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DOI
10.1002/cssc.202001633

Publication date
2020

Document Version
Final published version

Published in
ChemSusChem

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Citation for published version (APA):

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Butane Dry Reforming Catalyzed by Cobalt Oxide Supported on Ti$_2$AlC MAX Phase

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Introduction

The increase in anthropogenic CO$_2$ emissions and its contribution to the rising average global temperatures makes CO$_2$ capture and utilization a priority research area.$^{[1–4]}$ Catalytic dry reforming of lower alkanes to CO and H$_2$ is an interesting option, because the syngas product can be used as feedstock to obtain high-value chemicals through processes such as the Fischer-Tropsch synthesis.$^{[5–8]}$ However, as with any chemical process that uses CO$_2$, this reaction must overcome a high thermodynamic barrier, which usually means high reaction temperatures. Butane, which is a side product of crude oil refining and is widely available from shale gas,$^{[9]}$ is thermodynamically less stable ($\Delta G^\circ$ is $-16.6$ kJ·mol$^{-1}$) than smaller hydrocarbons such as methane ($\Delta G^\circ = -50.5$ kJ·mol$^{-1}$). Therefore, dry reforming of butane (DRB) allows us to bring down the reaction temperature to 500–600°C.$^{[10–13]}$ The problem is that dry reforming catalysts usually suffer from deactivation through sintering of active sites and coking.$^{[14]}$ Even if we can lower the reaction temperature by using butane, catalyst deactivation by coking will still occur by the Boudouard reaction (2CO→CO$_2$+C) and/or via the partial or total cracking of butane.

Traditionally, such reactions use catalysts containing alumina, silica, or titania as supports.$^{[15]}$ Most of the attention is typically focused on the active site. Yet the support plays a crucial role in real-life catalysis, as deactivation via coking and/or strong metal–support interaction (SMSI) preclude the industrial use of many catalysts that show good short-term activity.$^{[16]}$ To address this problem, we turned to a new family of support materials: MAX phases (M$_{n+1}$AX$_n$). MAX phases are ternary carbides or nitrides with layered hexagonal crystal structures (Figure 1). Their name reflects their chemical composition: M is an early transition metal, A is an A-group element (mostly from groups 13 and 14), X is carbon and/or nitrogen, and $n=1, 2, 3$. MAX phases combine an unusual set of thermal, mechanical, and electrical properties. Like ceramics, they show high-temperature strength and stiffness, and at the same time they are tough, ductile, and conduct electricity and heat like metals.$^{[17–19]}$

Due to their thermal stability and resistance to fracturing, MAX phases have mainly been used for mechanical and thermal...
realizing the yet unexplored potential of MAX phases as highly selective catalyst supports. Specifically, we were interested in exploring Ti₃AlC as a catalyst for dry reforming of butane.

**Results and Discussion**

**Catalyst synthesis**

Opting for Ti₃AlC as one of the most stable MAX phases, we prepared and tested Co₃O₄/Ti₃AlC as a catalyst for dry reforming of butane, and compared it to two benchmarks, Co₃O₄/Al₂O₃ and Co₃O₄/TiO₂. The catalyst samples, each containing 5 wt% of metallic cobalt, were prepared by wet impregnation, using Co(NO₃)₂·6H₂O as the cobalt precursor. The Ti₃AlC support was prepared by mixing Ti, Al, and TiC powders at 1350°C and high pressure, following the procedure of Boatemaa et al. The catalyst samples were then calcined in air at 450°C for 4 h (see the Experimental Section for detailed procedures).

