Matteo Guidotti[a], Beatriz Lázaro[b]
[a]CNR-Istituto di Scienze
e Tecnologie Molecolari
Dip. Chimica IMA "L. Malatesta"
Università di Milano
m.guidotti@istm.cnr.it
[b]Departamento de Química Orgánica
Instituto de Ciencia de Materiales de Aragón
Facultad de Ciencias
Universidad de Zaragoza
blazaro@unizar.es

DEACTIVATION OF MOLECULAR SIEVES IN THE ORGANIC SYNTHESIS

In industrial chemical processes, the progressive deactivation of heterogeneous catalysts is a major economic concern and a careful mastering on the stability of solids has become as essential as controlling their activity and selectivity. The following text gives a rapid overview about the main factors causing deactivation of molecular sieve-based catalysts in the synthesis of organic compounds for intermediate and fine chemical industry.

The term *deactivation* indicates any kind of progressive loss of activity of a catalyst with increasing reaction time. Any sort of catalyst, either homogeneous or heterogeneous, is subject to deactivation and the deactivating processes take place during the intermediate time between the status of fresh catalyst (as-synthesised or as-prepared) and the one of spent catalyst (when the catalytic activity is zero). Nevertheless, deactivation phenomena are particularly relevant for heterogeneous catalysts, since the factors leading to the deactivation of solid systems are more abundant than those occurring for homogeneous ones and, for these reasons, catalyst stability (or catalyst robustness) is one of the most sought-after properties in solid materials together with good activity (in terms of reaction rate and substrate conversion) and high selectivity to desired products.

In petrochemistry and bulk chemicals production, the importance of deactivation phenomena have been acknowledged since long time and a relevant section of literature deals with methods to minimize them by a careful process design [1]. The time scale of deactivation has indeed remarkable consequences on process design, as it may vary from few seconds (as in the case of fluid catalytic cracking, FCC) to several months or years (as in catalytic hydrodesulfurization or in ammonia synthesis). The choice of an appropriate process technology is therefore determined by the deactivation mechanism taking place on/in the het-

erogeneous catalyst and it is essential whenever a successful and economically-viable industrial process has to be developed.

On the contrary, in the field of high added-value organic chemicals synthesis, even if the problem of catalyst deactivation plays a remarkable role as well, since the use of bulky and functionalised reactants is typically a primary cause of activity loss, the importance of catalyst robustness towards deactivation is frequently underestimated, not only at a fundamental research level, but also at small industrial scale [2]. Actually, in the production of fine and speciality chemicals, where the high added-value of the final compounds may account for the use of valuable and costly reactants, the solid catalyst is often considered as a consumable reagent and it is not worth to be recovered, regenerated and reused. The spent catalyst is thus disposed of and substituted by a fresh one.

However, by following this simplicistic point of view, the peculiar advantages and benefits due to the use of a heterogeneously-catalysed production process instead of a non-catalytic stoichiometric one are lost. The ever-increasing attention towards the economical and environmental sustainability of organic chemical production is thus prompting the scientific community to develop solid catalysts that are less prone to deactivation [3].

Factors leading to deactivation of molecular sieves in organic synthesis

Catalyst deactivation can be either *irreversible* or *reversible*. In the first case, the catalyst undergoes a permanent modification that alters irremediably its catalytic functionalities. In the second case, the activity of the spent catalyst can be partially or totally restored by defined chemical and/or physical treatments, such as calcination, reduction, extraction with solvents, washing, etc. These methods are usually referred to

as *regeneration*, if the catalyst activity is totally (or almost totally) recovered or as *rejuvenation*, if only a part of the activity is restored, by simpler and less drastic treatments, so that the final disposal of the solid is postponed. It is worth underlining however that, practically in all cases, only a limited number of reactivation cycles is possible and the catalyst's life always ends with a form of irreversible deactivation.

