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Hydrogen bubbles dynamic template preparation of a porous Fe–Co–B/Ni foam catalyst for hydrogen generation from hydrolysis of alkaline sodium borohydride solution

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ABSTRACT

By using a modified electroless plating method, a porous Fe–Co–B catalyst is prepared on Ni foam support in order to generate hydrogen from an alkaline sodium borohydride (NaBH₄) solution. In this process, hydrogen bubbles originating from electroless deposition function as a dynamic template to form the porous catalyst. The effects of NaBH₄, NaOH concentration and reaction temperature on the hydrolysis reaction kinetics are investigated. It has been found that an average hydrogen generation rate of $22 \, l \, min^{-1} \, g^{-1}$ (Fe–Co–B) is achieved in a 15 wt.% NaBH₄ and 5 wt.% NaOH solution at 30 °C, and the apparent activation energy of the hydrolysis reaction is determined to be 27 kJ mol⁻¹. The catalyst exhibits a high activity due to its porous structure, which facilitates the access of reactants to the surface active sites of catalyst.

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1. Introduction

Hydrogen as an energy carrier possesses many advantages, but hydrogen storage is one of the main issues hindering "hydrogen economy" development [1,2]. The chemical hydrogen storage is a promising strategy, wherein hydrogen is stored in a chemical compound such as NaBH₄, NH₃BH₃, LiH and NaH, etc. [3,4], and released via an irreversible chemical reaction, in conjunction with off-board spent fuel regeneration [5–8]. Among the chemical hydrides, NaBH₄ receives the most extensive studies, as it provides a safe and practical means of hydrogen generation (HG). The studies of HG from hydrolysis of NaBH₄-base system mainly focus on hydrolysis catalyst, reaction kinetics, recycle of hydrolysis by-product and hydrogen generator, etc., which has been well discussed in some recent review papers [9–13]. Although a costeffective process for the recycle of hydrolysis by-product is still lacking, the hydrolysis of NaBH₄ is a convenient method of HG for portable or niche applications [12,13].

The hydrolysis of the NaBH₄ may be represented by the following equation:

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2\uparrow$$
(1)

The reaction takes place in excess of water due to the low solubility of NaBH₄ itself and the hydration of the by-product NaBO₂ [12-15]. The rate of HG at which NaBH₄ solution undergoes self-hydrolysis in water depends on the pH and solution temperature [16]. At room temperatures, only a small percentage of the theoretical amount of hydrogen is liberated by the reaction, but the hydrolysis can be accelerated and controlled by the use of a suitable catalyst. The catalyst, which acts as an on/off switch, plays a crucial role in developing on-demand HG system. Besides acid accelerators [17,18], a variety of noble or non-noble transition metals (TM)/their alloys or salts have been developed for HG from aqueous NaBH₄ solution, which include Ru [19-23], Pt [24,25], Pt-Ru [26,27], Pt-Pd [28], Ni-Ru [29], Raney Ni and Co [30], Co-Ni-B [31], Co-Ni-P [32], Co-Cr-B [33], Co-Ni-P-B [34], Co, Ni and Fe borides [35-42] or their salts [14,43], and so forth. While the noble TM catalysts show excellent catalytic activities, their use in practical applications is restricted by their high material cost. Therefore, it is important to search for the low-cost and high-efficiency non-noble TM catalysts in commercialization of NaBH₄-base on-demand HG system.

In comparison with various metals powder or their salts catalysts, the supported catalysts are highly appreciated in the practical applications owing to their easy separation from fuel solution, and consequently the ready controllability of the hydrolysis reaction and reusability of the catalyst. The activity of catalyst is highly dependent on the metal species, particle size, crystal structure, catalyst precursor and support materials employed, and so on [9]. In this regard, preparation of the porous catalyst with large surface

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area can offer a choice [44]. The porous structures with large real surface area ensure the access of reactants to the surface active sites of catalysts, thereby increasing the reaction activity of the materials. Recently, the hydrogen bubbles acting as dynamic template were proposed to prepare the self-supported 3D porous metals and alloys by using the electroplating method [45-47]. Electroless plating (EP) has several unique advantages over the conventional electroplating [48], it is an autocatalytic redox reaction process which provides a uniform and dense coating on all surface area of the plating support regardless of the configuration or geometry of the support. However, its application in preparation of hydrolysis catalyst is greatly frustrated. In our previous studies [49,50], we have developed a modified EP method for preparation of the supported cobalt-based porous catalyst for HG from alkaline NaBH₄ solution. Compared to the conventional EP method, this newly developed technology is more efficient and capable of producing catalysts with much higher catalytic activity. For example, the Co-B and Co-W-B/Ni foam catalysts prepared by using this method in the 20 wt.% alkaline NaBH₄ solutions can achieve the HG rates of 11 and $151 \text{ min}^{-1} \text{ g}^{-1}$, respectively.

