

# EFFECTS OF TiO<sub>2</sub> ADDITIVE ON ELECTROCHEMICAL HYDROGEN STORAGE PROPERTIES OF NANOCRYSTALLINE /AMORPHOUS Mg<sub>2</sub>Ni INTERMETALLIC ALLOY

A. Shahcheraghi, F. Dehghani, K. Raeissi\*, A. Saatchi and M. H. Enayati

\* k\_raeissi@cc.iut.ac.ir

Received: July 2012

Accepted: January 2013

Department of Materials Engineering, Isfahan University of Technology, Isfahan, Iran.

**Abstract:** Mg<sub>2</sub>Ni alloy and Mg<sub>2</sub>Ni-x wt% TiO<sub>2</sub> (x = 3, 5 and 10 wt %) composites are prepared by mechanical alloying. The produced alloy and composites are characterized as the particles with nanocrystalline/amorphous structure. The effects of TiO<sub>2</sub> on hydrogen storage properties are investigated using anodic polarization and electrochemical impedance spectroscopy. It is demonstrated that the initial discharge capacity and exchange current density of hydrogen are increased by adding 5wt% TiO<sub>2</sub>, while the cycle stability and bulk hydrogen diffusivity don't change. It is found that the charge transfer resistance of Mg<sub>2</sub>Ni-5wt% TiO<sub>2</sub> composite is lower than that of Mg<sub>2</sub>Ni alloy. On the other hand, the hydrogen oxidation during the discharge process proceeds more easily on the electrode surface containing TiO<sub>2</sub> additive.

**Keywords:** Magnesium-Nickel alloy; hydrogen storage; mechanical alloying; oxide addition; electrochemical property

## 1. INTRODUCTION

Rechargeable alkaline Ni-MH batteries use hydrogen storage alloys as the negative electrode due to their high energy density, great electrochemical properties and non toxicity [1]. Magnesium-based alloys have been studied because of their high hydrogen storage capacity and low cost [2]. However, rapid degradation of capacity in alkaline solutions and slow charge/discharge kinetics prevent their practical applications [3-6]. The attempts have been focusing on improving the electrochemical properties of Mg-based alloys in alkaline solutions [7,8].

In spite of techniques such as casting and powder metallurgy, promotion of appropriate nano/amorphous structures and defects makes the mechanical alloying (MA) as an exclusive method to modify the structure and surface characteristics of materials used in negative electrodes [7,9]. Numerous works show that the MA improves charge/discharge kinetics by reducing the grain size to nanoscale dimension, which consequently increases the specific surface area. It creates many defects including fine cracks on the surface, which are highly

permeable to hydrogen and thus facilitates the activation of powders [10-15].

Some transition metal oxides could be used as catalysts to improve the hydriding/dehydriding kinetics of nanocrystalline Mg-based materials [16,17]. The electrochemical performance of nanocrystalline LaMg<sub>12</sub>-Ni composite produced by MA method was modified significantly with a small amount of TiO<sub>2</sub> and Fe<sub>3</sub>O<sub>4</sub> additives [18]. Cui and Luo [19] studied the electrochemical performance of Mg<sub>2</sub>Ni-type hydrogen storage alloys and found that the discharge capacity and discharge rate of these alloys were greatly improved with metal oxides addition such as RuO<sub>2</sub> and V<sub>2</sub>O<sub>5</sub>.

The surface modification obtained by milling Mg-based alloy with an additive has been adopted to improve the electrochemical cycle stability of alloys [20]. Wang et al. [21] reported that the cycle stability of La<sub>2</sub>Mg<sub>17</sub> + 200 wt% Ni composite was improved by mixing of 1wt% Bi<sub>2</sub>O<sub>3</sub> through ball-milling.

In this work, the effects of TiO<sub>2</sub> on the electrochemical hydrogen storage properties and charge/discharge kinetic behavior of nanocrystalline /amorphous Mg<sub>2</sub>Ni alloy produced by MA were investigated.

## 2. MATERIAL AND METHODS

Mg<sub>2</sub>Ni alloy was prepared through MA. The metal powders of Mg and Ni elements were obtained from Merck and mixed in a planetary ball-mill at stoichiometric ratio of 2:1 for 50 h, under an argon protective atmosphere. The rotational speed during the ball milling was 500 rpm and the ball-to-powder weight ratio was 20:1. Mg<sub>2</sub>Ni-xTiO<sub>2</sub> (x = 3, 5 and 10 wt %) composites were also produced by ball-milling of produced Mg<sub>2</sub>Ni and different amounts of TiO<sub>2</sub> powders for 2 h, by similar process described above. The crystalline structure of the produced alloys was characterized by means of X-ray diffractometer (XRD) (model Philips Xpert-MPD). The surface configuration was characterized by using transmission electron microscope (TEM) (model Philips CM120) and scanning electron microscope (SEM) (model Philips XL30).

