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Enhanced hydrogen storage property of MgH₂ caused by a BaCrO₄ nanocatalyst†

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Magnesium hydroxide (MgH₂) has a broad application prospect in solid hydrogen storage, but the associated higher dehydrogenation temperature and undesirable cycling capacity limit its large-scale application. In this study, a BaCrO₄ nanocatalyst prepared *via* a wet chemistry method was added to MgH₂ to achieve better kinetic and thermodynamic performances. Kinetic tests suggested that the onset hydrogen desorption temperature was decreased for milled MgH₂ from 390 °C to below 280 °C after the introduction of a 5 wt% BaCrO₄ nanocatalyst and the maximum dehydrogenation amount was up to 6.32 wt%. With regard to hydrogen absorption, MgH₂ incorporated with 10 wt% BaCrO₄ could fully absorb 5.78 wt% H₂ within 10 min at 300 °C and recharge 3.1 wt% H₂ at a low temperature of 250 °C. In comparison, the hydrogen uptake amounts for MgH₂ under the same conditions were only 3.98 wt% and 1.52 wt%. With regard to hydrogen desorption, 5 wt% BaCrO₄-modified MgH₂ could discharge 4.25 wt% H₂ within 10 min at 325 °C and 4.81 wt% H₂ at 300 °C, while MgH₂ could not dehydrogenate at 300 °C. Meanwhile, only 5% of the performance decayed for 5 wt% BaCrO₄-modified MgH₂ during ten cycles. Dehydrogenation E_a reduced to 106.75 kJ mol⁻¹ in contrast to 156.55 kJ mol⁻¹ for MgH₂. In addition, DFT results verified that the BaCrO₄ nanocatalyst reduced the band gap from 2.78 eV to 2.16 eV to improve the thermodynamic property of MgH₂ and contributed to the decrease in the dehydrogenation energy barrier from 2.27 eV to 1.54 eV. This work provides an insight into the performance of ternary transition metal nanocatalysts for MgH₂ hydrogen storage systems.

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1 Introduction

Since the 20th century, with the large-scale consumption of traditional fossil energy sources, which produce a large amount of greenhouse gases, researchers have conducted in-depth studies on renewable energy sources.^{1–5} Regarded as one of the ideal energy carriers, hydrogen energy possesses the advantages of abundant resources, a high calorific value (33.3 kW h kg⁻¹), environment friendliness and intrinsic clean nature characteristics, which are of great significance to sustainable energy systems.^{6–10} However, the key problem hindering the widespread application of hydrogen energy is the shortage of effective and secure storage systems. At present, hydrogen storage techniques mainly consist of the following categories: high-pressure gaseous state,¹¹ liquid state,¹² and solid state.¹³ Gaseous state storage requires high pressures, and

the compression process is hazardous. Liquid state storage can increase the hydrogen content to a certain extent, but energy consumption in the liquefaction process is high.^{14,15} In contrast, owing to its excellent hydrogen storage performance (7.6 wt%), non-toxicity, excellent reversibility, abundant resources, and hydrogen purification function characteristics, MgH₂ is proven as an excellent system in the solid hydrogen storage field.^{16–18} Nevertheless, the stable thermodynamic and sluggish kinetic properties limit the large-scale applications of MgH₂ to some extent.^{19–21} In order to overcome these challenges, nanosizing,^{22–25} alloying,^{26–29} and catalyst doping^{30–33} have been specifically studied.

Alloying improves kinetic/thermodynamic properties by changing the reaction path. However, the lower hydrogen storage density of Mg-based alloys needs to be improved further. Nanosizing could reduce the grain size and shorten the diffusion path length to improve the hydrogen storage performance of MgH₂. High-energy ball milling (HEBM) is the most commonly used method for nanotization. Schulz *et al.*³⁴ prepared MgH₂ nanoparticles with high specific surface area by HEBM, which could adsorb 7 wt% H₂ at 300 °C and desorb completely at 350 °C. Varin *et al.*³⁵ prepared MgH₂ with different particle sizes and found that when the particle size was reduced to 600 nm, the dehydrogenation temperature was reduced by

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60 °C. However, HEBM will lead to agglomeration and growth, reducing the cycling stability of the material.

The combination of nanosizing with transition metal catalyst doping is an approach that takes into account both kinetic and cycling properties. The corresponding interaction force between the d electrons of the metal catalysts and the electrons in the H₂/H orbital can dramatically cut down the dehydrogenation E_a of MgH₂. After ball milling, the catalyst coated on the surface of MgH₂ can inhibit the agglomeration of MgH₂ and achieve ideal cycling performance.^{36–38} Wang *et al.*³⁹ prepared a highly refined cadmium-based catalyst on nitrogen-doped carbon (Cr–N–C) and added it to MgH₂ *via* HEBM. Theoretical calculations showed that the dehydrogenation E_a of MgH₂ was reduced from 156.5 kJ mol^{−1} to 133 kJ mol^{−1}, and the hydrogen storage amount did not decay after cycling (volume retention rate is 95%). The Cr element could interact strongly with H and destabilize the interaction of the Mg–H bond. Kurdyumov *et al.*⁴⁰ fabricated a MgH₂–MIL-101 (Cr) compound system through milling technology, and the results indicated that chromium oxide particles and MIL-101 (Cr) were dispersed uniformly on the surface of MgH₂. The compound system could discharge 5.0 wt% H₂ within 3000 s at 255 °C and recharge 4.8 wt% within 2000 s at 320 °C, while MgH₂ did not hydrogenate and dehydrogenate. It was obvious that Cr-based catalysts could dramatically ameliorate the kinetic capacity of MgH₂.

Compared with single-metal catalysts, multiple metal oxides have higher brittleness, which are more easily dispersed in a MgH₂ matrix by ball milling technology. Sazelee *et al.*⁴¹ prepared MgH₂ doped with BaFe₁₂O₁₉, which could start dehydrogenation at 270 °C compared to MgH₂ (418 °C). No obvious capacity decay phenomenon occurred during cycling. MgO-, Fe- and Ba-based substances achieved heterogeneous catalytic effects on MgH₂, thereby ameliorating the hydrogen storage performance. Chen *et al.*⁴² prepared BaTiO₃ to catalytically modify MgH₂, and MgH₂–20 wt% BaTiO₃ could fully discharge 6.0 wt% H₂ within 20 min at 310 °C. The E_a value of the composite decreased to 60 kJ mol^{−1} in contrast to that of pure MgH₂ (101 kJ mol^{−1}). It is worth noting that MgH₂–20 wt% BaTiO₃ could absorb 3.5 and 4.0 wt% H₂ in 120 minutes at 50 °C and 100 °C, respectively, whereas milled MgH₂ only absorbed ~1.0 wt% H₂. Ismail *et al.*⁴³ fabricated MgH₂–10 wt% BaMnO₃. Benefiting from the strong electron-withdrawing effect of O, as well as the kinetic modulation of Ba or Ba-based substances, the T_{onset} value of MgH₂–10 wt% BaMnO₃ reduced from 343 °C to 282 °C, with an ideal hydrogen absorption content of 5.22 wt% at 250 °C and a hydrogen desorption content of 5.36 wt% at 300 °C. Without doubt, ternary transition metal oxides, particularly Ba-based oxides, have exhibited generally distinguished catalytic effect on MgH₂.

In view of the ideal catalytic effect of Cr-based catalysts/Ba-based transition metal catalysts and the high-energy ball milling nanotization method, we successfully synthesized a BaCrO₄ nanocatalyst through wet chemical technology to reveal the catalytic effect on MgH₂. Up to now, there are no relevant research studies on the introduction of the BaCrO₄ catalyst into MgH₂ to improve the hydrogen storage performance. We focused on investigating the dynamic and

thermodynamic performances of MgH₂–*x* wt% BaCrO₄ (*x* = 5, 10, and 15) through a series of kinetic test and theoretical calculation. Meantime, the structural evolution and catalytic mechanism were explored deeply.

2 Experimental details

2.1 Synthesis of BaCrO₄ nanocatalysts

A BaCrO₄ nanocatalyst was fabricated through the wet chemical technology. In detail, 0.174 g dodecylbenzene sulfonic acid sodium salt (DBSS) and 0.88 g Na₂CrO₄ (AR, 98%, Sigma-Aldrich) were dissolved in 100 mL of distilled water in a beaker. After that, vigorous stirring was carried out for two hours at room temperature to ensure that all the reagents were evenly dispersed in the solution. Then 20 mL 0.1875 mol L^{−1} Ba(NO₃)₂ (AR, 99%, Sigma-Aldrich) was added dropwise to the above solution for 10 min at room temperature under magnetic stirring. Yellow precipitates were produced during the addition process. After finishing the addition process, the mixture was deposited *via* continuous stirring for another 30 min, which was conducive to the formation of BaCrO₄ nanocrystals. Finally, precipitates were washed three times with distilled water and absolute ethanol to remove the remaining DBSS and dried at 150 °C for 2 h in a vacuum oven. The detailed procedure is shown in Fig. S1(a).†

2.2 Preparation of MgH₂–*x* wt% BaCrO₄ compounds

The MgH₂ (AR, 98%, Langfang Beida Trading Co., Ltd)–*x* wt% BaCrO₄ (*x* = 5, 10, and 15) compound system were prepared *via* ball milling technology under vacuum in planetary ball milling equipment (JX-4GL, Shanghai Jingxin). Each sample was milled for 4 h (ball milling for 25 minutes and rest for 5 minutes in different directions to prevent the ball mill tank from overheating) at a speed of 400 rpm. The ratio of ball to powder was 40/1. To prevent oxidation, the loading and sampling processes were carried out in a glove box filled with 5 bar argon gas and a water oxygen content less than 0.1 ppm.