As an extension of this study, we further explore the preparation of the supported iron-based catalysts with this modified EP method. In the present work, we prepare a cheap porous Fe–Co–B/Ni foam catalyst for HG from alkaline NaBH₄ solution. It has been found that the Fe–Co–B/Ni foam catalyst exhibits an excellent catalytic activity for the hydrolysis reaction, and the hydrolysis conditions exert the considerable influences on the reaction kinetics. Preliminary analyses have been carried out to understand the influences of the preparation conditions of EP process on the catalyst coating structure.

2. Experimental

2.1. Preparation of the catalyst

The Fe–Co–B/Ni foam prepared by the modified EP method involved the usage of solutions A and B with compositions and operating conditions given in Table 1. For comparison, a conventional EP method was also used for preparation of Fe–Co–B/Ni foam catalyst. Its compositions and operation conditions were given in Table 2. All the chemical reagents were of analytical grade and used as received. Ni foam is selected as the catalyst support material due to its porous structure, low density, high thermal and chemical stability under the alkaline hydrolysis conditions. The Ni foam (1.80 mm in thickness, 99.9% purity) was supplied by Inco ATM (Shenyang) Co., Ltd. It has a network structure with an area density of about 57.5 mg cm⁻² and an average pore size of 0.20–0.50 mm. Before usage, the Ni foam is cleaned by sonicating in ethanol for 10 min, followed by immersing in a 10 wt.% HCl solution for 1 min.

The Fe–Co–B/Ni foam catalyst was prepared following the procedure detailed in our previous studies [49,50]. The modified EP process was repeated for four times to obtain a catalyst (Fe–Co–B) loading of about 12.5 mg cm⁻² (Ni foam), as determined by the weight change before and after plating. The chemical reactions involved in the EP process can be described as Eqs. (2)–(5).

$$BH_4^- + 2Co^{2+} + 4OH^- \rightarrow BO_2^- + 2Co \downarrow + 2H_2 \uparrow + 2H_2O$$

Table 1

Bath compositions and operating conditions of the modified electroless Fe-Co-B plating.

Bath solutions	Chemicals	Concentrations $(g l^{-1})$
Solution A	FeCl ₂ ·4H ₂ O	49
	CoCl ₂ ·6H ₂ O	15
	Na ₃ C ₆ H ₅ O ₇ ·2H ₂ O (sodium citrate, complex agent)	31
	NH ₄ Cl	25
	$NH_3 \cdot H_2O(ml l^{-1})$	60
Solution B	NaBH ₄	40
	NaOH	10
Bath temperature (°C)		25
Plating times		4

Table 2

Bath compositions and operating conditions of the conventional electroless Fe–Co–B plating.

Chemicals	Concentrations (gl^{-1})
FeCl ₂ ·4H ₂ O	19
CoCl ₂ ·6H ₂ O	6
NaBH ₄	2
NH4Cl	40
$NH_3 \cdot H_2O(ml l^{-1})$	45
Na ₃ C ₆ H ₅ O ₇ ·2H ₂ O (sodium citrate, complex agent)	45
H ₂ NCH ₂ CH ₂ NH ₂ (ethylenediamine, complex agent)	40
H ₂ SeO ₄ ·7H ₂ O (selenic acid, stabilizer)	4
Bath temperature (°C)	50
Plating time (h)	1.2

$BH_4^- + 2Fe^{2+} + 4OH^- \rightarrow BO_2^- + 2Fe \downarrow + 2H_2 \uparrow + 2H_2O$	(3)
$2BH_4^- + 2H_2O \rightarrow 2B\downarrow + 2OH^- + 5H_2\uparrow$	(4)
$BH_4^-+2H_2O \rightarrow BO_2^-+4H_2 \uparrow$	(5)

2.2. Characterization of the catalyst

The Fe–Co–B/Ni foam catalysts were characterized by powder X-ray diffraction (XRD, Rigaku D/max-2500, Cu K α radiation) and scanning electron microscopy (SEM, LEO Supra 35) that is equipped with an energy dispersive X-ray (EDX) analysis unit (Oxford). The specific surface areas of the catalyst samples were measured by N₂ adsorption at 77 K using the Brunauer–Emmett–Teller (BET) method (Micromeritics ASAP 2010). To minimize the measurement error, each sample was measured three times, from which an average value was given. The composition of the catalyst was analyzed by inductively coupled plasma-atomic emission spectrometry (ICP-AES, Iris Intrepid).

