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Short Communication

Catalytic dehydrogenation of isobutane over ordered mesoporous Cr_2O_3 -Al₂O₃ composite oxides



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ABSTRACT

A series of ordered mesoporous Cr₂O₃–Al₂O₃ composite oxides synthesized via improved one-pot evaporation induced self-assembly strategy were investigated as the catalysts for catalytic dehydrogenation of isobutane. These mesoporous catalysts with good structural properties and thermal stability performed excellent catalytic properties. Besides, the effect of the ordered mesopore structure on improving catalytic properties was also studied. Compared with non-mesoporous catalyst, the current mesoporous catalyst could accommodate the gaseous reactant with more "accessible" active sites. Therefore, the present materials were considered as promising catalyst candidates for catalytic dehydrogenation of isobutane.

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1. Introduction

In recent years, there has been increasing demand for light alkenes, such as ethylene, propylene, and isobutene, which are extensively utilized as the raw materials for polymer industry and other commodity chemicals [1-3]. Further, isobutene is often utilized as the basic building block for producing MTBE, which commonly acts as the additive to lead-free gasoline to enhance its octane number [4]. Fortunately, the catalytic dehydrogenation of isobutane process could provide an attractive as well as inexpensive route for producing isobutene [4–6]. In addition to this, another additional advantage of this process is that it could provide low-cost hydrogen, which is a greatly valuable feedstock for ammonia industry, petroleum refinery, fuel cell, etc. [1]. However, this process is usually carried out at high temperatures due to its intensely endothermic feature. Therefore, the thermal cracking of isobutane and the following formation of coke seem to be inevitable under this high temperature condition [3,7]. Thus, developing catalysts with high activity, selectivity as well as excellent endurance are the present research focus.

As we know, both Pt and Cr based catalysts have been widely used for alkane dehydrogenation [3–5,8–12]. Although, compared with Cr based catalysts, the Pt based catalysts usually performed better resistance towards coke and long-term catalytic stability, their higher cost and poorer

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reusability are main obstacles. Therefore, it is more practical to develop Cr based catalysts with outstanding properties due to its high initial activity. In order to achieve this goal, various strategies, including using different preparation methods [3,13,14], introducing auxiliary agents [15,16], employing various carriers [17–20], etc., have been widely used.

In this communication, a series of ordered mesoporous Cr_2O_3 – Al_2O_3 composite oxides were facilely synthesized via one-pot evaporation induced self-assembly strategy (EISA). The obtained materials with excellent textural properties and good thermal stability were investigated as the catalysts of catalytic dehydrogenation of isobutane. To the best of our knowledge, there was almost no report on catalytic dehydrogenation of isobutane over ordered mesoporous Cr_2O_3 – Al_2O_3 composite oxides. More details related with their catalytic properties would be described specifically in the main text.

2. Experimental

Detailed description concerning the synthesis, characterization, and catalytic property measurement of ordered mesoporous Cr_2O_3 - Al_2O_3 composite oxides was presented in Supporting Information S1 Experimental.

3. Results and discussion

3.1. XRD analysis

The small-angle XRD (SXRD) patterns exhibited in panel A of Fig. 1 (1) provided the evidence for the presence of ordered mesostructures



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for OMA-xCr. As shown in the figure, each sample presented a strong diffraction peak around 0.7° and another weak peak around 1.4°, respectively. Therefore, a good mesoscopic order was successfully maintained even after calcined at temperature as high as 700 °C, revealing high thermal stability of the mesoporous structures of OMA-xCr. Part B of Fig. 1 (1) presented the wide-angle XRD (WXRD) patterns of OMA-xCr. It was noticeable that all the samples gave rise to γ phase alumina (JCPDS card no. 10-0425) diffraction peaks with low intensity, illustrating that the crystallinity of the OMA framework was not very good. However, the diffraction peaks for Cr_2O_3 were absent when the Cr/Al ratio was lower than 7%, demonstrating the high dispersion of Cr species among the mesoporous framework. When the Cr/Al ratio increased from 7% to 15%, the Cr₂O₃ diffraction peaks (JCPDS card no. 84-1616) gradually appeared. This indicated that the dispersion became poorer with the increase of Cr containing.

