

Materials comprising carbon-embedded iron nanoparticles, processes for their manufacture, and use as heterogeneous catalysts

Background

5 The present invention relates to a material, comprising grains of non-graphitizing carbon with iron nanoparticles dispersed therein. The material according to the invention is catalytically active in a variety of chemical reactions and can be obtained by a facile procedure.

The carbon phase of the invention is largely amorphous and does not appear to be activated
10 carbon, carbon black, graphite, graphitized carbon black or paracrystalline carbon.

The prior art

Significant prior art-efforts have been directed at synthesizing transition metal nanoparticles, including transition metal nanoparticles with catalytic activity in particular. As nanoparticles per se,
15 however, cannot be employed in most heterogeneously catalyzed processes, further endeavors were conducted to develop materials containing transition metal nanoparticles attached to suitable supports, substrates or wafers. Prior art approaches for this purpose were mostly based upon impregnation or chemical vapor deposition of metal precursors onto porous or mesoporous supports (Sietsma, Jelle R. A., et al. „Highly active cobalt-on-silica catalysts for the fischer-tropsch
20 synthesis obtained via a novel calcination procedure.“ Studies in Surface Science and Catalysis (2007); Van Deelen, T. W., et al. "Assembly and activation of supported cobalt nanocrystal catalysts for the Fischer–Tropsch synthesis." Chemical Communications (2018).) or using well defined ligands for the metal species and applying high temperature treatment (Westerhaus, Felix A., et al. „Heterogenized cobalt oxide catalysts for nitroarene reduction by pyrolysis of molecularly
25 defined complexes“ Nature Chemistry (2013); Banerjee, Debasis, et al. „Convenient and Mild Epoxidation of Alkenes Using Heterogeneous Oxide Catalysts“ Angewandte Chemie, International Edition (2014).) Interactions of nanoparticles and support, however, were found to bring about significant limitations (Oschatz, M., et al. „Effects of calcination and activation conditions on ordered mesoporous carbon supported iron catalysts for production of lower olefins from synthesis
30 gas“ Catalysis Science & Technology (2016).) Prior art procedures, in particular, failed to yield materials exhibiting high dispersion and uniform coordination of transition metal- / metal oxide-nanoparticles in combination with high metal content. Most prior art transition metal nanoparticle materials in fact, exhibit rather low active metal concentrations of less than 20 wt% as a result of clustering and a corresponding loss of dispersion of metal particles at higher metal concentrations
35 (Hernández Mejía, Carlos, Tom W. van Deelen und Krijn P de Jong. „Activity enhancement of

cobalt catalysts by tuning metal-support interactions“ Nature Communications (2018); Oschatz, M., et al. „Effects of calcination and activation conditions on ordered mesoporous carbon supported iron catalysts for production of lower olefins from synthesis gas.“ Catalysis Science & Technology (2016)). In view of the fact that materials exhibiting high dispersion and uniform coordination of transition metal- / metal oxide-nanoparticles in combination with high metal content are currently unavailable while such properties are considered as desirable, in order to obtain material with high catalytic activity, there is a need in the art for providing such materials as well as processes for their manufacture.

The present invention provides materials exhibiting the properties desired and a facile process for their manufacture.

The present invention

The present invention relates to catalytically active material, comprising grains of non-graphitizing carbon with iron nanoparticles dispersed therein,

15 wherein

d_p , the average diameter of iron nanoparticles in the non- graphitizing carbon grains, is in the range of 1 nm to 20 nm,

D , the average distance between iron nanoparticles in the non- graphitizing carbon grains, is in the range of 2 nm to 150 nm, and

20 ω , the combined total mass fraction of metal in the non- graphitizing carbon grains, is in the range of 30 wt% to 70 wt% of the total mass of the non- graphitizing carbon grains,

wherein d_p and D are measured by TGZ-TEM as described herein,

25 and wherein

d_p , D and ω conform to the following relation:

$$4.5 d_p / \omega > D \geq 0.25 d_p / \omega.$$

30 Material according to the present invention can be obtained by a process comprising the following steps:

- (a) providing an aqueous solution comprising metal precursor and organic carbon source, wherein the metal precursor comprises one or a combination of more than one organic, at

least partially water soluble, salts of iron, and
wherein the organic carbon source is one or a combination of more than one saturated,
aliphatic di-, tri-, or polycarboxylic acids,

- 5 (b) spray drying or freeze drying the aqueous solution of metal precursor and organic carbon source and, thus, obtaining intermediate product P,
- (c) thermo-treating intermediate product P at a temperature in the range from 200 °C to 380 °C.