2.3. Catalytic hydrolysis performance testing

Catalytic hydrolysis performance of the preparation of Fe–Co–B/Ni foam catalyst was measured using a batch apparatus of hydrogen production, as seen in Scheme 1. In a typical measurement, a fuel solution was thermostated in a sealed tubular glass reactor fitted with an outlet for collection of evolved hydrogen gas, and then one piece of the Fe–Co–B/Ni foam catalyst attracted on a magnetic stirring



(2)

Scheme 1. Schematic diagram of the apparatus used for catalytic hydrolysis performance testing.



Fig. 1. SEM morphologies of the Fe–Co–B/Ni foam catalysts prepared by using conventional EP method (a, c and e) and modified EP method (b, d and f), respectively, and a representative EDX result of the catalyst sample (g). The preparation conditions of the samples are given in Tables 1 and 2.

bar was dropped into the solution to initiate hydrolysis reaction. During the measurements, the solution temperature was monitored and carefully controlled within ± 2 °C by adding ice-water blend. The HG rate (S.T. P) after cooling through a water trap/heat exchanger and removing the moisture through a silica drier was measured by a mass flow meter, and recorded with a computer (one datum every five seconds generally). The HG volume was calculated by integrating the experimentally measured HG rate over time.

3. Results and discussion

3.1. Preparation and characterization of the Fe–Co–B/Ni foam catalyst

As mentioned above, EP is an autocatalytic redox reaction process, and it has been widely used in the preparation of functional coating on numerous supports. In a typical electroless deposition case, hydrogen evolution as a by-product according to Eqs. (2)–(5)is deliberately inhibited in order to produce a uniform and dense metallic coating by using strong complex agents and stabilizers in the bath solution, which is a feature of the conventional EP method. In this work, however, we favor the formation of gas by increasing the concentrations of reducing agent (NaBH₄) and main salts (FeCl₂ and CoCl₂), as well as elimination of the use of stabilizer. In consequence of these modified preparation conditions, the nucleation and deposition rates of the metals are greatly increased, and a large number of hydrogen bubbles are evolved. These hydrogen bubbles play crucial roles in the formation of the porous structure; they function as a dynamic template. Where there is a bubble, there will be no deposition of metals simple because there are no metal ions available [45-47]. Therefore, metal is chemically deposited and grows within the interstitial spaces between the hydrogen bubbles and forms a porous coating of metallic particles on the support.

By carefully controlling the EP process, the Fe-Co-B alloy coating with rough and porous surface structure was prepared. Fig. 1 compares the SEM morphologies of the Fe-Co-B/Ni foam catalysts prepared by using the conventional EP and modified EP methods, respectively, at the varied magnifications. In contrast to the relatively smooth and dense surface of the catalyst prepared by the conventional method (in Fig. 1a and c), a rough and porous coating has been produced by using this modified method (in Fig. 1b and d). As seen clearly in Fig. 1d, the catalyst coating contains many pores, which are believed to be related to the rapid release of large amounts of hydrogen during the preparation reaction. Additionally, as seen in Fig. 1f at a high magnification, some particles with short chain structure are distributed randomly on the rough surface of the coating. These small particles should originate from the spontaneous decomposition of the bath solution [50]. It is believed that the strong magnetic particles prepared in the presence of a magnetic field are easily connected to form chain structure [51]. However, no external magnetic field in the preparation of the Fe-Co-B/Ni foam catalyst is applied. Based on the presumption of Zhang and Manthirama [52], the chain structure is probably resulted from the earth magnetic field. Furthermore, it should be noted that the Ni foam surface as seen in Fig. 1b after repeating the EP process for four times is completely covered by the catalyst coating, which is composed of Co, Fe, B and O elements, as indicated by the EDX analysis shown in Fig. 1g. The O element in the coating probably results from oxidation of the catalyst upon exposure to air and the bath solution. Subtracting the O and Ni element content in the Fe-Co-B/Ni foam catalyst, the quantitative elemental analysis using ICP-AES determines that the catalyst coating contains 56.4 wt.% Co, 38.8 wt.% Fe and 4.8 wt.% B.