Besides, the comparative analyses of XRD patterns for OMA-10Cr, NPA-10Cr, and 10Cr/Al₂O₃ samples were also displayed in Fig. 1 (2). As shown in the panel A, dissimilar to the OMA-10Cr, both 10Cr/Al₂O₃ and NPA-10Cr performed not any diffraction peak in the small angle region, suggesting the absence of ordered mesostructure. Hence, the P123 template played an essential role in constructing ordered mesoporous framework. Their WXRD patterns were also presented in panel B of Fig. 1 (2). As described above, the OMA-10Cr behaved remarkable Cr_2O_3 diffraction peaks; as a comparison, the NPA-10Cr showed no obvious Cr_2O_3 diffraction peak. This phenomenon implied that the presence of P123 template was in favor of the formation of crystalline Cr_2O_3 . As for 10Cr/Al₂O₃, it performed characteristic diffraction peaks for both γ phase alumina and Cr_2O_3 species, which ought to be derived from γ -Al₂O₃ carrier and the thermal decomposition of $Cr(NO_3)_3 \cdot 9H_2O$ precursor, respectively.

3.2. Nitrogen adsorption-desorption analysis

Nitrogen adsorption-desorption isotherms for OMA-xCr samples were displayed in Fig. 2 (1) A. All isotherms were attributable to type IV with H1-shaped hysteresis loops, which were the typical features for the presence of mesopores with cylindrical shape. Besides, the pore size distributions of these samples were shown in Fig. 2 (1) B. For the adsorption isotherms with steep condensation steps, the corresponding pore size distribution curves performed very narrow distribution around 10.0 nm. In order to further investigate the role of P123 template in forming uniform mesopores, the comparative analysis between OMA-10Cr and NPA-10Cr was conducted and the results were displayed in Fig. 2 (2). As shown in Fig. 2 (2) A, different from OMA-10Cr with IV H1-shaped hysteresis loop, the NPA-10Cr exhibited IV H3-shaped hysteresis loop, implying the absence of uniform mesopores. Moreover, as shown in Fig. 2 (2) B, dissimilar to OMA-10Cr with narrow pore size distribution, NPA-10Cr performed greatly wide pore size distribution. These phenomena once again demonstrated the crucial role of P123 template in shaping ordered mesopore. Besides, the N₂ adsorption-desorption isotherm and pore size distribution curve of 10Cr/Al₂O₃ catalyst were also depicted in Fig. 2 (2). Compared with OMA-10Cr, it also behaved IV H3-shaped hysteresis loop and wide pore size distribution. It was speculated that the mesopores existing among the 10Cr/Al₂O₃ might be stemmed from the disordered accumulation of Al₂O₃ particles.

Moreover, the textural properties of above samples were summarized in Table 1. It was noticeable that all the samples calcined at 700 °C were provided with large BET specific surface areas up to 198.8 m^2/g , big BJH pore volumes up to 0.629 cm³/g, and average pore diameters around 10.0 nm. As a comparison, the NPA-10Cr possessed much smaller surface area and pore volume.



Fig. 1. Small-angle XRD (A) and wide-angle XRD (B) patterns of Cr based catalysts: (1) OMA-xCr with different Cr loadings: (a) OMA-3Cr, (b) OMA-5Cr, (c) OMA-7Cr, (d) OMA-10Cr, (e) OMA-15Cr; (2) comparative analyses of OMA-xCr, NPA-10Cr, and 10Cr/Al₂O₃ catalysts: (a) OMA-10Cr, (b) 10Cr/Al₂O₃, (c) NPA-10Cr.



Fig. 2. Isotherms (A) and pore size distributions (B) of Cr based catalysts: (1) OMA-xCr with different Cr loadings; (2) comparative analyses of OMA-xCr, NPA-10Cr, and 10Cr/Al₂O₃ catalysts.

