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Molybdenum Oxide Supported on Ti₃AlC₂ is an Active Reverse Water–Gas Shift Catalyst

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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 Ti₃AlC₂ 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 MoO₃/TiO₂ and MoO₃/Al₂O₃ catalysts, due to the outstanding electronic properties of the Ti₃AlC₂ support. We observed a charge transfer effect from the electronically rich Ti₃AlC₂ MAX phase to the catalyst surface, which in turn enhances the reducibility of MoO₃ species during reaction. The redox properties of the MoO₃/Ti₃AlC₂ catalyst improve its RWGS intrinsic activity compared to TiO₂- and Al₂O₃-based catalysts.

KEYWORDS: CO₂ hydrogenation, MAX phases, RWGS, syn gas, molybdenum

INTRODUCTION

There is a global interest on reducing anthropogenic CO₂ emissions into the atmosphere.¹,² The main sources of CO₂ are power generation and manufacturing, which emitted 12.4 and 3.9 Gt of CO₂ in 2015.³,⁴ However, CO₂ is a valuable C₁ feedstock that should not be thrown away. After CO₂ 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 CO₂.⁹ This reaction produces CO, a basic building block for a variety of valuable chemicals and fuels, such as methanol, paraffins, and olefins.⁹,¹⁰ However, RWGS is an equilibrium-limited reaction, favored at high temperatures (>700 °C) because it is endothermic.¹¹ At lower temperatures, the exothermic CO methanation (eq 2) and Sabatier reaction (eq 3) also take place, consuming a substantial amount of H₂ and producing undesired methane. Therefore, catalyst development is focused on improving the catalytic performance at <500 °C.¹²,¹³

CO₂ + H₂ ⇌ CO + H₂O
ΔH₂₅°C = 41.2 kJ mol⁻¹

CO + 3H₂ ⇌ CH₄ + H₂O
ΔH₂₅°C = −206.5 kJ mol⁻¹

CO₂ + 4H₂ ⇌ CH₄ + 2H₂O
ΔH₂₅°C = −165.0 kJ mol⁻¹

Traditionally, RWGS catalysts are based on Cu, Pt, and Rh nanoparticles supported on metal oxides (Al₂O₃, TiO₂, and CeO₂, 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 MoO₃ will affect the reaction performance, whether it takes place via the redox mechanism (where CO₂ adsorbs and dissociates on the reduced sites previously created by H₂) 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.35−37 More importantly, the support can prevent catalyst deactivation and boost the industrial application of high-temperature reactions.38 Here, we explored a new type of supports, MAX phases, and their application in catalysis. MAX phases (M<sub>n</sub>A<sub>n</sub>X<sub>n</sub>) 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 3.28 MAX phases stand out by their unusual set of high-temperature structural components and protective coatings.32−34 Their potential as catalysts has recently emerged, as we reported the activity and improved selectivity of the Ti<sub>3</sub>AlC<sub>2</sub> MAX phase during butane oxidative dehydrogenation.25 We also showed that MAX phases are promising supports for CO<sub>2</sub> conversion reactions.36 The thermal stability and acid−base properties of the Ti<sub>3</sub>AlC<sub>2</sub> MAX phase increased the stability and coking resistance of a Co<sub>3</sub>O<sub>4</sub>/Ti<sub>2</sub>AlC catalyst during dry reforming of butane.36 Elsewhere, Tranadaf et al. recently showed the potential of Pd/Ti<sub>3</sub>SiC<sub>2</sub> as a chemo-selective catalyst in the hydrogenation of functionalized nitro derivatives.37

Here, we use for the first time the Ti<sub>3</sub>AlC<sub>2</sub> MAX phase as a support for molybdenum oxide RWGS catalysts. We study the properties and the RWGS activity of the MoO<sub>3</sub>/Ti<sub>3</sub>AlC<sub>2</sub> 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.8 X-ray photoelectron spectroscopy (XPS) was performed using a K-α 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).8

![Figure 1. Scheme of the formation of oxygen vacancies on MoO<sub>3</sub> particles during RWGS, and its ability to dissociate CO<sub>2</sub> via the redox pathway and/or to stabilize carbon-containing species (indicated by R) via the associative pathway.](https://doi.org/10.1021/acssuschemeng.0c07881)

