porosity is often the cause that a coating failure from corrosion. During the sol-enhanced electroplating process, the in-situ formed nanoparticles well distributed in the grain boundary areas can decrease the quantity of defects in the coating layer, making the coating more compact and less penetrable. Additionally, the nanoparticle itself is an inert compound, in the form of uniformly distributed nanoparticles in the coating, does not form micro galvanic cells. Instead, it may play a role of reducing the reactivity of matrix metal, therefore improving the corrosion resistance of the nano-composite coatings. However, when excessive sol was added into the electrolyte, the nanoparticles tend to agglomerate which increases the quantity of defects (voids) and lead to a porous structure in the coating, resulting in significant deterioration of corrosion resistance [19].

3.4. The other properties of sol-enhanced coatings

Metallic coatings and thin films have very wide applications which require not only mechanical and corrosion properties but also some functional properties. Here we use sol-enhanced Au-Ni coatings as an example to present the effect of sol addition on the surface gloss and conductivity property.

3.4.1. Surface gloss of sol-enhanced coatings

Surface gloss and color is important properties for gold and many other coatings as it dictates the quality and value of many products. Delta E (ΔE) is widely used to present the colour difference between samples being compared. It is generally accepted that if the difference of ΔE value between two samples is less than 1.0, they can be considered as the same colour, while 3.0 is the smallest colour difference that can be recognized by human naked eyes.

Fig. 10 presents the ΔE -values of Au-Ni coatings with different dopants. It can be seen that the sol addition impose a weak influence on the surface gloss and colors of coatings, which even cannot be detected by human naked eyes. The sol-enhanced coatings present almost identical surface gloss with the traditional coating due to the highly dispersed nano-structure [25].

3.4.2. Conductivity of sol-enhanced coatings

Both electrical conductivity and wear resistance are important properties for Au and Ag based coatings as these are required by applications of electric contacts. Traditional solid state alloying hardening techniques improve the wear resistance of Au and Ag coatings but severely reduce the conductivity due to the lattice distortion. The sol-enhanced strengthening technique improves the hardness of the coatings significantly but does not cause severe lattice distortion, therefore keeping the good conductivity for electrical applications.

Conductivity is frequently expressed in terms of IACS percent for convenience. An IACS value of 100% refers to a conductivity of 5.80×10^7 siemens per meter (58.0 MS/m) at 20°C. Fig. 11 shows the electrical resistivity and conductivity of sol-enhanced Au-Ni-TiO₂ coatings as a function of TiO₂ sol concentration. Comparing with the Au-Ni coating, the electrical conduc-

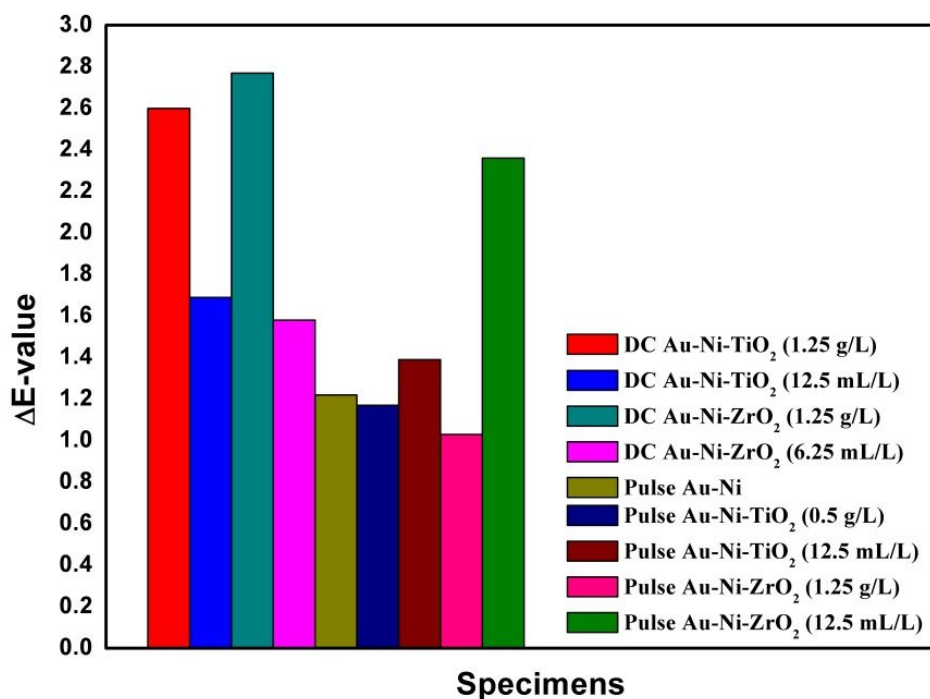


Figure 10. ΔE -values of Au-Ni coatings with different dopants

tivity of sol-enhanced coatings show a slight decrease (~4%) but keep at the same level with increasing sol content. After adding 50 mL/L TiO₂ sol, the electrical conductivity of coating is still higher than 50% IACS.