3.3. TEM analysis

In order to further confirm the presence of ordered mesopores, TEM characterization for OMA-xCr was carried out. OMA-3Cr, OMA-7Cr, and OMA-10Cr samples were selected as representatives and their TEM images were displayed in Fig. 3. For all the samples, the alignment of cylindrical pores along [1 1 0] direction was distinctly observed, which were` well consistent with the deduction based on nitrogen adsorption–desorption analysis. Besides, the EDX measurement of the ordered mesostructure region for OMA-10Cr was also conducted and its profile was shown in Fig. 3 (e). The characteristic peaks for Cr, Al, and O elements were clearly observed, suggesting that all the metallic elements were successfully introduced into ordered mesoporous framework.

Table 1		
Textural properties	of OMA-xCr, NPA-10Cr, and	$10Cr/Al_2O_3$ catalysts.

Samples	Specific surface area (m²/g)	Pore volume (cm ³ /g)	Average pore diameter (nm)	Isotherm type	Surface Cr ³⁺ /Cr ⁶⁺ ratio
OMA-3Cr	189.0	0.528	9.91	IV H1	2.10
OMA-5Cr	199.7	0.620	11.3	IV H1	1.73
OMA-7Cr	198.8	0.576	10.6	IV H1	1.06
OMA-10Cr	191.0	0.629	11.9	IV H1	0.98
OMA-15Cr	158.3	0.473	11.4	IV H1	1.45
NPA-10Cr	13.1	0.126	-	IV H3	1.72
$10Cr/Al_2O_3$	155.8	0.372	-	IV H3	2.33

Surface Cr^{3+}/Cr^{6+} ratio is obtained by peak fitting of the Cr2P profiles.

3.4. H₂-TPR and XPS analyses

The redox properties of the OMA-xCr catalysts were investigated by H_2 -TPR and the resulting profiles were shown in Fig. 4 (1). It could be clearly observed that the intensities of H₂ consumption peaks gradually increased with the augment in the Cr containing. It was also noticeable that most of the samples behaved similar profiles of hydrogen consumption in shapes regardless of Cr content, specifically displaying one pronounced H₂ reduction peak around 550 °C and one small shoulder peak around 300 °C. However, it was reported in the previous literatures that the consumption of hydrogen was mainly caused by the reduction of Cr ions from +6 to +3[10,16,21,22]. Therefore, these two reduction peaks should be ascribed to the reduction of Cr⁶⁺ species in different coordination environments. As for the peaks around 300 °C, they might be assigned to the reduction of surface Cr⁶⁺. On the one hand, the unsaturated coordination of surface Cr^{6+} ions made them easier to reduce; on the other hand, the surface Cr⁶⁺ ions could be more easily accessible to H₂ stream owing to their large surface areas and uniform pore channels. As a result, they could be easily reduced in lower temperature region. The reduction peaks at higher temperature region around 550 °C might be ascribed to the reduction of bulk Cr⁶⁺ ions, which had strong interaction with the mesoporous framework. Most of the Cr atoms were inlayed among the matrix of ordered mesoporous skeleton due to the current one-pot synthesis strategy, accounting for the bigger reduction peaks at higher temperature region.

Furthermore, the H_2 -TPR profiles of NPA-10Cr and $10Cr/Al_2O_3$ were also summarized in Fig. 4 (1). As for the NPA-10Cr, dissimilar to OMA-10Cr, its reduction peak was not conspicuous, only displaying



Fig. 3. TEM images of the OMA-xCr catalysts: (a) OMA-3Cr, (b) and (c) OMA-7Cr, (d) OMA-10Cr, (e) EDX measurement of OMA-10Cr.

a small uptake around 476 °C. The reason for this might be derived from relatively smaller surface area of NPA-10Cr than that of OMA-10Cr. As a result, it could not provide sufficient "accessible" Cr^{6+} species for the H₂ stream. As regards the supported 10Cr/Al₂O₃ catalyst, it only performed one reduction peak in low temperature region around 453 °C, which was extremely common for Cr based catalyst supported Al₂O₃ according to previous literatures [15,19,21]. Compared with the reduction peak of OMA-10Cr at higher temperature region around 550 °C, the Cr⁶⁺ species could be reduced at lower temperature for the present supported catalyst. Therefore, the interaction between Cr₂O₃ species and γ -Al₂O₃ support for 10Cr/Al₂O₃ was somewhat weaker than that for OMA-10Cr. This situation might be caused by the different catalyst preparation methods, which had been detailedly described in Supporting Information S1 Experimental.

