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Influence of counter electrode material during accelerated durability test of non-precious metal electrocatalysts in acidic medium

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ABSTRACT

Significant progress has been made in the development of non-precious metal electrocatalysts (NPMEs) during the past decade. Correspondingly, there is an urgent demand for an appropriate measurement method to be established for the reliable evaluation of NPMEs. In this study, platinum and graphite counter electrodes were used to investigate the impact of counter electrode material on the accelerated durability testing (ADT) of NPMEs in acidic medium. Platinum used as the counter electrode in a traditional three-electrode electrochemical cell was found to dissolve in acidic medium and re-deposit on NPME coated on the working electrode during ADT. Such re-deposition causes the oxygen reduction reaction (ORR) performance of NPMEs to remarkably improve, and thus will seriously mislead our judgment of NPMEs if we are unaware of it. The phenomenon can be avoided using a graphite counter electrode.

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1. Introduction

Proton exchange membrane fuel cells (PEMFCs) have become a focus of intensive research owing to their environmental friendliness and high energy conversion efficiency [1]. In PEMFCs, H₂ fuel is electrochemically oxidized at the anode side and O₂ is electrochemically reduced at the cathode side. The cathode reaction is a slow four-electron transfer reaction, which results in a high overpotential and thus high performance electrocatalysts are required to accelerate the oxygen reduction reaction (ORR). To date, platinum and platinum-based alloy nanoparticles dispersed on carbon supports have been dominantly employed as ORR electrocatalysts [2,3].

The ORR activity and durability of commercial Pt/C and Pt-based electrocatalysts are routinely characterized by casting a thin layer of the electrocatalyst on a rotating disk electrode (RDE) and measuring its ORR performance in acidic medium in a three-electrode electrochemical cell, which is composed of a working electrode, a reference electrode, and a counter electrode [4–9]. It has been shown that the three-electrode electrochemical cell setup can be used to effectively evaluate the performance of electrocatalysts [10]. The performance of commercial Pt/C and Pt-based electrocatalysts is normally measured by cyclic voltammetry (CV) in N₂-saturated electrolyte with ORR polarization on the RDE in the presence of O₂. To assess the durability of an electrocatalyst, accelerated durabil-

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ity testing (ADT) is carried out by potential cycling in the three-electrode system with CV and ORR measurements taken at certain cycle numbers to evaluate the degradation of the electrocatalyst in terms of electrochemical surface area (ECSA) and mass activity (MA) [5,6].

Commercial Pt/C electrocatalysts have been widely accepted as state-of-the-art electrocatalysts for ORR. However, platinum is scarce and expensive, so there is an urgent demand for the replacement of Pt-based electrocatalysts with high performance NPMEs. NPMEs have attracted much attention recently [11–16], and significant progress has been made in the investigation of novel synthetic approaches and the creation of NPME with high performance in acidic media [17–22]. For example, Feng and Müllen [20] reported a hierarchically porous NPME with an almost identical ORR half-wave potential to that of commercial 20 wt% Pt/C under alkaline conditions when the loading of both electrocatalysts was 0.1 mg/cm². Liao and co-workers [23] synthesized a graphene-like NPME with a ORR half-wave potential only 60 mV more negative than that of commercial Pt/C in 0.1 mol/L HClO₄. The electrochemical characterization of NPMEs has spontaneously inherited the characterization method used for commercial Pt/C, including as the same working electrode, reference electrode, and counter electrode in the three-electrode system, the same CV and ORR measurement sweep rate, and the same ADT conditions. However, the active sites and ORR reaction mechanism of NPMEs are more than likely to be different from those of commercial Pt/C, and therefore the effect of electrochemical characterization parameters on the evaluation of NPMEs should be paid special attention [24–26].

Herein, we focus on the effect of the counter electrode [27,28] on the evaluation of NPMEs using the three-electrode cell in an acidic medium. For the three-electrode measurement system, almost all of the literature has used a platinum counter electrode when evaluating Pt-based electrocatalysts, but different counter electrodes in the case of NPMEs, such as platinum [29], graphite [19], and gold [30]. Only a few studies have addressed the selection of the counter electrode. In this study, we investigated the impact of counter electrode material on the performance of NPMEs during ADT in acidic medium. We found that the platinum counter electrode dissolved in acidic electrolyte and re-deposits on the NPME during ADT, which will seriously interfere with the measurement of the durability of NPMEs. This finding demonstrates that graphite counter electrodes should be used for ADT in acidic medium instead of platinum to allow the reliable judgment of NPME performance.

