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Characterization of Supported Cobalt and Cobalt–Rhodium Catalysts

I. Temperature-Programmed Reduction (TPR) and Oxidation (TPO) of Co–Rh/Al₂O₃

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Temperature-programmed reduction and oxidation (TPR and TPO) have been used to study the state of cobalt and rhodium in a series of Co–Rh/γ-Al₂O₃ catalysts. The results show that rhodium enhances the reducibility of part of the cobalt, but that it does not prevent the formation of cobalt aluminate, which is irreducible below 773 K. TPR of the coimpregnated Co–Rh/γ-Al₂O₃ catalyst shows a reduction peak at a much lower temperature than that of Co/Al₂O₃. This and the slight shift relative to the peak of Rh/Al₂O₃ indicates that cobalt and rhodium ions are not far apart after compregnation, which explains the easy formation of bimetallic particles during reduction. Passivation (oxidation at room temperature) of the reduced bimetallic catalyst leaves the structure of the bimetallic particles largely intact, but cobalt is oxidized to a great extent while rhodium remains metallic. Passivated Co–Rh particles thus consist of a rhodium kernel covered by cobalt oxide.

TPR of passivated catalysts also suggests that already in the reduced state the bimetallic particles are surface-enriched in cobalt. A thorough oxidation of the bimetallic catalysts, on the other hand, leads to a restructuring, i.e., the formation of metal oxide particles which are in close proximity.

INTRODUCTION

Bimetallic catalysts are of interest for several industrial processes. The attractiveness of these catalysts lies in their superior stability and selectivity for many reactions (1–3). For example, Wise and co-workers (4) reported a maximum in selectivity for C₂ and C₃ hydrocarbons in Fischer–Tropsch synthesis for unsupported Fe–Co catalysts. Bhasin et al. (5) observed an increase in selectivity for methanol and ethanol in synthesis gas conversion over a bimetallic Fe–Rh/SiO₂ catalyst, compared with the supported monometallic catalysts.

In our laboratory we are interested in supported Co–Rh catalysts. Recently, Villeger et al. (6) have shown that addition of Rh to Co results in an increase of the selectivity to ethene and propene during CO hydrogenation. In order to understand the catalytic behavior of bimetallic catalysts the most fundamental question that has to be answered is whether the minute particles indeed contain atoms of both metals. On purely statistical grounds, one might expect the particles to be bimetallic. But direct experimental verification is difficult because of limitations in physical techniques.

The temperature-programmed reduction and oxidation techniques (TPR, TPO) may, however, be used to obtain evidence for the interaction between the atoms of the two metallic components. Thus, Robertson et al. (7, 8) were the first to study Cu–Ni/SiO₂ by means of TPR. They were able to confirm complete reduction and to identify alloying. Using TPR, evidence has also been found for an intimate contact between the constituent metals in Pt–Re/Al₂O₃ (9).
that study it was demonstrated that calcina-
tion of Pt-Re/Al₂O₃ at temperatures above
473 K caused segregation of platinum oxide
and rhenium oxide. Paryjczak et al. (10)
demonstrated the power of TPO in the
characterization of bimetallic Rh-Ag/SiO₂
catalysts. The TPO profiles for these sys-
tems showed features intermediate be-
tween the characteristics of the pure com-
ponents. Furthermore, it was found that the
shape of the TPO profiles and the relative
contributions of individual peaks depended
on the degree of metal dispersion.

In this paper we present the results of a
characterization study of the Co-Rh sys-
tem supported on alumina by TPR and
TPO. The formation of the bimetallic parti-
cles during reduction of the impregnated
catalysts and their stability during oxida-
tion will be discussed.

EXPERIMENTAL

The bulk metals Co and Rh and the bulk
Co-Rh alloy with a Co/Rh atomic ratio of 1
were prepared by heating the correspond-
ing aqueous solutions of the metal salts
Co(NO₃)₂ · 6H₂O (Merck P. A.) and RhCl₃ ·
3H₂O (39 wt%). Drijfhout) at 393 K, fol-
lowed by a direct reduction of the resulting
solid in hydrogen by heating at 5 K min⁻¹
from room temperature to 1073 K and
maintaining that temperature for 5 h. The
monometallic bulk oxides Co₃O₄ and Rh₂O₃
were prepared by oxidizing the reduced
metals at 1073 K for 72 h, while CoO was
obtained from Merck. The mixed oxide
CoRhOₓ was prepared by evaporating an
aqueous solution of the metal salts followed
by a direct oxidation at 1073 K (heating rate 5 K min⁻¹) for 48 h. γ-Al₂O₃ (Ketjen,
000-1.5 E, surface area 200 m² g⁻¹, pore vol-
ume 0.6 cm³ g⁻¹) was (co)impregnated with
aqueous solutions of the metal salts via the
incipient wetness technique to prepare
monometallic Co and Rh and bimetallic
Co-Rh catalysts. The catalysts were dried
in air at 393 K for 24 h after which a part of
each batch was stored for further use. The
other part was directly reduced in flowing