**Catalyst characterization**

The X-ray diffraction (XRD) pattern of the as-prepared Co₃O₄/Ti₃AlC catalyst (Figure 2) shows the characteristic peaks of the Ti₃AlC MAX phase structure. It also shows the presence of Co₃O₄ at 2θ = 31.4, 36.9, 59.5, and 65.6°. Conversely, the Co₃O₄ characteristic peaks are absent from the patterns of Co₃O₄/TiO₂ and Co₃O₄/Al₂O₃ (see Figure S1). Co₃O₄ and CoAl₂O₄ both have a spinel structure with almost identical diffraction patterns, which are also similar to those of the γ-Al₂O₃ support. These peaks are visible in the diffraction pattern of the Co₃O₄/Al₂O₃ catalyst at 2θ = 31.5, 37.0, 45.7, and 59.4°. The pattern of Co₃O₄/TiO₂ only shows the characteristic peaks of TiO₂ anatase, indicating that the Co₃O₄ particles are smaller when supported on TiO₂ compared to Ti₃AlC or Al₂O₃. Scanning transmission electron microscopy (STEM) combined with high-angle annular dark field (HAADF) imaging of Co₃O₄/Ti₃AlC (Figure 3) showed significant agglomeration of cobalt oxide particles, between 90–500 nm in diameter. These particles are hollow, with very small voids. TEM images gave a better insight into the distribution of the hollow structure. The voids are typically 6–30 nm in diameter. These voids result from the Kirkendall effect, where the diffusion rates of the cations and anions differ during oxidation. Using Al₂O₃ as a support gives smaller cobalt oxide particles compared to Ti₃AlC, but they also form agglomerates on the support (Figure S2a). The Co₃O₄/TiO₂ catalyst shows the best Co₃O₄ dispersion (Figure S2b). Similar Co₃O₄ hollow structures were reported by Wang et al., following CoCl₂ impregnation-reduction-oxidation treatment on a carbon support.

The low surface area of the Ti₃AlC support (typically <40 m²·g⁻¹) explains the low surface area of Co₃O₄/Ti₃AlC, as well as the low dispersion and the large Co₃O₄ particle size. Co₃O₄/TiO₂ and Co₃O₄/TiO₂ catalysts are mesoporous materials with a Brunauer–Emmett–Teller (BET) surface area of 187 and 76 m²·g⁻¹, respectively (see Figure S3 and Table S1 in the Supporting Information for details).

We then studied the reducibility of Co₃O₄ particles and their interaction with the different supports by hydrogen temperature-programmed reduction (TPR) (Figure S4). The reduction of Co₃O₄ particles to CoO is known to occur at lower temperatures. Thereafter, CoO is reduced to metallic Co at higher temperatures.
The catalytic tests were performed in an automated six-flow parallel reactor system, with six quartz tube reactors.\(^{[37]}\) 100 mg of catalyst (in the form of pellets) was placed in the reactor. We ran two types of catalytic tests: temperature screening between 450 and 650 °C, and long-term stability tests at 650 °C for 18 h. The reactants ratio (\(\text{CO}_2/\text{C}_3\text{H}_8 = 4:1\)), pressure (atmospheric), and total flow rate were kept constant.

Control experiments comparing fresh and calcined samples of Ti,AlC did not show any conversion (Figure S5), confirming the need for a metal or metal oxide as the active site. In addition, the pre-reduction of the supported catalysts at 650 °C for 1 h did not show any improvement on the catalytic performance compared to the unreduced catalysts (Figure S5). Therefore, we focus on discussing the catalytic tests of the as-prepared materials, without pre-reduction.

The temperature screening tests showed that the Co,Al/Ti,AlC catalyst is active for dry reforming at 450 °C and above (Figure 4). The CO conversion reached 38% at 650 °C. This is a promising result as it shows that the catalyst is active despite the low surface area of the MAX phase support and the larger size of the cobalt oxide particles. The catalyst is highly selective towards CO and \(\text{H}_2\) (64 and 35 %, respectively), giving only trace amounts of olefins (<1% of the total mixture). We used a stoichiometric ratio of the reactants (4:1 \(\text{CO}_2/\text{C}_3\text{H}_8\)), and therefore expected a \(\text{H}_2/\text{CO}\) ratio of 0.6:1. However, the actual \(\text{H}_2/\text{CO}\) ratio ranged between 0.3–0.5 from 550 to 650 °C (Figure S6). This indicates extra production of CO and/or consumption of \(\text{H}_2\), possibly caused by reverse water gas shift (RWGS), which is a common side reaction during dry reforming reactions.\(^{[38,39]}\)

Encouraged by the activity of this low-surface-area catalyst, we also tested its long-term stability at 650 °C for 18 h (Figure 5). The catalyst converted 24% \(\text{CO}_2\) in the beginning of the reaction, and it was stable over time, with only a slight deactivation (2.5% for butane conversion and 1.6% for \(\text{CO}_2\) conversion) after 18 h (Figure 5). Moreover, its carbon balance (expressed as \(\text{C}_{\text{out}}/\text{C}_{\text{in}}\)) was 93%, confirming that very little carbon was deposited on the catalyst.