Then, five causes of deactivation are generally considered, namely (Fig. 1):
1) poisoning;
2) fouling;
3) thermal degradation;
4) detrimental interaction with the reaction mixture;
5) mechanical degradation.

Such classification, that is valid for any kind of heterogeneous catalyst, can be applied also to the specific case of catalysts based on microporous and mesoporous materials.

Poisoning

Poisoning is caused by the strong, specific chemisorption of inhibiting species onto the catalytically active sites. Such inhibiting compounds can be impurities, feed components (reactants, solvent) and/or reaction products, possessing a remarkable affinity towards the reactive site and hinder the adsorption of less strongly bound compounds. Adsorbed poisoning species not only can block the catalytically active centres by occupying its free coordination sites, but also can change the electronic and/or the geometric structure of the active sites, thus affecting the catalytic behaviour of the whole system. Especially, in fine organic chemicals synthesis, where the reaction are typically carried out in liquid phase and the reaction mixture may contain a wide variety of by-products originated during the previous synthetic steps, a
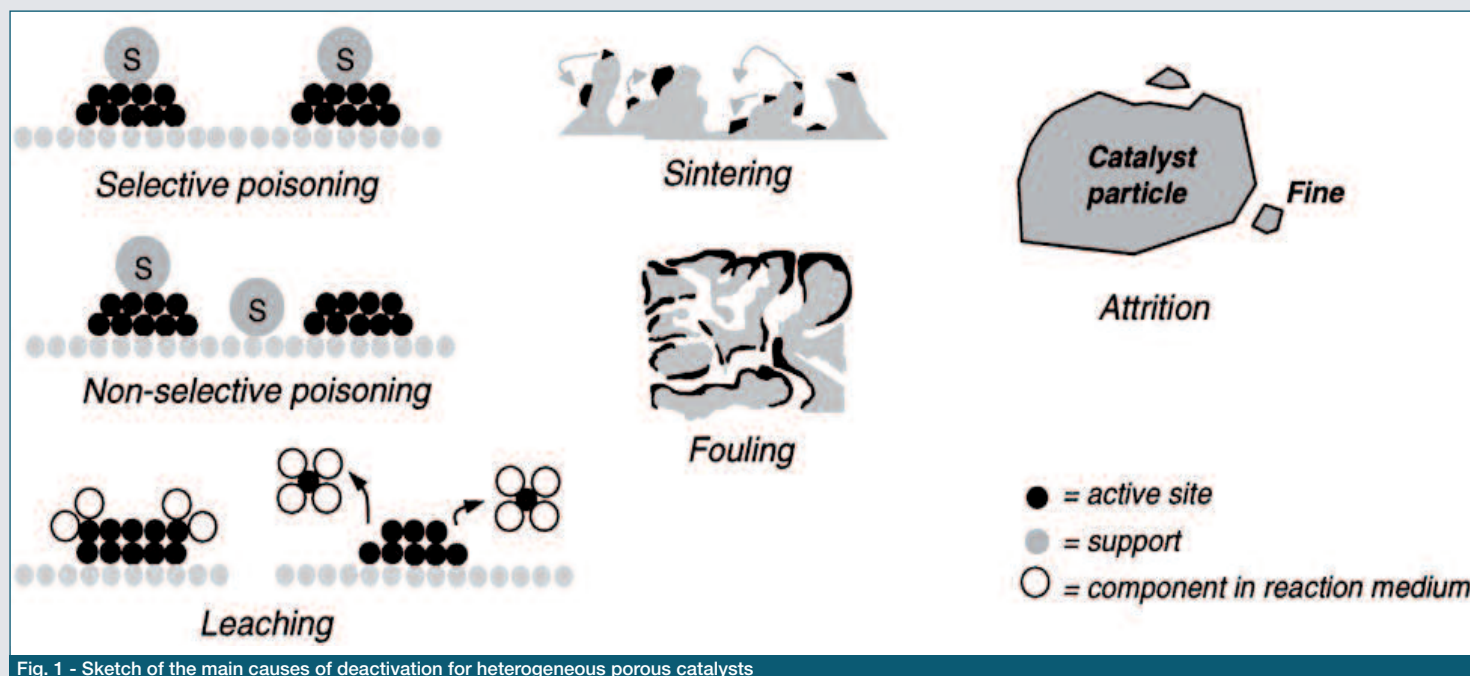