10 As a result of research underlying the present invention it was found that grains of non-graphitizing carbon with iron nanoparticles dispersed therein, can be obtained from aqueous solutions of metal precursors and organic carbon sources by combining

- (i) spray drying or freeze drying of the aqueous solution, with
- (ii) thermal treatment at moderate temperatures of the intermediate obtained from step (i).

15 The final product was found to exhibit catalytic activity in a variety of chemical reactions. In the context of the present invention, any material or substance lowering the activation energy of a chemical reaction and thus increasing its rate at a particular temperature, without being consumed by the catalyzed reaction itself, is considered as catalytically active.

Variation of process conditions and examination of the materials obtained, uncovered process conditions and material properties as claimed herein.

20 It was found that forming aqueous solutions of metal precursors and organic carbon sources in glass beakers and slowly drying these solutions overnight in a drying cabinet did not yield intermediate products that could be transformed into grains of non-graphitizing carbon with iron nanoparticles dispersed therein by thermal treatment at moderate temperatures. Specifically, it was found that if the drying process was performed too slowly, significant decomposition of polycarboxylic acids and formation of carbon dioxide started too early, leading to an early loss of oxygen functionalities of the carbon source. An early loss of oxygen functionalities, however, appears to correlate with an agglomeration of metal components and a segregation of metal precursor and carbon source, ultimately yielding an irregular distribution of large size metal clusters within the carbon matrix. Without wanting to be bound by theory, thus, it appears that sufficient availability of oxygen containing functional groups during parts of the drying procedure appears to be essential for fixing metal precursors within the carbon source in a highly dispersed and regular manner.

30

35 It was, furthermore, found that thermo-treating intermediate product P at temperatures below 200 °C and above 380 °C did not yield grains of non-graphitizing carbon according to the invention with iron nanoparticles dispersed therein. In particular, it was found that the proportion of the non-graphitizing carbon phase according to the invention itself decreased when the temperatures

selected for thermo-treating were too high. These phases, however, are putatively related to expedient hydrogen conductivity which, in turn, is essential for efficiently catalyzing reactions involving the conversion of hydrogen. If on the other hand, temperatures selected for thermo-treating were too low or the duration of thermo-treating was too short, the level of residual oxygen
5 in the carbon phase obtained was too high and reduction of metal precursors remained incomplete, leading to lowered catalytic activity as a result.

It should be noted, in addition, that, in view of the prior art, formation of the non-graphitizing carbon phase of the invention, as a result of the process of the present invention, may appear to be surprising. However, without wanting to be bound by theory, it is assumed that formation of non-graphitizing carbon under low temperature conditions of the process of the present invention, is
10 facilitated by the presence of high concentrations of metal precursors in a highly dispersed manner in intermediate product P before subsequent thermo-treating.

The process of the invention yields non-graphitizing carbon material in granular form. Non-graphitizing carbon can be identified by a person of skill using TEM-analysis (cf. P.W. Albers, Neutron scattering study of the terminating protons in the basic structural units of non-graphitizing
15 and graphitizing carbons, Carbon 109 (2016), 239 - 245, page 241, figure 1c).

Experimental results obtained in conjunction with the present invention indicate that catalytic activity of material obtained by the process of the invention, correlates well with its content of grains
20 of non-graphitizing carbon exhibiting the features of the invention.

Typically, 90% of the non-graphitizing carbon grains obtained by the process of the present invention exhibit moderate size, i.e. diameters between 2 μm and 200 μm . It was presently found that, generally, more than 95% of those moderately sized non-graphitizing carbon grains, obtained
25 by the process of the present invention, contain iron nanoparticles dispersed therein that conform to the relation $4.5 d_p / \omega > D \geq 0.25 d_p / \omega$ (with d_p denoting the average diameter of iron nanoparticles in the non-graphitizing carbon grains, D , denoting the average distance between iron nanoparticles in the non-graphitizing carbon grains, and ω , denoting the combined total mass fraction of metal in the non-graphitizing carbon grains). The process of the present invention,
30 typically, yields grains wherein, only the fraction of very small and the fraction of very large grains, i.e. the particle-fractions outside of the moderate size range between 2 μm and 200 μm , contain significant portions of grains wherein iron nanoparticles do not conform to the relation $4.5 d_p / \omega > D \geq 0.25 d_p / \omega$. Accordingly, the process of the present invention, generally, yields materials with a high content of grains containing iron nanoparticles, wherein iron nanoparticles conform to the
35 relation $4.5 d_p / \omega > D \geq 0.25 d_p / \omega$. However, materials with lower contents of these grains may be

obtained by other processes or dilution with other materials and are thus comprised by the present invention as well.