For preparing the working electrode, 1 g of alloy powders produced (Mg<sub>2</sub>Ni or Mg<sub>2</sub>Ni-xTiO<sub>2</sub>) was mixed thoroughly with 5 g Ni powder and then compressed under 500 MPa pressure into tablet of 16 mm diameter and 0.6 mm thickness.

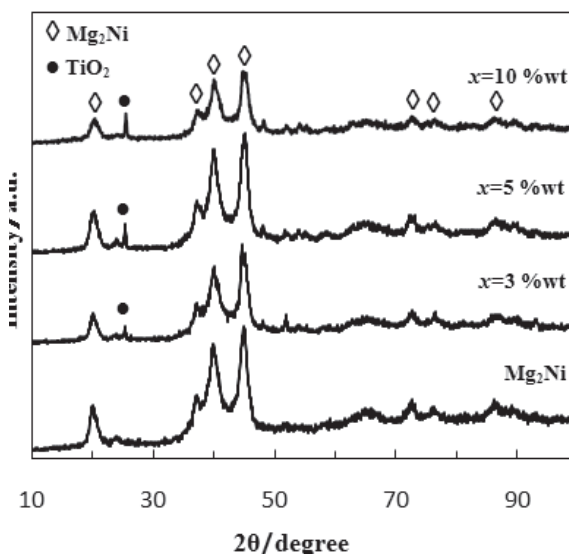
The electrochemical measurements were performed through an open tri-electrode measurement system in 6 M KOH electrolyte at 298°K. The Pt and Hg/HgO electrodes were served as the counter and reference electrodes, respectively. Before the measurements, the working electrode was activated in 6 M KOH electrolyte for 1 h. The discharge capacity was then measured as follows. The working electrode was first charged at 100 mA g<sup>-1</sup> cathodic current for 9500 s. Then, it waited for 5 min and then discharged by applying 100 mA g<sup>-1</sup> anodic current until the potential reached to -0.5 V vs. Hg/HgO. In order to measure the cyclic stability, a charge/discharge current of 100 mA g<sup>-1</sup> was applied for 8 cycles. Electrochemical impedance spectroscopy (EIS) measurements were carried out using voltage amplitude of 10 mV in the frequency range of 100 kHz-10 mHz. The anodic polarization curves of the electrodes were also measured with the scan rate of 1 mVs<sup>-1</sup> from 0-1200 mV vs. open circuit potential at fully-charged state.

## 3. RESULT AND DISCUSSION

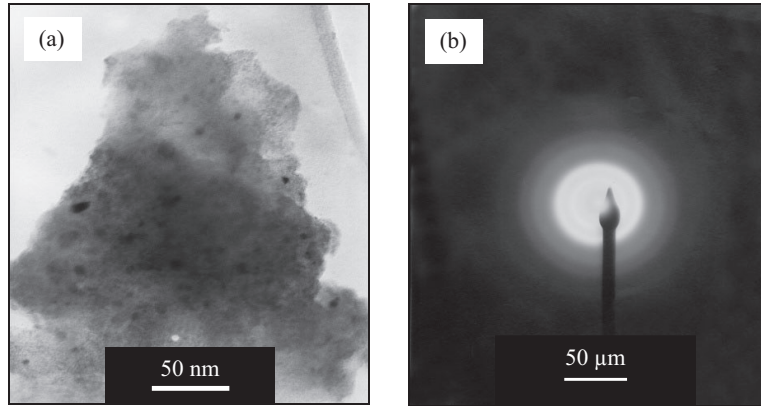
### 3. 1. Structural Characterization

The surface area and particle size are the most important factors influencing the hydridation characteristic of particles. Ball-milling process produces fine particles with fresh surfaces which increase hydridation rate [10]. Fig. 1 shows XRD patterns of Mg<sub>2</sub>Ni alloy and Mg<sub>2</sub>Ni-x wt% TiO<sub>2</sub> (x = 3, 5 and 10 wt %) composites. The peaks of Mg<sub>2</sub>Ni phase have appeared after 50 h milling and are wide in appearance. This may indicate a nanocrystalline/amorphous structure of Mg<sub>2</sub>Ni which is in agreement with the results obtained by Yuan et al. [7]. As is seen in Fig. 1, the XRD pattern has not been changed by introducing TiO<sub>2</sub> particles. The average crystalline sizes calculated by applying Williamson-Hall formula [22] using XRD patterns are around 6 nm for both Mg<sub>2</sub>Ni and Mg<sub>2</sub>Ni-x wt% TiO<sub>2</sub> specimens. It seems that the crystal size of Mg<sub>2</sub>Ni has not been affected by TiO<sub>2</sub> addition.