Fig. 1 - Sketch of the main causes of deactivation for heterogeneous porous catalysts

careful purification of the reactant feed is crucial to minimize the occurrence of undesired poisoning phenomena. Nevertheless, in several cases, deactivation can also be originated by poisoning of the active sites by desired reaction products (*autoinhibition*) and this often occurs when the products possess a higher polar character than that of the starting reagents.

Fouling

Fouling is a general term to describe all the phenomena in which the catalyst surface is covered by species from the fluid phase and which block the connection between the active sites and the reaction mixture. Fouling is not selective and occurs on the catalytically active sites as well on the non-active support. In particular, in the case of metal sites supported onto an oxidic support fouling species can also encapsulate the metal particles, thus hindering any activity. This kind of deactivation is particularly frequent on microporous and mesoporous materials, since complex mixtures of (undefined) carbonaceous deposits and/or species resulting from catalyst degradation (*e.g.* extra-framework species resulting from dealumination of a zeolite) are the primary causes limiting or blocking the access of reactant molecules to the active sites [4]. The effects of fouling can be even more dramatic in the case of solids with one-dimensional porous network systems, such as MOR or MWW (MCM-22) zeolites or HMS and MCM-41 mesoporous materials. In these cases, even minimal amounts of carbonaceous compounds deposited at pore openings are able to block the access to the entire pore and lead to a quick and complete deactivation of the catalyst. For such reasons, if the formation of carbonaceous deposit is a major problem, the use of porous catalysts with a open three-dimensional channel system is recommended. In addition, in the synthesis of organic chemicals, the use of highly-functionalised molecules may easily lead to the formation of heavy and bulky deposit and this phenomenon is the main cause of deactivation for nanostructured porous catalysts. However, the large variety in the composition of heavy non-desorbed carbonaceous deposit led to some confusion in literature and the general term *coke* has often been used with different meanings. Most authors designate as *coke* only the polyaromatic species that is formed, typically, in petroleum processing industry (reforming, fluid catalytic cracking, hydroisomerization, hydrotreatment, etc.) and whose composition is similar to polycondensated hydrocarbons, as 'carbon coke'. Anyway, in several examples, complex mixtures of non-desorbed products formed during the synthesis of organic chemicals are called *"coke"* as well, even though they may contain high percentages of heteroatoms, such as oxygen or nitrogen. The composition of fouling species depends mainly on the type of catalyst, the nature of the feed and operating conditions (in particular, temperature) and the mechanism leading to the formation of them can change remarkably from one reaction to another. In general, a great deal of work has been done in understanding the reasons leading to fouling in petroleum processing or in bulk chemical synthesis. In these cases, a deep comprehension of the mechanism of fouling formation can allow one to set up better reaction conditions and to develop more robust catalysts. On the contrary, in the case of fine and speciality chemicals synthesis (in particular at laboratory scale) the study of the fouling mechanism, case by case, can be often cumbersome and time-consuming and the approach to minimize the effect of it is mostly based on non-specific removal of the fouling species by calcination or solvent washing, rather than on targeted countermeasures.
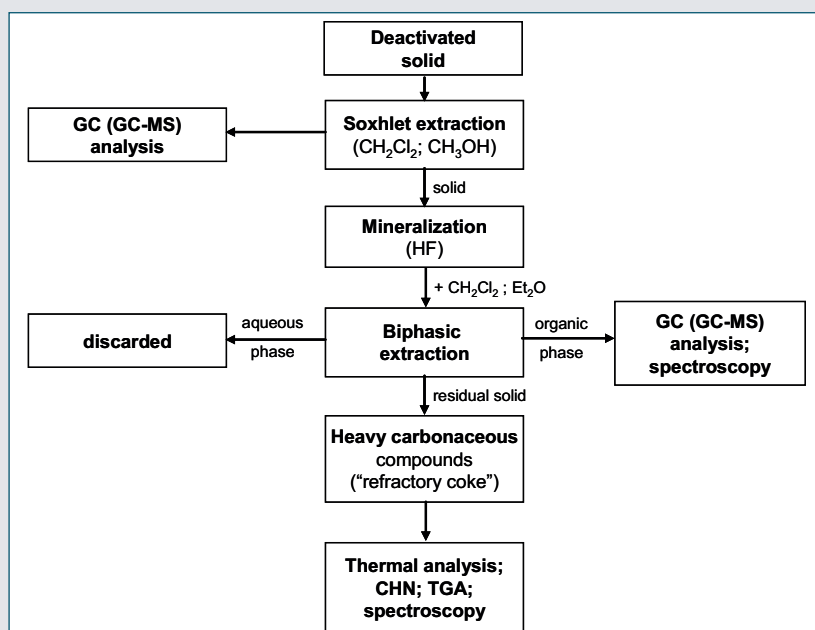
Thermal degradation

