Molybdenum Oxide Supported on Ti$_3$AlC$_2$ is an Active Reverse Water–Gas Shift Catalyst

Maria Ronda-Lloret, Liuqingqing Yang, Michelle Hammerton, Vijaykumar S. Marakatti, Moniek Tromp, Zdeněk Sofer, Antonio Sepulveda-Escribano, Enrique V. Ramos-Fernandez, Juan Jose Delgado, Gadi Rothenberg, Tomas Ramirez Reina, and N. Raveendran Shiju*

Cite This: ACS Sustainable Chem. Eng. 2021, 9, 4957−4966

ABSTRACT: MAX phases are layered ternary carbides or nitrides that are attractive for catalysis applications due to their unusual set of properties. They show high thermal stability like ceramics, but they are also tough, ductile, and good conductors of heat and electricity like metals. Here, we study the potential of the Ti$_3$AlC$_2$ MAX phase as a support for molybdenum oxide for the reverse water–gas shift (RWGS) reaction, comparing this new catalyst to more traditional materials. The catalyst showed higher turnover frequency values than MoO$_3$/TiO$_2$ and MoO$_3$/Al$_2$O$_3$ catalysts, due to the outstanding electronic properties of the Ti$_3$AlC$_2$ support. We observed a charge transfer effect from the electronically rich Ti$_3$AlC$_2$ MAX phase to the catalyst surface, which in turn enhances the reducibility of MoO$_3$ species during reaction. The redox properties of the MoO$_3$/Ti$_3$AlC$_2$ catalyst improve its RWGS intrinsic activity compared to TiO$_2$- and Al$_2$O$_3$-based catalysts.

KEYWORDS: CO$_2$ hydrogenation, MAX phases, RWGS, syn gas, molybdenum

INTRODUCTION

There is a global interest on reducing anthropogenic CO$_2$ emissions into the atmosphere.$^{1,2}$ The main sources of CO$_2$ are power generation and manufacturing, which emitted 12.4 and 3.9 Gt of CO$_2$ in 2015.$^{3,4}$ However, CO$_2$ is a valuable C$_1$ feedstock that should not be thrown away. After CO$_2$ capture, either from the atmosphere or from industrial flue gases, it should be efficiently converted into high value-added products via catalytic processes.$^{5-8}$

The reverse water−gas shift (RWGS) reaction (eq 1) using renewable hydrogen is a sustainable way for converting CO$_2$.

$$\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \quad \Delta H_{25^\circ \text{C}} = -165.0 \text{ kJ mol}^{-1}$$ (3)

Traditionally, RWGS catalysts are based on Cu, Pt, and Rh nanoparticles supported on metal oxides (Al$_2$O$_3$, TiO$_2$, and CeO$_2$, among others).$^{9,14,15}$ Molybdenum is more abundant and cheaper than precious metals, increasing the potential for the large-scale industrial application of Mo-based catalysts. While previous work only focused on its promoting effect,$^{16-20}$ we are interested in molybdenum oxide as an active phase itself due to its redox properties.$^{21,22}$ The oxygen vacancies created when reducing MoO$_3$ will affect the reaction performance, whether it takes place via the redox mechanism (where CO$_2$ adsorbs and dissociates on the reduced sites previously created by H$_2$) or via the associative pathway (where oxygen vacancies can stabilize adsorbed carbon-containing intermediates), see Figure 1.$^{10,23,24}$

Another important factor is the choice of support. Although typically inert, supports can enhance the reaction performance...
by increasing the active sites’ dispersion, facilitating charge transfer, and modifying the morphology of the supported particles. More importantly, the support can prevent catalyst deactivation and boost the industrial application of high-temperature reactions. Here, we explored a new type of supports, MAX phases, and their application in catalysis. MAX phases (M_{n+1}AX_n) are a group of layered ternary carbides or nitrides, where M is an early transition metal, A is an element mostly from groups 13 and 14, X is carbon or nitrogen, and n = 1, 2, or 3. MAX phases stand out by their unusual set of properties. They are stiff and high-temperature shock resistant like ceramics, but they are also tough, ductile, and good conductors of heat and electricity like metals. They are typically used in mechanical and thermal applications, such as high-temperature structural components and protective coatings. Their potential as catalysts has recently emerged, as we reported the activity and improved selectivity of the Ti₃AlC₂ MAX phase during butane oxidative dehydrogenation. We also showed that MAX phases are promising supports for CO₂ conversion reactions. The thermal stability and acid–base properties of the Ti₃AlC₂ MAX phase increased the stability and coking resistance of a Co₄O₃/Ti₃AlC₂ catalyst during dry reforming of butane. Elsewhere, Trandafer et al. recently showed the potential of Pd/Ti₃SiC₂ as a chemo-selective catalyst in the hydrogenation of functionalized nitro derivatives.