2. Experimental

2.1. Materials

Two types of electrocatalysts were used in the ORR performance tests. Commercial Pt/C (20 wt% Pt on Vulcan XC-72) was purchased from Johnson Matthey, and a non-precious metal electrocatalyst was prepared in our lab. Nafion perfluorinated resin solution (5 wt% in a mixture of lower aliphatic alcohols and water) was supplied by Sigma-Aldrich. All aque-

ous solutions were prepared with ultrapure water (18.2 MΩ·cm at 25 °C) from a Millipore water system (Synergy® UV, France).

2.2. Electrode preparation

A 5.0 mm diameter glassy carbon RDE (geometric area of 0.19625 cm², Pine Research) was coated with a thin film of electrocatalyst. A slurry of NPME (2 mg/mL) was prepared by blending the electrocatalyst with water, ethanol, and Nafion solution ($V_{\text{water}}:V_{\text{ethanol}}:V_{\text{Nafion}} = 1:9:0.06$) under sonication in a water bath for 2 min. The suspension was pipetted onto the RDE and evaporated in air, resulting in an electrocatalyst loading of 0.6 mg/cm². For comparison, commercial 20 wt% Pt/C electrocatalyst ink (1 mg/mL) was prepared in a similar manner, and the Pt/C loading on the resulting RDE was 20 μg_{Pt}/cm².

2.3. Electrochemical measurements

All electrochemical measurements were carried out using an Autolab potentiostat/galvanostat (Echo Chemie BV Model PGSTAT-302N, The Netherlands) and a standard three-electrode electrochemical cell with the glassy carbon RDE as the working electrode, platinum mesh or graphite rod as the counter electrode, and a saturated calomel electrode (SCE) as the reference electrode, which was connected to the cell by a salt bridge (agar gel containing saturated KNO₃). All potentials in this study are referenced to that of the reversible hydrogen electrode (RHE).

All of the electrochemical tests were carried out at 25 °C in N₂-saturated or O₂-saturated aqueous 0.1 mol/L HClO₄ solution. The CV curves of the electrocatalysts were recorded at a positive scan rate of 100 mV/s. ORR polarization curves collected on the RDE were obtained at a rotation rate of 1600 rpm and a scan rate of 10 mV/s.

The electron transfer number of the electrocatalysts for ORR was determined using the Koutecky-Levich (K-L) equation:

$$1/I_D = 1/I_K + 1/B\omega^{1/2} \quad (1)$$

where I_D is the measured current density at the glassy carbon RDE, I_K is the kinetic current in amperes at a constant potential, ω is the electrode rotation speed (r/min), and B is the reciprocal of the slope, which can be determined from the slope of the K-L plot using the Levich equation:

$$B = 0.62nFAC_0D_0^{2/3}\nu^{1/6} \quad (2)$$

where n is the number of electrons transferred per oxygen molecule, F is the Faraday constant (96485 C/mol), D_0 is the diffusion coefficient of O₂ (1.93×10^{-5} cm²/s), C_0 is the bulk concentration of O₂ (1.26×10^{-3} mol/cm³), and ν is the kinematic viscosity of the electrolyte (0.01009 cm²/s) [21,31].

For ADT, the potential cycling was conducted between 0.6–1.2 V (vs RHE) at a scan rate of 100 mV/s in an O₂-saturated acidic solution that provided a harsh degradation environment. CV curves and ORR polarization curves were collected at certain cycle numbers during the test to monitor the degradation of the electrocatalyst.

2.4. Physical characterization

Transmission electron microscopy (TEM) images, energy dispersive X-ray spectra (EDS), and the elemental composition of the samples were investigated on a JEM-2100 microscope operated at 200 keV.