Accordingly, in a preferred embodiment the present invention relates to catalytically active material, comprising grains of non-graphitizing carbon with iron nanoparticles dispersed therein, wherein iron nanoparticles in more than 90% of moderately sized non-graphitizing carbon grains, i.e. non-graphitizing carbon grains with a diameter between 2 μm and 200 μm conform to the relation $4.5 \text{ dp} / \omega > D \geq 0.25 \text{ dp} / \omega$, and wherein further dp, the average diameter of iron nanoparticles in the non-graphitizing carbon grains, is in the range of 1 nm to 20 nm, D, the average distance between iron nanoparticles in the non-graphitizing carbon grains, is in the range of 2 nm to 150 nm, and ω , the combined total mass fraction of metal in the non-graphitizing carbon grains, is in the range of 30 wt% to 70 wt% of the total mass of the non-graphitizing carbon grains.

In another preferred embodiment, the present invention relates to catalytically active material, comprising grains of non-graphitizing carbon with iron nanoparticles dispersed therein, wherein iron nanoparticles in more than 95% of moderately sized non-graphitizing carbon grains, i.e. non-graphitizing carbon grains with a diameter between 2 μm and 200 μm conform to the relation $4.5 \text{ dp} / \omega > D \geq 0.25 \text{ dp} / \omega$, and wherein further dp, the average diameter of iron nanoparticles in the non-graphitizing carbon grains, is in the range of 1 nm to 20 nm, D, the average distance between iron nanoparticles in the non-graphitizing carbon grains, is in the range of 2 nm to 150 nm, and ω , the combined total mass fraction of metal in the non-graphitizing carbon grains, is in the range of 30 wt% to 70 wt% of the total mass of the non-graphitizing carbon grains.

The iron nanoparticles in the non-graphitizing carbon material of the invention are mainly composed of elementary iron but may also contain, for example, iron oxide and/or dopant metal and/or secondary metal.

Computer aided analysis of TEM-pictures (TEM = transmission electron microscopy) coupled with Degussa derived TGZ method allows to determine diameters of individual iron nanoparticles as well as statistical measures of sets thereof (cf. Parker et al. "The effect of particle size, morphology and support on the formation of palladium hydride in commercial catalysts" Chemical Science, 2019, 10, 480).

In the context of the present invention, the average diameter of iron nanoparticles, d_p , and the average distance D is determined by the TGZ-TEM method, as described in the following:

1. Sample Preparation

In most cases, the samples to be tested are available as powders.

The powders are usually dispersed in solvents under ultrasonic application. The ultrasonic application breaks down agglomerates into aggregates and the result is an aggregate distribution rather than a mixture of aggregates and agglomerates. A micro pipette is then used to drop a drop

onto a film-coated mesh lying on a piece of filter paper. The excess liquid is quickly sucked off through the filter paper so that agglomerate formation is prevented by the drying process. The suspended grains must not be too dense, as the shape and outline of the nanoparticles cannot be clearly seen through contact and overlapping of grains. An optimal dilution must be determined by test experiments with a dilution series.

In general, it can be stated that the type of preparation has hardly any effect on the result of the primary nanoparticle size evaluation.

2. Performance of the test

The individual nanoparticles to be characterized on the basis of the TEM images must be imaged with sufficiently sharp contours.

A distribution of the nanoparticles that is not too dense with few overlaps or particles that are as separated from each other as possible on the TEM images facilitates the measurement on the TGZ3, but does not influence the measurement result.

After examining various image sections of a TEM preparation, suitable areas are selected accordingly. It should be noted that the ratio of small, medium and large nanoparticles for the respective sample is representative and characteristic and no selective preference of small or large particles is given by the operator.

The total number of primary nanoparticles to be measured depends on the scattering range of the primary nanoparticle size: the larger the scattering range, the more particles have to be measured to obtain an adequate statistical statement. For metal catalysts approx. 1500 single particles are measured. For all TGZ analysis a calibrated Hitachi H-7500 field transmission electron microscope operated at 100 keV, equipped with a CCD-Camera was used.

3. Description of the measurement procedure

The measurement procedure is done according to the TGZ3 manual by Carl ZEISS ("Teilchengrößenanalysator (particle size analyser) TGZ3"; Manual Fa. Carl ZEISS).

4. Measurement data processing

A detailed description of the measurement data processing is given in (F. Endter u. H. Gebauer, "Optik (Optics)" 13 (1956), 97) and (K. Seibold und M. Voll, "Distribution function for describing the particle size distribution of Soot and pyrogenic oxides". Chemiker-Zeitung, 102 (1978), Nr. 4, 131-135).

The statistical summary is compiled in the form of a report. A detailed statistical description is given in (Lothar Sachs, "Statistical methods", 5. Auflage, Springer-Verlag, Berlin (1982)).

