STUDIES ON COMOX CATALYST – PART 1: A study on fresh γ-Al₂O₃-CoO, γ-Al₂O₃-MoO₃ and γ-Al₂O₃-CoO-MoO₃ systems by ESR technique

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STUDIES ON COMOX CATALYST-PART 1

A study on fresh $\gamma$-Al$_2$O$_3$-CoO, $\gamma$-Al$_2$O$_3$-MoO$_3$ and $\gamma$-Al$_2$O$_3$-CoO-MoO$_3$ systems by ESR technique

By


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Abstract

It is found that cobalt doped $\gamma$-alumina tends to incorporate the cobalt ions in the bulk forming cobalt aluminate spinel. Molybdenum doped $\gamma$-alumina contains molybdenum on the surface only and shows the presence of Mo(V) in small concentrations. Interaction between support and molybdenum starts at 300°C. In doubly doped (cobalt and molybdenum) samples two competitive processes occur. Previously present surface layer of molybdenum favours cobalt molybdate formation, otherwise cobalt diffuses in the bulk forming spinel. Magnetic susceptibility data are also reported.

Introduction

Comox is used extensively in industry for hydrofining purposes. In general, it contains cobalt and molybdenum oxides, which are the active constituents, supported on a refractory base. Although the use of this catalyst is very common but the roles played by individual constituents in the catalytic composition, structure etc., as reported by various workers, are not consistent.

The optimum atomic ratio of cobalt and molybdenum from activity point of view reported in literature ranges from 0.2 to 1. Even the nature of distribution of cobalt and molybdenum and their different compounds detected by various workers differ considerably. Mitchel et al. found that cobalt is present as Co(II) with 50% in octahedral and 50% in tetrahedral coordination in well dispersed state and with very little magnetic interaction. Molybdenum has been found in hexavalent state and tetrahedral coordination. None of well defined compounds of Al, Co and Mo could be detected. On
the other hand SCHÜTT et al. have reported that Co is distributed throughout the bulk as spinel CoAl₂O₄ and Mo is present in hexavalent state as a monolayer covering about 20% of the carrier surface.

RICHARDSON found that of the samples having Co: Mo ratio higher than 0.3, the final composition depended on the cobalt concentration and the curing temperature. The extent of CoAl₂O₄ formation increased with increase in temperature up to 650°C at the expense of CoO and active cobalt. Above 650°C, the formation of CoMoO₄ starts at the expense of CoAl₂O₄. DUFAX et al. detected the presence of Mo(V) in γ-Al₂O₃-Molybdenum system cured at 477°C but they also concluded that Mo stabilises only in hexavalent state.

Keeping above facts in view a detailed investigation on Comox catalyst and its constituents with special reference to mechanism of hydrodesulphurisation has been undertaken. The present paper deals with study on the state of combination of γ-Al₂O₃-CoO, γ-Al₂O₃-MoO₃ and γ-Al₂O₃-CoO-MoO₃ systems by ESR technique.

**Experimental**

**Preparation:**

(a) γ-Al₂O₃: Aluminium hydroxide was precipitated from Al(NO₃)₃ solution by NH₄OH at pH 8~9. The precipitate was filtered, washed free from NO₃⁻ and dried at 120°C. Dried mass was cured at 500°C for 8 hrs. Alumina so prepared was used for all sample preparations.

(b) γ-Al₂O₃-CoO: Al₂O₃ grits prepared as mentioned above were soaked in Co(NO₃)₂ solution to build up 6~7% cobalt concentration as CoO by weight. After soaking the alumina grits were separated, dried at 120°C and finally cured at 500°C in the air for 8 hrs. Mechanical mixture containing 5% CoO by weight was prepared for detection and confirmation of interaction between CoO and Al₂O₃. Cobalt oxide for preparing mechanical mixture was obtained by thermal decomposition of Co(NO₃)₂ at 500°C for 8 hrs in air.