Thermal degradation summarizes all the processes leading to deactivation induced by high temperatures, such as sintering, chemical transformations, evaporations, etc. In the case of metal-supported catalyst, sintering of the catalytically-active sites is a primary cause of activity loss, in particular when the reactions are carried out in gas/vapour phase and under non-inert atmosphere (*e.g.* under hydrogen or oxygen). The active sites, that in the fresh catalyst are well separated as metal nanoparticles or, ideally, as isolated sites, can move and coalesce by volatilization or surface mobility, both induced by high temperatures. Such processes cause a loss of exposed and available catalytic surface area and therefore a diminution of the global activity. Furthermore, in some specific cases, the increase in the dimension of the active phase can also lead to the loss of specific catalytic features due to its nanometric size.

The loss in catalytic activity can also be due to a decrease in support surface area, because of a (partial/total) collapse of the porous structure, induced by high temperatures, and hence the encapsulation of active centres. In fact, the formation of hot spots throughout the catalyst structure during the reaction and a poor diffusion of heat flows (especially in fixed-bed catalysts) can cause the partial melting of the support or the collapse of the porous network. The loss of structural stability and, therefore, of catalytic activity is often a critical factor in the case of mesoporous oxidic materials. As an example, the co-presence of high temperatures and water or of high temperatures and alkaline compounds can be particularly detrimental for silica based mesoporous materials and such kind of deactivation is, for its nature, irreversible. Thermal degradation can occur in all stages of the life cycle of the catalyst and, curiously, can also take place during regeneration of rejuvenation treatment of the catalysts, where the high temperature reached to remove the poisoning or fouling species adsorbed onto the catalyst surface, can induce and accelerate sintering mechanisms.

Detrimental interaction with the reaction mixture

The interaction of the solid catalyst with the reaction mixture (either under gas/vapour or liquid phase) can affect negatively the activity of the latter in several ways. Catalyst deactivation can be induced by chemical reaction between the components of the reaction medium and the catalyst. Leaching of active species out of the catalyst is a primary reason of gradual loss of activity and it is particularly critical in liquid-phase reactions [5]. In fact, the presence of highly polar species,

Scheme 1 - Extraction and characterization of fouling compounds in a deactivated molecular sieve catalyst