5. Evaluation and Display of Results

- a. Total number of particles (N)
- b. Particle size distributions $q_0(x)$ and $q_3(x)$ evaluated of 1500 isolated nanoparticles per sample
- c. Particle diameter d_n , mean diameter (d_n)

$$d_n = \frac{\sum n_i d_i}{\sum n_i} = \frac{\sum n_i d_i}{n}$$

n_i = number of particles with diameter d_i

- d. Average distance D on rectangular plane

$$D = \frac{1}{a^2 b^2} \int_0^b dy^* \int_0^b dy \int_0^a dx^* \int_0^a \sqrt{(x^* - x)^2 + (y^* - y)^2} dx$$

a, b = length, width of the rectangular plane

x, y, x^* , y^* = particle coordinates.

The combined total mass fraction of metal, ω , is defined as the fraction of the combined total masses of iron and all dopant and secondary metals, of the total mass of the material under consideration: $\omega = (m(\text{iron}) + m(\text{dopant metals}) + m(\text{secondary metals})) / m(\text{material})$; with $m(\text{iron})$ = total mass of iron in elemental form contained in the material in the form of elemental iron itself and/or in the form of any compounds of iron, $m(\text{dopant metals})$ = combined total mass of all dopant metals in elemental form contained in the material in the form of the elemental dopant metals themselves and/or in the form of any compounds of the dopant metals, $m(\text{secondary metals})$ = combined total mass of all secondary metals in elemental form contained in the material in the form of the elemental secondary metals themselves and/or in the form of any compounds of the secondary metals, and $m(\text{material})$ = total mass of material under consideration.

The combined total mass fraction of metal, ω , can be determined by means of all methods for quantitative elementary analysis, in particular XRF (X-ray fluorescence) and ICP-AES (Inductively coupled plasma atomic emission spectroscopy).

A suitable choice of conditions in the process according to the present invention allows to control the combined total mass fraction of metal, ω , in the material obtained:

Processes providing in step (a), solutions with a high metal content (iron and dopant and secondary metals combined), yield materials with a higher combined total mass fraction of metal, ω , than processes providing in step (a) solutions with a lower metal content.

Processes with thermo-treating in step (c) at high temperatures in the range from 200 °C to 380 °C yield materials with a higher combined total mass fraction of metal, ω , than processes with thermo-treating in step (c) at lower temperatures.

The process of the present invention yields granular material. The size of individual particles of this material as well as statistical measures of sets thereof can be determined by means of laser diffraction analysis (e.g. Cilas 1190 Series), well known to persons of skill in this field.

Typically, the process of the present invention yields granular material exhibiting the following
 5 particle size distribution: $d_{10} = 5\mu\text{m}$, $d_{50} = 40\mu\text{m}$, $d_{90} = 150\mu\text{m}$.

In view of the fact that material obtained by the process according to the present invention was found to be very suitable for manufacturing shaped catalysts, in a preferred embodiment the present invention relates to catalytically active material, comprising grains of non-graphitizing carbon with iron nanoparticles dispersed therein,

10 wherein

d_p , the average diameter of iron nanoparticles in the non-graphitizing carbon grains, is in the range of 1 nm to 20 nm,

D , the average distance between iron nanoparticles in the non-graphitizing carbon grains, is in the range of 2 nm to 150 nm, and

15 ω , the combined total mass fraction of metal in the non-graphitizing carbon grains, is in the range of 30 wt% to 70 wt% of the total mass of the non-graphitizing carbon grains,

and wherein

d_p , D and ω conform to the following relation:

$$4.5 d_p / \omega > D \geq 0.25 d_p / \omega,$$

20 and wherein

the non-graphitizing carbon grains exhibit the following particle size distribution: $d_{10} = 5\mu\text{m}$, $d_{50} = 40\mu\text{m}$, $d_{90} = 150\mu\text{m}$.

There may be applications for materials according to the present invention, where the presence of Nitrogen is detrimental. Accordingly, in a preferred embodiment, the present invention relates to
 25 material according to the invention wherein the total mass fraction of nitrogen is less than 1 wt% of the total mass of the material.

Experimental results indicate, that material with relatively small iron nanoparticles may exhibit particularly attractive catalytic properties. Accordingly, in a preferred embodiment, the present invention relates to material according to the invention wherein d_p is in the range of 4 nm to 18 nm.

30 In a particularly preferred embodiment, the present invention relates to material according to the invention wherein d_p is in the range of 6 nm to 14 nm.