3 Characterization

An X-ray diffractometer (XRD, Bruker D8 ADVANCE A25) with Cu K α radiation was used to detect the phase evolution with 2θ ranging from 10–80° at a step of 10° min^{−1}. The microstructures and element distributions were researched through Scanning electron microscopy (SEM, JEOL JSM-6610LV) and transmission electron microscopy (TEM, JEOL JEM-2100F) with an energy-dispersive spectroscopy (EDS).

A differential scanning calorimetry (DSC, NETZSCH STA449F3) instrument was used at different heating rates (5, 8, 10, and 12 °C min^{−1}) to analyze the dehydrogenation capacity. The hydrogenation kinetics was studied using a high-pressure gas absorption instrument (BSD 3H-2000 PH) at different temperatures under 3.3 MPa hydrogen pressure, and the dehydrogenation kinetics was studied under 0.001 MPa hydrogen pressure. The temperature-programmed desorption



(TPD) test was applied with a temperature range from 20 °C to 500 °C at a speed of 5 °C min⁻¹.

4 Computational details

The density functional theory (DFT) calculations were performed using the CASTEP package with the Perdew–Burke–Ernzerhof (PBE) generalized gradient approximation (GGA) exchange–correlation functional. Interactions between core and valence electrons were described using Vanderbilt ultra-soft pseudopotentials. The energy cut-off for the plane-wave basis set was 400 eV.

The threshold values of the convergence criteria are specified as follows: 0.002 Å for maximum displacement, 0.05 eV Å⁻¹ for maximum force, 0.1 GPa for maximum stress, 10⁻⁵ eV per atom for energy, and 2.0 × 10⁻⁶ eV per atom for self-consistent field tolerance. The 1.5 Å thickness of the MgH₂(101) surface was cleaved with *a* = 25.8 Å and *b* = 8.16 Å. A 15 Å vacuum space was implemented into the model to eliminate undesirable interactions between the bottom side of the slab and the molecules in the vacuum space. The (4 × 2) unit cell of MgH₂ (101)–BaCrO₄ (203) was used to inhibit the lateral interactions between the molecules on the surface.

The charge density difference of MgH₂-10 wt% BaCrO₄ was calculated, which is defined as $\Delta\rho = \rho_{\text{tot}} - \rho_{\text{substrate}} - \rho_{\text{cluster}}$, where ρ_{tot} , $\rho_{\text{substrate}}$, and ρ_{cluster} are the total charge densities of the MgH₂-10 wt% BaCrO₄ compound, the MgH₂ substrate, and the BaCrO₄ catalyst, respectively.

When the optimization was completed, the density difference calculations were performed. Moreover, the diffusion barrier energy was located utilizing the well-known linear synchronous transit (LST) and quadratic synchronous transit (QST) methods.

5 Results and discussion

5.1 Characterization of BaCrO₄ nanocatalysts

Fig. S1(b)† exhibits the XRD patterns of the BaCrO₄ catalyst. Obviously, the diffraction peaks coincide with the standard card (JCPDS No. 78-1401), with no detection of impurity peaks. Fig. S1(c and d)† present the morphology and particle size distribution of the BaCrO₄ nanocatalyst. Obviously, the BaCrO₄ nanocatalyst exists in a relatively nano-blocky structure with a particle size ranging from 100 to 500 nm with an average size of 225 ± 17.68 nm. The micronano structure and composition of the nanocatalyst were further determined through the TEM images shown in Fig. S1(e and f)†. The nano-blocky morphology can be seen in Fig. S1(e)†. Meantime, the high-resolution transmission electron microscopic (HRTEM) images shown in Fig. S1(f)† detect interplanar crystal spacings of 0.399, 0.352, and 0.275 nm, corresponding to the (111), (210), and (200) planes of the BaCrO₄ crystal respectively, which confirms the XRD pattern above. The diffraction rings observed in the SAED image correspond to the (111), (210), and (200) planes of BaCrO₄ (Fig. S1(g)†). Further, the EDS test of BaCrO₄ indicates the

uniform distribution of Ba, Cr and O (Fig. S1(h–k))†, and the elemental composition is shown in Fig. S2.†

5.2 Hydrogen storage property of MgH₂-BaCrO₄

MgH₂ with different contents of BaCrO₄ samples was fabricated to investigate the catalytic action of BaCrO₄ on MgH₂. The TPD test shown in Fig. 1(a and b) reveals the occurrence of the hydrogenation desorption process for the four groups of MgH₂-*x* wt% BaCrO₄ (*x* = 5, 10, and 15) samples at 390, 310, 280, and 275 °C, which have total hydrogen contents of 6.80, 6.77, 6.32 and 5.74 wt%. The onset dehydrogenation temperature and the maximum dehydrogenation amount continue to decrease with the increase in BaCrO₄ nanocatalyst. It is obvious that the excellent *T*_{onset} and higher hydrogen storage capacity are taken into account for the MgH₂-10 wt% BaCrO₄ sample. The *T*_{onset} value of MgH₂-10 wt% BaCrO₄ is 110 °C lower than that of milled MgH₂. In comparison to milled MgH₂ (6.80 wt%), the hydrogen storage content of the MgH₂-10 wt% BaCrO₄ sample is 6.32 wt%, which is attenuated to some extent, but it still meets the practical application standard. The lower *T*_{onset} value of MgH₂-10 wt% BaCrO₄ remarkably exceeds those of other catalyst-MgH₂ systems, which are reported in Fig. 1(c).^{44–51}

Based on the above-mentioned conclusions, we selected 10 wt% BaCrO₄-modified MgH₂ for an in-depth study. The hydrogenation recharge and discharge kinetic tests were carried out at different temperatures. Fig. 2(a) depicts that milled MgH₂ absorbs 1.22, 3.15, 5.38 and 6.35 wt% H₂ at 250, 275, 300 and 350 °C within 60 min, respectively. Fig. 2(c) presents the kinetics of 10 wt% BaCrO₄-modified MgH₂. It is proposed that a complete hydrogen uptake of 5.78 wt% H₂ is achieved within 10 min at 300 °C. Additionally, 3.09 and 4.30 wt% of H₂ are absorbed from 10 wt% BaCrO₄-modified MgH₂ at 250 and 275 °C within 60 min. The considerable hydrogen storage performance is in sharp contrast to milled MgH₂, which indicates that the BaCrO₄ nanocatalyst exhibits excellent catalytic effects at low temperatures.

To understand the kinetics of the dehydrogenation process, Fig. 2(b and d) illustrate the hydrogen discharge curves of MgH₂ and 10 wt% BaCrO₄-modified MgH₂. The desorption content of milled MgH₂ is only 0.11 wt% in 60 min at 300 °C. While 10 wt% BaCrO₄-modified MgH₂ could desorb 4.50 wt% H₂ under the same operating conditions, and the rate of dehydrogenation is remarkably faster than that of milled MgH₂. Meantime, 10 wt% BaCrO₄-modified MgH₂ achieves complete dehydrogenation capacities of 5.03 wt% and 5.53 wt% within 40 min at 325 and 350 °C. In contrast, only 3.76 wt% H₂ and 4.38 wt% H₂ are released within 40 min at 350 and 375 °C for milled MgH₂. To sum up, it is obviously observed that after the incorporation of 10 wt% BaCrO₄ nanocatalyst, the hydrogen recharge and discharge kinetic performances of MgH₂ has been strikingly promoted.