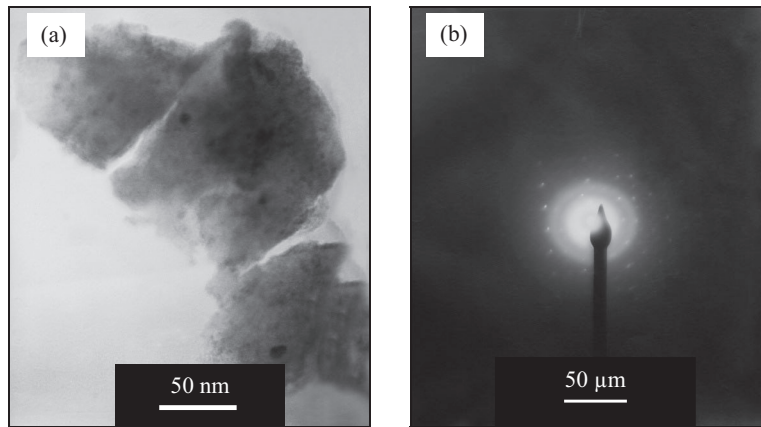
TEM images of Mg<sub>2</sub>Ni particles and 5%wt TiO<sub>2</sub>-containing composite particles after 50 h alloying are shown in Figs. 2 and 3. A feature which consists of nanocrystalline grains embedded in an amorphous matrix can be



**Fig. 1.** XRD patterns of Mg<sub>2</sub>Ni alloy and Mg<sub>2</sub>Ni-x wt% TiO<sub>2</sub> (x = 3, 5 and 10 wt%) composites.



**Fig. 2.** TEM image of  $Mg_2Ni$  alloy: (a) light-field image (b) electron diffraction pattern.



**Fig. 3.** TEM image of  $Mg_2Ni-5$  wt%  $TiO_2$  composite: (a) light-field image (b) electron diffraction pattern.

recognized on bright-field images of both specimens (Figs. 2a and 3a). As seen in Figs. 2a and 3a, the average grain size is about 10 nm which confirms the results obtained by XRD patterns. The presence of halo rings in electron diffraction (ED) patterns (Figs. 2b and 3b) indicates the existence of amorphous structure [14]. Also, the diffraction rings appeared around the halo confirms the presence of nanocrystalline grains coexisted with the amorphous phase. A very similar results have been obtained for  $Mg_{1.8}Ti_{0.2}Ni$  alloy after ball-milling [9] and the melt-spun  $Mg_{20-x}La_xNi_{10}$  ( $x = 2, 4$ ) electrode [23]. On the other hand, The diffracted spots observed on the corresponding ED pattern (Fig. 3b) confirms the presence of micro size particles related to  $TiO_2$ .

## 3. 2. Electrochemical Characteristics

### 3. 2. 1. Discharge Capacity

Electrochemical galvanostatic charge /discharge curves were used to evaluate the hydrogen discharge capacity. For charging, water break down was performed in 6 M KOH solution by imposing a 100 mA  $g^{-1}$  cathodic current for 9500 s. The atomic hydrogen is absorbed into the interstitial sites of  $Mg_2Ni$  alloy and saturates it. After that, a 100 mA  $g^{-1}$  anodic current was applied on the hydrogen saturated  $Mg_2Ni$  to release the hydrogen. Fig. 4 shows the discharge curves of  $Mg_2Ni$  alloy together with  $Mg_2Ni-x$  wt%  $TiO_2$  ( $x = 3, 5$  and 10 wt %) composites for the first cycle. The discharge capacity was calculated using the following Eq. (1).

$$Q_{\text{discharge}} = It \quad (1)$$

where  $Q$  is the discharge capacity ( $\text{mAh g}^{-1}$ ),  $I$  is the discharge current density ( $\text{mA g}^{-1}$ ) at cut-off potential ( $-0.5 \text{ V vs. Hg/HgO}$ ), and  $t$  is the overall discharge time (h). The first-cycle discharge capacities of the samples with 0, 3, 5 and 10 wt%  $\text{TiO}_2$  were 62, 27, 80 and 66  $\text{mAh g}^{-1}$ , respectively. It is seen that the  $\text{TiO}_2$  addition exerts no systematic effect on discharge capacity. The lowest amount of  $\text{TiO}_2$  (3 wt%) destroys the discharge capability of the electrode strongly. However, 5 wt%  $\text{TiO}_2$  improves the discharge capacity. On the other hand, the highest amount of  $\text{TiO}_2$  (i.e. 10 wt%) shows no significant improvement as compared to pure  $\text{Mg}_2\text{Ni}$  alloy. This is in agreement with the results obtained by Wang et al. [18]. They found that although 5 wt%  $\text{TiO}_2$  increased the discharge capacity of ball-milled nanocrystalline  $\text{LaMg}_{12}\text{-Ni}$  alloy, a decrease in discharge capacity was obtained by 3 wt%  $\text{TiO}_2$ .