As indicated by experimental results, addition of dopant metals affects catalytic activity of the materials of the present invention. Accordingly, in a preferred embodiment, the present invention

relates to material according to the invention wherein the iron nanoparticles have been doped with dopant metal, and wherein the dopant metal is selected from Na (sodium) or K (potassium) or Ca (calcium) or Mg (magnesium) or mixtures thereof, and wherein the material exhibits a molar ratio $RDM = n(\text{iron}) : n(\text{dopant metal})$ in the range of 5 to 1000.

- 5 In a particularly preferred embodiment, the present invention relates to material according to the invention wherein the iron nanoparticles have been doped with dopant metal, and wherein the dopant metal is selected from Na (sodium) or K (potassium) or Ca (calcium) or Mg (magnesium) or mixtures thereof, and wherein the material exhibits a molar ratio $RDM = n(\text{iron}) : n(\text{dopant metal})$ in the range of 10 to 500.
- 10 In another preferred embodiment, the present invention relates to material according to the invention wherein the iron nanoparticles have been combined with a secondary metal, and wherein the secondary metal is selected from group 1 or group 2,
- with group 1 defined as: Mo (molybdenum) or W (tungsten) or mixtures thereof, and
- with group 2 defined as: Co (cobalt) or Cu (copper) or Mn (manganese) or mixtures thereof,
- 15 and wherein the material exhibits a molar ratio $RSM = n(\text{iron}) : n(\text{secondary metal})$ in the range of 1 to 50.

The present invention, further, relates to a process for the manufacture of the materials of the invention. As indicated above, a combination of two process steps was found to be crucial:

- 20 (i) spray drying or freeze drying of the aqueous solution of metal precursor and organic carbon source, and
- (ii) thermal treatment at moderate temperatures of the resulting intermediate.

Accordingly, in another aspect, the present invention is, further, directed at a process for the manufacture of material according to the invention, comprising the following steps:

- (a) providing an aqueous solution comprising metal precursor and organic carbon source,
- 25 wherein the metal precursor comprises one or a combination of more than one organic, at least partially water soluble, salts of iron, and
- wherein the organic carbon source is one or a combination of more than one saturated, aliphatic di-, tri-, or polycarboxylic acids,
- (b) spray drying or freeze drying the aqueous solution of metal precursor and organic carbon
- 30 source and, thus, obtaining intermediate product P,
- (c) thermo-treating intermediate product P at a temperature in the range from 200 °C to 380 °C.

Each of the process steps may be performed in a batch-wise or continuous format.

In another aspect the present invention is, further, directed at materials obtainable by the process of the invention.

As indicated above, formation of the materials of the present invention requires a combination of
5 spray drying or freeze drying and suitable thermal treatment at moderate temperatures.

Accordingly, it appears reasonable to assume that only material present in solution, i.e. in dissolved
form in the solution provided in step (a) of the process, can be transformed into material according
to the invention. However, undissolved matter in solid form may be suspended in solution provided
in step (a) as long as it does not interfere with the process forming the material of the present
10 invention. Such solids, which may, for example, originate from undissolved metal precursor or
organic carbon source, may form solid diluents of the material of the invention in the solid product
obtained after step (c) of the process of the invention. Similarly, organic solvents may be dissolved
or emulsified in the solution provided in step (a) as long as their presence does not interfere with
the process forming the material of the present invention. However, in order to avoid interference
15 with the process forming the material of the present invention, in preferred embodiments, the
process of the invention is performed with aqueous solutions, provided in step (a), that are free of
undissolved matter in solid form as well as free of organic solvents.

If no dopant metal and no secondary metal is used, the metal precursor in the solution provided in
step (a) of the process of the present invention, is one or a combination of more than one organic,
20 at least partially water soluble, salts of iron. In the present context a salt is considered as being at
least partially water soluble, if at least a fraction of the salt dissolves in the aqueous solution
provided in step (a) under the conditions employed in the process. Preferably, if no dopant metal is
used and no secondary metal is used, the metal precursor in the solution provided in step (a) of the
process of the present invention, is one or a combination of more than one, organic salts of iron,
25 whereof the amounts desired to be included into the solution are completely soluble in the aqueous
solution of step (a).

In a preferred embodiment of the present invention no dopant metal and no secondary metal is
used.

In another preferred embodiment of the present invention dopant metal is used but no secondary
30 metal is used.

If dopant metal is used, the metal precursor in the solution provided in step (a) of the process of the
present invention is a combination of one or more organic, at least partially water soluble, salts of
iron, with one or more organic, at least partially water soluble, salts of one or more dopant metals.
Preferably, if dopant metal is used, the metal precursor in the solution provided in step (a) of the
35 process of the present invention, is a combination of one or more organic salts of iron with one or

more organic salts of one or more dopant metals, whereof the amounts desired to be included into the solution are completely soluble in the aqueous solution of step (a).