Moreover, the long-term stable cycle dynamic capacity is an important parameter that inhibits the application of hydrogen storage materials. Therefore, the ten-cycle performance was studied, as shown in Fig. 2(e and f). The 10 wt% BaCrO₄-



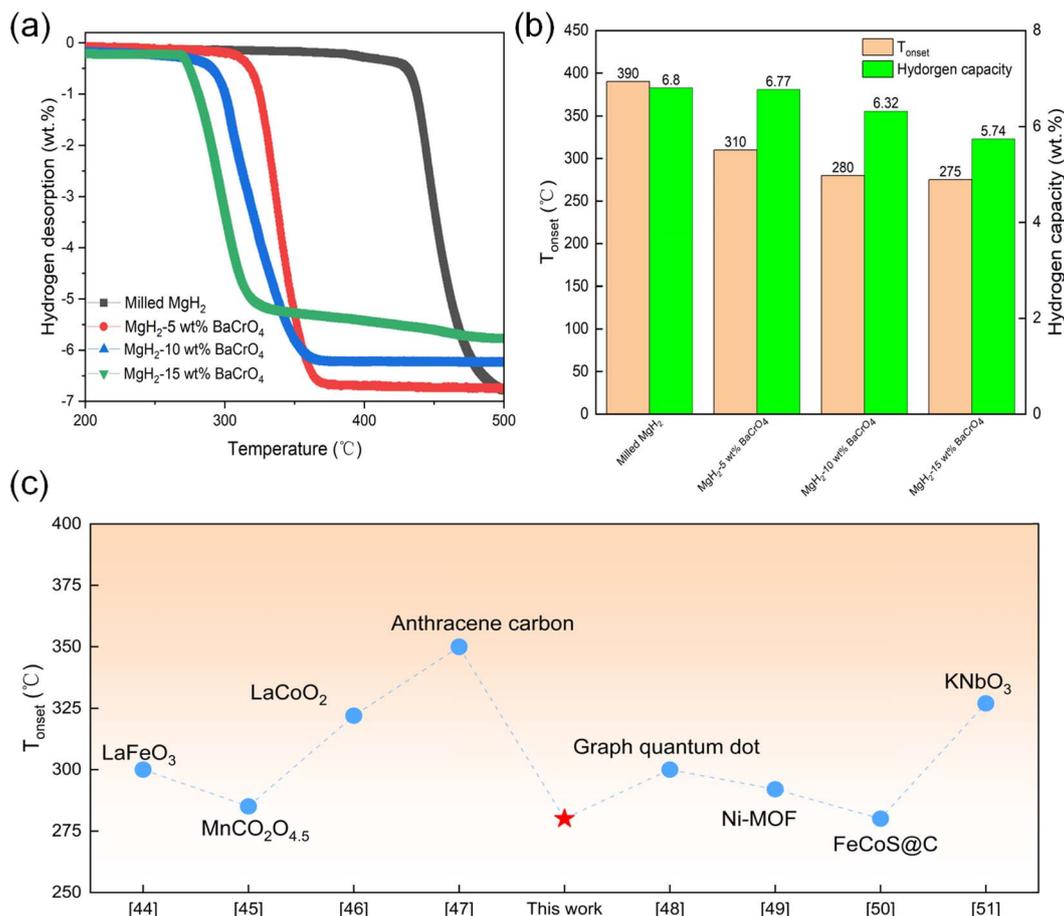


Fig. 1 (a) TPD curves and (b) several performance factors of milled MgH₂ and MgH₂-x wt% (x = 5, 10, and 15) BaCrO₄ systems. (c) Comparison of the onset desorption temperature of MgH₂-10 wt% BaCrO₄ with other catalyst-MgH₂ systems.

modified MgH₂ sample has a hydrogen storage content of 6.47 wt% and desorption content of 5.66 wt% in the first cycle, during the second to tenth cycle, the amounts of hydrogenation and dehydrogenation is maintained at approximately 5.95 wt% and 5.2 wt%, and the volume retention rate is as high as 95%, which exhibits excellent cycling dynamic performances. Meanwhile, the SEM morphology and particle size distribution shown in Fig. S3(a)† manifest that the average size decreases from 225 ± 17.68 nm of BaCrO₄ to 125 ± 6.23 nm after ball milling treatment, which has an excellent nano-refinement effect. Additionally, as shown in Fig. S3(b),† with an average size of 175 ± 8.52 nm, 10 wt% BaCrO₄-modified MgH₂ does not show obvious agglomeration after 10 cycles. This fine particle size provides a lot of diffusion channels and reaction sites for H₂ recharge and H discharge processes, which contribute to ameliorate the hydrogen storage property and achieve ideal cycling stability.

Fig. 3(a and c) show the DSC curves of milled MgH₂ and 10 wt% BaCrO₄-modified MgH₂ to further study the dehydrogenation kinetic property. The peak hydrogen desorption temperatures of milled MgH₂ at heating rates of 5, 8, 10 and 12 °C min⁻¹ are 390, 394, 399 and 410 °C. While the peak hydrogen desorption temperatures of 10 wt% BaCrO₄-modified MgH₂ are

343, 355, 360 and 368 °C at the same rates. It is proposed that the peak hydrogenation desorption temperature increases with the increase in heating rate. Furthermore, it is obvious that the peak temperature decreases after the introduction of the BaCrO₄ nanocatalyst. This ameliorative capacity is related to the E_a value of MgH₂. Combined with the heating rate peak temperature, we used the Kissinger equation to calculate the dehydrogenation E_a value of the MgH₂-BaCrO₄ compound system and MgH₂ to explore the kinetics in depth. The detailed equation is expressed as follows:⁵²

$$\ln(\beta/T_p^2) = -E_a/RT_p + A \quad (1)$$

where β represents the heating rate, T_p represents the peak hydrogen desorption temperature, E_a represents the activation energy barrier, R represents the gas constant and A represents the linear constant. Fig. 3(b and d) illustrate the E_a value of the milled MgH₂ calculated to be 156.55 kJ mol⁻¹, while that of the MgH₂-BaCrO₄ system is only 106.75 kJ mol⁻¹. It is suggested that the catalyst of BaCrO₄ realizes a reduction in dehydrogenation E_a and improves the dynamics of MgH₂. Notably, 10 wt% BaCrO₄-modified MgH₂ exhibits a lower hydrogenation desorption activation energy than that of MgH₂ added with other catalysts, as shown in Table 1.



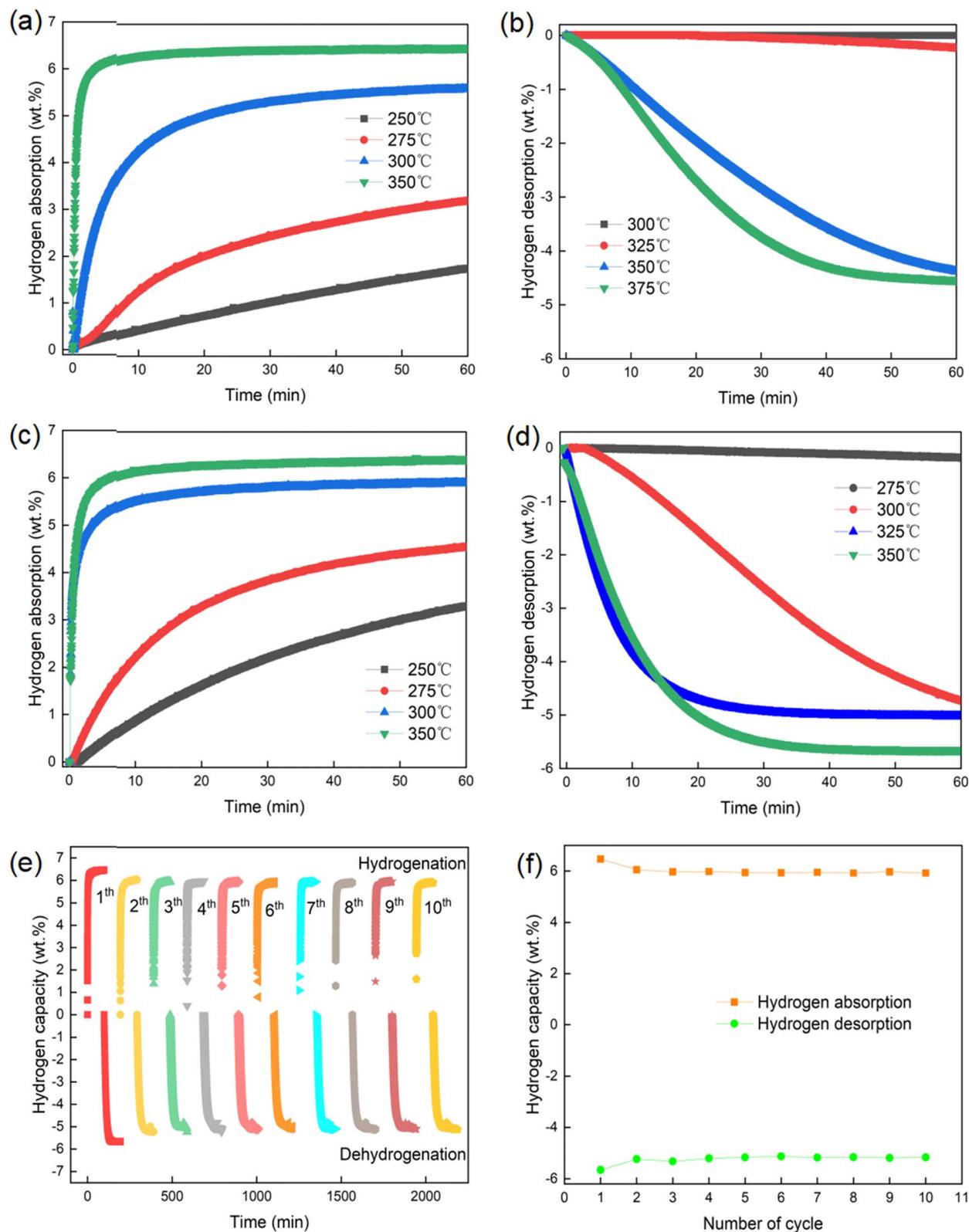


Fig. 2 (a) Hydrogen release curves of milled MgH₂ and (c) 10 wt% BaCrO₄-modified MgH₂. (b) Hydrogen uptake curves of milled MgH₂ and (d) 10 wt% BaCrO₄-modified MgH₂. (e) De/hydrogenation cycle curves and (f) decay curves of 10 wt% BaCrO₄-modified MgH₂.