3. Results and discussion

The durability of an electrocatalyst is a key factor for its practical application in a PEMFC. However, evaluating this durability in operating PEMFCs requires a long time, up to over 10,000 hours. ADT was developed to shorten the test period by imposing artificially harsh conditions on the electrocatalyst system [32]. The potential cycling approach is a well-known method of testing the durability in a relatively short time, using RDEs in a three-electrode setup and simulation of the real operating conditions in PEMFCs [33]. The ADT of an electrocatalyst is normally conducted by consecutive potential cycling with suitable lower and upper potential limits. The degradation process is then macroscopically studied by measuring the loss of the ECSA and the MA of ORR over time. In this study, ADT was performed by cycling the electrocatalyst coated RDE be-

tween 0.6 and 1.2 V vs RHE at a scan rate of 100 mV/s in O₂-saturated 0.1 mol/L HClO₄ solution at 25 °C, consistent with the conditions used in the literature [34–36]. Commercial Pt/C is commonly used as a baseline electrocatalyst for comparison in ADT. As shown in Fig. 1(a), the CV curve of commercial Pt/C continuously shrank with increasing potential cycle. In this case, the counter electrode was platinum. The calculated ECSA of the commercial Pt/C electrode rapidly decreased with increasing ADT cycle number, and after 2500 cycles the ECSA loss was 58.2%, as shown in Fig. 1(a) and (b). Such a decrease in ECSA was caused by platinum nanoparticle agglomeration and dissolution and re-deposition during the ADT [37]. This was also responsible for the shift in the ORR half-wave potential toward lower potential with increasing ADT cycle number, as shown in Fig. 1c and d. The negatively shifted half-wave potential was 25 mV after 2500 ADT cycles. This well-known ADT experiment with platinum counter electrode reveals the degradation of commercial Pt/C well and is basically suitable for the evaluation of this kind of Pt-based electrocatalyst.

For the measurement of NPME in acidic medium, not much attention has been paid to the detailed test conditions of the ADT experiment. Therefore, in most of the literature the same test conditions have been chosen to perform the ADT of NPME

Fig. 1. CV curves (a, b) and ORR curves (c, d) of commercial 20 wt% Pt/C measured during ADT experiments. Potential cycling was carried out between 0.6 and 1.2 V (vs RHE) in O₂-saturated 0.1 mol/L HClO₄, with the scan rate of 100 mV/s.

[17,21,29,38], including the employment of a platinum counter electrode. Superficially, it seems that the same test conditions might be appropriate for the ADT of NPME. In this study, the durability of our in-house-made NPME was detected by cycling the electrocatalyst coated RDE for 3000 cycles in the three-electrode system (Fig. 2). Unlike the commercial Pt/C, the double layer capacity of our NPME did not show any decrease and surprisingly increased a little bit after potential cycling, which may be caused by a better contact between the NPME and the electrolyte with time and/or enlarged surface area of the NPME by electrochemical corrosion. The ORR performance of the NPME showed different behavior as compared with commercial Pt/C during ADT. The half-wave potential negatively shifted about 19 mV after 1500 ADT cycles, but more potential cycles obviously made the half-wave potential positively shift about 86 mV, which is 67 mV higher than the initial one. This abnormal shift during ADT rendered the final ORR activity of the NPME is comparable with the final activity of commercial Pt/C after ADT in terms of half-wave potential (Fig. 3).

To elucidate the origin of the abnormal ORR performance during ADT, CV curves were collected in O_2 -saturated electrolyte (Fig. 4). The peak of oxide reduction was found to contin-

Fig. 3. ORR polarization curves of commercial Pt/C and in-house-made NPME before and after potential cycling in O_2 -saturated 0.1 mol/L $HClO_4$. Potential cycling was carried out from 0.6 to 1.2 V (vs RHE) at 100 mV/s.

uously shift during the ADT, consistent with the change in the half-wave potential in the ORR polarization curves (Fig. 2(c)). The peak initially shifted to a lower potential, and then shifted

Fig. 2. CV (a, b) and ORR polarization (c, d) curves of the in-house-made NPME measured in N_2 -saturated and O_2 -saturated electrolyte during ADT experiments. Potential cycling was carried out between 0.6 and 1.2 V (vs RHE) in O_2 -saturated 0.1 mol/L $HClO_4$ at a scan rate of 100 mV/s.