If secondary metal is used, the metal precursor in the solution provided in step (a) of the process of the present invention is a combination of one or more organic, at least partially water soluble, salts of iron, with one or more organic, at least partially water soluble, salts of one or more secondary metals. Preferably, if secondary metal is used, the metal precursor in the solution provided in step (a) of the process of the present invention, is a combination of one or more organic salts of iron with one or more organic salts of one or more secondary metals, whereof the amounts desired to be included into the solution are completely soluble in the aqueous solution of step (a).

If dopant and secondary metal is used, the metal precursor in the solution provided in step (a) of the process of the present invention is a combination of one or more organic, at least partially water soluble, salts of iron, with one or more organic, at least partially water soluble, salts of one or more dopant metals and one or more organic, at least partially water soluble, salts of one or more secondary metals. Preferably, if dopant and secondary metal is used, the metal precursor in the solution provided in step (a) of the process of the present invention, is a combination of one or more organic salts of iron with one or more organic salts of one or more dopant metals and one or more organic, at least partially water soluble, salts of one or more secondary metals, whereof the amounts desired to be included into the solution are completely soluble in the aqueous solution of step (a).

Preferred organic anions of the metal precursors in the solution provided in step (a) of the process of the present invention are acetate, carbonate, oxalate, citrate, malonate, tartrate and glutarate. If nitrogen does not need to be avoided, nitrate is another preferred anion of the metal precursors in the solution provided in step (a).

Saturated, aliphatic di-, tri-, or polycarboxylic acids, alone or as part of a mixture, may be used as organic carbon sources of the aqueous solution provided in step (a), as long as they support formation of the materials of the present invention. In preferred embodiments, malonic acid, glutaric acid, citric acid or mixtures thereof are used as organic carbon source of the aqueous solution provided in step (a) of the process of the present invention. In a particularly preferred embodiment of the present invention, citric acid is used as organic carbon source of the aqueous solution provided in step (a) of the process of the present invention.

The aqueous solution provided in step (a) is spray dried or freeze dried in step (b) of the process of the present invention. The product obtained therefrom is referred to as intermediate product P in the context of the present invention. Process parameters for spray drying and freeze drying can be varied over a wide range as long as the drying process is performed without interruption and the combined content of water and organic solvents exhibited by intermediate product P, is below 10 wt%. In a preferred embodiment of the present invention the aqueous solution provided in step (a) is spray dried in step (b) of the process of the present invention.

Thermo-treating according to step (c) of the process of the present invention is performed under defined temperature conditions and inert gas atmosphere, e.g. nitrogen, or air. A wide range of suitable furnaces for this purpose is available commercially. In preferred embodiments, thermo-treating is performed under inert gas atmosphere, e.g. nitrogen. Heating rates during thermo-treating should be small enough to allow homogeneous distribution of heat, i.e. typically smaller than 15 K/min, preferably smaller than 10 K/min, and particularly preferred smaller than 5 K/min. Thermo treating intermediate product P is performed at a temperature in the range from 200 °C to 380 °C. In preferred embodiments of the present invention, thermo treating intermediate product P is performed at a temperature in the range from 255 °C to 375 °C. In particularly preferred
10 embodiments, thermo-treating intermediate product P is performed at a temperature in the range from 300 °C to 350 °C. Typically, thermo treating intermediate product P is performed for a duration of 1 to 4 hours, but thermo-treating for longer or shorter intervals of time may work as well. Heating and cooling intervals are not accounted for when determining the duration of thermo treating. In preferred embodiments thermo-treating intermediate product P is performed for a duration of 1 to 4
15 hours.

As indicated above, materials according to the present invention exhibit catalytic activity.

Accordingly, in another aspect, the present invention, further, relates to the use of materials of the present invention as catalysts.

Materials according to the present invention can be used, for example, as catalysts in liquid phase
20 hydrogenations of organic compounds, specifically unsaturated compounds like alkenes and alkynes, aldehydes and ketones, esters and imines, nitro compounds and nitriles. Materials according to the present invention are, further, very active catalysts for the reductive amination of carbonyl compounds. Accordingly, in another aspect, the present invention, further, relates to the use of materials of the invention as catalysts for the hydrogenation of organic compounds and/or
25 the reductive amination of carbonyl compounds.

Materials according to the present invention can also be used as catalysts in the conversion of carbon monoxide, carbon dioxide or mixtures thereof, with hydrogen, to alkenes, alkanes or mixtures thereof. Accordingly, in another aspect, the present invention, further, relates to the use of materials of the invention as catalysts for the conversion of carbon monoxide, carbon dioxide or
30 mixtures thereof with hydrogen, to alkenes, alkanes or mixtures thereof.