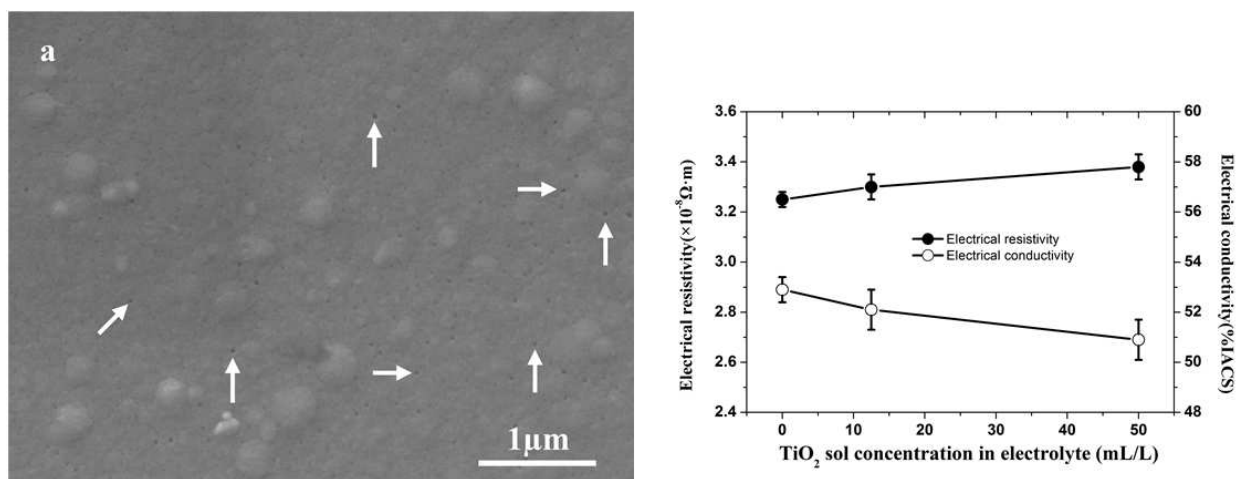


Figure 11. Electrical resistivity and electrical conductivity of sol-enhanced Au-Ni-TiO₂ nano-composite coatings

The same level conductivity of sol-enhanced coatings can be mainly attributed to the highly distribution of small nano-particles in the coating. The electron wave can bypass these small nano-particles and form a conductive network during the transportation process. Furthermore, the sol addition does not change the alloy solubility and cause lattice distortion. The

slight decrease of electrical conductivity can be attributed to the increment of scattering effect. The increase of grain boundaries and the scattering effect of electron wave strengthened by the second phase lead to the decrease of electrical conductivity [13].

4. Dopant technology derived from sol-enhanced plating and future industrial application of sol-enhanced coatings

In order to utilize this novel sol-enhanced technology and promote this technology into real production, the dopant technology has been developed based on the sol-enhanced method. Different types of sol were added into various commercial electrolytes to study their effects on the plating bath and property of coatings. Comprehensive investigations on the technical datasheet for different types of sol are being conducted. Table 2 briefly summarized the different types of sol which can take significant effect on commercial baths according to our studies. It can be seen that this sol dopant technology can be used in almost all types of commonly used commercial baths, which gives a broad application prospect.

Types of sol	Name of sol	Types of commercial bath
Inorganic	Al ₂ O ₃	Zn-Ni [26]
Organic	TiO ₂	Ni, Ni-P, Ni-B, Ni-Co [27-28], Cu [29], Au, Au-Ni, Ag, Co, Co-W, Sn, Ni-P(EP), Ni-B(EP) ^[*]
	ZrO ₂	Ni, Ni-P, Ni-B, Ni-Co, Au, Au-Ni, Au-Co, Ni-P(EP), Ni-B(EP)
	Al ₂ O ₃	Cu
Note: ^[*] EP means electroless plating, (eg. Ni-B(EP) means electroless Ni-B)		

Table 2. The sols have significant effect on the commercial baths

The sol-enhanced coatings have a highly dispersed nano-structure with superior performance. This sol-enhanced technology based on a simple and feasible process which is also compatible with the commercial solution. Therefore, it has great economic potential and market value in the future industrialization. For example, the micro-hardness of sol-enhanced Ni-P and Ni-B coating can reach up to above ~1000 HV, the same level of the widely used hard chrome coatings which require an environmentally harmful fabrication process. Hence, this sol-enhanced coating technology provides a potential replacement to the hard chrome coatings process [4]. On the other hand, the mechanical property of sol-enhanced Au and Ag coating can be increased up to more than 20% while keep the same level of conductivity and surface gloss. These research outcomes will find wide applications such as jewelry, craftwork and electronics.

A combination of different coatings can maximize the performance and functionality of coating by utilizing the different properties of each layer. Recently, we apply multi-layer technology to new sol-enhanced coatings systems in order to optimize the surface properties of coatings [20, 30-31]. Electroless double-layered Ni-P/Ni-P-XZrO₂ coatings with different phosphorus

(P) contents have been prepared. The high P inner layer provides high corrosion resistance while the sol-enhanced composite outer layer provides excellent mechanical properties. This controllable duplex electroless coating system possesses excellent anticorrosion and mechanical properties. Pilot scale production and tests are being conducted in order to realize the future industry applications.

5. Conclusion

A novel sol-enhanced method was developed to prepare nano-composite coatings. A small amount of oxide contained sol was added into the traditional electrolyte to in-situ form nanostructured composite coatings with highly dispersed nano-particles. The effect of sol addition on the microstructure and properties of composite coatings has been elaborated. The sol-enhanced nano-composite coatings have much improved mechanical property than that of the traditional coatings without sacrificing corrosion resistance, surface gloss and electrical conductivity. Dopant technology was developed to promote the real application of sol-enhanced coating method. Multiple sol-enhanced coatings were also developed in order to further improve the property of coatings. Scaling up tests is being conducted in an effort to realize industrial applications.

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