We then compared the catalytic performance of MAX phase supported cobalt oxide with titania and alumina supported cobalt oxide. \(\text{Co,Al/Ti}_2\text{O}_3\) catalyst gave very low conversion: 12% of butane was converted at the beginning of the reaction, but this quickly decayed to 5% butane conversion. However, this observed conversion corresponds to the thermal cracking of butane to \(\text{C}_2\) compounds. Neither \(\text{CO}\) or \(\text{H}_2\) were detected as...
products (Figure S7). HAADF-STEM images of the spent catalyst (Figure S8) show the sintering of cobalt oxide particles compared to the fresh sample, which explains the deactivation of this catalyst.

$\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$ showed a higher conversion than cobalt on MAX phase. However, its temperature-screening profile (Figure 4) shows a decrease in conversion at 600 °C compared to the conversion at 550 °C. This is due to the predominance of coking by butane cracking and/or the Boudouard reaction, which leads to a significant amount of deposited carbon (33–22%) that deactivates the catalyst. During the stability test, $\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$ deactivates more (7.3% for butane conversion and 5.7% for CO$_2$ conversion) than the MAX phase catalyst. The carbon balance is only 85%, indicating considerably more carbon deposition (15%) on the catalyst surface (see Figure S7). Thermogravimetric analysis (TGA, Figure S9) of the spent catalyst confirms the deposition of coke during reaction, since there is a mass loss between 300 and 600 °C corresponding to the combustion of soft coke.$^{[40,41]}$ Typically, the rate and extent of coke formation increase with increasing acidity of the catalyst.$^{[42]}$ Since $\text{Co}_3\text{O}_4/\text{Ti}_2\text{AlC}$ is significantly less acidic than $\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$ [see NH$_3$ temperature-programmed desorption (TPD) results in Table S2], it can inhibit coke formation more efficiently. We also ran CO$_2$ chemisorption experiments, but the low porosity and surface area of Ti$_2$AlC hinders the adsorption of molecules like CO$_2$ and no useful information was obtained from these experiments.

Dry reforming is a structure-sensitive reaction, where the catalyst particle size affects its performance.$^{[43]}$ Thus, we compared the intrinsic activity of $\text{Co}_3\text{O}_4/\text{Ti}_2\text{AlC}$ and $\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$ catalysts based on their turnover frequency (TOF, Table 1). The $\text{Co}_3\text{O}_4/\text{Ti}_2\text{AlC}$ catalyst shows lower CO uptake, indicating that it contains fewer surface active sites due to its significant larger particle size. Nevertheless, $\text{Co}_3\text{O}_4/\text{Ti}_2\text{AlC}$ shows slightly lower

![Figure 4. CO$_2$ and butane conversion during temperature screening of the 5 wt% catalysts. Reaction conditions: 100 mg of catalyst, CO$_2$/C$_4$H$_{10}=4:1$, total flow 20 mL·min$^{-1}$, atmospheric pressure.](image)

![Figure 5. CO$_2$ and butane conversion during stability test of the 5 wt% catalysts. Reaction conditions: 650 °C, 100 mg of catalyst, CO$_2$/C$_4$H$_{10}=4:1$, total flow 20 mL·min$^{-1}$, atmospheric pressure.](image)

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>CO uptake [μmol CO$<em>2$ g$</em>{catalyst}$$^{-1}$]</th>
<th>TOF CO$<em>2$ [mol$</em>{converted}$ cobalt site$^{-1}$ min$^{-1}$]</th>
<th>TOF butane [mol$_{converted}$ cobalt site$^{-1}$ min$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Co}_3\text{O}_4/\text{Ti}_2\text{AlC}$</td>
<td>5.4</td>
<td>76.0</td>
<td>14.8</td>
</tr>
<tr>
<td>$\text{Co}_3\text{O}_4/\text{Al}_2\text{O}_3$</td>
<td>8.5</td>
<td>104.8</td>
<td>21.2</td>
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TOF values, indicating that it is intrinsically less active than CoOx/Al2O3.