Fig. 4. (a) CV curves of the in-house-made NPME measured in O₂-saturated electrolyte at selected ADT cycle numbers; (b) CV curves recorded in O₂-saturated electrolyte before and after the ADT experiments; (c) Position of the oxide reduction peak at the different cycle numbers in (a); (d) Linear sweep voltammetry (LSV) curves of the in-house-made NPME collected in N₂-saturated electrolyte during the ADT experiments. Potential cycling was carried out between 0.6 and 1.2 V (vs RHE) in O₂-saturated 0.1 mol/L HClO₄ at a scan rate of 100 mV/s.

to a higher potential. Two peaks appeared in the CV curve measured after the ADT experiment (Fig. 4(b)). One peak was negatively shifted and the other was positively shifted compared with the position of the oxide reduction peak observed before the ADT (Fig. 4(a)). These two peaks might be correlated to different types of active site. We speculate that the negatively shifted peak may have arisen from degraded NPME active sites, while the positively shifted peak may be attributable to uncertain generated active sites. To further our understanding, the background capacitive current was measured in N₂-saturated electrolyte at a scan rate of 10 mV/s (Fig. 4(d)). At the beginning, no peaks were observed between 0–0.1 V. After 400 potential cycles, an apparent peak appeared in this potential range and continuously evolved with increasing potential cycle number from 400 to 3000. It is worth pointing out that a peak in the potential range of 0–0.1 V generally corresponds to H₂ desorption [39], and so may have originated from generated active sites.

As the potential cycle number was increased from 3000 to 8000, the shift in the position of the oxide reduction peak in the CV curves and the change in the current density at 0.75 V (vs

RHE) in the ORR curves agreed well with those observed in the first 3000 potential cycles (Fig. 5). Many more potential cycles led to a higher and higher ORR activity. This was attributable to possible new active sites that continuously built up on the NPME. After 8000 potential cycles between 0.6–1.2 V (vs RHE) in O₂-saturated electrolyte, the NPME showed an identical ORR polarization curve to that observed for the commercial Pt/C before the ADT experiment (Fig. 6).

To identify the nature of the active sites possibly generated during the ADT, the electrocatalyst samples were analyzed with TEM. Before the ADT, the in-house-made NPME contained no particles (Fig. 7(a)). However, after the ADT a few irregular nanoparticles were observed on the surface of the NPME (Fig. 7(b)). As shown in Fig. 7(c), the crystalline lattice spacing of the particles was 0.229 nm, corresponding to the (111) plane of platinum. EDX analysis of the sample also clearly revealed the presence of Pt (Fig. 7(d)), in good agreement with the HRTEM results. It is clear that Pt nanoparticles grew on the NPME during the ADT process.

Furthermore, ORR polarization curves were measured at different RDE rotation rates to determine the electron transfer

Fig. 5. (a) CV curves of the measured in O_2 -saturated electrolyte at different potential cycle numbers; (b) CV curves of the in-house-made NPME recorded in O_2 -saturated electrolyte before and after the ADT experiments; (c) ORR polarization curves; (d) Current density at 0.75 V (vs RHE) measured during the ADT experiments. Potential cycling was carried out between 0.6 and 1.2 V (vs RHE) in O_2 -saturated 0.1 mol/L $HClO_4$ at a scan rate of 100 mV/s.

number before and after the ADT. As shown in Fig. 8(a) and (b), the electron transfer number before ADT was calculated to be 3.7, indicating that H_2O_2 formed during the ORR process. After

Fig. 6. ORR polarization curves of commercial Pt/C and in-house-made NPME before and after potential cycling in O_2 -saturated 0.1 mol/L $HClO_4$. Potential cycling was carried out from 0.6 to 1.2 V (vs RHE) at 100 mV/s.

potential cycling, the electron transfer number was calculated to be 4.0 (Fig. 8(c) and (d)), which means that the electrocatalyst behaved like a typical Pt electrocatalyst with the 4e⁻ ORR process. Therefore, the Pt nanoparticles confirmed above to have been deposited on the in-house-made NPME after the ADT led to the abnormal performance.

It is necessary to figure out the process of platinum nanoparticle deposition on the NPME during ADT in acidic medium. The degradation mechanism of Pt-based electrocatalysts has been widely studied under potential cycling conditions [40,41]. A major mechanism is Ostwald ripening via dissolution and re-deposition of Pt [42]. During the potential cycling process, Pt dissolution starts above 1.0 V (vs RHE) and drastically increases when the upper potential limit is increased above 1.2 V (RHE) [43]. In our case, a potential of 0.6–1.2 V (vs RHE) was applied to the working electrode. Simultaneously, the platinum counter electrode experiences an opposite electrochemical process [44]. Namely, the counter electrode functions as a cathode whenever the working electrode is operating as an anode and vice versa, which balances the reaction occurring at the working electrode. For example, in aqueous solution, if electrochemical reduction occurs at the working electrode,