### 3. 2. 2. Cycle Stability

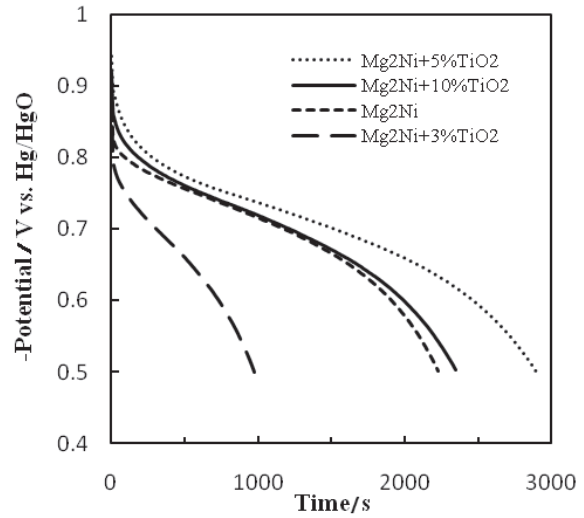
The cycle stability curves of  $\text{Mg}_2\text{Ni}$  alloy and  $\text{Mg}_2\text{Ni-x wt\% TiO}_2$  ( $x = 5$  and  $10 \text{ wt\%}$ ) composites are shown in Fig. 5. From these curves, the cycling capacity retention rates expressed by Eq. (2) are calculated after 8 cycles and listed in Table 1.

$$R_n(\%) = (C_n/C_1) \times 100 \quad (2)$$

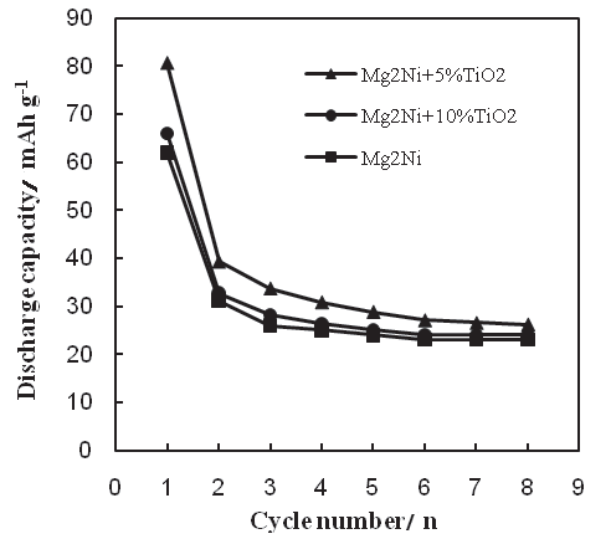
where  $C_1$  is the discharge capacity at the first

**Table 1.** Maximum discharge capacity ( $C_{\text{max}}$ ) and capacity retention rate ( $R_8$ ) of  $\text{Mg}_2\text{Ni}$  alloy and  $\text{Mg}_2\text{Ni-x wt\% TiO}_2$  ( $x = 5$  and  $10 \text{ wt\%}$ ) composites.

| Sample                               | $C_{\text{max}}$ ( $\text{mAh g}^{-1}$ ) | $R_8$ (%) |
|--------------------------------------|--|-----------|
| $\text{Mg}_2\text{Ni}$               | 62                                       | 37        |
| $\text{Mg}_2\text{Ni-5 wt\% TiO}_2$  | 80                                       | 32        |
| $\text{Mg}_2\text{Ni-10 wt\% TiO}_2$ | 66                                       | 36        |



**Fig. 4.** Discharge curves of the  $\text{Mg}_2\text{Ni}$  alloy and  $\text{Mg}_2\text{Ni-x wt\% TiO}_2$  ( $x = 3, 5$  and  $10 \text{ wt\%}$ ) composites for the first cycle.



**Fig. 5.** The cycle stability curves of  $\text{Mg}_2\text{Ni}$  alloy and  $\text{Mg}_2\text{Ni-x wt\% TiO}_2$  ( $x = 5$  and  $10 \text{ wt\%}$ ) composites.

cycle and  $C_n$  is the discharge capacity at the  $n$ -th cycle ( $n$  is 8 for current study). As is seen in Fig. 5 and Table 1, no improvement in cyclic performance has been obtained by adding  $\text{TiO}_2$  into  $\text{Mg}_2\text{Ni}$  alloy. As reported in previous studies [18-20], the addition of transition metal oxides has not improved the cycle stability of Mg-based alloys.

Cui and Luo [19] reported that the main reason

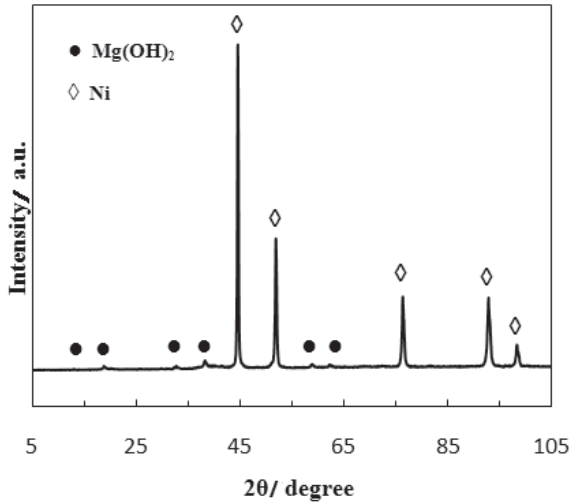


Fig. 6. XRD patterns of the  $Mg_2Ni$  alloy after the eighth electrochemical charging/discharging cycle.