Here, we use for the first time the Ti₃AlC₂ MAX phase as a support for molybdenum oxide RWGS catalysts. We study the properties and the RWGS activity of the MoO₃/Ti₃AlC₂ catalyst and compare it to titania and alumina-based catalysts.

**EXPERIMENTAL SECTION**

**Materials and Instrumentation.** X-ray diffraction (XRD) patterns were recorded on a MiniFlex II X-ray diffractometer, described previously by Ronda-Lloret et al. X-ray photoelectron spectroscopy (XPS) was performed using a Kα spectrometer from Thermo Scientific (Al–K radiation), with a source of electrons and ions for automated charge balancing. The binding energies were referenced to the C 1s line at 284.6 eV, with an accuracy of ±0.2 eV (a detailed description of the analysis procedure is published elsewhere).

Thermogravimetric analysis (TGA) was carried out using an NETZSCH Jupiter STA 449F3 instrument, under air (20 mL·min⁻¹, O₂:N₂ mixture) between 30 and 1000 °C.

Scanning transmission electron microscopy (STEM) spectra combined with high-angle annular dark field (HAADF) images were obtained using a double Cs aberration-corrected FEI Titan Themis 60–300 microscope (operated at 200 kV).

We performed X-ray absorption spectroscopy (XAS) using the SuperXAS beamline of the SLS Synchrotron at the PSI (Switzerland). We prepared the samples by mixing with cellulose and pressing into pellets of approximately one absorption length in thickness. We performed the measurements at the Mo K-edge (20,000 eV) in the QEXAFS mode using an oscillating monochromator and collected spectra with a fluorescence detector (sensor silicon drift detector) and with a transmission detector (ionization chambers) simultaneously. A spectrum was recorded every second and averaged over 1 min to improve the signal-to-noise ratio. We calibrated with respect to the edge position of a metal foil measured simultaneously and normalized spectra using Python-based graphical interface ProQEXAFS software. The edge position (E₀) of each sample spectrum was set to the most intense peak of the first derivative (see Figure S7). Further processing of X-ray absorption near-edge spectroscopy (XANES) and extended X-ray absorption fine structure (EXAFS) was carried out using the Demeter software package (0.9.25, using Iffefit 1.2.12). We used Athena for background subtraction of long-range oscillations and linear combination fitting (LCF) of supported catalyst spectra using Python-based graphical interface ProQEXAFS software. CO chemisorption analyses were performed with a Micromeritics Pulses Chemisorb 2705 apparatus. Before the analysis, the samples were pretreated under a helium gas flow of 80 mL·min⁻¹ at 350 °C for 3 h and then reduced at 500 °C for 6 h under pure hydrogen. More details on the analysis procedure can be found in Ronda-Lloret et al.

![Scheme of the formation of oxygen vacancies on MoO₃ particles during RWGS, and its ability to dissociate CO₂ via the redox pathway and/or to stabilize carbon-containing species (indicated by R) via the associative pathway.](image-url)
impregnation, using ammonium molybdate tetrahydrate as a precursor. γ-Al2O3 and anatase TiO2 were purchased from commercial sources. Ti3AlC2 was prepared by mixing elemental powders of Ti, Al, and graphite, followed by heating at 1450 °C under argon. Samples of a molybdenum-containing MAX phase, Mo7TiAlC2, and bulk MoO3 were also tested as reference materials (see the Experimental Section for details).