Besides, the surface Cr species on OMA-xCr, NPA-10Cr, and 10Cr/Al₂O₃ catalysts were examined by XPS measurements. The XPS spectra of Cr2P were shown in Fig. 4 (2). It was apparent to find that the curves were identical in shapes and the intensities of the peaks gradually became stronger with the increase of Cr/Al ratio from 3% to 15% for OMA-xCr catalysts. Besides, the peaks around 577.3 eV and 579.9 eV for Cr2P_{3/2} could be observed over all the samples, which ought to be assigned to Cr^{3+} and Cr^{6+} , respectively, according to pioneer literatures [3,4,21]. As for the 10Cr/Al₂O₃ and NPA-10Cr catalysts, they performed similar patterns to OMA-xCr, illustrating that the surface Cr species also mainly existed in the form of Cr^{3+} and Cr^{6+} . Besides, the exact surface Cr^{3+}/Cr^{6+} ratios for all the samples were calculated by peak fitting of the Cr2P profiles and their results were summarized in Table 1. As

shown in the table, the Cr³⁺/Cr⁶⁺ ratio decreased from 2.10 to 0.98 when the Cr content increasing from 3% to 10% for OMA-xCr; however, further augment in Cr containing up to 15% made the Cr³⁺/Cr⁶⁺ ratio increase a lot. As for NPA-10Cr and 10Cr/Al₂O₃ catalysts, they performed much bigger Cr³⁺/Cr⁶⁺ ratios than OMA-10Cr, although they possessed identical Cr loading. The reason for these phenomena remained unclear due to current level of cognition.

3.5. Catalytic performances

The catalytic performances of the OMA-xCr with different Cr containing for catalytic dehydrogenation of isobutane reaction at different temperatures under given condition (GHSV = 1500 mL/(g·h), 1 atm) were summarized in Table 2. As shown in the table, with the reaction temperature elevated, the conversion of isobutane suffered some increase, reflecting the endothermic feature of this reaction [3,7]. However, for most of the samples, the selectivity of isobutene suffered some decline with the increase of the reaction temperature from 580 °C to 610 °C. The reason for this might be derived from the thermal cracking of the isobutane and/or isobutene at higher temperature.

Besides, the relationship between the catalytic activity and Cr containing also could be expressed in Table 2. With the augment in Cr content, the conversion of isobutane as well as the yield of isobutene initially increased rapidly and reached summit at 7% or 10% Cr/Al ratio in the temperature region investigated because of the increase in active sites. But further increase of Cr/Al ratio up to 15% led some decline in isobutane conversion and isobutene yield.



Fig. 4. H_2 -TPR profiles (1) and XPS spectra (2) of OMA-xCr catalysts calcined at 700 °C: (a) OMA-3Cr, (b) OMA-5Cr, (c) OMA-7Cr, (d) OMA-10Cr, (e) OMA-15Cr, (f) NPA-10Cr, (g) 10Cr/Al₂O₃.

Its reason might derive from the agglomeration of Cr_2O_3 based on XRD characterization in Fig. 1 (1) B, finally causing the decrease in active sites.

In order to investigate the influence of ordered mesoporous structure on catalytic performance, OMA-10Cr and NPA-10Cr with and without uniform mesopore were selected as the representatives and their results were listed in Table 2. It was noticeable that both isobutane conversion and isobutene selectivity of NPA-10Cr were all much lower than those of OMA-10Cr, respectively, which might be attributed to the difference in structural properties. Specifically, compared with NPA- 10Cr, the OMA-10Cr behaved much larger surface area, bigger pore volume, and more ordered pore channels. As a result, the mesoporous catalyst could provide more "exposed" or "accessible" Cr active sites for the gaseous feedstock, which finally accounted for the better catalytic performance of mesoporous catalyst.