Fig. 2 presents the XRD patterns of the Fe–Co–B/Ni foam prepared by using the conventional EP and modified EP methods. The wide and diffuse peaks centre at around $2\theta = 45^{\circ}$, indicative of their amorphous structures, which may enhance the catalytic activity due to its unique short-range ordering but long-range disordering



Fig. 2. XRD patterns of the Fe–Co–B/Ni foam catalyst prepared by using the conventional EP method (a) and modified EP method (b).

structure, surface coordinating unsaturated sites and the lack of crystal defects [53].

3.2. HG from catalytic hydrolysis of NaBH₄ using the Fe–Co–B/Ni foam catalyst

The Fe-Co-B/Ni foam catalysts with a loading of about 12.5 mg cm⁻² (Ni foam) were used as catalysts for HG from hydrolysis of NaBH₄ solution. Fig. 3 presents a comparison of catalytic activities of the catalysts prepared by using the conventional EP and modified EP methods. As seen in Fig. 3a and b, the Fe-Co-B/Ni foam catalyst prepared by the modified EP method exhibits an average HG rate of 550 ml min⁻¹, corresponding to 221 min⁻¹ g⁻¹ (Fe-Co-B), over six times higher than that of the Fe-Co-B/Ni foam prepared by the conventional EP method. These two kinds of catalysts with the amorphous structures are all composed of Fe, Co and B element, and their contents are almost same, the observed enhancement on catalytic effectiveness of Fe-Co-B/Ni foam prepared by the modified EP method may be largely attributed to the catalyst/coating with a porous microstructure. This is consistent with the specific surface area of the catalyst sample. By using the BET method, the specific surface areas of the catalysts prepared by using the conventional EP and modified EP methods were determined to be 3.6 and 9.7 m² g⁻¹, respectively. The porous catalyst



Fig. 3. Comparison of the catalytic effectiveness of Fe–Co–B/Ni foam catalyst $(1 \text{ cm} \times 2 \text{ cm}, 25 \text{ mg})$ prepared by using the conventional EP method (a) and modified EP method (b), respectively, employing a 15 wt.% NaBH₄ and 5 wt.% NaOH solution at 30 °C.



Fig. 4. HG volume (a) and HG rate (b) as a function of time using Fe–Co–B/Ni foam catalyst (1 cm \times 2 cm, 25 mg) at 30 $^\circ$ C in a 20 ml solution of 10 wt.% NaBH₄ and 5 wt.% NaOH.

with a large real surface area facilitates the access of reactants to the surface active sites of catalyst.

Fig. 4 shows a typical HG behavior for the hydrolysis of alkaline NaBH₄ solution at 30 °C in the presence of this catalyst prepared by the modified EP method. As shown in Fig. 4a, the total HG vield is nearly 100% of the theoretical value that can be expected based on Eq. (1). In addition, as seen in Fig. 4b, the HG rate rapidly increases and reaches a maximum value at the initial stage of the hydrolysis reaction, and then gradually decreases with the hydrolvsis reaction proceeding. This result clearly indicates that, under the applied experimental conditions, the catalyzed hydrolysis of NaBH₄ follows no zero-order kinetics with respect to NaBH₄ concentration. Theoretically, the maximum reaction rate occurs at the beginning of the reaction since the concentration of the reactant is the highest. Shang and Chen claimed the maximum reaction rate was delayed because of the pore diffusion resistance [21]. We believe that this phenomenon may be related to reaching the equilibrium of hydrogen desorption/absorption in the catalyst to need a time. In this regard, better understanding the mechanism of the hydrolysis kinetics of NaBH₄ in the presence of catalyst is still required.

In the present study, the maximum HG rate is applied to investigate the effects of NaBH₄ and NaOH concentrations on reaction kinetics. Fig. 5 shows the effect of NaBH₄ concentration on HG rate in the presence of Fe–Co–B/Ni foam catalyst at 30 °C. It is found



Fig. 5. Effect of NaBH₄ concentration on the HG rate, fixed the NaOH concentration (5 wt.%) and Fe–Co–B catalyst amount (1 cm \times 2 cm, 25 mg) at 30 °C.