for capacity decay of  $Mg_2Ni$ -type hydrogen storage material during the charge/discharge cycles is due to the surface oxidation of alloy powder. This layer may inhibit the reduction of hydrogen ions on the surface of electrode and also acts as a diffusion barrier for the hydrogen transport in the bulk of alloy [10]. On the other hand, Wang et al. [18] reported that the degradation of discharge capacity is ascribed to the corrosion of Mg during the cycling in 6 M KOH solution. It seems that  $TiO_2$  addition have no influence on degradation of the electrode during the cycling processes.

XRD pattern of  $Mg_2Ni$  alloy taken after the eighth electrochemical charging/discharging

cycle is shown in Fig. 6. The peaks of  $Mg(OH)_2$  which is due to the oxidation of Mg on surface of the alloy particles, confirm the formation of hydroxide layer on the alloy surface and the subsequent loss of cycle performance. Another factor responsible for the discharge capacity degradation of Mg-based hydride electrodes is the pulverization of this alloy due to the expansion and contraction of cell volume during charge/discharge cycles [24].

Fig. 7 shows SEM images of  $Mg_2Ni$  alloy before and after the eighth electrochemical charging/discharging cycle. It is obvious that the smooth surface of alloy particles has changed to a rough one after the eighth cycling indicating the pulverization of electrode.

### 3. 2. 3. Electrochemical Impedance Spectroscopy (EIS)

Fig. 8 shows the Nyquist plot of  $Mg_2Ni$  alloy and  $Mg_2Ni$ -5 wt%  $TiO_2$  composite in 6 M KOH solution. The semicircle loop represents the characteristic of charge transfer process at alloy/electrolyte interface which gives rise to the formation of adsorbed hydrogen and hydroxide ions at the interface according to Eq. (3). On the other hand, the straight line at low frequencies with an angle near  $45^\circ$  against the real axis represents Warburg diffusion behavior. The Warburg behavior is due to the difficulties for hydrogen diffusion in the bulk of alloy as represented by Eq. (4). Therefore, the discharge process of the alloy is controlled by both charge transfer process at the electrode /electrolyte

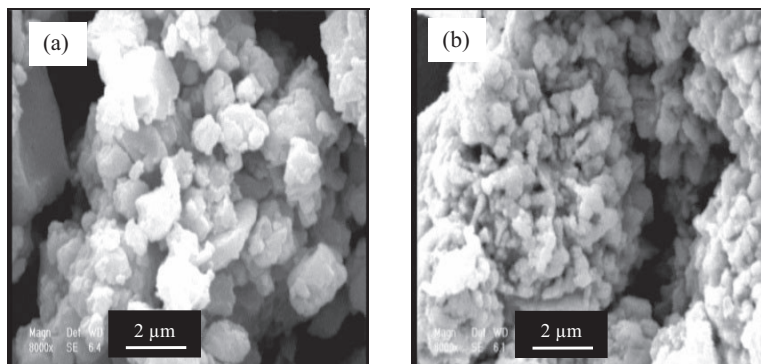
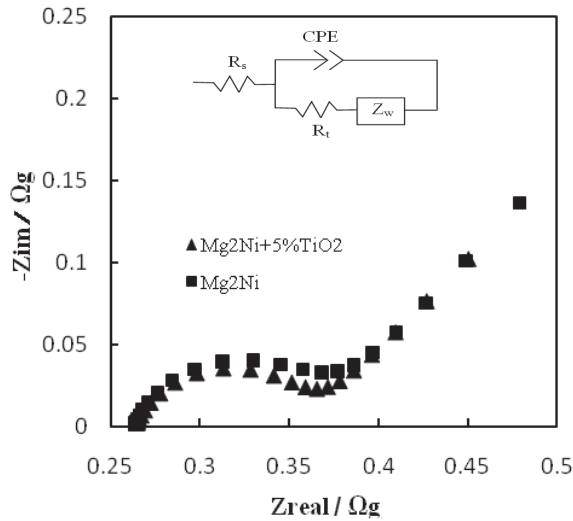
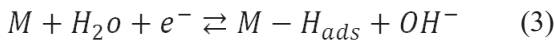


Fig. 7. SEM images of the  $Mg_2Ni$  alloy before and after 8 charging/discharging cycles. (a) before cycle; (b) after 8 cycles.



**Fig. 8.** Electrochemical impedance spectra (Nyquist plot) of the Mg<sub>2</sub>Ni alloy and Mg<sub>2</sub>Ni-5 wt% TiO<sub>2</sub> composite.

interface and diffusion of hydrogen atom in the alloy at the 0% depth of discharge [25].