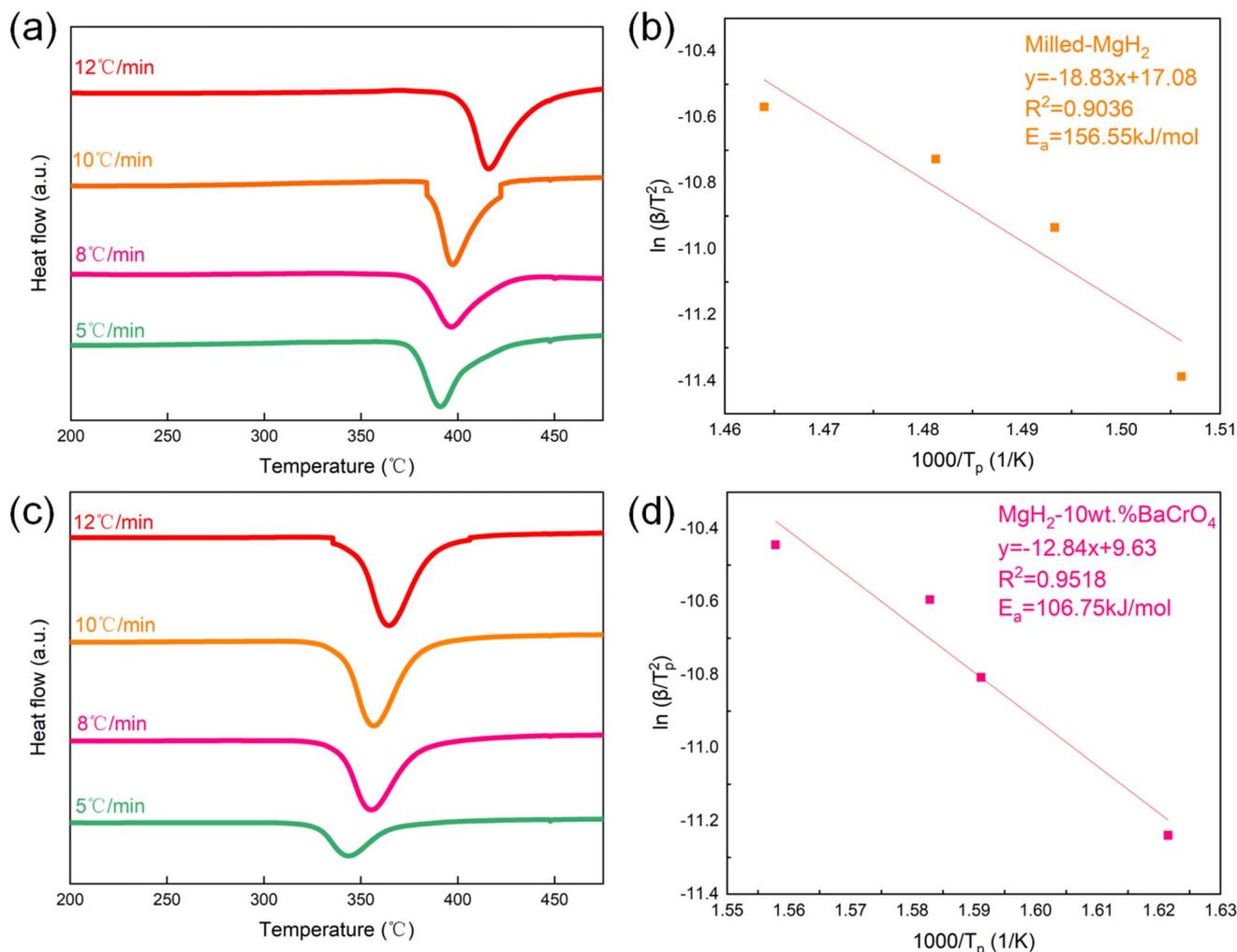


Fig. 3 (a) DSC profiles of milled MgH_2 and (c) 10 wt% BaCrO_4 -modified MgH_2 . (b) Kissinger plots of milled MgH_2 and (d) 10 wt% BaCrO_4 -modified MgH_2 .

Table 1 Hydrogen desorption activation energies of MgH_2/Mg compound systems reported in recent years

Compound	E_a (kJ mol ⁻¹)	Ref.
$\text{MgH}_2\text{-LaFeO}_3$	107.00	44
$\text{MgH}_2\text{-BaFe}_{12}\text{O}_{16}$	115.00	41
$\text{MgH}_2\text{-MnFe}_2\text{O}_4$	108.40	53
$\text{MgH}_2\text{-K}_2\text{Ti}_8\text{O}_{17}$	116.00	54
$\text{MgH}_2\text{-Sc}_2\text{TiO}_3$	109.00	55
$\text{MgH}_2\text{-MoO}_3$	114.70	56
$\text{MgH}_2\text{-Na}_3\text{AlF}_6$	129.00	57
$\text{MgH}_2\text{-Zn}_2\text{TiO}_4$	105.50	58
$\text{MgH}_2\text{-BaCrO}_4$	106.75	This work

5.3 Rate-controlling step kinetic model of dehydrogenation

Aiming to further analyze the kinetic behavior of hydrogen desorption, we employed the approach proposed by Sharp and Jones to explore the possible models of rate-controlling step kinetics.^{59,60} Table 2 presents the specific description of some

common kinetic models, which include diffusion control, geometric contraction, nucleation at growth and first-order reaction model. The specific kinetic expression is as follows:

$$d_a/d_t = kf(\alpha) \quad (2)$$

where k is a reaction rate constant, α represents the reaction extent and $f(\alpha)$ is a function depending on the reaction mechanism. $f(\alpha)$ could be represented using the following formula:

$$f(\alpha) = A(t/t_{0.5}) \quad (3)$$

where A represents the constant in connection with the kinetic model and $t_{0.5}$ represents the time when α achieves 0.5. The model with the fitting slope closest to 1 is the most suited kinetic model. Fig. 4(a) displays the hydrogen desorption curve at 350 °C for various kinetic models. It is proposed that the slope of the R3 model (0.937) is closest to 1.0. Moreover, Fig. 4(b) displays $g(\alpha)$ at different temperatures. It is worth noting that the linear fitting constants are 0.9716, 0.9930, which



Table 2 Common theoretical kinetic models for desorption curve analysis

Symbol	$g(\alpha)$	Mechanisms	Sharp's equation
D1	α^2	One-dimensional diffusion	$0.2500(t/t_{0.5})$
D2	$\alpha + (1 - \alpha)\ln(1 - \alpha)$	Two-dimensional diffusion	$0.1534(t/t_{0.5})$
D3	$[1 - (1 - \alpha)^{1/3}]^2$	Three-dimensional diffusion (Jander equation)	$0.0426(t/t_{0.5})$
D4	$1 - (2\alpha/3) - (1 - \alpha)^{2/3}$	Three-dimensional diffusion (Ginstling-Brounstein equation)	$0.0367(t/t_{0.5})$
F1	$-\ln(1 - \alpha)$	First-order reaction	$-0.6931(t/t_{0.5})$
R2	$1 - (1 - \alpha)^{1/2}$	Two-dimension phase boundary (contracting area)	$0.2929(t/t_{0.5})$
R3	$1 - (1 - \alpha)^{1/3}$	Three-dimension phase boundary (contracting volume)	$0.2063(t/t_{0.5})$
A2	$[-\ln(1 - \alpha)]^{1/2}$	Avrami eqn (1)	$0.8326(t/t_{0.5})$
A3	$[-\ln(1 - \alpha)]^{1/3}$	Avrami eqn (2)	$0.8850(t/t_{0.5})$

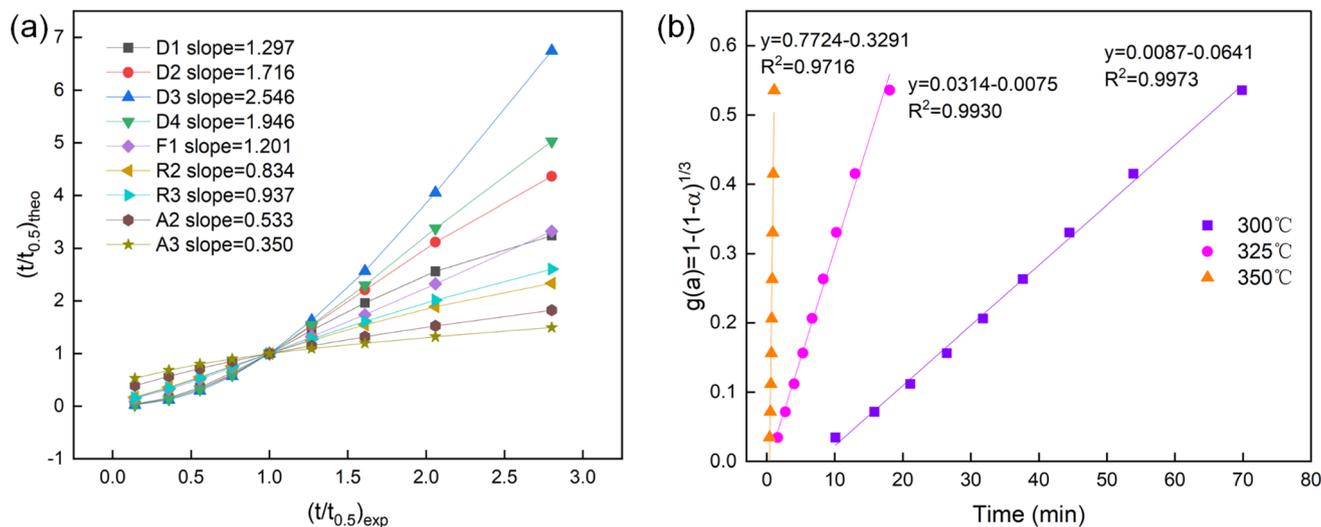


Fig. 4 (a) $(t/t_{0.5})_{\text{theo}}$ vs. $(t/t_{0.5})_{\text{exp}}$ of 10 wt% BaCrO₄-modified MgH₂ at 350 °C through fitting different kinetic models. (b) Time dependence of kinetic modeling equations $g(\alpha)$ with $0.1 < \alpha < 0.9$ for 10 wt% BaCrO₄-modified MgH₂ at different temperatures.