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>wt% Co</th>
<th>wt% Rh</th>
<th>H/M 773°C</th>
<th>H/M b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co/Al₂O₃</td>
<td>4.44</td>
<td>0.09</td>
<td>0.14</td>
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<tr>
<td>Co₄Rh/Al₂O₃</td>
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<td>1.39</td>
<td>0.13</td>
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<tr>
<td>CoRhAl₂O₃</td>
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<td>3.43</td>
<td>0.39</td>
<td>0.57</td>
</tr>
<tr>
<td>Rh/Al₂O₃</td>
<td>2.30</td>
<td>1.53</td>
<td></td>
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<tr>
<td>RhAl₂O₃</td>
<td>8.53</td>
<td>0.81</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Based on H₂ adsorption at room temperature after
reduction at 773 K.
b Dispersion of the metallic part of Co + Rh, cor-
rected for the presence of CoAl₂O₄.

H₂ by heating at 5 K min⁻¹ to 773 K, main-
taining that temperature for 1 h, and subse-
quently cooling in H₂ to room temperature.
Thereafter, it was passivated at room tem-
perature by replacing the H₂ flow by N₂
and subsequently slowly adding O₂ up to
20%. The Co and Rh contents of the dried
catalysts were determined by using, respec-
tively, atomic absorption spectroscopy and
colorimetry. The catalysts which have been
prepared are summarized in Table 1.

Hydrogen chemisorption measurements
were carried out in a conventional volumet-
ric glass apparatus after reduction of the
passivated catalysts at 773 K (heating rate 5 K min⁻¹) in flowing hydrogen for 1 h, fol-
lowed by evacuation at 773 K for Rh/Al₂O₃
and at 573 K for the cobalt-containing cata-
lysts for another hour. The cobalt-contain-
ing catalysts were evacuated at lower tem-
peratures in order to avoid formation of
water by dehydroxylation of the support
and thus to avoid reoxidation of cobalt (see
Results). After evacuation, H₂ was admit-
ted at 473 K, the catalyst was cooled to
room temperature and desorption iso-
therms were measured at room tempera-
ture. The H/M value was obtained by ex-
trapolating the linear higher pressure region
(P > 30 kPa, above which monolayer cov-
erage has been reached) of the isotherm to
zero pressure and by subtraction of the
contribution of the bare support. The H/Rh
values thus obtained for the various catalysts are presented in Table 1. A typical isotherm for a Rh catalyst is presented in Fig. 1.

TPR, TPO, and TPD experiments were carried out with 5% H₂ in Ar, 5% O₂ in He, and 100% Ar, respectively, with about 200 mg catalyst in an apparatus similar to that described by Boer et al. (11). The flow rate of gases through the reactor was 5 cm³ min⁻¹ and the temperature was raised at 5 K min⁻¹ during TPR and TPO and at 15 K min⁻¹ during TPD within the temperature range of 223 to 773 K.

The following typical sequence of treatments in the TPR apparatus has been used:
— the impregnated, passivated, or oxidized sample was flushed under Ar flow at 223 K;
— Ar was replaced by the Ar/H₂ mixture, causing at least an apparent H₂ consumption (first switch peak);
— the sample was heated under Ar/H₂ flow at 5 K min⁻¹ to 773 K;
— after 1 h at 773 K the sample was cooled down at 10 K min⁻¹ to 223 K;
— the reduced sample was flushed with Ar;
— Ar flow was replaced by the Ar/H₂ mixture once again, now causing only an apparent H₂ consumption (second switch peak). The difference between the first and second switch peak reveals the real hydrogen consumption at 223 K, if there is any (12).

A similar sequence has been followed during TPO, albeit that the final temperature was varied. When the TPR was followed by a TPO the TPR sequence was extended by heating the catalyst at 573 K for half an hour under helium flow, in order to desorb hydrogen, after which the catalyst was cooled down to 223 K again.