Thermogravimetric analysis (TGA) was carried out using a NETZSCH Jupiter STA 449F3 instrument, under air (20 mL−min<sup>−1</sup>, O<sub>2</sub>/N<sub>2</sub> 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 ProXEXAFS software.39 The edge position (E<sub>d</sub>) 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 Ife 1.2.12).39 We used Athena for background subtraction of long-range oscillations and linear combination fitting (LCF) of supported catalyst spectra using α-MoO<sub>3</sub> and MoO<sub>3</sub>-NP references. We then used Artemis to carry out EXAFS fitting using scattering paths generated from crystallographic α-MoO<sub>3</sub> data (COD ID 1537654) which were summed to simulate the EXAFS spectrum.39 Fitting parameters are reported in Tables S3−S5, where Debye-Waller factors (Δσ<sup>2</sup>), path distances (R), and energy shift (ΔE<sub>o</sub>) were refined, but coordination numbers (N) were set according to the crystal structure. The amplitude reduction factor (S<sub>0</sub>) was determined by first fitting Mo<sub>x</sub> foil data measured at the same time as the sample spectra. We carried out the fits in the ranges indicated in R in Tables S3−S5 and evaluated the quality of fit using an R-factor.

N<sub>2</sub> adsorption−desorption analysis was performed in a Thermo Scientific Surfer instrument at 77 K. The samples were previously evacuated in vacuum at 200 °C for 16 h. 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<sup>−1</sup> 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.36
Procedure for Catalyst Synthesis. 10 wt % molybdenum (in metal-basis) materials were prepared using the wet impregnation method. (NH₄)₆Mo₇O₂₄·4H₂O (Sigma Aldrich) was used as a metal oxide precursor. Ti₅AlC₂, TiO₂ (Hombikat M311), and γ-Al₂O₃ (CK-300, Ketjen) were used as supports. In a typical procedure, 0.40 g of (NH₄)₆Mo₇O₂₄·4H₂O and 2 g of support were mixed in 20 mL of water and stirred at 65 °C for 24 h. The resulting solid was dried at 120 °C for 2 h and then calcined under air at 350 °C for 4 h (heating rate 4 °C·min⁻¹). The Ti₅AlC₂ MAX phase was prepared by mixing the elemental powders purchased from STRTEM chemicals: Ti (325 mesh, 99.5%), Al (325 mesh, 99.5%), and graphite (325 mesh, 99.9%). The composition corresponding to Ti₅AlC₂ was mixed in a 3D blender (40 rpm) in hexane for 8 h, using 5 mm zirconia balls. The resulting mixture was placed in an alumina crucible covered with an alumina lid and heated to 1450 °C for 2 h under an argon atmosphere (heating and cooling rate was 2 °C·min⁻¹). The resulting powder was mechanically grinded in an agate mortar. The Mo₅TiAlC₂ MAX phase was prepared by mixing the elemental powders purchased from STRTEM chemicals: Ti (325 mesh, 99.5%), Mo (2–4 microns, 99.9%), Al (325 mesh, 99.5%), and graphite (325 mesh, 99.9%). The composition corresponding to Mo₅TiAlC₂ was mixed in a 3D blender (40 rpm) in hexane for 8 h, using 5 mm zirconia balls. The resulting mixture was placed in an alumina crucible covered with an alumina lid and heated to 1500 °C for 2 h under an argon atmosphere (heating and cooling rate was 2 °C·min⁻¹). The resulting powder was mechanically grinded in an agate mortar. A bulk MoO₃ sample was obtained from the calcination of MoO₃·4H₂O at 100 °C for 2 h (heating ramp 5 °C·min⁻¹).

Procedure for Catalytic Testing. The catalysts were tested in the RWGS reaction in a vertical fixed bed reactor. A total of 200 mg of catalyst was placed on quartz wool in the middle of the reactor, which had 7 mm inner diameter. The samples were heated under N₂ to 400 °C. The catalytic tests were then performed at atmospheric pressure and at a H₂:CO₂ ratio of 4:1. We performed temperature screening tests between 400 and 750 °C using compressed air (50 mL·min⁻¹) and stability tests for 48 h at 550 °C. The Ti₃AlC₂ MAX phase was prepared by mixing the elemental powders purchased from STRTEM chemicals: Ti (325 mesh, 99.5%), Mo (2–4 microns, 99.9%), Al (325 mesh, 99.5%), and graphite (325 mesh, 99.9%). The composition corresponding to Mo₅Ti₅AlC₂ was mixed in a 3D blender (40 rpm) in hexane for 8 h, using 5 mm zirconia balls. The resulting mixture was placed in an alumina crucible covered with an alumina lid and heated to 1500 °C for 2 h under an argon atmosphere (heating and cooling rate was 2 °C·min⁻¹). The resulting powder was mechanically grinded in an agate mortar. A bulk MoO₃ sample was obtained from the calcination of MoO₃·4H₂O at 100 °C for 2 h (heating ramp 5 °C·min⁻¹).

