

Energy storage ability and photocathodic protection

properties of $\text{TiO}_2\text{-WO}_3$ system

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Abstracts: $\text{TiO}_2 / \text{WO}_3$ and $\text{TiO}_2 - \text{WO}_3$ coatings can be charged with reductive energy under UV irradiation. In this work, $\text{TiO}_2 / \text{WO}_3$ coating is compared with $\text{TiO}_2 - \text{WO}_3$ coating in terms of energy storage ability and photocathodic protection property. The self-discharging time of the $\text{TiO}_2 / \text{WO}_3$ coating is slower than that of the $\text{TiO}_2 - \text{WO}_3$ coating. The slow discharging may be suitable for an anticorrosion application for metal. In the case where $\text{TiO}_2 / \text{WO}_3$ coating electrode is electrochemically charged at -0.34 V (vs. SCE) for 1 h, it can maintain a good cathode protection for type 304 stainless steel for 6 h in the dark, while the $\text{TiO}_2 - \text{WO}_3$ coating electrode can only maintain a good cathode protection for less 0.5 h in the dark.

Keywords: energy storage; photocathodic protection; coating; $\text{TiO}_2 / \text{WO}_3$; $\text{TiO}_2 - \text{WO}_3$

1. Introduction

The applications of the TiO_2 coatings for photocathodic protection of steels under UV illumination have been reported [1-6]. The reason why this field has attracted considerable interest is that TiO_2 coating functions as a non-sacrificial anode when used for cathode protection of steel. However, the pure TiO_2 coating cannot be used in the dark, because it suffers from the well-known charge recombination problem. The shortcomings of a plain TiO_2 coating can also be circumvented by coupling another semi-conductor that has a different energy level as that of TiO_2 , which accepts photogenerated electrons from the semiconductor under light illumination and donates those electrons to carry on some electrochemical reactions after the light is turned off. Based on the principle, in the past several years, there

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have been a number of studies related to TiO_2 coupled with a semiconductor, such as WO_3 [7-10] or SnO_2 [11-14] or MoO_3 [15] or phosphotungstic acid [16] or $\text{Ni}(\text{OH})_2$ [17] or Sb_2O_5 [18], etc. Such as, Ngaotrakanwivat [7-10] demonstrated that crystalline WO_3 could serve as an energy storage material, when it was combined with TiO_2 as a semiconductor. The TiO_2 - WO_3 separately coating could provide cathode protection for type 304 stainless steel for 4 h in the dark after it was irradiation by UV illumination for 1 h, which exhibited more discharge properties than the TiO_2 - WO_3 composite coating[7]. Subasri reported that an ITO glass coated with SnO_2 – TiO_2 film [11] and SnO_2 / TiO_2 film [12] had a good storage electrons ability. In addition, we have reported that type 304 stainless steel coated with TiO_2 / Sb_2O_5 bilayer coating could be protected from corrosion in 3 wt % NaCl solution, even after UV light was turned off [18].

In this work, TiO_2 / WO_3 and TiO_2 - WO_3 coatings were prepared on type 304 stainless steel by sol-gel method, respectively. TiO_2 / WO_3 coating is compared with TiO_2 - WO_3 coating in terms of energy storage ability and photocathodic protection property. First, electron storage behaviors for both coatings are investigated by electrochemical method. Then, the anticorrosion performances for both coatings are tested. Last, Surface morphology, structure and properties of the both coatings are characterized by scanning electron microscope (SEM), X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS).

2 experimental

2.1 Preparation of the coatings

TiO_2 sol was prepared from tetra-n-butyl titanate($\text{Ti}(\text{OBu})_4$) by sol-gel method as follows: firstly 30 ml ethanol and 1 ml ethyl acetoacetate (EAcAc) were mixed at room temperature, then 10 ml $\text{Ti}(\text{OBu})_4$ was added and the solution was continuously stirred for 30 min, and finally 1 ml distilled water and 0.5 ml HNO_3 as well as 10 ml ethanol were carefully added to the solution which was kept stirring for 2 h.