RESULTS AND DISCUSSION

Unsupported Bulk Co, Rh, and Co–Rh

It is known from the literature that Co and Rh are completely miscible (13). In Fig. 2 the X-ray diffraction (XRD) patterns (CuKα radiation) are shown for a physical mixture of cobalt and rhodium, for the Co–Rh alloy, for a physical mixture of Co₃O₄ and Rh₂O₃, and for the mixed CoRhOₓ oxide. The diffraction pattern in Fig. 2a is formed by two peaks, the larger one being the (111) diffraction peak of rhodium with fcc structure and the smaller one the (111) diffraction peak of cobalt with fcc structure. From the 2θ values the Rh–Rh and Co–Co interatomic distances are calculated to be 2.688 and 2.505 Å, respectively.
XRD pattern for the alloy (cf. Fig. 2b) shows a main peak at $2\theta = 42.30^\circ$ which is in between the peaks of the constituent alloy components. No information is available about the crystallographic structure of the alloy, but assuming that its structure is fcc and that the peak is due to the (111) diffraction, the shortest metal–metal distance is on the average 2.615 Å. This value is slightly higher (0.017 Å) than predicted by Végard’s rule (which assumes a linear relation between the interatomic distance in an alloy and the atomic ratio of the metals). Between $2\theta = 32^\circ$ and $38^\circ$ four diffraction peaks can be distinguished for the physical mixture of Co$_3$O$_4$ and Rh$_2$O$_3$ (Fig. 2c). The peaks at $2\theta = 33.00^\circ$, 34.30$^\circ$, and 34.90$^\circ$ are assigned to the (020), (114), and (200) diffractions of Rh$_2$O$_3$ (corundum structure), respectively, and the peak at $2\theta = 36.90^\circ$ to the (311) diffraction of Co$_3$O$_4$ (spinel structure). The XRD pattern of the mixed CoRhO$_x$ oxide is characterized by two peaks (Fig. 2d). We assign the larger peak to a diffraction of CoRh$_2$O$_4$. This compound can be formed at 1073 K and higher temperatures (14) and is a normal spinel with Co$^{2+}$ ions at tetrahedral positions and Rh$^{3+}$ at octahedral positions. In the preparation of the mixed oxide we started with equimolar amounts of cobalt and rhodium salts, and therefore, besides CoRh$_2$O$_4$, another cobalt oxide must be present. The position of the weaker diffraction peak in Fig. 2d is equal to the one in Co$_3$O$_4$ (cf. Fig. 2c) and therefore we conclude that the residual cobalt was oxidized to Co$_3$O$_4$.

In order to obtain more insight into the reducibility of the bulk oxides we recorded TPR profiles of the different oxides diluted with Al$_2$O$_3$. The results are presented in Fig. 3. The numbers next to the TPR profiles correspond to the ratios of hydrogen consumed to the total amount of metal in moles. The reduction process of bulk Co$_3$O$_4$ and CoO does not start until 573 K (cf. Figs. 3a and b). It is seen that the profiles for the two bulk oxide samples are very similar, with peak maxima of 685 K for CoO and 703 K for Co$_3$O$_4$. However, for Co$_3$O$_4$ a second maximum at 648 K is observed. The two maxima for Co$_3$O$_4$ suggest a two-stage reduction process. This result is in satisfactory agreement with investigations carried out by Brown et al. (15) and Paryjczak et al. (16). However, the latter group observed a maximum of the main peak in the Co$_3$O$_4$ TPR profile at 673 K, which is 12 K lower than in our case. They even used a higher heating rate as well as a higher gas flow, which in general are known to induce a shift of the peak maximum to higher temperature (17). The observed H$_2$/M value of 1.02 for CoO is consistent with the theoretically expected value of 1.00. Note that the H$_2$ consumption in the TPR has been calibrated by means of Co$_3$O$_4$ (i.e., CoO$_{1.33}$). The TPR profile of bulk Rh$_2$O$_3$ is characterized by a sharp single peak at 408 K (Fig. 3d). The observed H$_2$/M value of 1.56 is equal to the theoretical value within experimental error.

The reduction of the oxidized Co–Rh al-
loy with an atomic Co/Rh ratio of 1 takes place within the temperature range of 453–523 K (Fig. 3c). According to the XRD results the mixed oxide consists of CoRh$_2$O$_4$ and Co$_3$O$_4$; the theoretical H$_2$/M value is therefore 1.33. Within the experimental error, the observed H$_2$/M value of 1.39 is in accordance with this. A striking feature is that the reduction profile is characterized by a sharp single peak. This indicates that the phase-separated Co$_3$O$_4$ is nevertheless in intimate contact with CoRh$_2$O$_4$ and that the latter serves as a catalyst for the reduction of Co$_3$O$_4$, because the Co$_3$O$_4$ is already completely reduced at a temperature at which it would just start to reduce without the presence of cobalt rhodate (cf. Fig. 3a).

Co, Rh, and Co–Rh Supported on γ-Al$_2$O$_3$

The hydrogen chemisorption results for Co, Rh, and Co–Rh on γ-Al$_2$O$_3$ are summarized in Table 1. The H/M values for a 4.70 and a 8.53 wt% Rh/γ-Al$_2$O$_3$ are also given. By a linear interpolation between these two values one obtains a value of H/M = 0.84 for a 7.75 wt% Rh catalyst. This loading corresponds to the same ratio of moles of metal to surface area of the support as for the monometallic cobalt catalyst, and dramatically demonstrates the high difference in dispersion of cobalt and rhodium on Al$_2$O$_3$. The high ratio of H/Rh = 1.53 for the 2.3 wt% Rh/Al$_2$O$_3$ catalyst has been commented upon in another publication (18). It can be clearly seen that the dispersion of the bimetallic catalysts increases with rhodium content. As described in the Experimental section, we admitted hydrogen at 473 K. Although, in contradistinction to rhodium, adsorption of hydrogen on cobalt is an activated process (19), we did not observe an effect of temperature on the ultimate amount of adsorption. However, adsorption was accelerated, and equilibrium was reached much faster.