Catalyst Synthesis. We compared the properties and activity in RWGS of MoO₃-based catalysts, using the Ti₅AlC₂ 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. Ti₅AlC₂ 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, Mo₅TiAlC₂, 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/Ti₅AlC₂ catalyst shows the characteristic peaks of the Ti₅AlC₂ 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 Ti₅AlC₂. The characteristic peaks of MoO₃ are also visible at 2θ = 12.8 and 23.5°. The pattern of MoO₃/Ti₅AlC₂ 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/Ti₅AlC₂ 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 Ti₅AlC₂ 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 Ti₅AlC₂ 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/Ti₅AlC₂ 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 Mo 3d spectra of the catalysts (Figure 3) show two spectral lines, assigned to Mo 3d₅/₂ and Mo 3d₃/₂ spin–orbit components. The Mo 3d₅/₂ binding energy in MoO₃/Ti₅AlC₂ and MoO₃/TiO₂ spectra is 232.8 eV, which corresponds to MoO₃ species (Mo⁶⁺). The Mo 3d spectrum of the MoO₃/Ti₅AlC₂ catalyst shows two contributions at Mo 3d₅/₂ binding energies of 232.6 and 233.6 eV, corresponding to Mo⁶⁺ and Mo⁷⁺ species. In the O 1s spectrum, MoO₃/Ti₅AlC₂ and MoO₃/TiO₂ also show similar Mo–O binding energies (ca. 530.4 eV, cf. Figure S2). This indicates that the surface of the Ti₅AlC₂ undergoes oxidation and Mo predominantly sits on the oxidized titanium, as expected by the excess of titanium.
in this compound (Ti/Al ratio is 3 to 1). The excess of titanium on the MAX phase surface is also confirmed by the $I_{\text{Ti}}/I_{\text{Al}}$ 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.46

While the three catalysts have the same metal loading, the Mo and support intensity ratio ($I_{\text{Mo}}/I_{\text{Ti}}$ or $I_{\text{Mo}}/I_{\text{Al}}$) 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 $\gamma$-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 $\alpha$-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.51 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 $\alpha$-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 $\alpha$-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
bulk atoms and the exact proportion of those is unknown. For this study, we are interested in the trends observed when using different supports; thus, we use the LCF analyses to infer the differences in particle sizes between samples. Moreover, the XAS measures all Mo atoms in the sample. This means that Mo atoms present in amorphous compounds and/or present as single site species are not detected with other techniques such as XRD and HAADF. The shape of the XANES spectrum of the supported catalysts can be fitted into two contributions as we have no insights into the amount of Mo atoms contributing to the spectrum that is not accounted for by the nanoparticle or bulk α-MoO₃ data. More details on the LCF results are given in Figure S8 and Table S3.

In the EXAFS spectra (Figure S9), we observe in more detail the structural differences between MoO₃ nanoparticles and bulk α-MoO₃. In k-space, the oscillations of the MoO₃-NP spectrum are dampened compared to α-MoO₃, especially at higher wavenumbers, as expected. This results in an R-space spectrum in which the amplitude of the second shell is suppressed. The shape of the first shell in the MoO₃-NP spectrum is also affected, with just one main peak compared to the complex first shell of α-MoO₃. The EXAFS spectrum of MoO₃/Al₂O₃ is very similar to the MoO₃ nanoparticle reference. The spectrum of MoO₃/Ti₃AlC₂ is more similar to the bulk α-MoO₃ reference, 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 Mo₃TiAlC₂ 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 practivatation 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 catalyst in terms of their intrinsic activity, using their TOF (Figure 6a). MoO₃/Ti₃AlC₂ shows higher TOF values from 450 °C.
Figure 6. TOF values of the catalysts during (a) temperature-screening tests (reaction conditions: 200 mg catalyst, H2:CO2 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, H2:CO2 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 CO2 conversion unit. In addition, the MoO3/Ti3AlC2 catalyst shows higher CO2 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 MoO3/Ti3AlC2 catalyst is stable over time and it converts 20% CO2 (Figure S15). Methane was not detected. TGA analysis (Figure S15) 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 CH4 oxidation reactions when using MoO3-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 CO2 consumption, giving higher CO2 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 Ti3AlC2 MAX phase is stable under reaction conditions (Figure S1). As expected, the Al2O3 and TiO2 supports were also stable (Figure S1).