Additionally, we compared Ti3AlC MAX phase to commercial TiC and α-Al2O3 as cobalt oxide supports. During the temperature screening tests (Figure S10), the CoOx/TiC catalyst (SBET = 28 m²·g⁻¹) showed significant conversion only at 650°C. During the stability test at 650°C (Figure S11), TiC decomposed to rutile TiO2 and graphite (Figure S12a), clogging the reactor after 2 h under stream. This demonstrates the enhanced stability of Ti3AlC ternary carbide compared to a traditional carbide under dry reforming conditions. CoOx/α-Al2O3 (SBET = 8 m²·g⁻¹) already showed activity at 450°C, but the presence of coke clogged the reactor. The XRD pattern of the spent catalyst confirms the formation of graphite oxide (Figure S12b). Similarly to the γ-Al2O3-based catalyst, CoOx/α-Al2O3 shows strong deactivation during the stability test at 650°C (Figure S11). Even though it shows higher conversion than CoOx/Ti3AlC, the carbon balance was only 85–89%, indicating its higher tendency to form coke.

Further insight into the workings of these catalysts was gained from X-ray photoelectron spectroscopy (XPS) studies of pristine and spent catalyst samples. The spectra of the pure Ti3AlC show the characteristic peaks of the MAX phase structure (Figure 6): the Ti 2p spectrum exhibits the Ti–C bond peak at 453.6 eV, and the Al 2p spectrum shows the Al–Ti bond peak at 71.6 eV.[43] The presence of oxygen on the surface of the MAX phase is also detected (Ti–O and Al–O peaks), showing that the MAX phase contains an oxide layer on the surface, in agreement with previous observations.[44,45]

During the calcination of the CoOx/Ti3AlC catalyst, the surface of the MAX phase changes (Figure 6). The absence of characteristic Ti–C and Al–Ti peaks indicates that the surface is partially oxidized during the preparation of the catalyst. The C 1s spectrum affirms these findings (Figure S13). The Ti–C peak that appears at 281.1 eV in the Ti3AlC sample is not visible after impregnation and calcination. This surface restructuring was observed by Frodelius et al., who studied the oxidation behavior of Ti3AlC at 500°C.[46] They showed that at this temperature, Al diffuses out of the crystal lattice and migrates to the surface. Oxygen from the atmosphere then reacts with the Al, forming amorphous Al2O3. In parallel, the Al vacancies enable oxygen inward diffusion, which promotes the formation of TiO2C. The transport of Al to the surface is much faster than that of Ti atoms. This is because the Ti–Al bond is of metallic character, whereas the transport of Ti atoms is limited by the Ti–C covalent bond.[47] Surface TiO2C and Al–TiO2C species were detected for the CoOx/Ti3AlC catalyst (Figure 6).

The Co 2p spectrum is characterized by the doublet of two spin-orbit components, Co 2p1/2 and Co 2p3/2. Literature reported that CoOx shows its main peak at 779.6 eV (Co 2p1/2), with different satellite signals originating from Co3+ and Co2+ species.[48] Figure 7 shows that CoOx species have different binding energies depending on the support. The main peak appears at 779.6, 780, and 782 eV for CoOx/Ti3AlC, CoOx/TiO2, and CoOx/Al2O3, respectively. The Co 2p spectrum of CoOx/Ti3AlC catalyst shows the main Co 2p peak at lower binding energy compared to the other catalysts. Moreover, it has an additional contribution at 777.5 eV, showing the metallic character of the surface of this sample, induced by the Ti3AlC.

![Figure 6. XPS spectra of the Ti3AlC MAX phase support, fresh CoOx/Ti3AlC catalyst and CoOx/Ti3AlC after stability test (spent, 650°C).](image)

![Figure 7. Co 2p XPS spectra of the fresh CoOx/Ti3AlC, CoOx/Al2O3, and CoOx/TiO2 catalysts.](image)
support. In addition, the intensity ratio between cobalt and support particles (I_{Co}/I_{Al} or I_{Co}/I_{Ti}) is the largest among the three catalysts (see Table S3). As all three catalysts have the same cobalt oxide loading, the smaller surface area of the MAX phase results in a poor particle dispersion.