Characterization of the Fresh Catalysts. The XRD pattern of the fresh MoO3/Ti3AlC2 catalyst shows the characteristic peaks of the Ti3AlC2 MAX phase structure (Figure 2), indicating that the bulk of the support remains stable after calcination. Anatase and rutile TiO2 peaks are also present at 2θ = 25.7 and 27.4°, indicating a slight oxidation of Ti3AlC2. The characteristic peaks of MoO3 are also visible at 2θ = 12.8 and 23.5°. The pattern of MoO3/TiO2 only shows broad peaks of anatase TiO2 at 2θ = 25.4, 38.2, 48.1, 54.8, 62.7, 70.0, 75.4, and 82.9°. Similarly, the pattern of MoO3/Al2O3 only shows the peaks of γ-Al2O3 at 2θ = 37.8, 45.8, 60.7, and 67.0° (Figure S1). The absence of MoO3 diffraction peaks indicates that molybdenum particles are small and well-dispersed over the oxide supports.

We studied the surface composition of the fresh catalysts with XPS. The Ti 2p and Al 2p spectra of the MoO3/Ti3AlC2 catalyst only show the Ti—O and the Al—O bonds at 458.8 eV (Ti 2p3/2) and 74.3 eV (Al 2p3/2), respectively (Figure 3). The distinctive peaks of the Ti3AlC2 structure (Ti—C bond at 454 eV (Ti 2p3/2) and Al—Ti bond at 72 eV (Al 2p3/2)) are absent. This indicates that the Ti3AlC2 surface completely oxidizes to titania and alumina under our calcination conditions (i.e., under air at 350 °C for 4 h). The Ti—O and Al—O peaks of MoO3/Ti3AlC2 shift to lower binding energies compared to MoO3/TiO2 and MoO3/Al2O3. This indicates a charge transfer effect from the bulk MAX phase to the surface oxide layer, enriching the surface with electrons.

The XRD patterns of the MoO3/Ti3AlC2 catalyst and the Ti3AlC2 MAX phase used as a support.

Figure 2. XRD patterns of the MoO3/Ti3AlC2 catalyst and the Ti3AlC2 MAX phase used as a support.

We compared the properties and activity in RWGS of MoO3-based catalysts, using the Ti3AlC2 MAX phase, γ-Al2O3, and TiO2 as supports. The catalysts, each containing 10 wt % on Mo metal basis, were prepared by wet impregnation, using ammonium molybdate tetrahydrate as a precursor. γ-Al2O3 and anatase TiO2 were purchased from commercial sources. Ti3AlC2 was prepared by mixing elemental powders of Ti, Al, and graphite, followed by heating at 1450 °C under argon. Samples of a molybdenum-containing MAX phase, Mo7TiAlC2, and bulk MoO3 were also tested as reference materials (see the Experimental Section for details).

Characterization of the Fresh Catalysts. The XRD pattern of the fresh MoO3/Ti3AlC2 catalyst shows the characteristic peaks of the Ti3AlC2 MAX phase structure (Figure 2), indicating that the bulk of the support remains stable after calcination. Anatase and rutile TiO2 peaks are also present at 2θ = 25.7 and 27.4°, indicating a slight oxidation of Ti3AlC2. The characteristic peaks of MoO3 are also visible at 2θ = 12.8 and 23.5°. The pattern of MoO3/TiO2 only shows broad peaks of anatase TiO2 at 2θ = 25.4, 38.2, 48.1, 54.8, 62.7, 70.0, 75.4, and 82.9°. Similarly, the pattern of MoO3/Al2O3 only shows the peaks of γ-Al2O3 at 2θ = 37.8, 45.8, 60.7, and 67.0° (Figure S1). The absence of MoO3 diffraction peaks indicates that molybdenum particles are small and well-dispersed over the oxide supports.