TPR, TPO, and TPD profiles of the aluminasupported Co, Co$_4$Rh, and Rh catalysts are shown in Fig. 4. The numbers next to the profiles correspond to the ratio of the amount of gas consumed to the total amount of metal. Reduction of the 4.44 wt% Co/γ-Al$_2$O$_3$ catalyst after impregnation and drying occurs within the temperature range 443–653 K and is characterized by a single broad peak with its maximum at 543 K (Fig. 4a). The theoretical H$_2$/M value for the reduction of Co$^{2+}$ to metallic Co is 1.00. The observed H$_2$/M value of 1.75 exceeds the theoretical value because of the simultaneous reduction of residual nitrate
TPR AND TPO OF Co–Rh/Al₂O₃, I

The reduction of the impregnated and dried 2.30 wt% Rh/γ-Al₂O₃ catalyst already starts at 273 K (Fig. 4a). The TPR profile peaks at 363 K and has a weak tail up to 773 K. This peak is assigned to the reduction of well-dispersed RhCl₃, probably bound to the support in the form of −(OH)₃−RhCl₃ complexes (the hydroxyl groups of which belong to the support), or of hydrolyzed Rh³⁺ ions (18). The reduction behavior of these species might be similar to the one of passivated or oxidized highly-dispersed rhodium. No crystalline RhCl₃ is present because in that case the peak maximum would have been at about 413 K (20).

As hydrogen consumption is only caused by the reduction of rhodium ions to metallic rhodium the observed H₂/M value of 1.50 indicates that the starting material was indeed in the +3 oxidation state.

A striking feature of the TPR profiles for the bimetallic catalysts is that the impregnated and dried Co₄Rh and CoRh supported catalysts are already reduced to a great extent before the reduction of the monometallic cobalt catalysts even starts. This indicates that the initiation of the reduction of the cobalt salt is aided by the presence of rhodium. The catalytic effect of rhodium can be explained by assuming that the very first formed metallic rhodium acts as a nucleation center. (Note that supported rhodium chloride is reduced before the reduction of cobalt nitrate starts.) At these sites hydrogen molecules are dissociated to yield hydrogen atoms which are more reactive in reduction than the molecules and consequently reduce the cobalt nitrate earlier. The maxima of the TPR profiles corresponding to the bimetallic systems are shifted to higher temperatures compared to the one of the impregnated monometallic rhodium catalysts. The shift is more pronounced with increasing cobalt content. The positions of the maxima are at about 413 K, the same temperature at which crystalline RhCl₃ is reduced. For the same reason as mentioned for the reduction of supported Co(NO₃)₂ the observed H₂/M values for both supported bimetallic catalysts cannot be used to determine the degree of reduction of the catalysts.

The TPR results demonstrate that the more noble metal Rh catalyzes the reduction of the salt of the less noble metal. For such a catalyzed reduction to take place, the metal salts should either be close together, or the reduced metal atoms must be able to diffuse over the support surface and aid in the reduction of the metal ions they encounter. Since cobalt and rhodium are completely miscible, it is logical to assume that bimetallic Co–Rh particles will be formed during reduction. On the other hand, an alternative explanation for the catalyzed reduction of the cobalt salt might be that hydrogen atoms are being spilled over from metallic rhodium particles to the support and that these hydrogen atoms reduce the cobalt ions. In that case, separate rhodium and cobalt particles might be formed. In the following we shall demonstrate, however, that the TPR profiles of passivated Co–Rh catalysts are different from those of monometallic Co or Rh catalysts (vide infra). This proves that metallic Co and Rh particles are not separately present on the support after reduction. Furthermore, we shall demonstrate in a subsequent publication on Co–Rh/SiO₂ catalysts that the EXAFS (Extended X-Ray Absorption Fine Structure) Rh K-edge spectrum shows that rhodium atoms in the reduced catalyst have rhodium as well as cobalt neighboring atoms (21). Because of the fact that part of the cobalt dissolves in the Al₂O₃ support (vide infra), this EXAFS experiment did not give unequivocal results for Co–Rh/Al₂O₃ catalysts. Furthermore, Mössbauer and ESR experiments on comparable Fe–Rh and Ni–Rh catalysts, respectively, demonstrated that also after reduction of these catalysts bimetallic (alloyed) catalysts were formed. Thus the Mössbauer spectrum of a Fe–Rh/SiO₂ catalyst showed a single peak due to alloyed Fe and no peaks of monometallic Fe (22), while ESR showed a strong peak due to superparamagnetic Ni in a re-
duced monometallic Ni/SiO₂ catalyst, and no ESR signal in a reduced Ni-Rh/SiO₂ catalyst. Apparently, alloying of Ni with Rh suppresses the Curie temperature substantially (23).