Fig. 7. TEM images of the in-house-made NPME before (a) and after (b) the ADT experiments; (c) High resolution TEM image of a nanoparticle grown on the NPME (inset is selected area diffraction pattern of the nanoparticle); (d) EDX spectrum of the nanoparticle in (c).

oxygen may evolve from the platinum counter electrode. Therefore, the dissolution and re-deposition of Pt from the counter electrode also occurs in the three-electrode electrochemical cell. This phenomenon has not been paid enough at-

tention in the past, because it is generally assumed that the platinum counter electrode is inert and can be used in electrochemical tests without any issues. Actually, the Pt of the counter electrode dissolves and diffuses to the working electrode, where it is re-deposited. This process takes time, and will not affect the test until enough Pt has been deposited on the working electrode. In this scenario, the presence of deposited Pt will influence the measurement and mislead our judgment of the electrocatalyst coated on the working electrode. In our case, during the first 200 potential cycles, the amount of Pt deposited on the working electrode was low enough that its influence on the electrochemical measurement could not be observed (Fig. 4(d)). After more than 400 cycles, a sufficient amount of Pt had been deposited for its effects to become observable, which became more and more serious with increasing cycle number, which definitely should be avoided.

In the three-electrode system used for the evaluation of NPMEs, the dissolution and re-deposition of Pt from the counter electrode misleadingly enhances NPME performance during the ADT process in acidic medium. Therefore, selection of an appropriate counter electrode is vital. Besides platinum, a recent report has shown that palladium and rhodium can also dissolve during potential cycling in acidic solution [45]. There-

Fig. 8. ORR polarization curve of the in-house-made NPME before ADT recorded at different rotation rates in O_2 -saturated 0.1 mol/L $HClO_4$ (a) and corresponding K-L plots (b); ORR polarization curve of the un-house-made NPME after ADT collected at different rotation speeds in O_2 -saturated 0.1 mol/L $HClO_4$ (c) and corresponding K-L plots (d).

fore, graphite was chosen as an alternative counter electrode in this study [19,25,46]. Other stable counter electrodes have also been used in the literature, such as glassy carbon plate [47] and gold wire [30]. ADT was performed on the in-house-made NPME under the same conditions except for the counter electrode. With the graphite counter electrode, the CV curves measured during 3000 potential cycles were similar to those collected with the Pt counter electrode (Fig. 9(a) and (b)). However, the ORR polarization curve continuously negatively shifted with cycle number. After the ADT process, the half-wave potential had negatively shifted by about 31 mV, without any positive shift (Fig. 9(c) and (d)). In terms of the current density at 0.75 V during the ADT (Fig. 10), at less than 1000 cycles, the current density was the same no matter which counter electrode was used. However, when the potential cycle number was greater than 1000, the current density measured with the platinum counter electrode became higher than that with the graphite counter electrode. This result and the polarization curves measured in N_2 -saturated electrolyte (Fig. 4) further confirmed that Pt dissolved from the Pt counter electrode and deposited on the working electrode. When the potential cycle number was lower than 200, only a small amount of Pt had deposited on the working electrode and so no characteristic H_2 desorption peak appeared. When the potential cycle number

Fig. 10. Current density at 0.75 V (vs RHE) for the ORR polarization curves of the in-house-made NPME during ADT with platinum and graphite counter electrode. Potential cycling was carried out in O_2 -saturated 0.1 mol/L $HClO_4$ from 0.6 to 1.2 V (vs RHE) at 100 mV/s.

was greater than 400, the much larger amount of deposited Pt led to the appearance of the H_2 desorption peak. However, the deposited Pt did appear to have an effect on the ORR performance, possibly because of its small size [48]. Further increasing the potential cycle number allowed the deposited Pt nanoparticles to grow larger. When the potential cycle number was

Fig. 9. CV curves (a, b) and ORR polarization curves (c, d) of the in-house-made NPME collected in N_2 - and O_2 -saturated electrolyte, respectively. Potential cycling was carried out between 0.6 and 1.2 V (vs RHE) in O_2 -saturated 0.1 mol/L $HClO_4$ using a graphitic rod as the counter electrode and a scan rate of 100 mV/s.

greater than 1000, the deposited Pt nanoparticles had an obvious effect, enhancing the ORR performance of the in-house-made NPME.