Materials according to the present invention may be used as catalysts in unmodified form or may be transformed into catalyst bodies by shaping processes (e.g. tableting, pelletizing, extrusion, coating, 3D-printing), well known to persons of skill in the art.

Examples

Examples Fe a,b – Preparation of carbon embedded Fe-nanoparticles

Carbon embedded Fe-nanoparticles were prepared by dissolving 14.4 g citric acid (puriss, Sigma Aldrich) in 75 mL of deionized water under constant stirring at room temperature. In a second
 5 beaker 18.7 g Iron(II)-acetate ($\text{Fe}(\text{CH}_3\text{COO})_2$, Sigma Aldrich) was dissolved in 75 mL of deionized water under constant stirring at room temperature. The Iron-acetate solution was slowly added to the citric acid solution and stirred for another 30 min at room temperature. The resultant solution was spray dried using a conventional mini spray dryer (Büchi, Mini Spray Dryer B-290) with constant inlet temperature of 220°C, outlet temperature of 120°C and 20% pump speed. The
 10 obtained powder was split into two fractions with identical mass for the final thermo-treatment.

The first sample was thermo-treated in a tubular furnace under nitrogen atmosphere, with a 180 min ramp to 300°C, where temperature was maintained for another 4 h followed by natural cooling down. The resultant catalyst powder was labeled FeCat. 1a.

The second sample was thermo-treated in a similar fashion under nitrogen atmosphere. The
 15 sample was heated up to 350°C within 180 min where temperature was maintained for 4 h followed by natural cool down. The resultant catalyst powder was labeled FeCat. 1b.

The materials exhibit the following characteristics which were determined by XRF (X-ray fluorescence) and TGZ analysis using a calibrated Hitachi H-7500 field transmission electron microscope operated at 100 keV, equipped with a CCD-Camera:

ID	d_p	ω	D
FeCat. 1a	10 nm	0,56	17 nm
FeCat. 1b	12 nm	0,61	14 nm

20

Comparative examples

For comparison a highly loaded catalyst with 20 wt% Iron on a conventional Vulcan XC72R Carbon support was prepared by means of incipient wetness impregnation and is labeled as FeCat. Ref.

The materials exhibit the following characteristics which were determined by XRF (X-ray
 25 fluorescence) and TGZ analysis using a calibrated Hitachi H-7500 field transmission electron microscope operated at 100 keV, equipped with a CCD-Camera:

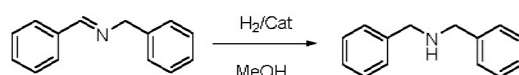
ID	d_p	ω	D
FeCat. Ref	72 nm	0,20	n.d.*

Testing catalytic activity

Experiments to determine Catalytic activity and selectivity of the materials were performed in a batch-wise fashion using 200 mg of catalyst and 5 mmol of substrate in 5 ml of methanol.

- Autoclaves were heated to the desired reaction temperature and agitated under a constant hydrogen pressure of 50 bar for all experiments. Reaction products were filtered and analyzed by means of GC-MS.

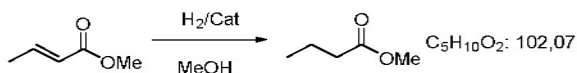
I. Hydrogenation of N-benzylidene-benzylamine



ID	Cat. ID	Duration h	Temp T °C	Reactant %	product %	side-product %
1	FeCat. 1 a	20,00	100,00	66,1	29,5	4,40
2	FeCat. 1 b	20,00	100,00	64,0	31,9	4,10
3	FeCat. Ref	20,00	100,00	89,8	0	10,2

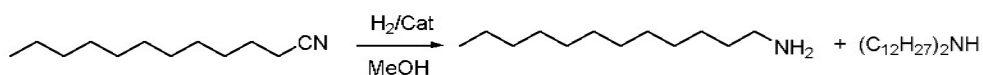
10

II. Hydrogenation of methyl crotonate to methyl butyrate



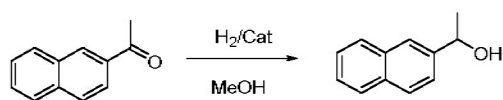
ID	Cat. ID	Duration h	Temp. T °C	reactant %	product %
4	FeCat. 1 a	20,00	80,00	5,00	95,00
5	FeCat. 1 b	20,00	80,00	0,00	100,00
6	FeCat. Ref	20,00	80,00	38,7	61,3