WO_3 sol was prepared by oxidation with hydrogen peroxide according to the following process: firstly 50 ml H_2O_2 (30%) was carefully added to 10 g W powders (purity, 99 %), then 50 ml ethanol and a small amount of triethanolamine were added

to the solution and it was continuously stirred and refluxed for 5 h at temperature 80 °C.

TiO₂-WO₃ sol was prepared by the following process: firstly the appropriate amount of (NH₄)₂WO₄ solution (W / Ti = 3 %) was added to TiO₂ sol. Then, the solution was kept stirring for 2 h.

Type 304 stainless steel (2 cm × 5 cm) was polished as a substrate. The stainless steel substrate was polished to a mirror finish with Al₂O₃ powders and ultrasonically cleaned in acetone, ethanol and still water for 30 min, respectively. The TiO₂/WO₃ coating was prepared by successive coating with WO₃ and TiO₂. The WO₃ underlayer was prepared from WO₃ sol solution by dip-coating method. The substrate was annealed at 400 °C for 1 h. The average thickness of WO₃ coating was 120 nm (measured by SEM). The TiO₂ overlayer (average thickness measured by SEM, ca. 80 nm) was then prepared from TiO₂ sol solution in a similar way. In addition, TiO₂-WO₃ coating was prepared from TiO₂-WO₃ sol solution in a similar way. The average thickness of the composite coating was controlled with 80 nm (measured by SEM).

2.2 Characterization

The surface morphologies of the both coatings were characterized by scanning electron microscope (SEM) using LEO 1530 microscope with 15 kV accelerating voltage of the electron beam at various magnifications. The phase analysis of all samples was carried out using a D/max-III A X-ray diffractometer by employing Cu Kα as the incident radiation. The X-ray diffraction (XRD) patterns of the samples were collected over a 2θ range from 10° to 80° at a scan rate of 5°/min. The composition of both coatings were obtained with X-ray photoelectron model (XPS) with Al as the X-ray source and with 15 kV working voltage and 150 W working power.

2.3 Photo-electrochemical measurement

Each electrochemical experiment was performed in a three-electrode cell using a CHI660 electrochemical measurement system. All the measurements were done at room temperature in 3 wt% aqueous NaCl in an electrochemical cell equipped with a quartz glass window. A saturated calomel electrode (SCE) served as the reference

electrode. A stainless steel plate (8 cm × 8 cm) with a rectangular hole about 2 cm × 2 cm served as the reference electrode. TiO₂ / WO₃ and TiO₂ - WO₃ coatings electrodes were used as working electrodes (2 cm × 2 cm), respectively. The variations of open circuit potential (OCP) and the polarization curves of the two electrodes in the presence and absence of UV illumination were investigated, respectively. The potential swept amplitude was from 0 V to 0.5 V and the scan rate of 0.005 V/s for the polarization measurements. A 125 W high pressure Hg lamp with wavelength 365 nm was used as the source of irradiation.

3. Results and Discussion

3.1 Photo-electrochemical performance

First, electron storage behavior of TiO₂ / WO₃ and TiO₂ - WO₃ coatings are examined. Fig. 1 illustrates the potential changes for those coatings. During the UV irradiation, TiO₂ / WO₃ and TiO₂ - WO₃ coatings can keep their potentials more negative than the corrosion potential of type 304 stainless steel, indicating that these substrates are maintained under a photocathode protection condition. Moreover, the TiO₂ - WO₃ coating electrode shifts more negative value than that of the former, indicating the former may have less photo-electrochemical performance than that of the latter. The cause of the difference photo-electrochemical performance may be the difference surface area of WO₃ on surface of those coatings. This is discussed further below. After the potential application, the colors of those coatings are changed to blue, suggesting that those coatings are reduced. It is known that WO₃ (transparent) is electrochemically reducible to a tungsten bronze, and the charging process should be as follows



After the UV light is turned off, the OCP of the electrodes is gradually shifted to the positive direction due to the reoxidation by O₂. This is a so-called self-discharging process. That is to say, M_xW(IV, V)O₃ is gradually reoxidized to W(VI)O₃ by giving electrons to oxidation state matters or dissolved oxygen. As can also be seen from Fig.1, those coatings are irradiated by UV illumination for 1 h, TiO₂ / WO₃ coating electrode can be maintained cathode protection for more than 6 h, which is

longer than that of the TiO_2 - WO_3 coating. That is to say, the TiO_2 / WO_3 coating shows longer self-discharging time than does the TiO_2 - WO_3 coating, indicating that the former may have greater capacity than the latter. This may be because the content of WO_3 of the TiO_2 / WO_3 coating is much more than that of the TiO_2 - WO_3 coating, so that much more the photogenerated electrons from TiO_2 are stored by WO_3 in the former.