The hydrogen chemisorption results show that the dispersions of the bimetallic catalysts and the monometallic cobalt catalyst are significantly lower than that of the monometallic rhodium catalyst (cf. Table 1). This raises the intriguing question by what factors the dispersions of these catalysts are determined. We will first focus our attention on the monometallic systems. Beyond all doubt the interaction between cobalt and alumina is stronger than the interaction between rhodium and the support. It appears that in Co/Al₂O₃ cobalt always forms a cobalt spinel, possibly as an epitaxial layer between the γ-Al₂O₃ and the cobalt metal (24). Interactions based on interdiffusion of metal oxides with the oxidic support are strong. However, from the hydrogen chemisorption results it is clear that rhodium is much better dispersed on alumina than is cobalt. Although we must make a correction for the loss of cobalt metal caused by cobalt aluminate formation (see below), which when taken into account leads to an increase of the cobalt H/M value, the H/M value for the really metallic part of the monometallic cobalt catalyst will not exceed 0.20. The low dispersion can only be understood when it is assumed that before reduction the cobalt was poorly dispersed on alumina. This might be explained by sintering of cobalt oxide, which is formed by decomposition of Co(NO₃)₃ during drying of the impregnated catalyst. The change in color during drying of the impregnated catalyst from violet to black proves the decomposition of Co(NO₃)₃. Another explanation might be that no sites for the adsorption of cobalt ions are present. The pH of the aqueous solution of cobalt nitrate used for the impregnation is about 3, which means that the hydroxyl groups of the support are protonated to —OH⁺. Therefore, the adsorption of cobalt ions which are present as Co(H₂O)₆³⁺ in solution might be hindered by repulsion.

RhCl₃ does not suffer from adsorption problems because it is present as a neutral molecule RhCl₃(H₂O)₃ in an acidic aqueous solution, or even as an anionic chloride complex. An explanation for the relatively low H/M values observed for the bimetallic catalysts might be that during coimpregnation and drying the metal salts have not been homogeneously spread over the support. This view is supported by the TPR results. The TPR profiles obtained for the impregnated bimetallic catalysts peak at about the same temperature (413 K) as crystalline RhCl₃, whereas well-dispersed RhCl₃ gives rise to a TPR profile with a maximum at 363 K. Apparently, the presence of cobalt nitrate hinders the formation of a well-dispersed RhCl₃ phase on the alumina surface. During the impregnation a cobalt surface spinel (CoAl₂O₄) might be formed, through which a modification of the alumina surface occurs. Adsorption of RhCl₃ might then be hampered. It is obvious that the upper level of dispersion for a metal catalyst is already determined in an early stage of preparation with the choice of metal precursor.

The TPO profiles (Fig. 4b) of the four systems supported on alumina show oxygen consumption already at 223 K due to chemisorption. From the observed O₂/M values one can determine the degree of reduction of the catalyst after the first TPR by assuming that after oxidation CoO and Rh₂O₃ are formed. Oxidation of the reduced monometallic cobalt catalyst already starts at 223 K and is complete at about 650 K. Maximum oxygen consumption takes place at 483 K. The observed O₂/M value of 0.43 indicates that the average oxidation state of cobalt after the first TPR, and before the TPO measurement, was +0.71. TPO profiles of a reduced 1.00 and a 2.02 wt% Co/γ-Al₂O₃ catalyst (not shown) displayed hardly any O₂ consumption. The average oxidation states of cobalt in these catalysts after reduction were calculated to be, respec-
The formation of CoAl₂O₄ in the three cobalt catalysts, mentioned above, after the first TPR and a subsequent passivation has been determined using UV reflectance spectroscopy. The CoAl₂O₄ signal hardly differed in intensity for these catalysts. Therefore, we conclude that after reduction of the 4.44 wt% Co/γ-Al₂O₃ catalyst CoAl₂O₄ as well as metallic cobalt were formed and that during the subsequent TPO only the metallic cobalt was oxidized to Co₃O₄. It is known that after calcination of a Co/Al₂O₃ catalyst several types of cobalt species exist on the catalyst surface: these are (i) a species resulting from diffusion of Co ions into tetrahedral lattice sites of γ-Al₂O₃ (often referred to as a "surface spinel" (25)), (ii) Co ions in octahedral sites of the support and/or (iii) "bulk-like" Co₃O₄.