(c) γ-Al₂O₃-MoO₃: Alumina grits were soaked in ammonium paramolybdate solution to build up the requisite concentration of molybdenum. Later on grits were separated, dried and cured at 500°C for 8 hrs. Since in single soaking the molybdenum concentration of the order of 19~20% could not be attained so the process of soaking and curing was repeated. To investigate the effect of heat treatment on interaction between Al₂O₃ and molybdenum, samples were prepared by single soaking and curing in the temperature range of 250 to 500°C in steps of 50°C.
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(d) \( \gamma \)-\( \text{Al}_2\text{O}_3 \)-CoO-MoO_3: Samples containing approximately 6 to 7\% CoO and 19 to 20\% MoO_3 by weight were prepared by soaking in Co\((\text{NO}_3)_2\) and \((\text{NH}_4)\text{MoO}_4 \cdot 4 \text{H}_2\text{O}\) solutions respectively. Process employed for CoO and MoO_3 incorporation in \( \gamma \)-Alumina was same as mentioned earlier. Since incorporation of MoO_3 required two soakings, so three samples with different combination were prepared to investigate the effect of different sequence of incorporation. The sequence observed for incorporation was (1) CoO followed by two successive soaking and curing in air of MoO_3 (2) MoO_3 followed by cobalt and finally again MoO_3 and (3) two MoO_3 soaking and curing and finally followed by CoO. The samples so prepared were termed as sample No. 1, 2 and 3 respectively.

The electron spin resonance spectra were recorded on a Brüker-Physik, Model B-ER 402, X-band ESR spectrometer operating at 9.6 GHz and fitted with a TE_{022} mode rectangular cavity. The magnetic field was modulated at 100 kHz. Thin walled silica tube was utilised for keeping samples in the cavity and the first derivative of the spectra was recorded. The magnetic field was measured by a proton resonance gaussmeter and the \( g \) values measured using polycrystalline DPPH as reference \((g = 2.0036)\). Quantitative measurements of Mo\((V)\) in different samples were done by comparing the areas under the adsorption curves obtained by integrating the recorded signals for the different samples with those of standards supplied by the instrument manufacturers.

The magnetic susceptibility of the samples at the room temperature were determined by a Faraday type magnetic balance where pure CuSO_4 \cdot 5\text{H}_2\text{O} was used as standard.

All the chemicals and reagents used were of A. R. grade. For estimation of molybdenum and cobalt the sample was digested in \text{conc.} \text{H}_2\text{SO}_4 and evaporated to dryness. Subsequently the dried-up mass was dissolved in \text{dil.} \text{HCl}. Molybdenum was estimated gravimetrically by precipitating it as PbMoO_4. Cobalt was estimated volumetrically by EDTA using mureoxide as indicator. In mixtures containing molybdenum and cobalt, the molybdenum was separated out as PbMoO_4 by lead acetate. After separation of molybdenum the excess lead was removed by \text{dil.} \text{H}_2\text{SO}_4 and subsequently the cobalt was estimated as mentioned above.

**Results and Discussion**

The ESR spectra of pure MoO_3 produced no signal. The \( \gamma \)-\( \text{Al}_2\text{O}_3 \) used as support gave a very weak signal at high \( g \)-value. This is probably due to presence of some impurity in the sample. Similar signal in \( \text{Al}_2\text{O}_3 \) support
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was observed by Ueda and Todo et al. Cobalt oxide exhibited a broad signal at $g = 2.24$ with peak to peak width of 2400 gauss. Its magnetic susceptibility at 30°C and 6 k gauss magnetic field was $26.7 \times 10^{-6}$ CGS units. Although pure alumina and MoO$_3$ did not exhibit any signal but MoO$_3$–γ-Al$_2$O$_3$ system cured at 500°C exhibited signal at $g = 1.9318$ indicating presence of Mo (V) in the sample and interaction between support and molybdenum. The interaction between support and molybdenum oxide started at 300°C (Fig. 1). Formation of Mo (V) increased with temperature up to 400°C and thereafter the concentration of Mo (V) started decreasing (Table 1). Probably at higher temperature the Mo (V) formed due to interaction of support and molybdenum is oxidised to hexavalent state. At present the mechanism of interaction between support and molybdenum oxide was studied further.