demonstrates that the R3 model is the most suited kinetic model for the 10 wt% BaCrO₄-modified MgH₂ system, which reveals that the hydrogen desorption of 10 wt% BaCrO₄-modified MgH₂ is controlled by the three-dimension phase boundary kinetic model. Specifically, the kinetics of hydrogen emission is controlled by the migration of the gas–solid interface towards the center of the nanoparticles.

5.4 Catalytic mechanism of BaCrO₄ on MgH₂

To further understand the catalytic mechanism in connection with the hydrogen storage capacity of 10 wt% BaCrO₄-modified MgH₂, XRD and TEM were employed aiming to clarify the phase evolution of the MgH₂–BaCrO₄ system after ball milling, dehydrogenating and rehydrogenating processes. The XRD patterns are shown in Fig. 5. Owing to the grain refinement during ball milling, the crystallinity and diffraction peak intensity of MgH₂–BaCrO₄ are attenuated to some extent.⁶¹ After milling, BaCrO₄ could still be detected and there is no MgO generation during this process, which reflects that there is no obvious oxidation during the preparation process. For the system after dehydrogenation, MgH₂ is fully transformed into Mg, and BaCrO₄ still remains without any changes. The diffraction peaks of MgH₂

are found again in the hydrogen release process, which reflects the reversible phase conversion process among the Mg and MgH₂ phases.

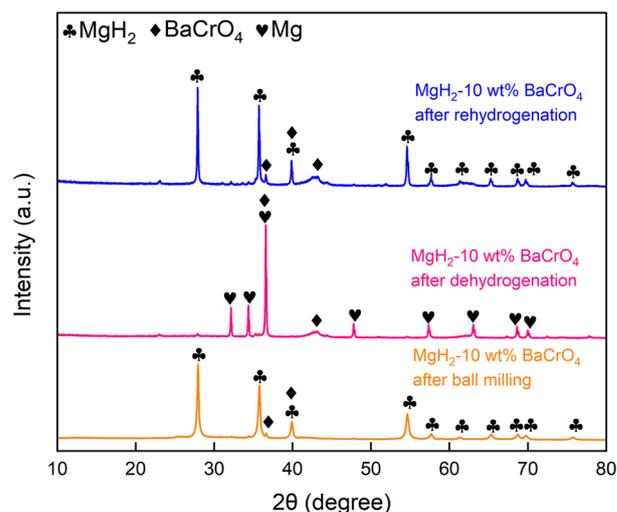


Fig. 5 XRD patterns of 10 wt% BaCrO₄-modified MgH₂ at different processes.



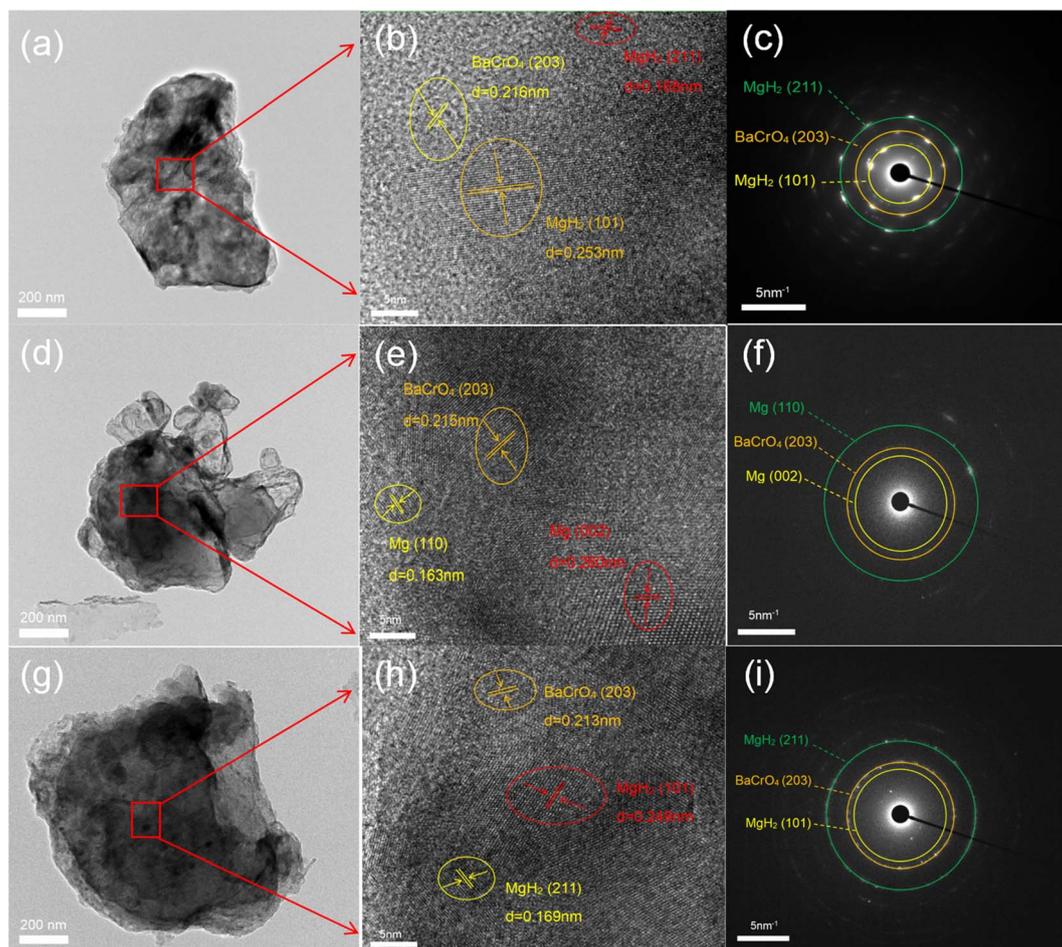


Fig. 6 TEM, HRTEM and SAED patterns of the 10 wt% BaCrO₄-modified MgH₂ sample (a–c) after milling, (d–f) after dehydrogenation and (g–i) after rehydrogenation.

Afterward, the HRTEM images and SAED patterns were acquired to verify the phase and structural evolution. The (203) crystal plane of BaCrO₄ and the (211) and (101) crystal planes of MgH₂ after milling state with interplanar crystal spacings of 0.216, 0.168 and 0.253 nm are shown in Fig. 6(a–c), which indicate that the BaCrO₄ phase exists stably during the milling process. As shown in Fig. 6(d–f), three groups with interplanar crystal spacings of 0.211 nm, 0.163 nm and 0.260 nm were detected, corresponding to the (410), Mg (110) and Mg (002) crystal planes of BaCrO₄, respectively. Meanwhile, the HRTEM and SAED characterizations of 10 wt% BaCrO₄-modified MgH₂ after rehydrogenation are exhibited in Fig. 6(g–i). It is proposed that Mg is transformed into MgH₂. Interplanar crystal spacings of 0.213, 0.169, and 0.249 nm correspond to the (203) plane of BaCrO₄, and the (101) and (211) planes of MgH₂, respectively. Moreover, the uniform Cr Ba and O elements distributed on the Mg/MgH₂ system can be detected obviously through the EDS mapping test, as shown in Fig. 7(a–c), which exerts a positive effect on the hydrogen storage capacity of MgH₂.

Aiming to thoroughly investigate the action mechanism of BaCrO₄ on the Mg–H bonds, theoretical calculations were performed using DFT (density functional theory). Based on the

HRTEM and XRD characterization, we selected the MgH₂ (101) and BaCrO₄ (203) crystal planes to successfully construct the MgH₂/BaCrO₄ heterojunction optimization model, and the results are shown in Fig. 8. The bond length analysis presented in Table S1† illustrates that with the addition of BaCrO₄, the average Mg–H bond length is significantly extended from 1.935 Å to 2.904 Å, which reflects that the BaCrO₄ catalyst is favorable for weakening the Mg–H bond strength to ameliorate hydrogen release. To reveal the nature of the Mg–H bond interaction in the 10 wt% BaCrO₄-modified MgH₂ optimized model, the density-of-states maps of MgH₂ and 10 wt% BaCrO₄-modified MgH₂ were calculated.