The present results demonstrate that even after a direct reduction of the impregnated and dried cobalt catalyst a significant amount of the so-called "surface spinel" is formed. From the observed O₂/M value it is calculated that the amount of cobalt which had been converted to CoAl₂O₄ was 1.58 wt%.

The TPO profile recorded for the reduced 2.3 wt% Rh/γ-Al₂O₃ catalyst (Fig. 4b) is characteristic for an ultradispersed system. This has been discussed in a previous publication (18). The observed O₂/M value of 0.73 indicates that after the TPR run all rhodium was completely reduced and that all rhodium was oxidized to Rh₂O₃ during the TPO run. The TPO profiles for the two reduced bimetallic catalysts demonstrate that oxidation of the catalyst is more difficult with increasing rhodium content. The TPO profiles of the bimetallic catalysts resemble the TPO profile of an 11.64 wt% Rh/γ-Al₂O₃ catalyst with H/M = 0.67 (18). Two areas of oxygen consumption showed up in that profile, namely a peak around room temperature, attributed to corrosive chemisorption and one around 723 K, attributed to thorough oxidation, respectively (18). The dispersions of the bimetallic systems are lower than that of the 11.64 wt% Rh/γ-Al₂O₃ catalyst (see below). Since the latter shows the same TPO profile we assign the oxygen consumption above 573 K to thorough oxidation of rhodium.

From the observed O₂/M values, we cannot calculate the exact amounts of CoAl₂O₄ in the bimetallic catalysts formed after the first TPR, but upper and lower limits can be determined. On the basis of the TPR/TPO results obtained for the monometallic rhodium catalyst we assume that rhodium in the bimetallic system can be reduced to Rh⁰ during TPR and completely oxidized to Rh₂O₃ during TPO. The upper limit of the amount of CoAl₂O₄ formed after the first TPR is obtained when assuming that the metallic cobalt during TPO was oxidized to Co³O₄, and the lower limit when it is assumed that the cobalt was oxidized to CoO. We thus calculated that the amounts of Co in the form of CoAl₂O₄ for the Co₄Rh and CoRh supported catalysts were 1.43–1.87 and 0.99–1.23 wt%, respectively. We feel that the upper limits are more realistic than the lower limits. For the monometallic catalysts we assumed the formation of Co₃O₄ and calculated 1.58 wt% Co in CoAl₂O₄. This indicates that the presence of the Rh does not prevent the formation of CoAl₂O₄ very much.

Having obtained an indication of the amount of CoAl₂O₄ present in the catalysts, one can calculate the dispersion of the truly metallic part of the catalyst. The results of this calculation are presented in the last column of Table 1 (upper limits for CoAl₂O₄ have been used). These results indicate that metal dispersion improves appreciably with increasing rhodium content. Since, as we shall see, the surface of Co–Rh particles is enriched in Co, this suggests a way of obtaining high Co dispersions.

Reduction of the oxidized monometallic cobalt is difficult (Fig. 4c) and incomplete at 773 K. The TPR profile is characterized by two peaks, one at about 600 K and the other at about 680 K. Comparison of the profile for bulk Co₃O₄ (Fig. 3a) with the one for
supported cobalt oxide indicates that also in the catalyst the reduction of Co$_3$O$_4$ is a sequential process. This result is in accordance with the TPR results reported by Paryjczak et al. (16). TPR experiments carried out in another TPR apparatus, in which higher final reduction temperatures could be reached, demonstrated that the temperature had to be raised to 1373 K in order to reduce the oxidized cobalt catalyst completely. Hydrogen was consumed to a great extent between 1073 and 1373 K probably caused by reduction of the surface CoAl$_2$O$_4$ spinel. The ratio of the hydrogen consumed during the second TPR and the oxygen consumed during the TPO preceding the TPR should be 2, because the oxygen consumed is converted to H$_2$O in the subsequent TPR. The values observed in the TPO and subsequent TPR run agree with this factor of 2 within the uncertainty of the measurements. This indicates that the oxidized cobalt formed during TPO was reduced completely during the subsequent TPR up to 773 K and that during TPO no new surface spinel CoAl$_2$O$_4$ was formed.

Reduction of supported Rh$_2$O$_3$ is complete by 400 K. The TPR profile is characterized by a single consumption peak around 363 K followed by desorption of H$_2$. The net H$_2$ consumption amounted to H$_2$/Rh = 1.52, indicating a reduction degree of rhodium after reduction of 100%.