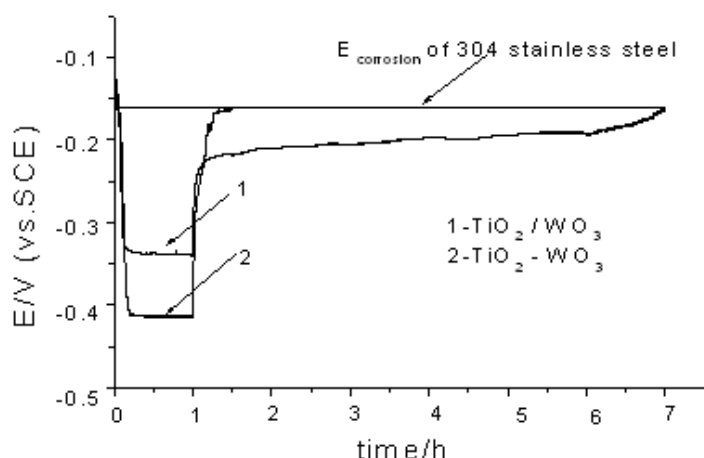


Fig.1. Potential changes of the photo-electrochemically charged TiO_2 / WO_3 and TiO_2 - WO_3 coatings in 3 wt% aqueous NaCl.

Fig.2 shows the polarization curves of TiO_2 / WO_3 and TiO_2 - WO_3 coatings electrodes in the presence and absence of UV irradiation, and of bare type 304 stainless steel in the dark in 3 wt% aqueous NaCl, respectively. The corrosion potential of the type 304 stainless steel is -0.16 V (vs. SCE). The photopotentials of TiO_2 / WO_3 and TiO_2 - WO_3 coatings are displaced to more positive values in comparison with bare 304 stainless steel in the dark. As a result, those coatings are able to act as optimal barrier layers to metallic substrates without a photo effect. In addition, the photopotential of -0.41 V (vs, SCE) is obtained for TiO_2 - WO_3 coating, which is more negative than that of TiO_2 / WO_3 under UV irradiation. The difference in the photopotentials of those coatings may be the difference surface area of TiO_2 on surface of those coatings. Moreover, the two of electrodes yield higher anodic currents when compared to bare type 304 stainless steel under UV irradiation. It can be attributed to the creation of a part of the photogenerated electrons from the two of

coatings. Generally, the occurrence of a positive stable potential is related to the presence of a higher corrosion resistance layer. That is to say, the two of coatings offer better corrosion protection under the free corrosion potential condition.

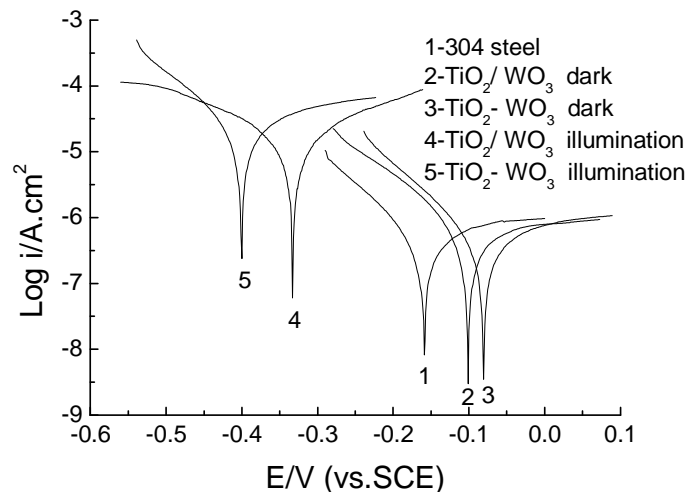


Fig.2. Tafel curves of a type 304 stainless steel electrode in the dark, and $\text{TiO}_2 / \text{WO}_3$ and $\text{TiO}_2 - \text{WO}_3$ coatings electrodes under UV illumination on and off