Following the stability test at 650 °C, the Co 2p spectra of Co_{3}O_{4}/Ti_{x}AlC (Figure S14) shift to higher binding energies (for instance, the main Co 2p_{3/2} peak shifts to 781.1 eV). This indicates that the Ti_{x}AlC surface oxidizes under reaction conditions. A thicker layer of oxide between the Co_{3}O_{4} and the bulk Ti_{x}AlC reduces the metallic character of the sample, shifting the Co 2p spectrum to higher binding energies. In addition, the Ti 2p and Al 2p spectra show lines corresponding to the Ti–O and Al–O bonds, with no contributions of TiO_{2}, and Al–TiO_{x}C_{y} (Figure 6). This indicates the total oxidation of the Ti_{x}AlC surface during the reaction, probably due to the prolonged exposure of the catalyst to CO_{2} at 650 °C. Studies on the oxidation of Ti_{x}AlC at 1200 °C showed that a continuous inner layer of α-Al_{2}O_{3} and a discontinuous outer layer of TiO_{2} (rutile) form on the surface. These layers are responsible for the "high thermal stability" of Ti_{x}AlC, because they protect the rest of the material that is not oxidized. The XRD pattern of the spent sample (Figure S15) has the characteristic peaks of the MAX phase, indicating that the bulk of the Ti_{x}AlC remains stable.

As the Ti_{x}AlC surface composition changes during reaction, the supported Co_{3}O_{4} is also affected. HAADF-STEM images of the spent catalyst show a change in morphology and absence of voids (Figure S16). Co_{3}O_{4} particles migrate over the support under reaction, resulting in a very heterogeneous surface in terms of size and morphology. Large and small Co_{3}O_{4} particles are observed, but their irregular shape makes it difficult to determine the particle size distribution. Carbon nanotubes are also observed, covering some cobalt oxide particles (Figure S17). These structural changes did not significantly affect the number of active sites, as its activity remained stable over time (Figure 5). Figure 8 summarizes the compositional and structural changes on the surface of the Co_{3}O_{4}/Ti_{x}AlC catalyst during calcination and reaction.

Conclusions

Overall, this study shows the importance of the support in dry reforming catalysis. MAX phases are promising supports, as they show reasonable activity and high stability. The low surface area of Ti_{x}AlC influences the size and morphology of Co_{3}O_{4}, forming large hollow Co_{3}O_{4} particles. A charge transfer effect is observed in the shift of the Co 2p spectrum to lower binding energies, probably caused by the conductive and metallic properties of the support. While this catalyst is less active than Co_{3}O_{4}/γ-Al_{2}O_{3}, its conversion is remarkable given the difference in particle size and surface area. In addition, it is less prone to coking, making the catalyst more stable. This is an advantage compared to using acidic materials such as γ-alumina as the support, where their acidic properties favor the formation of undesirable coke. Furthermore, compared to titania and titanium carbide, the MAX phase support is more stable. It does not deactivate by sintering or thermal decomposition. Thus, we conclude that MAX phases are promising supports for dry reforming reactions, thanks to their thermal stability and their electronic and acid-base properties. Nevertheless, the intrinsic activity of MAX phases is limited by the low number of active sites on the surface. Increasing the number of cobalt oxide active sites, which can be done by decreasing the particle size, would increase the performance of this catalyst. We hope that this exciting first account of using MAX phases as catalyst supports in CO_{2} conversion reactions may encourage more researchers to apply these fascinating materials in catalysis.

Experimental Section

Materials and instrumentation: Powder XRD patterns were recorded on a MiniFlex II diffractometer using CuKα radiation. The X-ray tube was operated at 30 kV and 15 mA. Measurements were recorded at an angle (2θ) range of 5–90° with a scanning speed of 2°·min^{-1}. N_{2} adsorption-desorption isotherms were measured on a Thermo Scientific Surfer instrument at 77 K. The samples were pre-treated in vacuum for 12 h at 200 °C. XPS was performed using
a K-Alpha spectrometer from Thermo-Scientific. AI–K radiation (1486.6 eV), monochromatized by a twin crystal monochromator was used. This resulted in a focused X-ray spot (400 μm diameter), at 3 mA × 12 kV when charge compensation was achieved with the system flood gun, which provides low energy electrons and low energy argon ions from a single source. The alpha hemispherical analyzer was operated in constant energy mode with survey scan pass energies of 200 eV to measure the whole energy band, and 50 eV in a narrow scan to selectively measure particular elements. The binding energies (BE) were referenced to the C 1s line at 284.6 eV, with an accuracy of ±0.2 eV. The intensity estimation was done by calculating each peak integral, subtracting the S-shaped a Lorentzian (30 %) and Gaussian (70 %) lines.