We studied the surface composition of the fresh catalysts with XPS. The Ti 2p and Al 2p spectra of the MoO3/Ti3AlC2 catalyst only show the Ti—O and the Al—O bonds at 458.8 eV (Ti 2p3/2) and 74.3 eV (Al 2p3/2), respectively (Figure 3). The distinctive peaks of the Ti3AlC2 structure (Ti—C bond at 454 eV (Ti 2p3/2) and Al—Ti bond at 72 eV (Al 2p3/2)) are absent. This indicates that the Ti3AlC2 surface completely oxidizes to titania and alumina under our calcination conditions (i.e., under air at 350 °C for 4 h). The Ti—O and Al—O peaks of MoO3/Ti3AlC2 shift to lower binding energies compared to MoO3/TiO2 and MoO3/Al2O3. This indicates a charge transfer effect from the bulk MAX phase to the surface oxide layer, enriching the surface with electrons.
in this compound (Ti/Al ratio is 3 to 1). The excess of titanium on the MAX phase surface is also confirmed by the \( \frac{I_{\text{Ti}}}{I_{\text{Al}}} \) intensity ratio obtained from XPS (Table S1). Previous work showed that during oxidation below 700 °C, Ti₃AlC₂ predominantly converts to titania rather than to alumina. While the three catalysts have the same metal loading, the Mo and support intensity ratio (\( \frac{I_{\text{Mo}}}{I_{\text{Ti}}} \) or \( \frac{I_{\text{Mo}}}{I_{\text{Al}}} \)) is the largest for the MAX phase-based catalyst (Table S1). This indicates that this catalyst has the largest Mo-containing particles on the surface.

HAADF–STEM imaging showed that MoO₃ is predominantly dispersed in the form of rods when deposited on Ti₃AlC₂ (Figure 4, see also Figures S3 and S4 in the Supporting Information). Some rods are in contact with the support, while others are “free” (i.e., unsupported). These rods are 480 ± 138 nm long and 88 ± 11 nm wide. The large size of MoO₃ particles when supported on Ti₃AlC₂ results from the low surface area of this support (ca. 1 m²/g). In agreement with XRD and XPS results, we see that the MoO₃ particles are very small and highly dispersed when supported on TiO₂ (average particle size: 0.42 nm, \( \sigma = 0.11 \) nm) and γ-Al₂O₃ (average particle size: 0.67 nm, \( \sigma = 0.19 \) nm, Figure S5). The MoO₃/TiO₂ and MoO₃/Al₂O₃ catalysts are mesoporous, with a BET surface area of 208 m²·g⁻¹ and 145 m²·g⁻¹, respectively (Figure S6 and Table S2).

We then studied the local structure of the molybdenum on each support using Mo K-edge XANES and EXAFS spectroscopy. We also measured MoO₃ nanoparticles (MoO₃-NPs) and bulk α-MoO₃ references for comparison. In the XANES spectra (Figure 5a), all catalysts show the edge position at 20016.4 eV, characteristic of Mo⁶⁺ (1s → 5p, measured at the maximum of the second peak of the first derivative, see Figure S7), and a triple peak feature above the edge. The distinct pre-edge corresponds to the quadrupole 1s→4d transition, indicating a distorted octahedral environment. The triple peak feature above the edge in the XANES is slightly different for each catalyst. The MoO₃/Ti₃AlC₂ spectrum is similar to that of bulk α-MoO₃, whereas the features of the MoO₃/Al₂O₃ spectrum are dampened similarly to that of MoO₃-NPs. MoO₃/TiO₂ shows the largest discrepancy from the reference spectra, with a more intense central peak compared to the first and third features. These differences can be partially explained by differences in nanoparticle size and shape, which affect the ratio of surface sites to bulk sites, as well as by particle–support interactions.

We used the MoO₃ nanoparticles and the bulk α-MoO₃ samples as references for LCF (Figure 5b) to get an indication of the relative amounts of surface versus internal Mo sites in the studied catalysts. The absolute numbers obtained from the LCF cannot be directly related to the number of surface versus bulk sites, since (i) we only have two reference samples and (ii) the NP reference consists of a combination of surface and...
single site species, which are not detected with other Mo atoms present in amorphous compounds and/or present as XAS measures all Mo atoms in the sample. This means that techniques such as XRD and HAADF