Diagram content:
- Deactivated solid
- → Soxhlet extraction (CH$_2$Cl$_2$; CH$_3$OH) → GC (GC-MS) analysis
- solid → Mineralization (HF)
- + CH$_2$Cl$_2$; Et$_2$O → Biphasic extraction
  - aqueous phase → discarded
  - organic phase → GC (GC-MS) analysis; spectroscopy
  - residual solid → Heavy carbonaceous compounds ("refractory coke")
- → Thermal analysis; CHN; TGA; spectroscopy

centres, in vacancies or defective sites of the zeolite framework, that are less selective for the studied reaction. Finally, corrosion too can be another sort of negative interaction of the solid catalyst with the reaction mixture. For instance, silica- or alumina-based porous support are not stable in highly alkaline media and the chemical resistance to extreme chemical environment can be also lower when the materials show an open porous structure (*e.g.* a mesoporous network system with thin walls). In such case, since the loss of catalytic properties can be total and irreversible, the only method to avoid deactivation is prevention.

Mechanical degradation
Mechanical degradation is a further factor that can cause catalyst deactivation. It typically appears in catalysts designed for long life cycles and it is mainly studied during the scaling-up or at a pre-competitive development of an industrial process, rather than during the basic investigation at a benchmark scale. Phenomena such as crushing, attrition, friction and/or erosion of the catalyst macroscopic particles shorten the catalyst lifetime and may affect negatively its performance. However, this kind of factors are scarcely treated in open literature papers dealing with the transformation of fine chemicals.

Description of the deactivating species
Four out of five factors of deactivation mentioned above are due to chemical reactions and to the formation of new chemical species that block, poison or, somehow, hinder the desired catalytic process. A thorough understanding of the processes taking place at the catalyst surface or, in the case of molecular sieves, in the catalyst pores relies on analytical investigation techniques. Spectroscopic, thermoanalytical, microscopic, kinetic and modelling studies can all contribute to have a deeper insight into the onset of deactivation mechanisms. However, some specific tests or methods designed to study the nature and the influence of deactivating processes in organic synthesis on molecular sieves will be reported as examples worth citing.

Characterization of fouling compounds
The nature of fouling species, that are the carbonaceous compounds formed and trapped within the pores of a molecular sieve during catalytic reactions, can be systematically studied and analysed by a method originally developed for the study of heavy by-products of hydrocarbon cracking over acid zeolites, that yet can be applied to other organic reactions in gas/vapour or liquid phase [6] (Scheme 1). First, the spent catalyst is treated by Soxhlet extraction with a polar solvent (typically, dichloromethane or methanol) in order to remove the species which are physisorbed on the external surface of the porous solid or loosely adsorbed at the pore openings. The collected extraction solution can be analysed by (gas)-chromatographic techniques, whereas the clean solid can undergo a mineralization step in which the

often bearing complexing and/or solvolytic moieties (such as -OH, -NH$_2$ or -COOH groups), may lead to the dissolution of the active components that are present on the catalyst surface (this is typically the case with metal sites) and thus to the progressive diminution of the amount of active species. Then, the metal species dissolved in liquid phase can be either active as homogeneous catalysts or inactive: in the first case, the homogeneous species can be often much more active in catalysis than the heterogeneous counterpart and, for this reason, the genuine heterogeneous nature of the catalyst must be carefully checked by specific 'heterogeneity tests' (*v. infra*); in the second case, the catalytic process can be defined as heterogeneous indeed, but after a limited number of reaction cycles the catalyst loses its activity, as no active metal sites remains on/in it. Actually, leaching is a relevant phenomenon in oxidation catalysis, where the presence of oxidants, oxidised compounds and polar side products (*e.g.* hydrogen peroxide, organic hydroperoxides, carboxylic acids, alcohols, polyols or water) is remarkable and causes the hydrolytic extraction of high-oxidation-state metal centres (Ti, Mn, V, Cr) out from the inorganic oxide matrix support. However, loss of active species can occur in gas/vapour phase as well. In such case, the phenomenon is described as 'volatilization' or volatile compound formation, rather than leaching. If water is present in the feed stream over crystalline aluminosilicates, a partial dealumination of the zeolite framework can take place causing a partial loss in the stability of the microporous structure and the formation of extra-framework aluminium oxide species. In this special case, if the dealumination process is uncontrolled, not only it may affect the catalyst activity by modifying the amount and the nature of the aluminium sites, but also may have a detrimental effect on its selectivity, since the undesired formation of mesoporous cavities can worsen the shape selectivity of the catalyst or create new catalytic
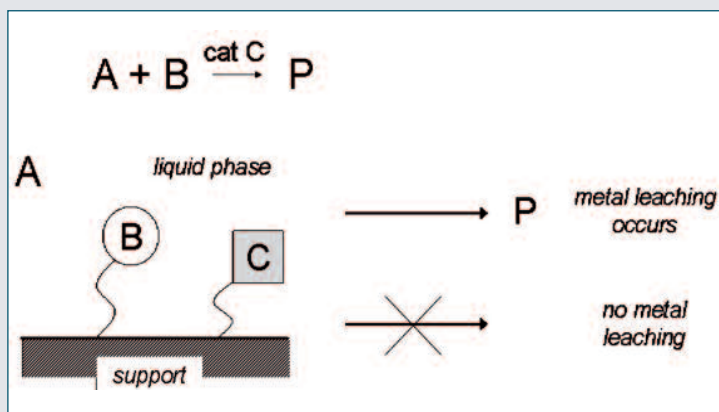
CATALISI