In addition to these, the comparison between mesoporous catalyst and traditional industrial catalyst was also carried out. As well known, Cr based catalyst supported Al₂O₃ carrier was usually used as industrial catalyst for catalytic dehydrogenation of isobutane. Therefore, OMA-10Cr and 10Cr/Al₂O₃ with identical Cr loading were selected as representatives and their results were also summarized in Table 2. It could be observed that the conversions of isobutane over 10Cr/Al₂O₃ catalyst were higher than those over OMA-10Cr for the reaction temperatures studied. But the selectivity to isobutene over 10Cr/Al₂O₃ catalyst was inferior to that over OMA-10Cr. It might be the strong Lewis acid sites over 10Cr/Al₂O₃ catalyst that caused seriously thermal cracking of the isobutane and/or isobutene, finally leading to low isobutene selectivity.

Finally, 300 min laboratory-scale stability tests (five dehydrogenation-regeneration cycles) were examined over OMA-10Cr and $10Cr/Al_2O_3$ catalysts under specific reaction condition: 610 °C, GHSV = 1500 mL/($g \cdot h$), 1 atm. The experimental results were exhibited in Fig. 5. As shown in Fig. 5 (1), the isobutane conversions over both catalysts suffered some decline for each run (60 min), which was the common feature for Cr based catalysts due to the carbon deposition over the active center. However, the catalytic stability over OMA-10Cr catalyst was much better than that over 10Cr/Al₂O₃. Taken the first cycle for example, the OMA-10Cr maintained ~67% of its initial activity; as a comparison, 10Cr/Al₂O₃ only retained ~54% of its initial activity. Further, compared with the original catalyst, the regenerated OMA-10Cr performed similar or even higher isobutane conversion only after a simple heating treatment in flowing air; however, the regenerated 10Cr/Al₂O₃ could not regain its original activity. After five cycles, the initial activity over 10Cr/Al₂O₃ suffered great decline from 63.7% for the first cycle to 56.3% for the fifth cycle. Besides, it was noticeable in Fig. 5 (2) that for both catalysts, the selectivity to isobutene only decreased slightly within each cycle and the value over the regenerated catalyst was even a little higher than that over original catalyst. But the isobutene selectivity over 10Cr/Al₂O₃ was always lower than that over OMA-10Cr. Therefore, all the phenomena mentioned above indicated that OMA-10Cr catalyst performed better catalytic stability than 10Cr/Al₂O₃ catalyst.

4. Conclusion

A series of ordered mesoporous Cr_2O_3 - Al_2O_3 composite oxides with various Cr content had been successfully prepared by improved one-pot EISA method. The obtained materials utilized as the catalysts for catalytic dehydrogenation of isobutane performed high catalytic activity, selectivity, and excellent stability. Besides, it was also found that the ordered mesoporous structure played a crucial role in promoting the catalytic activity by providing more "accessible" active sites for the gaseous reactant. Therefore, the present ordered

Table 2

Catalytic performances for dehydrogenation of isobutane over OMA-xCr, NPA-10Cr, and 10Cr/Al₂O₃ catalysts at different temperatures; reaction condition: GHSV = 1500 mL/(g · h), 1 atm.

Samples	580 °C		585 °C		590 °C		600 °C		610 °C	
	C _{i-C4H10}	S _{i-C4H8}								
OMA-3Cr	34.7	91.7	34.9	91.6	35.2	89.1	42.2	88.4	42.8	87.6
OMA-5Cr	37.0	92.6	35.6	91.6	44.9	92.8	44.2	93.2	46.1	90.3
OMA-7Cr	41.8	90.6	46.4	92.1	46.2	92.5	47.0	92.0	48.6	88.6
OMA-10Cr	39.2	91.6	42.7	92.2	46.6	91.8	48.1	91.5	51.2	89.6
OMA-15Cr	30.9	92.2	35.9	92.4	34.4	92.5	31.1	91.2	29.5	86.2
NPA-10Cr	10.0	71.3	12.7	75.4	14.9	86.4	14.8	86.9	22.6	89.8
10Cr/Al ₂ O ₃	51.9	87.9	55.6	87.8	57.4	86.7	59.2	86.2	63.7	84.6

C_{i-C4H10} stands for the conversion of isobutane. S_{i-C4H8} stands for the selectivity of isobutene.