As shown in Fig. 9(a and b), the binding energy at 0 is set to the Fermi level, as can be seen from the DOS diagram of MgH₂, and the conduction band is mainly composed of the s orbital of H, and the valence charge is mainly composed of the s and p orbitals of Mg. There is a certain hybridization between the s, p and H s orbitals of Mg at the valence band, indicating that MgH₂ is mainly composed of ionic bonds with a small amount of covalent bonds, which leads to the high thermodynamic property and undesirable dehydrogenation capacity. With the addition of BaCrO₄, the electrons of the MgH₂-10 wt% BaCrO₄



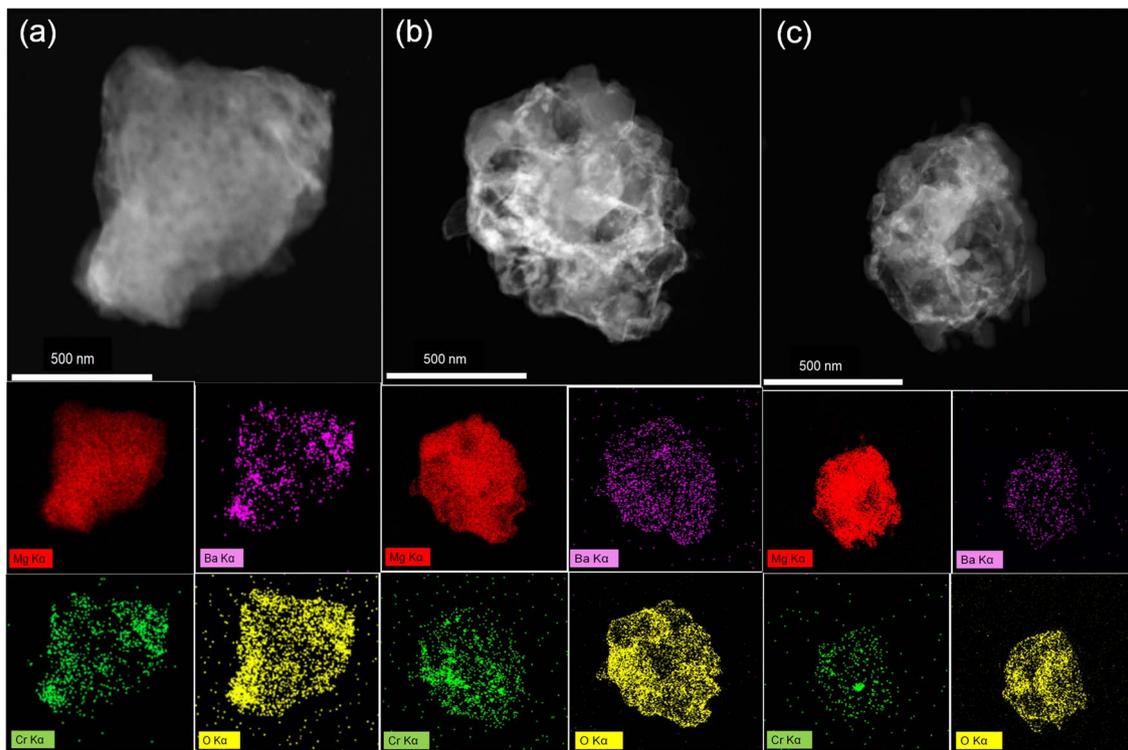


Fig. 7 EDS images of 10 wt% BaCrO₄-modified MgH₂ (a) at the milling state, (b) at the dehydrogenation state and (c) after rehydrogenation.

system are mainly contributed by Ba, Cr, and O orbitals. The hybridization between Mg and H in the valence band is weakened, and the band gap decreased from MgH₂ (2.78 eV) to 2.16 eV. This results in a decrease in the stability of the MgH₂ system and an increase in the electron mobility, thereby improving the dehydrogenation performance of MgH₂. Fig. 10 gives the differential charge density maps of 10 wt% BaCrO₄-modified MgH₂. It is obvious that the charges around Mg are lacking; in addition to being transferred to H, O will also attract part of the valence charges of Mg, weakening the strong interaction of Mg–H bonds and promoting the fracture of Mg–H bonds and the release of H.

According to the above-mentioned calculation analyses, BaCrO₄ ameliorates the thermodynamic capacity *via* weakening

the Mg–H bond. However, the kinetics of hydrogen emission in MgH₂ could also affect the hydrogen desorption performance. Specifically, H atoms need to overcome a certain hydrogen release energy barrier from the bond cleavage of Mg–H to the recombination of H molecules. As shown in Fig. 11(a), the transition state (TS) of MgH₂ has a higher dehydrogenation energy barrier of 2.27 eV, and the Mg–H bond energy is still stronger. Interestingly, with the modification of BaCrO₄, the dehydrogenation energy barrier of 10 wt% BaCrO₄-modified MgH₂ is decreased to 1.54 eV, indicating the significant improvement in the kinetics of hydrogen desorption. These results are consistent with the decreasing trend of activation energy calculated by DSC. The optimized models of 10 wt%

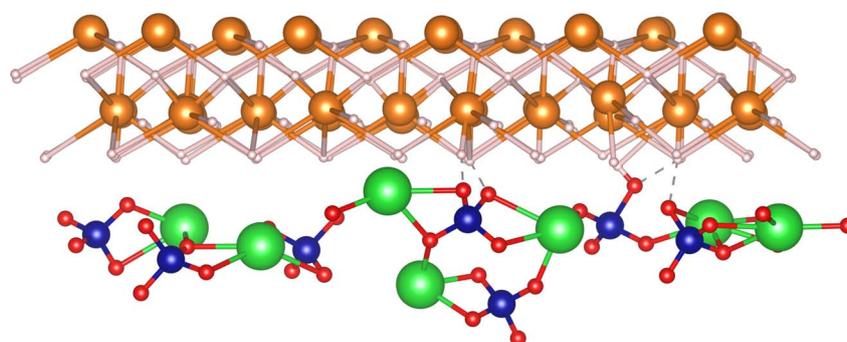


Fig. 8 Optimized structure of the 10 wt% BaCrO₄-modified MgH₂ heterojunction (green, blue, red, white and orange represent Ba, Cr, O, H and Mg atoms, respectively).



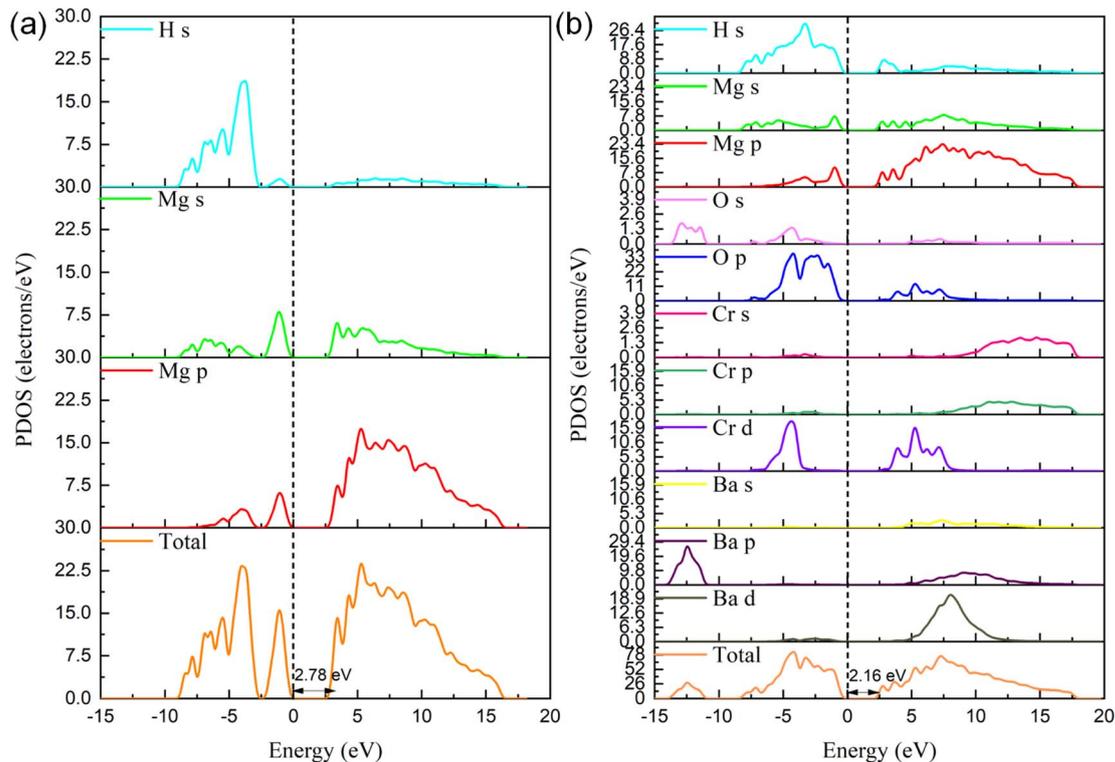


Fig. 9 DOS graphs of (a) MgH_2 and (b) 10 wt% BaCrO_4 -modified MgH_2 .