Fig. 6. Effect of NaOH concentration on the HG rate, fixed the NaBH₄ concentration (15 wt.%) and Fe-Co-B catalyst amount ($1 \text{ cm} \times 2 \text{ cm}, 25 \text{ mg}$) at $30 \degree$ C.

that the HG rate firstly increases with increasing the concentration of NaBH₄ from 1 to 15 wt.%. However, when the concentration of NaBH₄ is further increased to 20 wt.%, the HG rate levels off. The optimal NaBH₄ concentration at 30 °C is about 15 wt.%. Higher NaBH₄ concentration is highly favored for achieving high hydrogen capacity, but restricted by the solubility limitation of NaBH₄ itself and hydrolysis product (NaBO₂) in water [12-15]. The solubility of NaBH₄ and NaBO₂ at 30 $^{\circ}$ C is 57 and 32 g per 100 g (H₂O), respectively [25]. According to these data and Eq. (1), our calculation shows that NaBH₄ concentration at 30 °C (without taking into account the influence of NaOH stabilizer) is about 13.4 wt.% to keep the soluble state of NaBO₂, which precipitation could cause losses in the catalytic performances [12,23]. This value is only slightly inferior to that of our experimental result. One of the reasons for this may be that the temperature of the catalyst surface is higher than that of the bulk solution due to the exothermic hydrolysis reaction.

The effect of NaOH concentration on the HG rate at 30 °C using the Fe-Co-B/Ni foam catalyst is shown in Fig. 6. It is clear that the NaOH stabilizer exerts a negative effect on HG rate. As the NaOH concentration increases from 1 to 10 wt.%, the HG rate for a given weight percent NaBH₄ obviously decreases. This result is in agreement with those reported by using noble TM catalysts [19-21]. It seems reasonable to attribute this result to the inhibiting effect of hydroxide ions. Although the mechanism of the hydrolysis kinetics of NaBH₄ in the presence of catalyst has not been well established, Amendola et al. believed that the possible reason is the reduced activity of water at higher NaOH concentrations [20]. This occurs primarily because the ions, especially OH⁻, strongly complex water, thus decreasing the available free water needed for NaBH₄ hydrolysis. However, these results are opposite to the hydrolysis reactions using other non-noble TM catalysts [31,32,40,41], in which the NaOH was found to act as "accelerator" to promote the hydrolysis reaction, at least in a certain concentration range [31]. Walter et al. [54] suggested that this should be attributed to the different catalytic hydrolysis mechanism or intermediate reaction pathway in the presence of various catalysts.

The NaBH₄ reaction kinetics is further investigated at the varied temperatures. Taking into account the combined demands for high hydrogen capacity, high HG rate and long shelf of fuel solution in the practical on-demand HG system, this set of experiments were carried out by employing a 15 wt.% NaBH₄ and 5 wt.% NaOH solution. To minimize the effect of temperature changes due to the exothermic hydrolysis reaction, the amount of catalyst was reduced to 12.5 mg (1 cm \times 1 cm). The obtained kinetic curves are presented in Fig. 7a. As expected, the rate of HG rises dramatically with increas-



Fig. 7. HG kinetics curves of the 15 wt.% NaBH₄ and 5 wt.% NaOH solution in the temperature ranging from 25 to 45 °C (a), the inset shows the initial HG volume as a function of reaction time, an Arrhenius plot for determination of the apparent activation energy (b), employing the Fe–Co–B/Ni foam catalyst (1 cm × 1 cm, 12.5 mg) prepared by the modified EP method.