TEM characterization of the samples was performed using a double Cs aberration-corrected FEI Titan™ Themis 60–300 microscope. This equipment was operated at 200 kV and it is equipped with a monochromator, a X-FEG gun and a high efficiency XEDS Chem-STEM, which consists of 4-windowless SDD detectors. HR-STEM imaging was performed using a HAADF detector with a camera length of 11.5 cm. The HAADF-STEM technique is sensitive to the atomic number of the elements and it makes possible to distinguish small nanoparticles supported on light supports. Energy-dispersive X-ray spectroscopy mappings were performed using a beam current of 200 pA and a dwell time per pixel of 128 μs. To improve the visual quality of the elemental maps, these were filtered using a Gaussian blur of 0.8 using Velox software. TPR measurements were performed using a TPDRO Series 1100 from Thermo Scientific. 25 mg of catalyst was placed on a quartz wool plug in a tubular quartz reactor with an inner diameter of 4 mm. Each sample was heated from room temperature to 1000 °C (heating rate 5 °C·min⁻¹) under a flow of 5 % hydrogen in nitrogen mixture (20 mL·min⁻¹). The amount of hydrogen consumed by the sample was detected by a thermal conductivity detector (TCD). TGA was performed using a NETZSCH Jupiter® STA 449F3 instrument. The measurements were done under air (20 mL·min⁻¹) at 50 °C and then calcined under air at 450 °C for 4 h (heating rate 4 °C·min⁻¹), except for the TiC-based catalyst that was heated under N₂ (150 mL·min⁻¹) up to 300 °C. Ti₃AlC was prepared by mixing elemental powders of Ti, Al, and TiC, and heating to 1350 °C under a pressure of up to 50 MPa, following a published procedure.[34]

**Procedure for catalytic testing:** The catalysts were tested in the DRB reaction in an automated six-flow parallel reactor system. Typically, 100 mg of catalyst was placed in the reactor in form of pellets (1–0.71 mm pellet size). A stoichiometric ratio of reactants (CO₂/C₃H₈ = 4:1) and atmospheric pressure were used for all tests. The feed gas was diluted with 80 % of Ar and a total flow rate of 20 mL·min⁻¹ was passed through the reactors. We ran two types of catalytic tests: temperature screening between 450 and 650 °C, and stability test at 650 °C. The reactants and products were analyzed with a GC (Interscience microGC, with flame ionization detector and TCD).

Conversion, selectivity, and TOF were calculated using Equations (1)–(3):

\[
\text{Conversion reactant (\%)} = \frac{[\text{reactant}]_{\text{in}} - [\text{reactant}]_{\text{out}}}{[\text{reactant}]_{\text{in}}} \times 100
\]

\[
\text{Selectivity product A (\%)} = \frac{[\text{product A}]_{\text{out}}}{\sum [\text{products}]_{\text{out}}} \times 100
\]

\[
\text{TOF reactant (mol}_{\text{reactant converted}}\text{ site}^{-1}\cdot\text{min}^{-1}) = \frac{\text{flow reactant - conversion reactant}}{\text{CO uptake - weight catalyst}}
\]

**Acknowledgements**

We thank the Netherlands Organization for Scientific Research (NWO) for the grant "Developing novel catalytic materials for converting CO₂, methane and ethane to high-value chemicals in a hybrid plasma-catalytic reactor" (China.15.119). We also acknowledge financial support by MINECO (Spain) through projects MAT2017-86992-R and MAT2016-80285-P.

**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords:** butane dry reforming · cobalt oxide · CO₂ conversion · MAX phases · Ti₃AlC support