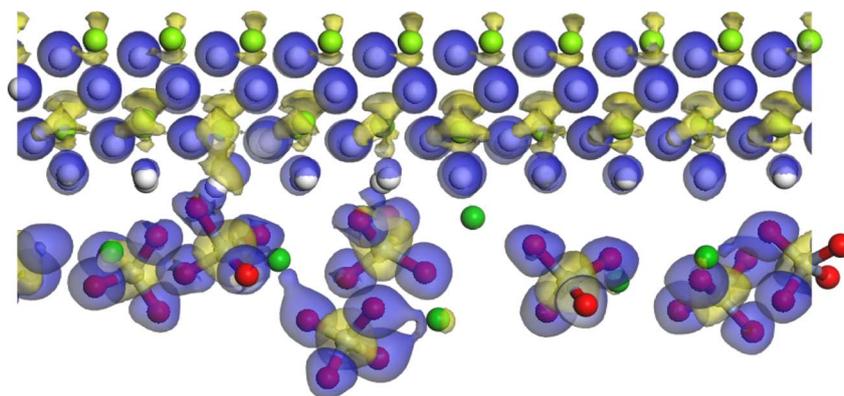


Fig. 10 Differential charge density maps of 10 wt% BaCrO_4 -modified MgH_2 (blue represents charge stacking and yellow represents charge lacking).

BaCrO_4 -modified MgH_2 in the initial state (IS), transition state (TS) and final state (FS) are shown in Fig. 11(b–d).

The specific catalytic mechanism of 10 wt% BaCrO_4 -modified MgH_2 is summarized in Fig. 12. The H atom preferentially diffuses on the BaCrO_4 nanocatalyst surface rather than the Mg/ MgH_2 surface during hydrogen absorption and desorption periods, because BaCrO_4 could shorten the length of the Mg–H bond and reduce the band gap as well as the diffusion energy barrier or E_a , which is shown in the calculation or DSC test section above. The strong electron-withdrawing effect of O and

the catalytic effect of Ba and Cr play an important role in improving the kinetic and thermodynamic properties of MgH_2 . Meantime, the BaCrO_4 nanocatalyst provides a number of sites for nucleation and channels for hydrogen diffusion to ameliorate the hydrogen storage capacity.

Additionally, after refinement of the high-energy ball mill technology, the BaCrO_4 nanocatalyst uniformly dispersed on the surface of MgH_2 efficiently prevents aggregation and crystal growth phenomenon, which results in excellent cycling property.



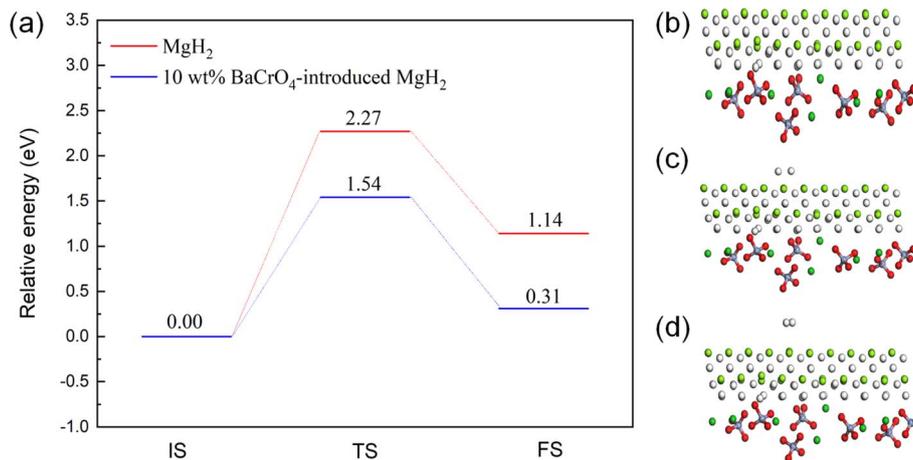


Fig. 11 (a) Dehydrogenation barrier energy of MgH₂ and 10 wt% BaCrO₄-modified MgH₂. (b–d) IS, TS, FS states of 10 wt% BaCrO₄-modified MgH₂.

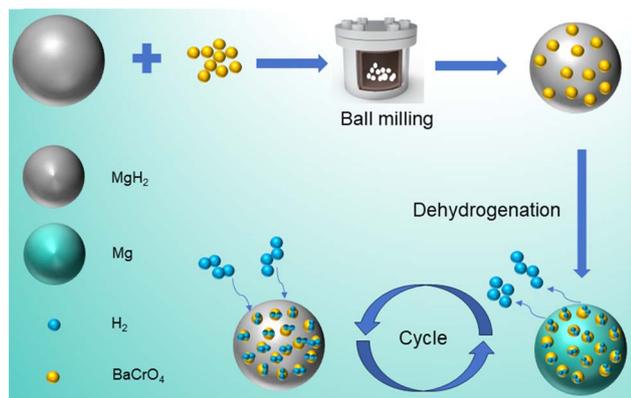


Fig. 12 Schematic catalytic mechanism of MgH₂ added with BaCrO₄.

6 Conclusions

In this work, we have successfully fabricated a BaCrO₄ nanocatalyst *via* wet chemical technology and introduced it into MgH₂ to study the catalytic effect in detail. The T_{onset} value of MgH₂ modified with 10 wt% BaCrO₄ was decreased to 280 °C, which is in sharp contrast to milled MgH₂ (390 °C). The 10 wt% BaCrO₄-modified MgH₂ sample could fully absorb 5.78 wt% H₂ within 10 min at 300 °C and release 4.25 wt% H₂ in 10 min at 325 °C, which is higher than that of undoped MgH₂ that adsorbed 1.25 wt% H₂ and desorbed 0.15 wt% H₂ during the same period. The desorption E_a value decreased from 156.55 kJ mol⁻¹ to 106.75 kJ mol⁻¹. Notably, the results of the cycle dynamic test indicated that BaCrO₄-modified MgH₂ could store 5.95 wt% H₂ after 10 cycles, with a 95% volume retention rate. The DFT calculations illustrated that BaCrO₄ could shorten the length of Mg–H bonds and reduce the band gap from 2.78 eV (milled MgH₂) to 2.16 eV, thereby improving the thermodynamic property. Impressively, the dehydrogenation energy barrier decreased from 2.27 eV (milled MgH₂) to 1.54 eV owing to the BaCrO₄ nanocatalyst. In conclusion, the above-

mentioned results reveal that BaCrO₄ is an ideal modified material to ameliorate the kinetics and thermodynamics of MgH₂, which could contribute to the strong electron-withdrawing effect of oxygen atoms and the catalytic effect of Ba and Cr elements.

Data availability

Data will be made available on request.

Conflicts of interest

The authors declare that they have no conflict of interest.

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References

- 1 C. Tarhan and M. A. Cil, *J. Energy Storage*, 2021, **40**, 102676–102686.
- 2 Z.-Y. Li, Y.-J. Sun, C.-C. Zhang, S. Wei, L. Zhao, J.-L. Zeng, Z. Cao, Y.-J. Zou, H.-L. Chu, F. Xu, L.-X. Sun and H.-G. Pan, *J. Mater. Sci. Technol.*, 2023, **141**, 221–235.
- 3 S. Dutt, A. Singh, R. Mahadeva, A. K. Sundramoorthy, V. Gupta and S. Arya, *Diamond Relat. Mater.*, 2024, **141**, 110554.
- 4 M. Thakur, A. Singh, A. Dubey, A. K. Sundramoorthy, P. Kumar and S. Arya, *Emergent Mater.*, 2024, DOI: [10.1007/s42247-024-00729-7](https://doi.org/10.1007/s42247-024-00729-7).
- 5 P. Murugan, A. K. Sundramoorthy, R. D. Nagarajan, R. Atchudan, R. Shanmugam, D. Ganapathy, S. Arya, A. A. Allothman and M. Ouladsmame, *J. Nanomater.*, 2022, **2022**, 9866111–9866121.
- 6 H. Ishaq, I. Dincer and C. Crawford, *Int. J. Hydrogen Energy*, 2022, **47**, 26238–26264.