ing the temperature, and the HG volume increases linearly with the reaction time at the initial stage of hydrolysis reaction as seen in the inset of in Fig. 7a. This is consistent with our finding in the relevant NaBH₄ hydrolysis reaction system. It was found that the initial stage of the first-order hydrolysis reaction of NaBH₄ (for the aqueous solutions containing NaBH4 concentration below the threshold value) can be fairly well described using quasi-zero-order kinetics model [39]. To minimize the measurement error, the initial HG rates at the varied solution temperature were used to determine the apparent activation energy. This is rationalized because the initial HG rate is proportional to the apparent reaction rate constant. An Arrhenius plot of ln r (the initial HG rate) versus the reciprocal of absolute temperature (1/T) is shown in Fig. 7b. From the slope of the straight line, the apparent activation energy of hydrolysis reaction using the Fe–Co–B/Ni foam catalyst is calculated to be 27 kJ mol⁻¹. This value of activation energy is close to the results reported for the hydrolysis of NaBH₄ catalyzed by the Co–B/Ni foam (33 kJ mol^{-1}) [49] and Co–W–B/Ni foam (29kJ mol⁻¹) [50] catalysts, but it is much less than the values of 47 and 65 kJ mol⁻¹ for the Ru/IRA-400 [19] and Co–B powder [40] catalysts. This further evidences the high effectiveness of the catalyst prepared by the modified EP method.

In the present study, the cycle test was performed to investigate the durability of the Fe–Co–B/Ni foam catalyst prepared by the modified EP method. Here, we use the reaction time required for fulfilling 50% conversion of NaBH₄ to denote the catalytic activ-



Fig. 8. Cyclic performance of the Fe–Co–B/Ni foam catalyst $(1 \text{ cm} \times 1 \text{ cm}, 12.5 \text{ mg})$, employing a 15 wt.% NaBH₄ and 5 wt.% NaOH solution.

ity of the catalyst. As seen in Fig. 8, the catalyst can remain 70% of its initial activity, and provides 98% of conversion at the 3rd cycle in the hydrolysis of NaBH₄. When the cycle time is increased to the 6th cycle, the catalyst only remains 54% of its initial activity, but it still provides about 95% of conversion. In all cases, above 90% conversion of NaBH₄ was obtained upon extending the reaction time. In the cyclic measurements, the catalyst was separated from the spent fuel solution, washed thoroughly with deionized water and re-used. Therefore, the reduced activity of the catalyst in this work should rule out the accumulation of hydrolysis by-product on the catalyst surface. During the cyclic usage, the brown precipitate, which may mainly be Fe(OH)₃, was observed. The gradual decline in activity of the catalyst, as well as the ferromagnetic particles with catalytic activity distributed randomly on the coating surface being broken off, may be attributed to the strong alkaline solution environment in the hydrolysis process of NaBH₄. It has been reported that the hydrolysis catalysts including noble [22,23] and non-noble [32,35] TM all might be deactivation. Deterioration of the catalyst activity remains to be overcome before the NaBH₄-base HG system can be put to practical use.

As demonstrated, the Fe–Co–B/Ni foam catalyst prepared by the modified EP method is able to produce a HG rate of 221 min⁻¹ g⁻¹ (Fe-Co-B) in a 15 wt.% NaBH₄ and 5 wt.% NaOH solution, whereas the HG rate for our reported Co-W-B/Ni foam catalyst prepared by using the same method is $15.31 \text{ min}^{-1} \text{ g}^{-1}$ (Co-W-B) at the same hydrolysis condition [50]. With regard to the catalytic activity towards hydrolysis of alkaline NaBH₄ solution, the obtained Fe-Co-B/Ni foam catalyst is superior to other non-noble TM catalysts, which is comparable to the levels of noble TM catalysts [50]. Our preliminary experimental results show that the cheap ironbased catalysts should not be dismissed from the large number of catalytic materials that are screened. However, the further investigations are required for the Fe–Co–B/Ni foam catalyst to provide an improvement of its durability. Anyway, a promising method was proposed for the preparation of porous catalyst, in which the hydrogen bubbles originating from electroless deposition function as a dynamic template to form the porous catalyst.

4. Conclusions

By using a modified EP method, a high-performance porous Fe–Co–B/Ni foam catalyst has been prepared for catalyzing HG from alkaline NaBH₄ solution. During the electroless deposition, the hydrogen bubbles acting as the dynamic template play a crucial role to form porous structure. The obtained catalyst is capable

of producing a HG rate of 22 l min⁻¹ g⁻¹ (Fe–Co–B) in a solution containing 15 wt.% NaBH₄ and 5 wt.% NaOH. Furthermore, the apparent activation energy of the hydrolysis reaction was determined to be 27 kJ mol⁻¹. The superior activity of the Fe–Co–B/Ni foam catalyst prepared by the modified EP method could be attributed to its favorable porous morphology. The porous structure with a large real surface area facilitates the access of reactants to the surface active sites of catalyst.

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