Figure 5b shows that the MoO3/Al2O3 catalyst can be forming rods or other species (amorphous and/or single site species). The contribution from bulk α-MoO3, indicating that MoO3 has bulk-like properties, interacting only weakly with the support. The MoO3/TiO2 spectrum exhibits dampened oscillations compared to the other spectra. This could result from destructive interference by an additional, non-MoO3, contribution to the spectrum or a different coordination geometry in this catalyst. From the EXAFS fitting (Figure S10), we can see that the supported catalysts can be fitted in the same way as α-MoO3, using three doubly degenerate O paths at three different distances from Mo (Tables S4–S6). This suggests that the {MoO6} octahedra are distorted in the supported MoO3 catalysts. The MoO3/TiO2 spectrum was fitted with an additional Ti path at 2.76 Å, giving rise to the destructive interference that dampens the EXAFS oscillations and indicating that there is a close metal–support interaction. More details on the EXAFS fitting are reported in the Supporting Information

**Catalytic Tests.** We then tested the catalysts in the RWGS reaction. A total of 200 mg of catalyst was placed in a vertical fixed bed reactor. As high H2:CO2 ratios improve CO2 conversion,54,55 we set the H2:CO2 ratio to 4:1. We ran temperature-screening tests between 400–750 °C (100 mL min−1 total flow) and long-term stability tests at 550 °C for 48 h (50 mL min−1 total flow).

Control experiments showed that Ti3AlC2 alone is active only above 700 °C, converting between 10–18% of CO2 (Figure S11). A Mo2TiAlC2 MAX phase, which contains molybdenum in the layered MAX phase structure,56 showed no activity within the entire temperature range. This confirms that a metal or metal oxide available on the surface as active sites are required to improve CO2 activation in RWGS. The prereduction of a MoO3/Al2O3 catalyst at 750 °C did not improve CO2 conversion and CO selectivity compared to the unreduced catalyst (Figure S12). Therefore, we focused on the catalytic tests of the pristine catalysts after calcination, without prereduction. This is an interesting advantage of our MAX phase-supported catalyst, as avoiding the pretreatment step results in significant process savings in a real industrial application.

The temperature-screening tests show that the MoO3/Ti3AlC2 catalyst is already active at 450 °C, reaching 50% conversion at 750 °C (Figure S13). Despite the low surface area and large particle size of this catalyst, its conversion is similar to MoO3/Al2O3 and MoO3/TiO2. All catalysts were highly selective to CO above 550 °C. Since the three catalysts show a similar conversion and selectivity, their CO production rate values are also similar (Table S7). Due to its low surface area, the Ti3AlC2-based catalyst has fewer available active sites compared to the other catalysts, as quantified by CO chemisorption (Table S8). Thus, we compared the catalysts in terms of their intrinsic activity, using their TOF (Figure 6a). MoO3/Ti3AlC2 shows higher TOF values from 450 °C

Figure 5. (a) Mo K-edge XANES spectra of the supported catalysts and reference structures. (b) Summary of the LCF analysis of the supported catalysts using reference spectra. The quality of the fit is indicated by the R-factor and reduced χ² value.
onward, indicating that it is intrinsically more active than MoO$_3$/Al$_2$O$_3$ and MoO$_3$/TiO$_2$.

![Figure 6](image)

Figure 6. TOF values of the catalysts during (a) temperature-screening tests (reaction conditions: 200 mg catalyst, H$_2$:CO$_2$ ratio = 4:1, 100 mL·min$^{-1}$ total flow, WHSV = 30,000 mL·g$^{-1}$·h$^{-1}$) and (b) stability tests (reaction conditions: 550 °C, 200 mg catalyst, H$_2$:CO$_2$ ratio = 4:1, 50 mL·min$^{-1}$ total flow, WHSV = 15,000 mL·g$^{-1}$·h$^{-1}$).