- 7 T. R. Somo, T. E. Mabokela, D. M. Teffu, T. K. Sekgobela, M. J. Hato and K. D. Modibane, *Chem. Pap.*, 2021, **75**, 2237–2251.
- 8 Z. Taie, G. Villaverde, J. Speaks Morris, Z. Lavrich, A. Chittum, K. White and C. Hagen, *Int. J. Hydrogen Energy*, 2021, **46**, 3365–3378.
- 9 J. J. Brey, *Int. J. Hydrogen Energy*, 2021, **46**, 17447–17457.
- 10 R. Kumar Mishra, G. Jin Choi, R. Verma, S. Hun Jin, R. Bhardwaj, S. Arya, J. Singh and J. Seog Gwag, *Mater. Sci. Eng., B*, 2024, **303**, 117292.
- 11 J. Q. Li, J. C. Li, K. Park and J. T. Kwon, *Case Stud. Therm. Eng.*, 2022, **37**, 102143–102155.
- 12 K. E. Lamb and C. J. Webb, *J. Alloys Compd.*, 2022, **906**, 164235–164245.
- 13 L. Jiang, *Engineering*, 2021, **7**, 731–733.
- 14 H. Zhong, H. Wang, J. W. Liu, D. L. Sun, F. Fang, Q. A. Zhang, L. Z. Ouyang and M. Zhu, *J. Alloys Compd.*, 2016, **680**, 419–426.
- 15 Y. Zhang, X. Wei, W. Zhang, Z. Yuan, J. Gao, Y. Qi and H. Ren, *Int. J. Hydrogen Energy*, 2020, **45**, 33832–33845.
- 16 X. Chen, H. Yang and F. Pan, *J. Magnesium Alloys*, 2021, **9**, 1835–1836.
- 17 Q. Li, Y. Lu, Q. Luo, X. Yang, Y. Yang, J. Tan, Z. Dong, J. Dang, J. Li, Y. Chen, B. Jiang, S. Sun and F. Pan, *J. Magnesium Alloys*, 2021, **9**, 1922–1941.
- 18 N. Patelli, A. Migliori, V. Morandi and L. Pasquini, *Nano Energy*, 2020, **72**, 104654–104664.
- 19 C. Duan, Y. Tian, X. Wang, M. Wu, D. Fu, Y. Zhang, W. Lv, Z. Su, Z. Xue and Y. Wu, *Renewable Energy*, 2022, **187**, 417–427.
- 20 X. Zhang, Y. Liu, Z. Ren, X. Zhang, J. Hu, Z. Huang, Y. Lu, M. Gao and H. Pan, *Energy Environ. Sci.*, 2021, **14**, 2302–2313.
- 21 Z. Y. Lu, H. J. Yu, X. Lu, M. C. Song, F. Y. Wu, J. G. Zheng, Z. F. Yuan and L. T. Zhang, *Rare Met.*, 2021, **40**, 3195–3205.
- 22 P. Vajeeston, P. Ravindran, M. Fichtner and H. Fjellvåg, *J. Phys. Chem. C*, 2012, **116**, 18965–18972.
- 23 Z. Ma, Q. Zhang, S. Panda, W. Zhu, F. Sun, D. Khan, J. Dong, W. Ding and J. Zou, *Sustainable Energy Fuels*, 2020, **4**, 4694–4703.
- 24 Z. Ma, S. Panda, Q. Zhang, F. Sun, D. Khan, W. Ding and J. Zou, *Chem. Eng. J.*, 2021, **406**, 126790–126800.
- 25 A. Singh, S. S. Shah, C. Sharma, V. Gupta, A. K. Sundramoorthy, P. Kumar and S. Arya, *J. Environ. Chem. Eng.*, 2024, **12**, 113032.
- 26 H. Yong, X. Wei, J. Hu, Z. Yuan, M. Wu, D. Zhao and Y. Zhang, *Renewable Energy*, 2020, **162**, 2153–2165.
- 27 X. Chen, J. Zou, X. Zeng and W. Ding, *Int. J. Hydrogen Energy*, 2016, **41**, 14795–14806.
- 28 X. Wei, W. Zhang, H. Sun, Z. Yuan, Q. Ge, Y. Zhang and Y. Qi, *Int. J. Hydrogen Energy*, 2022, **47**, 12653–12664.
- 29 S. Balu, D. Ganapathy, S. Arya, R. Atchudan and A. K. Sundramoorthy, *RSC Adv.*, 2024, **14**, 14392–14424.
- 30 K. Kajiwara, H. Sugime, S. Noda and N. Hanada, *J. Alloys Compd.*, 2022, **893**, 162206–162213.
- 31 P. Yao, Y. Jiang, Y. Liu, C. Wu, K.-C. Chou, T. Lyu and Q. Li, *J. Magnesium Alloys*, 2020, **8**, 461–471.
- 32 F. J. Antigueira, D. R. Leiva, G. Zepon, B. F. R. F. de Cunha, S. J. A. Figueroa and W. J. Botta, *Int. J. Hydrogen Energy*, 2020, **45**, 12408–12418.
- 33 H. C. S. Perera, V. Gurunanthanan, A. Singh, M. M. M. G. P. G. Mantilaka, G. Das and S. Arya, *J. Magnesium Alloys*, 2024, **12**, 1709–1773.
- 34 R. Schulz, J. Huot, G. Liang, S. Boily, G. Lalande, M. C. Denis and J. P. Dodelet, *Mater. Sci. Eng., A*, 1999, **267**, 240–245.
- 35 R. A. Varin, T. Czujko and Z. Wronski, *Nanotechnology*, 2006, **17**, 3856–3865.
- 36 X. Yang, J. Zhang, Q. Hou, X. Guo and G. Xu, *ChemistrySelect*, 2021, **6**, 8809–8829.
- 37 D. Pukazhselvan, K. S. Sandhya, D. Ramasamy, A. Shaula and D. P. Fagg, *ChemPhysChem*, 2020, **21**, 1195–1201.
- 38 P. Rizo-Acosta, F. Cuevas and M. Latroche, *J. Mater. Chem. A*, 2019, **7**, 23064–23076.
- 39 Y. Huang, C. An, Q. Zhang, L. Zang, H. Shao, Y. Liu, Y. Zhang, H. Yuan, C. Wang and Y. Wang, *Nano Energy*, 2021, **80**, 105535–105545.
- 40 V. N. Kudiyarov, N. Kurdyumov, R. R. Elman, R. S. Laptev, M. A. Kruglyakov, I. A. Ushakov, A. V. Tereshchenko and A. M. Lider, *J. Alloys Compd.*, 2023, **966**, 171534–171548.
- 41 N. A. Sazelee, N. H. Idris, M. F. Md Din, N. S. Mustafa, N. A. Ali, M. S. Yahya, F. A. Halim Yap, N. N. Sulaiman and M. Ismail, *Int. J. Hydrogen Energy*, 2018, **43**, 20853–20860.
- 42 J. Adedeji Bolarin, Z. Zhang, H. Cao, Z. Li, T. He and P. Chen, *J. Phys. Chem. C*, 2021, **125**, 19631–19641.
- 43 N. A. Sazelee, N. A. Ali, M. S. Yahya, M. F. M. Din and M. Ismail, *Int. J. Hydrogen Energy*, 2023, **48**, 30844–30857.
- 44 N. A. Sazelee, N. H. Idris, M. F. Md Din, M. S. Yahya, N. A. Ali and M. Ismail, *Results Phys.*, 2020, **16**, 102844–102851.
- 45 S. Zhou, D. Wei, H. Wan, X. Yang, Y. Dai, Y. a. Chen and F. Pan, *Inorg. Chem. Front.*, 2022, **9**, 5495–5506.
- 46 M. H. Abdul Rahman, M. A. Shamsudin, A. Klimkowicz, S. Uematsu and A. Takasaki, *Int. J. Hydrogen Energy*, 2019, **44**, 29196–29202.
- 47 N. Sazelee, M. F. Md Din, M. Ismail, S.-U. Rather, H. S. Bamufleh, H. Alhumade, A. A. Taimoor and U. Saeed, *Materials*, 2023, **16**(6), 2449–2463.
- 48 H. Gao, R. Shi, Y. Shao, Y. Liu, Y. Zhu, J. Zhang and L. Li, *Int. J. Hydrogen Energy*, 2022, **47**, 9346–9356.
- 49 Y. Fu, L. Zhang, Y. Li, S. Guo, Z. Yu, W. Wang, K. Ren, Q. Peng and S. Han, *J. Mater. Sci. Technol.*, 2023, **138**, 59–69.
- 50 R. Kesarwani, A. Bhatnagar, S. K. Verma, M. S. L. Hudson and M. A. Shaz, *Int. J. Hydrogen Energy*, 2024, **67**, 1026–1032.
- 51 Y. Cheng, W. Zhang, J. Chen, J. Wang, P. Pei and F. Li, *RSC Adv.*, 2023, **13**, 9091–9098.
- 52 H. E. Kissinger, *Anal. Chem.*, 1957, **29**, 1702–1706.
- 53 N. H. Idris, N. S. Mustafa and M. Ismail, *Int. J. Hydrogen Energy*, 2017, **42**, 21114–21120.
- 54 S. Hu, H. Zhang, Z. Yuan, Y. Wang, G. Fan, Y. Fan and B. Liu, *J. Alloys Compd.*, 2021, **881**, 160571–160579.
- 55 M. S. Yahya and M. Ismail, *J. Energy Chem.*, 2019, **28**, 46–53.
- 56 L. Dan, L. Hu, H. Wang and M. Zhu, *Int. J. Hydrogen Energy*, 2019, **44**, 29249–29254.
- 57 F. A. Halim Yap, N. N. Sulaiman and M. Ismail, *Int. J. Hydrogen Energy*, 2019, **44**, 30583–30590.



- 58 N. A. Ali, N. A. Sazelee, M. F. Md Din, M. M. Nasef, A. A. Jalil, H. Liu and M. Ismail, *J. Magnesium Alloys*, 2023, **11**, 2205–2215.
- 59 J. H. Sharp, G. W. Brindley and B. N. N. Achar, *J. Am. Ceram. Soc.*, 1966, **49**, 379–382.
- 60 L. F. Jones, D. Dollimore and T. Nicklin, *Thermochim. Acta*, 1975, **13**, 240–245.
- 61 H. Wan, X. An, Q. Kong, X. Wu, W. Feng, H. Wang, J. Wu, C. Lu, W. Zha, H. Sun and L. Huang, *Adv. Powder Technol.*, 2021, **32**, 1380–1389.