Fig. 2 - Sketch of a generic 'three-phase test' over a molecular sieve

oxidic matrix of the porous material is destroyed. Such mineralization step is based on an attack by means of mineral acids (and hydrofluoric acid, in the case of silicate or alumino-silicate solids), followed by biphasic extraction of the acidic aqueous phase with dichloromethane or diethyl ether. The organic phase typically contains bulky and highly polar compounds and can be analysed by spectroscopic or (gas)-chromatographic techniques as well. The aqueous phase, on the contrary, is not considered and is often discarded. However, it may contain some organic compounds that are soluble in aqueous solutions at very low pH. Whenever a solid residue is present at the end of the mineralization-extraction step, it is usually composed of heavy carbonaceous species (the 'refractory coke', such as the polycondensated graphenic species found in petrochemical processes) and it can be studied by elemental, thermoanalytical, spectroscopic or microscopic techniques. This approach has been also applied successfully to the acylation of aromatics with acetic anhydride, in benzene hydroxylation to phenol with nitrous oxide or in cyclohexanone ammoximation over titanosilicalite-1. As a drawback, this method, although versatile, cannot be used to determine products (or by-products) sensitive to hydrolysis which are present within the molecular sieve network (*e.g.* organic anhydrides, epoxides, acyl halides or metal alkoxides). In fact, the mineralization step in strong acids modify irreversibly the nature of such adsorbed compounds. Anyway, blank tests performed over inert solid samples (pure silica) impregnated with compounds of different reactivity show that the treatment with the acid solution does not cause remarkable chemical changes on the carbonaceous compounds, in most cases. In addition, the same method can also be used to perform competitive adsorption tests with solutions that contain one or more specific reactant(s), in order to measure the affinity of the porous material towards each species and evaluate their tendency to inhibit the reaction (*auto-inhibition*) [7].

Determination of leaching

In a previous section, the crucial role of a 'heterogeneity test' to assess the absence (or the presence) of leaching has been pointed out. It is common practice nowadays that all good-level papers in literature, claiming the use of a novel heterogeneous catalyst, report the *hot-fil-*

tration heterogeneity test as a basic requirement. Such test was originally established to verify the stability of zeolites and zeotypes in liquid-phase oxidations [5], but it can be (and it is actually) applied to any kind of catalytic reaction carried out in liquid phase over solids.

Generally, with respect to metal-containing molecular sieves, three different scenarios are considered for heterogeneous catalysts in a liquid phase: i) the metal is stable, it does not leach out and the catalyst is truly heterogeneous; ii) the metal leaches out from the solid, but it is not active in liquid phase as a homogeneous catalyst; iii) the metal leaches out from the solid and it works as a highly active homogeneous catalyst. Clearly, the solid catalyst is truly heterogeneous only in the first two cases, whereas in the third it is not.