The electrical equivalent circuit (EC) determined by using the Zview software is shown in Fig. 8. In the EC,  $R_t$  is the charge transfer resistance,  $R_s$  is the solution resistance,  $Z_w$  is the Warburg impedance and CPE is the constant phase element belonging to the high frequency capacitive loops. The Warburg impedance ( $Z_w$ ) is observed whenever the reaction is under partial or complete mass transport control by diffusion [26]. The term is reserved for the special case of

semi-infinite linear diffusion. In the condition of semi-infinite linear diffusion,  $Z_w$  for a system at equilibrium can be expressed by [26]:

$$Z_w = \sigma_\omega \omega^{-0.5} - j\sigma_\omega \omega^{-0.5} \quad (5)$$

where  $\sigma_\omega$  is the Warburg constant,  $\omega$  is the ac angular frequency.  $Z_w$  can be considered as a series combination of Warburg capacitance ( $C_w$ ) and a pseudoresistance ( $R_w$ ), which are given by the following equations [26]:

$$C_w = \sigma_w^{-1} \omega^{-0.5} \quad (6)$$

$$R_w = \sigma_\omega \omega^{-0.5} \quad (7)$$

The impedance of CPE is considered as the porosity, roughness and inhomogeneity of the electrode surface and is expressed by the following equation [25]:

$$Z_Q = [Y_0(j\omega)^n]^{-1} \quad (8)$$

where  $Z_Q$  is the CPE impedance ( $\Omega \text{ cm}^{-2}$ ),  $Y_0$  is the CPE admittance ( $\Omega^{-1} \text{ sn cm}^{-2}$ ). The parameter  $n$  is a constant, which shows the degree of deviation from ideal capacitive behavior.

The charge transfer resistance ( $R_t$ ) and its values derived from proposed EC are given in Fig. 8 and Table 2, respectively. It can be seen that the radius of semicircle for Mg<sub>2</sub>Ni-5 wt% TiO<sub>2</sub> composite is smaller than that of Mg<sub>2</sub>Ni alloy. Thus, the charge transfer resistance of Mg<sub>2</sub>Ni-5 wt% TiO<sub>2</sub> composite is lower than that of Mg<sub>2</sub>Ni alloy. The exchange current density ( $i_0$ ), which is a measure of electrocatalytic nature of the alloy electrode, was calculated by Cui and Luo [19] according to Eq. (9).

**Table 2.** The impedance values and exchange current density ( $i_0$ ) for the Mg<sub>2</sub>Ni alloy and Mg<sub>2</sub>Ni-5 wt% TiO<sub>2</sub> composite.

| Sample                                 | $R_t$<br>( $\Omega g$ ) | CPE-T<br>( $F g^{-1}$ ) | CPE-P | $Z_w$ -R<br>( $g^{-1}\Omega^{-1}s^{-0.5}$ ) | $Z_w$ -T<br>( $g^{-1}\Omega^{-1}s^{-0.5}$ ) | $Z_w$ -P | $i_0$<br>( $mA g^{-1}$ ) |
|--|-------------------------|-------------------------|-------|---|---|----------|--------------------------|
| Mg <sub>2</sub> Ni                     | 0.06                    | 1                       | 0.70  | $5.3 \times 10^{-8}$                        | $5.1 \times 10^{-10}$                       | 0.33     | 214                      |
| Mg <sub>2</sub> Ni-5% TiO <sub>2</sub> | 0.05                    | 0.5                     | 0.77  | $5.3 \times 10^{-8}$                        | $5. \times 10^{-10}$                        | 0.30     | 257                      |

$$i_0 = \frac{RT}{nR_t F} \quad (9)$$

where R is the gas constant, T is the absolute temperature, n is the number of transferred electrons, F is the Faraday constant. Table 2 show that the value of  $i_0$  is increased (43 mA g<sup>-1</sup>) by adding 5 wt% TiO<sub>2</sub> which indicates higher electrocatalytic nature of the electrode. By adding TiO<sub>2</sub>, surface of the alloy powder is covered with fine particles of TiO<sub>2</sub>, and thus, the overpotential is reduced [19]. This accelerates charge transfer on the surface of electrode. Thus, electrocatalytic activity on alloy surface will be improved by the presence of TiO<sub>2</sub>. This result is in a good agreement with the maximum discharge capacity obtained for Mg<sub>2</sub>Ni–5 wt% TiO<sub>2</sub> composite.

In the Nyquist plot (Fig. 8) at low frequencies, the similar behavior on Warburg diffusion indicates that the diffusion coefficient of hydrogen atoms is unchanged [18] in the presence of TiO<sub>2</sub>.