We also studied the long-term stability of the catalysts at a WHSV of 15,000 mL·g$^{-1}$·h$^{-1}$, which is a relatively high space velocity that would result in a compact RWGS reactor, potentially reducing the capital costs of a continuous CO$_2$ conversion unit. In addition, the MoO$_3$/Ti$_3$AlC$_2$ catalyst shows higher CO$_2$ conversion with considerable CO selectivity at lower space velocity (Figure S14). To be far from equilibrium conditions and study the potential of the MAX phase catalyst in low-temperature RWGS, we performed the stability tests at 550 °C. The MoO$_3$/Ti$_3$AlC$_2$ catalyst is stable over time and it converts 20% CO$_2$ (Figure S15). MoO$_3$/TiO$_2$ and MoO$_3$/Al$_2$O$_3$ catalysts give 20% and 30% CO$_2$ conversion, respectively. The increase in conversion at the start of the reaction might be related to the reduction of the MoO$_3$ species upon exposure to the hydrogen-rich reaction mixture (4H$_2$:1CO$_2$). Under these conditions, MoO$_3$/Ti$_3$AlC$_2$ showed a lower CO production rate (0.01 mol CO produced·g$^{-1}$·min$^{-1}$) than MoO$_3$/TiO$_2$ and MoO$_3$/Al$_2$O$_3$ catalysts (0.02 mol CO produced·g$^{-1}$·min$^{-1}$), see Table S9. When comparing their intrinsic activity by means of TOF (Figure 6b), MoO$_3$/Ti$_3$AlC$_2$ stands out as the most active catalyst. It converts 18 mol CO$_2$·site$^{-1}$·min$^{-1}$, while MoO$_3$/Al$_2$O$_3$ and MoO$_3$/TiO$_2$ convert 10 and 7 mol CO$_2$·site$^{-1}$·min$^{-1}$, respectively. Control experiments showed that a bulk MoO$_3$ sample is significantly less active than MoO$_3$/Ti$_3$AlC$_2$ (Figure S16). This indicates that the activity of the Mo sites is enhanced in the MoO$_3$/Ti$_3$AlC$_2$ catalyst due to metal-support interactions and/or the exposure of a particular set of planes when MoO$_3$ grows as rods.57,58

In the stability tests, CO selectivity followed the order MoO$_3$/TiO$_2$ (70–100%) > MoO$_3$/Al$_2$O$_3$ (60–80%) > MoO$_3$/Ti$_3$AlC$_2$ (60–65%), indicating the formation of side products (Figure S15). Methane was not detected. TGA analysis (Figure S17) of the spent catalysts shows the absence of carbon deposits, indicating the inhibition of coking reactions. We hypothesize that alcohols are produced as side products, as previous work reported the formation of alcohols from CO hydrogenation and CH$_4$ oxidation reactions when using MoO$_3$-based catalysts under similar conditions.59–62 In addition, the CO selectivity profiles oscillate with time (Figure S15). We hypothesize that this is due to changes in the molybdenum oxidation state during reaction. Depending on the balance of reduced/oxidized states, CO hydrogenation to alcohols can also occur, thus decreasing CO selectivity. The decrease in CO concentration in the reaction mixture might shift the equilibrium toward CO$_2$ consumption, giving higher CO$_2$ conversion with lower CO selectivity. To understand the working of the catalysts better, we also characterized them after the reaction. The XRD patterns of the spent catalysts show that the Ti$_3$AlC$_2$ MAX phase is stable under reaction conditions (Figure S1). As expected, the Al$_2$O$_3$ and TiO$_2$ supports were also stable (Figure S1).

In the LCF analysis of the MoO$_3$/Ti$_3$AlC$_2$ sample XANES spectrum (Figure 5), the percentage of bulk α-MoO$_3$ increases after stability testing. The EXAFS spectrum of the spent sample is also more similar to bulk α-MoO$_3$ compared to the fresh sample (Figure S9). This reflects a change in the molybdenum oxide particle morphology that increases the volume-to-surface ratio. HAADF–STEM images of the spent catalyst confirm that the size and morphology of MoO$_3$ particles change during the reaction, from large rods to agglomerates (Figures S17 and S18). These agglomerates are smaller than the rods, but their varied shape does not allow us to calculate the particle size. The nanoparticle sizes on MoO$_3$/TiO$_2$ (average particle size: 0.51 nm, σ = 0.18 nm) and MoO$_3$/Al$_2$O$_3$ (average particle size: 0.70 nm, σ = 0.15 nm) catalysts do not significantly change during the reaction compared to the fresh samples (Figure S19).