**Table 1.**

<table>
<thead>
<tr>
<th>No.</th>
<th>Details of samples</th>
<th>Magnetic susceptibility at 30°C, 6k Gauss CGS Unit.</th>
<th>No. of ESR lines</th>
<th>g-values</th>
<th>Peak to peak width (Gauss)</th>
<th>% MoO$_3$ by weight</th>
<th>Concentration of Mo (V) (Spins/gm)</th>
<th>Mo (V) $\times 10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al$_2$O$_3$+MoO$_3$ cured at 250°C</td>
<td>Diamagnetic</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>15.31</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Al$_2$O$_3$+MoO$_3$ cured at 300°C</td>
<td>do.</td>
<td>One</td>
<td>$g_1 = 1.9318$, $g_2 = 1.9423$, $g_3 = 1.9111$</td>
<td>62.47</td>
<td>15.31</td>
<td>191$\times 10^{14}$</td>
<td>29.9</td>
</tr>
<tr>
<td>3</td>
<td>Al$_2$O$_3$+MoO$_3$ cured at 350°C</td>
<td>do.</td>
<td>One</td>
<td>do.</td>
<td>do.</td>
<td>15.31</td>
<td>235$\times 10^{14}$</td>
<td>36.7</td>
</tr>
<tr>
<td>4</td>
<td>Al$_2$O$_3$+MoO$_3$ cured at 400°C</td>
<td>do.</td>
<td>One</td>
<td>do.</td>
<td>do.</td>
<td>15.31</td>
<td>453$\times 10^{14}$</td>
<td>80.8</td>
</tr>
<tr>
<td>5</td>
<td>Al$_2$O$_3$+MoO$_3$ cured at 500°C</td>
<td>$-0.25 \times 10^{-15}$</td>
<td>One</td>
<td>do.</td>
<td>do.</td>
<td>17.89</td>
<td>360$\times 10^{14}$</td>
<td>47.9</td>
</tr>
</tbody>
</table>

Colour of all the samples was whitish.
### Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Details of sample</th>
<th>Colour</th>
<th>Magnetic susceptibility at 30°C, 6k gauss CGS unit.</th>
<th>No. of ESR lines</th>
<th>( g )-values</th>
<th>Peak to peak width (gauss)</th>
<th>%CoO by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( \text{Al}_2\text{O}_3 )</td>
<td>White</td>
<td>Diamagnetic</td>
<td>Nil</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2.</td>
<td>CoO</td>
<td>Black</td>
<td>26.7 \times 10^{-6}</td>
<td>One</td>
<td>2.24</td>
<td>2400</td>
<td>100</td>
</tr>
<tr>
<td>3.</td>
<td>( \text{Al}_2\text{O}_3 + \text{CoO} ) cured at 250°C</td>
<td>Blackish</td>
<td>Zero</td>
<td>Nil</td>
<td>—</td>
<td>—</td>
<td>5.01</td>
</tr>
<tr>
<td>4.</td>
<td>( \text{Al}_2\text{O}_3 + \text{CoO} ) cured at 500°C</td>
<td>Greenish black</td>
<td>1.31 \times 10^{-6}</td>
<td>Nil</td>
<td>—</td>
<td>—</td>
<td>5.01</td>
</tr>
<tr>
<td>5.</td>
<td>( \text{Al}_2\text{O}_3 + \text{CoO} ) (5%) mechanically mixed.</td>
<td>Grey</td>
<td>2.08 \times 10^{-6}</td>
<td>Nil</td>
<td>—</td>
<td>—</td>
<td>5.00</td>
</tr>
</tbody>
</table>

### Table 3.

<table>
<thead>
<tr>
<th>No.</th>
<th>Details of sample</th>
<th>Colour</th>
<th>Magnetic susceptibility at 30°C, 6k gauss CGS unit.</th>
<th>No. of ESR lines</th>
<th>( g )-values</th>
<th>Peak to peak width (Gauss)</th>
<th>%CoO by weight</th>
<th>%MoO(_3) by weight</th>
<th>Concentration of Mo(V) (spins/gm)</th>
<th>Mo(V) \times 10^6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( \text{Al}_2\text{O}_3 + \text{MoO}_3 + \text{CoO} + \text{MoO}_3 ) cured at 500°C</td>
<td>Greenish black</td>
<td>0.789 \times 10^{-6}</td>
<td>One</td>
<td>( g_2 = 1.9318 )</td>
<td>62.47</td>
<td>6.31</td>
<td>19.93</td>
<td>420 \times 10^{14}</td>
<td>50.3</td>
</tr>
<tr>
<td>2.</td>
<td>( \text{Al}_2\text{O}_3 + \text{MoO}_3 + \text{CoO} + \text{MoO}_3 ) cured at 500°C</td>
<td>Dull Blue</td>
<td>1.07 \times 10^{-6}</td>
<td>One</td>
<td>( do. )</td>
<td>do.</td>
<td>6.00</td>
<td>20.2</td>
<td>145 \times 10^{14}</td>
<td>17.2</td>
</tr>
<tr>
<td>3.</td>
<td>( \text{Al}_2\text{O}_3 + \text{MoO}_3 + \text{MoO}_3 + \text{CoO} ) cured at 500°C</td>
<td>Blue</td>
<td>2.35 \times 10^{-6}</td>
<td>Nil</td>
<td>Nil</td>
<td>Nil</td>
<td>5.92</td>
<td>22.04</td>
<td>Nil</td>
<td>Nil</td>
</tr>
</tbody>
</table>
leading to Mo(V) formation is difficult to explain and needs further investigations. DuFaux et al.\textsuperscript{9} also observed a weak signal at \(g=1.93\) for Al\(_2\)O\(_3\)–MoO\(_3\) system cured at 477°C containing more than 10% by wt molybdenum. They also attributed it due to some interaction between molybdenum and support. The decrease in the Mo(V) signal intensity at the higher temperatures is consistent with their finding that molybdenum stabilises in the hexavalent state.