From a practical point of view, the 'heterogeneity test' consists in removing the solid catalyst (by filtration or ultracentrifugation) from the reaction mixture, at the reaction temperature, during the course of the reaction (typically when the conversion is almost the half of the maximum attainable value). Then, the liquid mixture (with no solid) is allowed to react further under identical conditions. If the reaction does not proceed further, there is a strong confirmation of the genuine heterogeneous nature of the catalyst. It is necessary to take care while removing the solid from the reaction mixture, to avoid eventual re-adsorption or change in the nature of the leached species (*e.g.* polymerization, degradation or oxidation/reduction to inactive secondary products). Furthermore, other kind of tests demonstrating that the solids can be recovered and recycled without apparent loss of activity or loss of active species (measured by elemental analysis after some catalytic runs) are not enough to prove that the reaction is heterogeneous in nature. In fact, very low amounts (hence difficult to be detected) of highly active species in solution are sometimes enough to have a fast homogeneously-catalysed process.

Nevertheless, it must be recalled that the occurrence and the extent of metal leaching depends on the kind of reaction and on the operating conditions. For this reason a catalyst heterogeneity test has to be proven for each reaction and/or for each combination of reactants/solvents/conditions under study.

Nevertheless, in some very particular cases, the *hot-filtration heterogeneity test* can be not exhaustive, since it may fail to detect active species which possess limited lifetime in solution, but which are continuously supplied by the solid catalyst. In this case, a more stringent (but more laborious) way to detect metal leaching is the so-called *three-phase test*, according to which one of the reactant and the catalytically active sites are irreversibly bound to an insoluble solid support (*e.g.* covalently) (Fig. 2) [8].

Under such conditions, only soluble active metal species, released by the active sites, are able to reach the heterogenised reactant and therefore the formation of a heterogenised reaction product is a conclusive proof for the existence of a metal leaching. The test was originally conceived as a mechanistic probe based on solid-phase chemistry for the detection of reactive intermediates, but it was later applied to several domains, including the evaluation of minimal traces of Pd in

the Heck and Suzuki coupling of aryl halides over a Pd-containing mercaptopropyl-modified mesoporous silica SBA-15 [9].

Deliberate and selective poisoning of catalytic sites

Deliberate poisoning of catalytically-active sites with selected molecules can also be a diagnostic tool to determine their nature and location within the porous catalyst. For instance, the strong acid-base interaction between base molecules (amines, pyridines, quinolines, etc.) and acid sites has been used to determine the Lewis or Brønsted character of the acid centres and to quantify them by IR spectroscopic analysis, in zeolite or zeotype catalysts used for hydrocarbon processing as well as in organic chemicals synthesis [10]. However, selective poisoning is also used as a tool to investigate reactivity, as reported in several papers. For instance, the targeted deactivation by poisoning of titanium sites in Ti-MWW zeolite (Ti-MCM-22) helped to clarify the causes of the outstanding stereoselectivity recorded on such catalyst, with respect to other widely-used titanosilicate systems [11]. Ti-MWW indeed is able to epoxidise selectively *trans* isomers starting from equimolar mixtures of *cis/trans* linear alkenes, with *trans*-stereoselectivity up to 80%. The use of amines of various molecular size and steric hindrance (such as tripropylamine, 2,4-dimethylquinoline and triphenylamine) allows one to poison either exclusively the Ti sites located at the external cups of the MWW structure or all the Ti sites indistinctly. Analogously, a similar use of amines with different molecular sizes (such as triethylamine and triphenylamine) helped in clarifying the key role of internal Ti sites in the ammoximation of cyclic ketones over TS-1 [12]. Only triethylamine, which is able to enter the micropore network of MFI zeolites, leads to a remarkable decrease in activity, whereas with triphenylamine, that is able to poison the outer surface only, a minimal decrease in activity was observed.