The Mo 3d XPS spectra of the spent catalysts show the reduction of MoO$_3$ species during the reaction (Figure 7). Interestingly, MoO$_3$/Ti$_3$AlC$_2$ shows MoO$_2$ (Mo$^{4+}$), MoO$_{11}$ (Mo$^{5+}$), and MoO$_3$ (Mo$^{6+}$) species on the surface, while the other two catalysts only contain MoO$_3$ and MoO$_2$.48,63 The percentage of reduced species is significantly higher on the MoO$_3$/Ti$_3$AlC$_2$ catalyst surface (Table 1), indicating that this catalyst is reduced more during the reaction. The higher
Table 1. Atomic Percentage of MoO$_3$ (Mo$^{4+}$), Mo$_4$O$_{11}$ (Mo$^{5+}$), and MoO$_3$ (Mo$^{6+}$) Species on the Spent Catalyst Surface, based on Mo 3d XPS

<table>
<thead>
<tr>
<th>catalyst</th>
<th>atomic percentage on the surface (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoO$_3$/Ti$_3$AlC$_2$ (spent)</td>
<td>24 41 35</td>
</tr>
<tr>
<td>MoO$_3$/Al$_2$O$_3$ (spent)</td>
<td>50 50 0</td>
</tr>
<tr>
<td>MoO$_3$/TiO$_2$ (spent)</td>
<td>80 20 0</td>
</tr>
</tbody>
</table>

The activation percentage observed with MoO$_3$/Ti$_3$AlC$_2$ during the stability test (around 8%, Figure S15) can be related to its higher reduction degree under reaction conditions. These results indicate that a more reduced MoO$_3$ surface leads to the formation of more oxygen vacancies, which in turn increases the RWGS activity.

Typically, RWGS results in catalyst reduction, especially in hydrogen-rich mixtures. Hydrogen can remove active oxygen sites from MoO$_3$, creating water and leaving surface oxygen vacancies. The CO$_2$ can regenerate the oxygen vacancies by dissociating on the surface to CO and O. The ability of the catalyst to enhance this redox cycle determines its activity. In this study, MoO$_3$ nanoparticles in close interaction with the support lead to poor redox properties, as seen with the MoO$_3$/TiO$_2$ and MoO$_3$/Al$_2$O$_3$ catalysts. The low surface area of the Ti$_3$AlC$_2$ MAX phase leads to large bulk-like MoO$_3$ rods. Nevertheless, MoO$_3$/Ti$_3$AlC$_2$ is the most intrinsically active catalyst in terms of TOF (Figure 5). We attribute this to the electronically rich Ti$_3$AlC$_2$ and MoO$_3$ facilitating the formation of surface oxygen vacancies that participate in the reaction (see Figure 8). In addition, electronically richer molybdenum sites are ideal for CO$_2$ activation, as the charge transfer from Mo to CO$_2$ antibonding orbitals can weaken the C–O bond, facilitating its reduction to CO.

**CONCLUSIONS**

In this work, we show for the first time the potential of MAX phase-based catalysts for application in CO$_2$ conversion via the RWGS reaction. When supporting molybdenum oxide on the Ti$_3$AlC$_2$ MAX phase, the low surface area of the MAX phase leads to the formation of large MoO$_3$ rods with bulk-like properties. Nevertheless, the presence of electronically rich Ti$_3$AlC$_2$ enhances the redox properties of MoO$_3$ under RWGS conditions, resulting in a highly reduced surface that contains a large amount of oxygen vacancies. The MoO$_3$/TiO$_2$ and MoO$_3$/Al$_2$O$_3$ catalysts contain small and highly dispersed MoO$_3$ nanoparticles, but their close contact with the support inhibits the formation of oxygen vacancies during the reaction. As MoO$_3$/Ti$_3$AlC$_2$ forms more oxygen vacancies under reaction, this catalyst showed the highest intrinsic activity in terms of TOF during the catalytic experiments. The electronically richer Mo sites when supported on MAX phases are ideal activation sites for CO$_2$ via electron transfer to CO$_2$ antibonding orbitals. Such an interaction weakens the C–O bond and favors its reduction to CO. All catalysts are selective to CO, inhibiting the formation of undesired methane and coke. However, unidentified side products, most likely alcohols, also form. This study, which brings more insights into the workings of MAX phase catalysts on CO$_2$ conversion reactions, shows the high potential of MAX phases as catalyst supports.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.0c07881.