The TPR profiles for the oxidized bimetallic Co–Rh/Al$_2$O$_3$ catalysts demonstrate that the reduction of cobalt oxide is catalyzed by the noble metal, rhodium. The maxima of the TPR profiles for the bimetallic catalysts are shifted toward higher temperatures in comparison with the monometallic rhodium catalyst: $\Delta T = 20$ and $25$ K for, respectively, CoRh/Al$_2$O$_3$ and Co$_3$Rh/Al$_2$O$_3$. Although the possibility of CoRh$_2$O$_4$ formation during TPO cannot be excluded, we are of the opinion that substantial CoRh$_2$O$_4$ formation is not likely because, first, the maximum oxidation temperature of 773 K during TPO is far below the formation temperature of bulk CoRh$_2$O$_4$ ($T = 1073$ K) and, second, on the basis of the TPR results of the bulk oxides we would have expected a peak around 500 K (cf. Fig. 3c). A shoulder around 500 K is observed in the TPR profile of Co$_3$Rh/Al$_2$O$_3$ and this shoulder may be assigned to CoRh$_2$O$_4$ or to cobalt oxide particles with a low rhodium oxide concentration. It is possible that during oxidation a segregation of both metal oxides has taken place and that after oxidation the oxides are not far apart from each other. In that way the very first formed rhodium may serve as a catalyst for the reduction. As in the case of Co/Al$_2$O$_3$, no significant amounts of CoAl$_2$O$_4$ were formed during TPO in the bimetallic catalysts, because the ratios of hydrogen consumed during the second TPR and oxygen consumed during TPO are within the experimental error equal to the theoretical value of 2.

The TPD profiles for the hydrogen-covered catalysts after the second TPR are presented in Fig. 4d. Note that the heating rate of 15 K min$^{-1}$ is slow, so readsorption of hydrogen will take place and therefore no kinetic parameters for hydrogen desorption can be determined. Nevertheless, we used TPD to obtain information about the dispersion via the total amount of hydrogen desorbed. The TPD profile for Rh/Al$_2$O$_3$ is characterized by a main peak at 483 K and a shoulder at 300 K. Above 673 K hardly any hydrogen is desorbed. From the amount of hydrogen desorbed one can calculate a H/M$_{TPD}$ value of 1.26, which is significantly lower than the value obtained by using the hydrogen chemisorption technique (H/M$_{HC}$ = 1.53). We have to take into account that the H/M$_{HC}$ value was obtained after a single reduction, and therefore the difference between the two values might be caused by sintering of rhodium during the TPO and subsequent TPR. The TPD profiles for the three cobalt-containing catalysts are characterized by two areas, one below 623 K which we assign to normal hydrogen desorption, and another above 623 K, which needs closer attention. Although the hydro-
gen adsorption energy for rhodium is reported to be higher than for cobalt, respectively, 113 and 100 kJ (26), our TPD's suggest the contrary. Even at 873 K desorption of hydrogen from cobalt was incomplete. Moreover, the total amounts of hydrogen desorbed largely exceeded the values calculated on the basis of the hydrogen chemisorption results. Therefore, we think that for the cobalt-containing catalysts the hydrogen detected above 623 K originated from another hydrogen source. It is obvious that this phenomenon only occurs in the presence of cobalt. We believe that dehydroxylation of the alumina support might play a very important role. It is known that alumina dehydroxylates above 673 K with the formation of water (27). Therefore, it is possible that during the TPD in the environment of the reduced cobalt crystallites the ratio of the partial pressures of water to hydrogen has become so high that the equilibrium $3 \text{Co} + 4 \text{H}_2\text{O} \rightleftharpoons \text{Co}_3\text{O}_4 + 4 \text{H}_2$ is shifted to the right. This phenomenon has been reported previously by Schuit and de Boer (28) for Ni supported on SiO$_2$. A TPR to 773 K subsequent to a TPD of a cobalt catalyst did indeed show hydrogen consumption caused by reduction of cobalt oxide. However, the amount of hydrogen consumed was a factor of 2 lower than expected on the basis of the TPD results. We think that during TPD between 773 and 873 K, temperatures which had never been reached in the foregoing treatments, part of the oxidized cobalt was converted to the cobalt surface spinel CoAl$_2$O$_4$ which is not reducible below 773 K.

Up to now no direct information about the structure of the bimetallic crystallites could be obtained from the TPR results. Cobalt and rhodium are completely miscible (13) and therefore we assume that the regular solution model is valid, in which case thermodynamics predict that the metal with the lowest sublimation energy will be preferentially in the surface region of the alloy (29). The sublimation energy of cobalt is lower than that of rhodium and as a consequence surface enrichment of cobalt in the reduced Co–Rh particle is to be expected. From Extended X-Ray Absorption Fine Structure measurements we indeed found evidence for cobalt surface enrichment in supported bimetallic Co–Rh particles (21). When a bimetallic Co–Rh particle is exposed to oxygen at room temperature the cobalt enrichment in the surface will be even more pronounced because the interaction between oxygen and cobalt is stronger than that between oxygen and rhodium. This phenomenon is known as “gas-induced surface enrichment” (30). In order to demonstrate the surface enrichment of cobalt we recorded TPR profiles for the passivated catalysts (see Experimental). The profiles are presented in Fig. 5. The TPR profile for the passivated monometallic cobalt catalyst is characterized by a single peak around 513 K. On the assumption that during passivation oxygen is adsorbed dissociatively and that only the surface was
covered by oxygen atoms with an O/M\textsubscript{surface} stoichiometry of 1, the dispersion determined from the amount of hydrogen consumed during TPR is 0.31. This value is much higher than the H/M value of 0.09 measured by hydrogen chemisorption. Therefore, the hydrogen consumed during TPR of the passivated Co/Al\textsubscript{2}O\textsubscript{3} catalyst indicates that corrosive chemisorption had taken place during passivation.