For comparison, a mechanical mixture of 5% CoO by weight with the \(\gamma\)-Alumina support was studied by ESR, as well as by magnetic balance. The signal to noise ratio was too poor to give any ESR signal. The magnetic susceptibility has the expected value (Table 2). In case of cobalt distributed over \(\gamma\)-Al\(_2\)O\(_3\) and cured at 250°C, the magnetic susceptibility turned out to be zero. This result obviously shows that an antiferromagnetic compound of Co, Al and O has formed, where the spin moments of the Co(II) ions have cancelled one another out. Schütz et al.\textsuperscript{6,7} have reported the formation of the spinel CoAl\(_2\)O\(_4\), evenly over the bulk. Presumably, it is same phase, with the Co(II) ions distributed equally between the tetrahedral and octahedral sites. For the sample cured at 500°C however the magnetic susceptibility has shown some increase, indicating thereby that the spinel structure has been disturbed either through migration of Co(II) ions from one type site to another, or through partial oxidation of Co(II) to Co(III) state.

It was seen in the case of \(\gamma\)-Alumina doped with molybdenum, there is interaction between support and molybdenum, giving rise to a Mo(V) species, which may serve as an index to the extent of the interaction. In case of the doubly doped samples, there are two competing processes. Cobalt may be incorporated in the system in the form of a spinel or it may form a compound with Mo, which according to Lipsch and Schütz could only be CoMoO\(_4\) involving Mo(VI). The observations on the doubly doped samples find a ready explanation in this light. In the sample No. 1 where Co was first incorporated in the \(\gamma\)-Alumina, fol-

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{Mo(V) signal of ESR for samples No. 1, 2 and 3, respectively.}
\end{figure}
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followed by two successive Mo soakings, spinel formation had already taken place and little Co was available for interacting with Mo. Formation of spinel is concluded from observed low magnetic susceptibility exhibited by the sample and strong ESR signal for Mo(V) confirms the interaction between molybdenum and the support (Table 3, Fig. 2).

In the sample No. 2 where an initial soaking with Mo was followed by Co treatment and finally another Mo soaking, the magnetic susceptibility is enhanced and at the same time the Mo(V) ESR signal intensity is reduced considerably showing the presence of Co in a state other than an antiferromagnetic one, as might be expected with CoMoO₄. Probably the chances of CoAl₂O₄ formation are reduced due to barrier formed by molybdenum layer initially present there, which reacts preferentially with cobalt leading to CoMoO₄ formation involving Mo(V) also. Weak signal for Mo(V) as exhibited by sample No. 2, probably results from fresh interaction between support and molybdenum due to final molybdenum treatment.

Finally, in conformity with the above, the magnetic susceptibility is the maximum and Mo(V) signal is the minimum (in fact zero) for sample No. 3, where Co soaking followed two initial soakings with Mo. Here Co reacted mainly with Mo, very little if at all being available for spinel formation. It also shows that molybdenum is confined to surface layer of the alumina support. Because had it been possible to incorporate it in the bulk, it should have been equally competitive in all the three samples in forming a compound with Co. The Mo surface layer hypothesis also finds support in the fact that in the first sample, where Co had formed spinel initially, the surface Mo layer had resulted in a lower magnetic susceptibility after curing at 500°C than in the corresponding sample with Co alone. It appears that the surface layer of molybdenum obstructs the oxidation of Co(II) to Co(III) state.

Acknowledgement

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References