Characterization of the fresh and spent catalysts (XRD patterns, XPS, temperature-programmed reduction profiles, nitrogen adsorption–desorption isotherms, CO chemisorption, TGA, and HAADF–STEM images); detailed analysis of XANES and EXAFS spectra; CO$_2$ conversion and CO selectivity values of control samples (Ti$_3$AlC$_2$, Mo$_4$TiAlC$_2$, reduced MoO$_3$/Al$_2$O$_3$, and bulk MoO$_3$) and studied catalysts (10 wt % MoO$_3$/Ti$_3$AlC$_2$, MoO$_3$/TiO$_2$, and MoO$_3$/Al$_2$O$_3$), and CO formation rates of the studied catalysts (PDF).

**AUTHOR INFORMATION**

**Corresponding Author**

N. Raveendran Shiju — Van’t Hoff Institute for Molecular Sciences, University of Amsterdam, Amsterdam 1090 GD, The Netherlands; orcid.org/0000-0001-7943-5864; Email: n.r.shiju@uva.nl

**Authors**

Maria Ronda-Lloret — Van’t Hoff Institute for Molecular Sciences, University of Amsterdam, Amsterdam 1090 GD, The Netherlands

Liuqingqing Yang — Department of Chemical and Process Engineering, University of Surrey, Guildford GU2 7XH, U.K.

Michelle Hammerton — Materials Chemistry, Zernike Institute for Advanced Materials, Groningen 9747AG, The Netherlands

Vijaykumar S. Marakatti — Molecular Chemistry, Materials and Catalysis (MOST), Institute of Condensed Matter and Nanosciences (IMCN), Université Catholique de Louvain (UCLouvain), Louvain-la-Neuve B-1348, Belgium; orcid.org/0000-0002-2586-5102

Monick Tromp — Materials Chemistry, Zernike Institute for Advanced Materials, Groningen 9747AG, The Netherlands; orcid.org/0000-0002-7653-1639

Zdeněk Sofer — Department of Inorganic Chemistry, University of Chemistry and Technology Prague, Prague 6 166 28, Czech Republic; orcid.org/0000-0002-1391-4448

Antonio Sepúlveda-Escribano — Laboratorio de Materiales Avanzados, Departamento de Química Inorgánica—Instituto Universitario de Materiales de Alicante, Universidad de
Direct Capture of CO2 from Ambient Air.

Stocker, T. F. High-Resolution Carbon Dioxide Concentration

McRae, G. J. Comparison of Solvents for Post-Combustion Capture

11840

20190956), Maarten Nachtegaal and Adam Clark, for support

in a hybrid plasma-catalytic reactor

REFERENCES

ACKNOWLEDGMENTS

We thank the Netherlands Organisation 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. Z.S. was

(21) Akande, S. O.; Chroneos, A.; Vasilopoulou, M.; Kennou, S.;

(20) Ro, I.; Sener, C.; Stadelman, T. M.; Ball, M. R.; Venegas, J. M.;


(18) Khairari, A. G.; Shariati, A.; Ostadi, M. Development of Ni/Mo/


(17) Khairari, A. G.; Shariat, A.; Takassi, M. A. A Novel γ-Alumina


(15) Ronda-Lloret, M.; Rico-Françès, S.; Sepúlveda-Escribano, A.;

Ramos-Fernandez, E. V. CuOx/Co2Ox Catalyst Derived from Metal


(16) Gazarhi Kharaji, A.; Shariati, A. Performance Comparison of


(15) Ronda-Lloret, M.; Rico-Françès, S.; Sepúlveda-Escribano, A.;

Ramos-Fernandez, E. V. CuOx/Co2Ox Catalyst Derived from Metal


(16) Gazarhi Kharaji, A.; Shariati, A. Performance Comparison of


(17) Khairari, A. G.; Shariat, A.; Takassi, M. A. A Novel γ-Alumina


(18) Khairari, A. G.; Shariati, A.; Ostadi, M. Development of Ni/Mo/

Al2O3 Catalyst for Reverse Water Gas Shift Reaction (RWGS) Reaction. J.


(20) Ro, I.; Sener, C.; Stadelman, T. M.; Ball, M. R.; Venegas, J. M.;


(21) Akande, S. O.; Chroniak, A.; Vasilopoulou, M.; Knnou, S.;


(22) Borgschulte, A.; Sambolava, O.; Delmelle, R.; Jenatsch, S.;