The TPR profile for the passivated Rh/Al\textsubscript{2}O\textsubscript{3} catalysts shows a single consumption peak around 300 K, followed by desorption of H\textsubscript{2}. Passivation of this ultradispersed Rh catalyst has led to corrosive oxygen chemisorption, but not to full oxidation since the hydrogen consumption amounted to 1.20 H\textsubscript{2}/M. Reduction of the passivated bimetallic Co\textsubscript{3}Rh/Al\textsubscript{2}O\textsubscript{3} catalyst occurs mainly in the temperature range 423–523 K, whereas a small shoulder is visible around 350 K. The maximum of the TPR profile is at about 483 K, only 30 K shifted to lower temperature compared to Co/Al\textsubscript{2}O\textsubscript{3}. Apparently, the presence of rhodium does not affect the reduction of the passivated cobalt as much as in the completely oxidized systems (cf. Fig. 4c). This can be explained by the assumption of covering of rhodium by cobalt oxide. Instead of the formation of the first rhodium metal atoms being the nucleation step, now the much more difficult formation of the first cobalt atoms is the nucleation step. The shift of 30 K might be caused by the presence of a few rhodium atoms in the surface. An X-ray photoelectron spectroscopy measurement confirmed that rhodium in the passivated Co\textsubscript{3}Rh/Al\textsubscript{2}O\textsubscript{3} catalyst is still mainly present as metallic Rh (binding energy of Rh 3d\textsubscript{5/2} = 307.2 eV), which indicates that rhodium is hardly affected by oxygen. From the hydrogen consumed during reduction the total amount of oxidized cobalt can be calculated. On the assumption that the total amount of cobalt is oxidized to Co\textsubscript{3}O\textsubscript{4} whereas rhodium is not affected, the theoretical H\textsubscript{2}/M value is 16/15 (4 Co\textsubscript{3}O\textsubscript{4} + 3 Rh + 16 H\textsubscript{2} → 16 H\textsubscript{2}O + 3 Rh + 12 Co). However, from the 3.18 wt\% cobalt 1.43–1.87 wt\% has been lost as cobalt surface spinel. Thus the experimental H\textsubscript{2}/M value of 0.46 must be compared with a theoretical value of 0.59–0.44, which indicates that cobalt was oxidized to a great extent during passivation. Thus, the passivated particles in Co\textsubscript{3}Rh/Al\textsubscript{2}O\textsubscript{3} consist of a rhodium-rich core and an outer shell consisting mainly of cobalt oxide. The shoulder around 350 K can be assigned to either bimetallic crystallites with a substantial amount of rhodium in the outer shell or to a rigorous passivation of small crystallites leading to the same situation as after a full oxidation. The structure of the TPR profile for the passivated CoRh/Al\textsubscript{2}O\textsubscript{3} catalyst is similar to the profile for CoRh/Al\textsubscript{2}O\textsubscript{3} (Fig. 5c), although the shoulder is more pronounced and the main peak is shifted to lower temperatures. The latter indicates an increase of the rhodium concentration in the outer shell.

All results obtained in the foregoing section have been rationalized by a model which represents the formation of bimetal-
lic Co–Rh particles supported on alumina and the change in structure of the particles after different treatments (cf. Fig. 6). After impregnation the metal salts are in intimate contact, as proven by the first TPR (Fig. 4a). During TPR bimetallic Co–Rh particles are formed, the outer shell of which is enriched in cobalt. Besides formation of Co–Rh particles, part of the cobalt reacts with alumina to produce CoA1204 which cannot be reduced below 773 K. When the reduced catalyst is exposed to oxygen, cobalt is oxidized to a great extent and the resulting cobalt oxide covers a rhodium-rich core. In this situation relatively high temperatures are needed to reduce the cobalt oxide because the covered rhodium cannot serve anymore as a reduction catalyst (Fig. 5b). A thorough oxidation of the catalyst induces a remodelling of the bimetallic particle in such a way that Rh2O3 is also exposed, so that a subsequent reduction is enhanced (Fig. 4c). During oxidation no new CoA1204 is formed. After reduction of the oxidized catalyst the bimetallic particles have been reformed. During the subsequent TPD the water formed by dehydroxylation of the alumina surface partly oxidizes cobalt and part of the oxide formed is converted to CoA1204.

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