Fig. 5. Catalytic performances for dehydrogenation of isobutane over OMA-10Cr and 10Cr/Al₂O₃ catalysts versus time on stream: (1) isobutane conversion; (2) isobutene selectivity. Reaction condition: T=610 °C, GHSV=1500 mL/(g·h), 1 atm; spent catalyst for each cycle was regenerated at 700 °C in flowing of air (40 mL/min) for 30 min.

mesoporous Cr₂O₃–Al₂O₃ composite oxides could be considered as a series of promising catalysts for dehydrogenation of isobutane reaction. Further studies related with further improving catalytic

activity and selectivity of targeted product would be presented in our future work.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.catcom.2013.02.011.

References

- [1] P. Sun, G. Siddiqi, M. Chi, A.T. Bell, Journal of Catalysis 274 (2010) 192–199.
- [2] S. Sahebdelfar, P.M. Bijani, M. Saeedizad, F.T. Zangeneh, K. Ganji, Applied Catalysis A: General 395 (2011) 107–113.
- [3] D. Shee, A. Sayari, Applied Catalysis A: General 389 (2010) 155-164.
- [4] F. Cavani, M. Koutyrev, F. Trifiro, A. Bartolini, D. Ghisletti, R. lezzi, A. Santucci, G. DelPiero, Journal of Catalysis 158 (1996) 236–250.
- [5] S.M. Stagg, C.A. Querini, W.E. Alvarez, D.E. Resasco, Journal of Catalysis 168 (1997) 75–94.
- [6] E. Novakova, N. Winterton, K. Jarosch, J. Brophy, Catalysis Communications 6 (2005) 586–590.
- [7] Y. Zhang, Y. Zhou, J. Shi, X. Sheng, Y. Duan, S. Zhou, Z. Zhang, Fuel Processing Technology 96 (2012) 220–227.
- [8] R.D. Cortright, J.A. Dumesic, Journal of Catalysis 148 (1994) 771-778.
- [9] R.D. Cortright, J.M. Hill, J.A. Dumesic, Catalysis Today 55 (2000) 213-223.
- [10] A. Hakuli, M.E. Harlin, L.B. Backman, A.O.I. Krause, Journal of Catalysis 184 (1999) 349–356.
- [11] Z. Nawaz, X. Tang, Q. Zhang, D. Wang, W. Fei, Catalysis Communications 10 (2009) 1925–1930.
- [12] Y. Zhang, Y. Zhou, Y. Li, Y. Wang, Y. Xu, P. Wu, Catalysis Communications 8 (2007) 1009–1016.
- [13] A. Hakuli, A. Kytokivi, A.O.I. Krause, Applied Catalysis A: General 190 (2000) 219–232.
- [14] S.M.K. Airaksinen, A.O.I. Krause, Industrial and Engineering Chemistry Research 44 (2005) 3862–3868.
- 15] M. Cherian, R. Gupta, M.S. Rao, G. Deo, Catalysis Letters 86 (2003) 179-189.
- [16] E. Rombi, M.G. Cutrufello, V. Solinas, S. De Rossi, G. Ferraris, A. Pistone, Applied Catalysis A: General 251 (2003) 255–266.
- [17] M. Hoang, J.F. Mathews, K.C. Pratt, Journal of Catalysis 171 (1997) 320–324.
 [18] S. De Rossi, M.P. Casaletto, G. Ferraris, A. Cimino, G. Minelli, Applied Catalysis A:
- General 167 (1998) 257–270.
- [19] S.B. Wang, K. Murata, T. Hayakawa, S. Hamakawa, K. Suzuki, Applied Catalysis A: General 196 (2000) 1–8.
- [20] S.T. Korhonen, S.M.K. Airaksinen, M.A. Banares, A.O.I. Krause, Applied Catalysis A: General 333 (2007) 30–41.
- [21] B. Grzybowska, J. Sloczynski, R. Grabowski, K. Wcislo, A. Kozlowska, J. Stoch, J. Zielinski, Journal of Catalysis 178 (1998) 687–700.
- [22] J.M. Kanervo, A.O.I. Krause, Journal of Catalysis 207 (2002) 57-65.