3.2 Phase structure

Fig.3 shows SEM images of the prepared $\text{TiO}_2 / \text{WO}_3$ and $\text{TiO}_2 - \text{WO}_3$ coatings. It is apparent that the $\text{TiO}_2 / \text{WO}_3$ coating is continuous and uniform, and the shape of these particles is irregular (see Fig.1a). In comparison with the $\text{TiO}_2 / \text{WO}_3$ coating, the surface of the $\text{TiO}_2 - \text{WO}_3$ coating is more uniform and compact (see Fig.1b). In addition, the particles of the $\text{TiO}_2 - \text{WO}_3$ coating are smaller than those in the $\text{TiO}_2 / \text{WO}_3$ coating. This degradation must give rise to the photo-electrochemical performance increase.

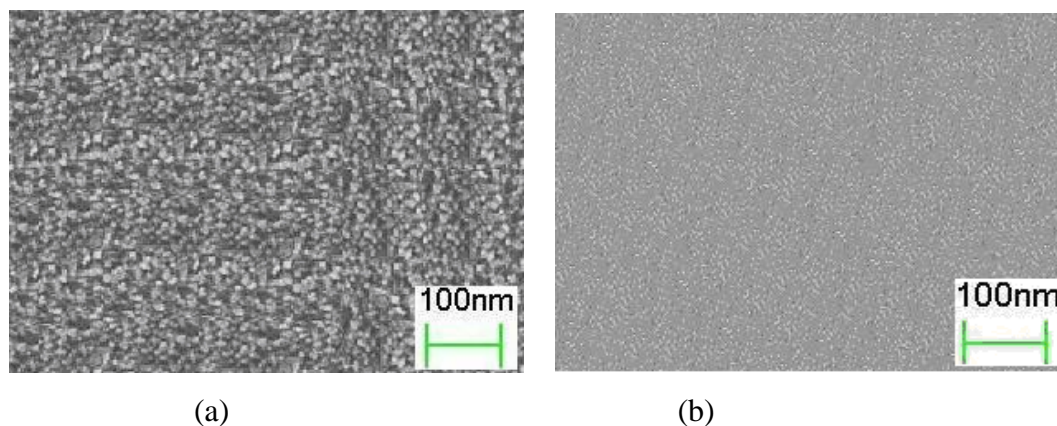


Fig.3. SEM images of the $\text{TiO}_2 / \text{WO}_3$ coating (a) and $\text{TiO}_2 - \text{WO}_3$ coating (b)

The Raman spectra for the TiO_2/WO_3 and $\text{TiO}_2 - \text{WO}_3$ coatings are shown in Fig.4.

It is known that TiO_2 photocatalyst in anatase phase has much higher photocatalytic properties than in other phases. Anatase in photoanode may also be important for the photocathodic protection effect because this effect came from the photoelectrochemical reactions on TiO_2 photocatalysts. It is obvious that TiO_2/WO_3 coating is made up of anatase TiO_2 and WO_3 . In compare with TiO_2/WO_3 coating, the $\text{TiO}_2 - \text{WO}_3$ coating is only made up of anatase TiO_2 , and no WO_3 characteristic peaks are shown in it. It may be due to too small WO_3 particles in it. This can be further verified by XPS analyses. In addition, the peak intensity and peak width of anatase TiO_2 in the $\text{TiO}_2 - \text{WO}_3$ coating turn stronger and wider, which indicate that the particles size becomes smaller.