### 3. 2. 4. Anodic Polarization

Fig. 9 shows the anodic polarization curves of Mg<sub>2</sub>Ni alloy and Mg<sub>2</sub>Ni–5 wt% TiO<sub>2</sub> composite at fully charged state. Because the hydrogen diffusivity rate is almost the same in the bulk of

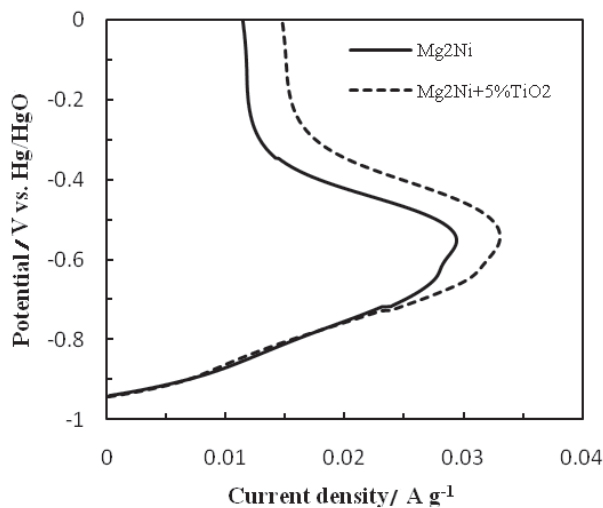


Fig. 9. Anodic polarization curves of the Mg<sub>2</sub>Ni alloy and Mg<sub>2</sub>Ni–5 wt% TiO<sub>2</sub> composite after full charging.

both electrodes, the anodic peak current can be attributed to the oxidation of absorbed hydrogen according to Eq. (3) [19]. As is seen, the anodic peak current density increases by the presence of TiO<sub>2</sub> indicating that the hydrogen oxidation reaction proceeds more easily on the surface of this electrode. This result is in a good agreement with the maximum discharge capacity obtained for Mg<sub>2</sub>Ni–5 wt% TiO<sub>2</sub> composite sample.

## 4. CONCLUSION

Nanocrystalline/amorphous Mg<sub>2</sub>Ni alloy was prepared by ball-milling and the effects of TiO<sub>2</sub> additive on the electrochemical hydrogen storage properties were investigated. The initial discharge capacities of the composites with 5 and 10 wt% TiO<sub>2</sub> were larger than that for pure Mg<sub>2</sub>Ni alloy. However, no improvement in cyclic performance has been obtained by adding TiO<sub>2</sub>. The charge/discharge kinetics of electrodes were studied by using anodic polarization and EIS techniques. It was shown that the exchange current density,  $i_0$ , which is a measure of electrocatalytic nature of the alloy electrode was greatly increased by adding 5wt%TiO<sub>2</sub>. This would be useful in enhancement of the charge/discharge rate. On the other hand, hydrogen diffusivity in the bulk of alloy showed no obvious variation by adding TiO<sub>2</sub>.

## REFERENCES

1. Xiangdong, L., Lihong, H., Xiao T., Hongwei, F. and Bo, C., "Activation characteristics and microstructure of Mg<sub>2</sub>Ni/Mm<sub>0.3</sub>Ml<sub>0.7</sub>Ni<sub>3.55</sub>Co<sub>0.75</sub>Mn<sub>0.4</sub>Al<sub>0.3</sub> composite hydrogen storage alloys prepared by two-step re-melting." *Int. J. Hydrogen Energ.*, 2007, 32, 4939.
2. Jiao, L. F., Yuan, H. T., Wang, Y. J. and Wang, Y. M., "Electrochemical properties of magnesium based hydrogen storage alloys improved by transition metal boride and silicide additives." *Int. J. Hydrogen Energ.*, 2009, 34, 1476.
3. Hsu, F. H., Lin, C. K., Lee, S. L., Lin, C. Y. and Bor, H. Y., "Effect of Mg<sub>3</sub>MnNi<sub>2</sub> on the electrochemical characteristics of Mg<sub>2</sub>Ni