4. Conclusions

The ADT has been widely used to evaluate the durability of electrocatalysts under harsh conditions in the standard three-electrode electrochemical cell. In the case of the assessment of NPMEs, the type of counter electrode will impact the apparent durability of the electrocatalyst in acidic medium. When platinum is used as the counter electrode, the Pt dissolves in the electrolyte during potential cycling and diffuses to the working electrode, where it is re-deposited on the NPME. With increasing potential cycle number, the deposited Pt grows larger and larger and significantly enhances the ORR on the NPME. This phenomenon causes NPMEs to exhibit abnormally high performance during ADT under these conditions. In contrast, when graphite is used as the counter electrode, the ADT experiment will not be affected by the counter electrode. This study demonstrates that platinum counter electrodes should be avoided when evaluating NPMEs using ADT experiments in acidic media.

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Graphical Abstract

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Influence of counter electrode material during accelerated durability test of non-precious metal electrocatalysts in acidic medium

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Graphite rather than platinum should be used as the counter electrode for the evaluation of non-precious metal electrocatalysts using accelerated durability tests in acidic media, because Pt dissolves and deposits on the electrocatalyst, affecting the assessment.

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对电极材料对非贵金属电催化剂耐久性评价的影响

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摘要: 质子交换膜燃料电池 (PEMFCs) 环境友好, 具有高的能量转换效率, 已受到了广泛的关注。目前, 铂基电催化剂广泛使用在 PEMFCs 中, 但铂的储量有限, 活性低, 耐久性差, 成本高, 急需开发高性能的非贵金属电催化剂替代铂基电催化剂。非贵金属电催化剂的电化学表征基本上都沿用了铂基电催化剂的评价体系和方法, 不一定适用于非贵金属电催化剂的表征。

本文选用铂和石墨为对电极考察其对非贵金属电催化剂在酸性电解质中耐久性测试的影响。当使用铂对电极时, 商业 Pt/C 电催化剂的氧还原 (ORR) 活性随着耐久性测试圈数的增加而降低, 而非贵金属电催化剂的氧还原活性在耐久性测试过程中的变化规律与商业 Pt/C 不同, 呈现先降低, 后升高的规律。耐久性测试前后的透射电镜 (TEM) 分析表明非贵金属电催化剂经过耐久性测试后, 在电催化剂表面生长了铂纳米颗粒。高分辨透射电镜 (HRTEM) 和能量色散 X 射线光谱 (EDX) 进一步证明以铂为对电极的三电极体系, 在进行非贵金属电催化剂耐久性测试的过程中, 非贵金属电催化剂表面生长了铂纳米颗粒, 使得非贵金属电催化剂的 ORR 活性在耐久性测试后得到显著提高。耐久性测试前后, 非贵金属电催化剂氧还原过程的电子转移数由 3.7 变为 4.0, 再次证明了耐久性测试过程中铂颗粒的生成。在三电极电化学体系中, 当工作电极发生阴极反应时, 对电极为阳极反应, 反之亦然, 即在工作电极上发生的任何电化学过程, 都会在对电极上完成相反的电化学过程。在循环电位扫描过程中, 当铂对电极的电压高于 1.0 V (vs RHE) 时, 开始发生铂的溶解现象, 并且当电压高于 1.2 V (vs RHE) 时, 铂的溶解量会急剧增加, 部分溶解的铂会扩散到工作电极附近, 并在工作电极的非贵金属电催化剂表面发生沉积作用。随着扫描圈数的增加, 沉积的铂纳米颗粒的数量增加, 颗粒变大, 从而使非贵金属电催化剂的表现 ORR 活性显著提高。该现象使得非贵金属电催化剂在酸性电解质中无法表现出其真实的耐久性。当选用石墨棒为对电极材料时, 非贵金属电催化剂在酸性电解质中的 ORR 活性不会受到对电极材料的影响。

通过考察对电极材料对非贵金属电催化剂在酸性电解质中耐久性能的影响, 可以得出结论, 即对非贵金属电催化剂在酸性电解质中的耐久性测试中, 不宜使用铂对电极, 应该使用石墨为对电极材料, 以防止对电极材料干扰耐久性测试。

关键词: 非贵金属电催化剂; 铂对电极; 石墨对电极; 加速老化测试; 酸性电解质

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