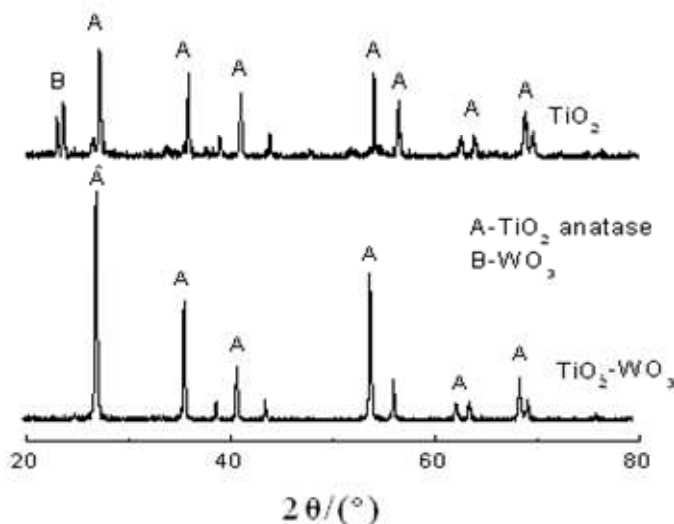


Fig.4.XRD spectra of the TiO_2/WO_3 and $\text{TiO}_2 - \text{WO}_3$ coatings

Fig. 5 shows the XPS survey scan of the TiO_2/WO_3 and $\text{TiO}_2 - \text{WO}_3$ coatings, in which only signals from Ti, W, O and C can be observed in those coatings. The carbon may mainly come from the surface contaminants. No signals steel from Fe, Co, Mn, or Ni, which are characteristic elements in stainless steel, can be detected in the XPS measurement. The results show that the stainless steel electrodes are entirely covered by the TiO_2/WO_3 and $\text{TiO}_2 - \text{WO}_3$ coatings, respectively. In addition, table.1 shows that the content of W element in the TiO_2/WO_3 coating is more than that of in the $\text{TiO}_2 - \text{WO}_3$ coating, which indicates a small amount of W ions diffusing to the TiO_2 coating in the former.

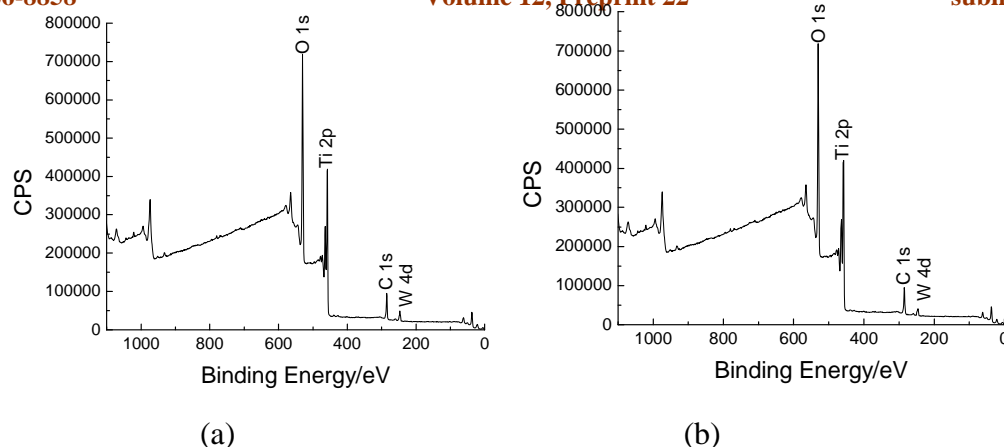


Fig.5 XPS survey spectra of TiO_2/WO_3 coating (a) and $\text{TiO}_2 - \text{WO}_3$ coating (b)

Table. 1 Contents of TiO_2/WO_3 coating and $\text{TiO}_2 - \text{WO}_3$ coating / %

element	Ti	W	O	C
TiO_2/WO_3 coating	17.898	0.149	51.301	28.945
$\text{TiO}_2 - \text{WO}_3$ coating	17.902	0.073	50.989	28.497

4. Conclusions

Continuous and uniform TiO_2/WO_3 and $\text{TiO}_2 - \text{WO}_3$ coatings were prepared on type 304 stainless steel substrates by sol-gel method. Both coatings can be charged with reductive energy under UV irradiation. The self-discharging time of the TiO_2/WO_3 coating is slower than that of the $\text{TiO}_2 - \text{WO}_3$ coating. Type 304 stainless steel with the TiO_2/WO_3 coating can maintain cathode protection for 6 h in the dark after irradiation by UV irradiation for 1 h. The slow discharging may be suitable for an anticorrosion application.

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