III. Hydrogenation of dodecannitrile



ID	Cat. ID	Duration h	Temp. T °C	Reactant %	product %	side-product %
7	FeCat. 1 a	20,00	80,00	85,9	7,60	6,40
8	FeCat. 1 b	20,00	80,00	73,0	16,7	10,3
9	FeCat. Ref	20,00	80,00	98,0	0,00	2,00

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IV. Hydrogenation of acetylnaphthalene

ID	Cat. ID	Duration h	Temp. T °C	Reactant %	product %	side-product %
10	FeCat. 1 a	20,00	80,00	62,6	37,4	0,00
11	FeCat. 1 b	20,00	80,00	51,6	48,4	0,00
12	FeCat. Ref	20,00	80,00	100,0	0,00	0,00

Claims

1. Catalytically active material, comprising grains of non-graphitizing carbon with iron nanoparticles dispersed therein,
 wherein
 5 d_p , the average diameter of iron nanoparticles in the non-graphitizing carbon grains, is in the range of 1 nm to 20 nm,
 D , the average distance between iron nanoparticles in the non-graphitizing carbon grains, is in the range of 2 nm to 150 nm, and
 ω , the combined total mass fraction of metal in the non-graphitizing carbon grains, is in the
 10 range of 30 wt% to 70 wt% of the total mass of the non-graphitizing carbon grains,
 wherein d_p and D are measured by TGZ-TEM as described herein,
 and wherein
 d_p , D and ω conform to the following relation:
 $4.5 d_p / \omega > D \geq 0.25 d_p / \omega$.
- 15 2. Material according to claim 1, wherein the non-graphitizing carbon grains exhibit the following particle size distribution: $d_{10} = 5\mu\text{m}$, $d_{50} = 40\mu\text{m}$, $d_{90} = 150\mu\text{m}$.
3. Material according to any one of claims 1 to 2, wherein the total mass fraction of nitrogen in the non-graphitizing carbon grains is less than 1 wt% of the total mass of the non-graphitizing carbon grains.
- 20 4. Material according to any one of claims 1 to 3, wherein d_p is in the range of 4 nm to 18 nm.
5. Material according to any one of claims 1 to 4, wherein d_p is in the range of 6 nm to 14 nm.
6. Material according to any one of claims 1 to 5, wherein the material has been doped with dopant metal,
 and wherein the dopant metal is selected from Na (sodium), K (potassium), Ca (calcium), Mg
 25 (magnesium) or mixtures thereof,
 and wherein the non-graphitizing carbon grains exhibit a molar ratio $RDM = n(\text{iron}) : n(\text{dopant metal})$ in the range of 5 to 1000.
7. Material according to any one of claims 1 to 5, wherein the material has been combined with secondary metal,
 30 and wherein the secondary metal is selected from group 1 or group 2,

with group 1 defined as: Mo (molybdenum) or W (tungsten) or mixtures thereof, and

with group 2 defined as: Co (cobalt) or Cu (copper) or Mn (manganese) or mixtures thereof,

and wherein the non-graphitizing carbon grains exhibit a molar ratio $RSM = n(\text{iron}) : n(\text{secondary metal})$ in the range of 1 to 50.

- 5 8. Process for the manufacture of material according to any one of claims 1 to 7, comprising the following steps:
 - (a) providing an aqueous solution comprising metal precursor and organic carbon source,

wherein the metal precursor comprises one or a combination of more than one organic, at least partially water soluble, salts of iron, and
 - 10 wherein the organic carbon source is one or a combination of more than one saturated, aliphatic di-, tri-, or polycarboxylic acids,
 - (b) spray drying or freeze drying the aqueous solution of metal precursor and organic carbon source and, thus, obtaining intermediate product P,
 - (c) thermo-treating intermediate product P at a temperature in the range from 200 °C to 380 °C.
- 15 9. Process according to claim 8, wherein the organic carbon source is selected from malonic acid, tartaric acid, citric acid and mixtures thereof.
- 10 10. Process according to any one of claims 8 to 9, wherein intermediate product P is thermo-treated at a temperature in the range from 255 °C to 375 °C for 1 to 4 hours.
- 20 11. Process according to any one of claims 8 to 10, wherein intermediate product P is thermo-treated at a temperature in the range from 300 °C to 350 °C for 1 to 4 hours.
12. Use of material according to any one of claims 1 to 7 as a catalyst.
13. Use according to claim 12, wherein the catalyst is a catalyst for the hydrogenation of organic compounds and/or the reductive amination of carbonyl compounds.
- 25 14. Use according to claim 12, wherein the catalyst is a catalyst for the conversion of carbon monoxide, carbon dioxide or mixtures thereof with hydrogen, to alkenes, alkanes or mixtures thereof.