In the LCF analysis of the MoO3/Ti3AlC2 sample XANES spectrum (Figure 5), the percentage of bulk α-MoO3 increases after stability testing. The EXAFS spectrum of the spent sample is also more similar to bulk α-MoO3 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 MoO3 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 MoO3/TiO2 (average particle size: 0.51 nm, σ = 0.18 nm) and MoO3/Al2O3 (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 MoO3 species during the reaction (Figure 7). Interestingly, MoO3/Ti3AlC2 shows MoO2 (Mo4⁺), MoO21 (Mo3⁺), and MoO3 (Mo6⁺) species on the surface, while the other two catalysts only contain MoO3 and MoO3. The percentage of reduced species is significantly higher on the MoO3/Ti3AlC2 catalyst surface (Table 1), indicating that this catalyst is reduced more during the reaction. The higher 

In the stability tests, CO selectivity followed the order MoO3/TiO2 (70–100%) > MoO3/Al2O3 (60–80%) > MoO3/Ti3AlC2 (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 CH4 oxidation reactions when using MoO3-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 CO2 consumption, giving higher CO2 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 Ti3AlC2 MAX phase is stable under reaction conditions (Figure S1). As expected, the Al2O3 and TiO2 supports were also stable (Figure S1).

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Figure 7. Mo 3d XPS spectra of the catalysts after the stability test at 550 °C.
activation percentage observed with MoO3/Ti3AlC2 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 MoO3 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 MoO3, creating water and leaving surface oxygen vacancies. The CO2 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, MoO3 nanoparticles in close interaction with the support lead to poor redox properties, as seen with the MoO3/TiO2 and MoO3/Al2O3 catalysts. The low surface area of the Ti3AlC2 MAX phase leads to large bulk-like MoO3 rods. Nevertheless, MoO3/Ti3AlC2 is the most intrinsically active catalyst in terms of TOF (Figure 5). We attribute this to the electronically rich Ti3AlC2, which transfers the charge to the active site. This charge transfer effect enhances the redox properties of MoO3, facilitating the formation of surface oxygen vacancies that participate in the reaction (see Figure 8). In addition, electronically richer molybdenum sites are ideal for CO2 activation, as the charge transfer from Mo to CO2 antibonding orbitals can weaken the C–O bond, facilitating its reduction to CO.

<table>
<thead>
<tr>
<th>catalyst</th>
<th>atomic percentage on the surface (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mo4+</td>
</tr>
<tr>
<td>MoO3/Ti3AlC2 (spent)</td>
<td>24</td>
</tr>
<tr>
<td>MoO3/Al2O3 (spent)</td>
<td>50</td>
</tr>
<tr>
<td>MoO3/TiO2 (spent)</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 1. Atomic Percentage of MoO2 (Mo4+), Mo4O11 (Mo5+), and MoO3 (Mo6+) Species on the Spent Catalyst Surface, based on Mo 3d XPS

CONCLUSIONS

In this work, we show for the first time the potential of MAX phase-based catalysts for application in CO2 conversion via the RWGS reaction. When supporting molybdenum oxide on the Ti3AlC2 MAX phase, the low surface area of the MAX phase leads to the formation of large MoO3 rods with bulk-like properties. Nevertheless, the presence of electronically rich Ti3AlC2 enhances the redox properties of MoO3 under RWGS conditions, resulting in a highly reduced surface that contains a large amount of oxygen vacancies. The MoO3/TiO2 and MoO3/Al2O3 catalysts contain small and highly dispersed MoO3 nanoparticles, but their close contact with the support inhibits the formation of oxygen vacancies during the reaction. As MoO3/Ti3AlC2 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 CO2 via electron transfer to CO2 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 CO2 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; CO2 conversion and CO selectivity values of control samples (Ti3AlC2, MoO3/TiAlC2, reduced MoO3/Al2O3, and bulk MoO3) and studied catalysts (10 wt % MoO3/Ti3AlC2, MoO3/TiO2, and MoO3/Al2O3), and CO formation rates of the studied catalysts (PDF).

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Notes

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