- electrode alloy." *J. Power Sources*, 2010, 195, 374.
- Kim, J. S., Lee, C. R., Choi, J. W. and Kang, S. G., "Effects of F-treatment on degradation of  $Mg_2Ni$  electrode fabricated by mechanical alloying." *J. Power Sources*, 2002, 104, 201.
  - Ruggeri, S., Roue, L., Huot, J., Schulz, R., Aymard, L. and Tarascon, J.M., "Properties of mechanically alloyed Mg–Ni–Ti ternary hydrogen storage alloys for Ni–MH batteries." *J. Power Sources*, 2002, 112, 547.
  - Zhang, Y., Jiao, L., Yuan, H., Miao, Y., Wang, Q., Liu, L., Liu, G., Liu, S. and Wang, Y., "Study on the electrochemical properties of  $MgNi-CuO$  hydrogen storage composite materials." *J. Alloy Compd.*, 2009, 481, 639.
  - Yuan, H., Li, Q., Song, H., Wang, Y. and Liu, J., "Electrochemical characteristics of  $Mg_2Ni$ -type alloys prepared by mechanical alloying." *J. Alloy Compd.*, 2003, 353, 322.
  - Cui, N. and Luo, J. L., "An AC impedance study of self-discharge mechanism of nickel–metal hydride (Ni–MH) battery using  $Mg_2Ni$ -type hydrogen storage alloy anode." *Electrochim. Acta*, 2000, 45, 3973.
  - Chen, J., Yao, P., Bradhurst, D. H., Dou, S. X. and Liu, H. K., " $Mg_2Ni$ -based hydrogen storage alloys for metal hydride electrodes." *J. Alloy Compd.*, 1999, 293–295, 675.
  - Niu, H., "Electrochemical performance of ball-milled  $Mg_2Ni$  electrodes", M. Sc. Thesis, University of Windsor, 1999.
  - Nohara, S., Fujita, N., Zhang, S. G., Inoue, H. and Iwakura, C., "Electrochemical characteristics of a homogeneous amorphous alloy prepared by ball-milling  $MgNi$  with Ni." *J. Alloy Compd.*, 1998, 267, 76.
  - Iwakura, C., Inoue, H., Zhang, S. G. and Nohara, S., "Hydriding and electrochemical characteristics of a homogeneous amorphous  $Mg_2Ni-Ni$  composite." *J. Alloy Compd.*, 1998, 270 142.
  - Cui, N., He, P. and Luo, J. L., "Synthesis and characterization of nanocrystalline magnesium-based hydrogen storage alloy electrode materials." *Electrochim. Acta*, 1999, 44, 3549.
  - Goo, N. H., Jeong, W. T. and Lee, K. S., "Effects of Zr addition on discharge properties of mechanically alloyed  $Mg_2Ni$  hydrogen-storage alloy electrode." *J. Power Sources*, 2000, 87, 118.
  - Zhang, P., Wei, X., Liu, Y., Zhu, J. and Yu G., "Effects of metal oxides addition on the performance of  $La_{1.3}CaMg_{0.7}Ni_9$  hydrogen storage alloy." *Int. J. Hydrogen Energ.*, 2008, 33, 1304.
  - Oelerich, W., Klassen, T. and Bormann R., "Metal oxides as catalysts for improved hydrogen sorption in nanocrystalline Mg-based materials." *J. Alloy Compd.*, 2001, 315, 237.
  - Gao, R. G., Tu, J. P., Wang, X. L., Zhang, X. B. and Chen, C. P., "The absorption and desorption properties of nanocrystalline  $Mg_2Ni_{0.75}Cr_{0.25}$  alloy containing  $TiO_2$  nanoparticles." *J. Alloy Compd.*, 2003, 356-357, 649.
  - Wang, Y., Gao, X. P., Lu, Z. W., Hu, W. K., Zhou, Z., Qu, J. Q. and Shen, P. W., "Effects of metal oxides on electrochemical hydrogen storage of nanocrystalline  $LaMg_{12}-Ni$  composites." *Electrochim. Acta*, 2005, 50, 2187.
  - Cui, N. and Luo J. L., "Effects of oxide additions on electrochemical hydriding and dehydriding of behavior  $Mg_2Ni$ -type hydrogen storage alloy electrode in 6M KOH solution." *Electrochim. Acta*, 1998, 44, 711.
  - Rongear, C., Grosjean, M. H., Ruggeri, S., Dehmas, M., Bourlot, S., Marcotte S., and Roue L., "Evaluation of different approaches for improving the cycle life of  $MgNi$ -based electrodes for Ni–MH batteries." *J. Power Sources*, 2006, 158, 747.
  - Wang, L., Wang, X. H., Chen, L. X., Chen, C. P., Xiao, X. Z., Gao, L. H. and Wang, Q. D., "Effects of ball-milling time and  $Bi_2O_3$  addition on electrochemical performance of ball-milled  $La_2Mg_{17} + 200$  wt.% Ni composites." *J. Alloy Compd.*, 2006, 416, 194.
  - Cullity, B. D., "Elements of X-ray Diffraction.", 2nd ed., Addison Wesley, London, 1978.
  - Zhang, Y., Li, B., Ren, H., Pang, Z., Guo, S. and Wang, X., "An electrochemical investigation of melt-spun nanocrystalline and amorphous  $Mg_2Ni$ -type electrode alloys." *J. Alloy Compd.*, 2009, 477, 759.
  - Huang, H., Huang, K. and Liu, S., "Microstructures and electrochemical properties of  $Mg_{0.9}Ti_{0.1}Ni_{1-x}M_x$  ( $M=Co, Mn$ ;  $x=0, 0.1, 0.2$ ) hydrogen storage alloys." *Powder Technol.*, 2010, 198, 144.



25. Cui, N. and Luo J. L., "AC impedance studies of the discharge process of a Mg<sub>2</sub>Ni-type hydrogen storage alloy electrode in 6 M KOH solution.", *J. Alloy Compd.*, 1998, 265, 305.
26. Khorrami, M. R., Raeissi, K., Shahban, H., Torkan, M. A. and Saatchi, A., "Corrosion behavior of carbon steel in carbon dioxide-loaded activated methyl diethanol amine solution." *Corros. Sci.*, 2008, 64, 124.