Finally, the selective poisoning can be also exploited not only as a means of investigation, but also as a tool to improve the catalytic performance of the materials.

Conclusion

There are hundreds of cases reported in open and patent literature, which are representative examples of the above mentioned general concepts. Deactivation is a widespread phenomenon when micro- or mesoporous molecular sieves are used as catalysts in the synthesis of organic compounds. Nevertheless, it is often overlooked, especially in fine and specialty chemical synthesis carried out under batch conditions and heterogeneous catalysts are frequently considered as consumable reactants that have to be changed and disposed of when they are inactive. Such approach can be the reason of the poor attention paid to a deep understanding of the deactivation mechanisms, in many research works at lab-scale, and of the most appropriate countermeasures to improve catalyst's lifetime. The lack of such piece of information is often a major limitation hindering or, at least, slowing down the development of processes at industrial level based on zeolites or zeotypes and induces many small-scale producers of fine chemicals to go on using conventional non-catalysed (or homogeneously-catalysed) synthetic pathways, even if they show scarce environmental sustainability. The proper comprehension of the various deactivation phenomena occurring the catalytic act is therefore a fundamental step when sustainable heterogeneously-catalysed organic chemical processes have to be studied and developed.

Bibliografia

[1] R.J. Farrauto, C.H. Bartholomew, Fundamentals of Industrial Catalytic Processes, Chapman & Hall, Kluwer Academic Publishers, London, 1997.

[2] D.Y. Murzin, T. Salmi, *Trends Chem. Eng.,* 2003, **8**, 137.

[3] M. Guisnet, Deactivation and regeneration of zeolite catalysts, Imperial College Press, London (UK), 2011, in press.

[4] M. Guisnet, in Handbook of Heterogeneous Catalysis, G. Ertl *et al.* (Eds.), VCH, Weinheim, 1997, Vol. 2, p. 626.

[5] R.A. Sheldon *et al., Acc. Chem. Res.,* 1998, **31**, 485.

[6] M. Guisnet, P. Magnoux, *Appl. Catal. A: Gen.,* 2001, **212**, 83.

[7] D. Rohan *et al., J. Mol. Catal. A: Chem.,* 1998, **129**, 69.

[8] J. Rebek, F. Gavina, *J. Am. Chem. Soc.,* 1974, **96**, 7112.

[9] J.M. Richardson, C.W. Jones, *J. Catal.,* 2007, **251**, 80.

[10] E. Selli, L. Forni, *Micropor. Mesopor. Mater.,* 1999, **31**, 129.

[11] P. Wu, T. Tatsumi, *J. Phys. Chem. B,* 2002, **106**, 748.

[12] A. Zecchina *et al., Catal. Today,* 1996, **32**, 97.

RIASSUNTO

Disattivazione di catalizzatori porosi nelle sintesi organiche

Nei processi chimici industriali basati sull'uso di catalizzatori eterogenei, uno dei problemi principali è rappresentato dalla progressiva disattivazione dei sistemi solidi, tanto che è ormai essenziale avere un attento controllo non solo sull'attività e sulla selettività di questi sistemi, ma anche sulla loro stabilità. Grazie alla comprensione dei meccanismi che conducono alla perdita dell'efficienza catalitica è possibile disporre di misure preventive adeguate e di metodi rigenerativi per i solidi disattivati. Solo catalizzatori solidi con una vita media sufficientemente lunga, soprattutto nel caso di materiali micro- e mesoporosi, possono infatti trovare una potenziale applicazione in processi industriali economicamente e ambientalmente sostenibili. Il presente testo vuole passare in rapida rassegna i fattori più comuni che portano alla disattivazione dei catalizzatori porosi impiegati nella sintesi di composti organici d'interesse per l'industria chimica fine e degli intermedi.

CATALISI