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(54) **Title: POLYETHYLENE COMPOSITION HAVING HIGH MECHANICAL PROPERTIES**

(57) **Abrégé/Abstract:**

Polyethylene composition with improved balance of environmental stress cracking resistance (FNCT) and impact resistance (Charpy), particularly suited for preparing pipes, said composition having the following features: 1) density from 0.945 to 0.955 g/cm³; 2) ratio MIF/MIP from more than 30 to 45; 3) Shear-Induced Crystallization Index SIC from 1.0 to 2.5; 4) Long Chain Branching index equal to or greater than 0.85.



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(54) Title: POLYETHYLENE COMPOSITION HAVING HIGH MECHANICAL PROPERTIES

(57) Abstract: Polyethylene composition with improved balance of environmental stress cracking resistance (FNCT) and impact res-
istance (Charpy), particularly suited for preparing pipes, said composition having the following features: 1) density from 0.945 to
0.955 g/cm³; 2) ratio MIF/MIP from more than 30 to 45; 3) Shear-Induced Crystallization Index SIC from 1.0 to 2.5; 4) Long Chain
Branching index equal to or greater than 0.85.



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POLYETHYLENE COMPOSITION HAVING HIGH MECHANICAL PROPERTIES

The present invention provides a polyethylene composition suitable for preparing various kinds of formed articles. In particular, due to its high balance of environmental stress cracking resistance (FNCT) and impact resistance (Charpy), the present composition is particularly suitable for making extruded articles such as pipes, even with large diameter.

The present invention also relates to a multi-stage polymerization process for preparing the said polyethylene composition.

Thus the composition of the present invention provides an unmatched balance of mechanical properties and process-ability with respect to the known polyethylene compositions for the same use, as disclosed in particular in US6201078 and US2004/0005424.

In fact, the polymers disclosed in such documents achieve a relatively low stress cracking resistance values at relatively high density, as shown in the examples.

The problem of achieving a high impact resistance is not mentioned in US6201078.

Thus the present invention provides a polyethylene composition having the following features:

- 1) density from 0.945 to 0.955 g/cm³, determined according to ISO 1183 at 23°C;
- 2) ratio MIF/MIP from more than 30 to 45, in particular from 31 to 45, where MIF is the melt flow index at 190°C with a load of 21.60 kg, and MIP is the melt flow index at 190°C with a load of 5 kg, both determined according to ISO 1133;
- 3) SIC Index from 1.0 to 2.5;
- 4) Long Chain Branching index equal to or greater than 0.85, in particular equal to or greater than 0.9;

wherein the SIC Index is the Shear-Induced Crystallization Index, determined according to the following relation:

$$\text{SIC Index} = (t_{\text{onset, SIC@1000}} \times t_{\text{onset, quiescent}}) / (\text{HLMI} \times 100)$$

where $t_{\text{onset, SIC@1000}}$ is measured in seconds and is the time required for a crystallization onset under shear rate of 1000 s⁻¹, the $t_{\text{onset, quiescent}}$ is measured in seconds and is the crystallization onset time at temperature of 125°C under no shear, determined in isothermal mode by differential scanning calorimetry (DSC); HLMI is the melt flow index determined at 190°C with a load of 21.6 kg, according to ISO 1133.

The expression “polyethylene composition” is intended to embrace, as alternatives, both a single ethylene polymer and an ethylene polymer composition, in particular a composition of two or more ethylene polymer components, preferably with different molecular weights, such composition being also called “bimodal” or “multimodal” polymer in the relevant art.

Typically the polyethylene composition of the present invention consists of or comprises one or more ethylene copolymers.

All the features herein defined, comprising the previously defined features 1) to 4), are referred to the said ethylene polymer or ethylene polymer composition. The addition of other components, like the additives normally employed in the art, can modify one or more of said features.

In particular, in the presence of carbon black the density can be increased up to 0.953-0.963 g/cm³.

Also the SIC index can be affected.

The ratio MIF/MIP provides a rheological measure of molecular weight distribution.

Another measure of the molecular weight distribution is provided by the ratio Mw/Mn, where Mw is the weight average molar mass and Mn is the number average molar mass, both measured by GPC (Gel Permeation Chromatography), as explained in the examples.

Preferred Mw/Mn values for the polyethylene composition of the present invention range from 25 to 45.

Moreover the polyethylene composition of the present invention has preferably at least one of the following additional features.

- Mw equal to or greater than 250000 g/mol, more preferably equal to or greater than 280000 g/mol, in particular equal to or greater than 300000 g/mol;
- MIP: 0.05 – 1 g/10 min., in particular 0.1 – 0.5 g/10 min;
- MIF: 1 – 15 g/10 min.;
- Comonomer content of 1 – 3% by weight, in particular from 1 to 2.5 % by weight, with respect to the total weight of the composition.

The comonomer or comonomers present in the ethylene copolymers are generally selected from olefins having formula CH₂=CHR wherein R is an alkyl radical, linear or branched, having from 1 to 10 carbon atoms.

Specific examples are propylene, butene-1, pentene-1, 4-methylpentene-1, hexene-1, octene-1 and decene-1. A particularly preferred comonomer is hexene-1.

In particular, in a preferred embodiment, the present composition comprises:

- A) 40 – 60 % by weight of an ethylene homopolymer or copolymer (the homopolymer being preferred) with density equal to or greater than 0.960 g/cm^3 and melt flow index MIE ($190^\circ\text{C}/2.16 \text{ kg}$, according to ISO 1133) of 50 – 200 g/10 min., preferably of 50 – 95 g/10 min.;
- B) 40 – 60 % by weight of an ethylene copolymer having a MIE value lower than the MIE value of A), preferably lower than 0.5 g/10 min.

The above percent amounts are given with respect to the total weight of A) + B).

The amount of comonomer in B) is preferably from 1 to 4 % by weight, with respect to the total weight of B).

As previously said, the present polyethylene composition can be advantageously used in the preparation of extruded articles, in particular pipes, thanks to its valuable mechanical properties.

In fact it is preferably characterized by the following properties.

- FNCT equal to or greater than 100 hours, in particular equal to or greater than 150 hours at 5 MPa, 90°C ;
- Charpy aFM (0°C) equal to or greater than 5 kJ/m^2 , in particular equal to or greater than 9.5 kJ/m^2 ;

The details of the test methods are given in the examples.

Moreover, the polyethylene composition of the present invention can be melt-processed at surprisingly high values of shear rate, still without undergoing pressure oscillations and flow-instabilities.

While no necessary limitation is known to exist in principle on the kind of polymerization processes and catalysts to be used, it has been found that the polyethylene composition of the present invention can be prepared by a gas phase polymerization process in the presence of a Ziegler-Natta catalyst.

A Ziegler-Natta catalyst comprises the product of the reaction of an organometallic compound of group 1, 2 or 13 of the Periodic Table of elements with a transition metal compound of groups 4 to 10 of the Periodic Table of Elements (new notation). In particular, the transition metal compound can be selected among compounds of Ti, V, Zr, Cr and Hf and is preferably supported on MgCl_2 .

Particularly preferred catalysts comprise the product of the reaction of said organometallic compound of group 1, 2 or 13 of the Periodic Table of elements, with a solid catalyst

component comprising a Ti compound and an electron donor compound (ED) supported on MgCl_2 .

Preferred organometallic compounds are the organo-Al compounds.

Thus in a preferred embodiment, the polyethylene composition of the present invention is obtainable by using a Ziegler-Natta polymerization catalyst, more preferably a Ziegler-Natta catalyst supported on MgCl_2 , even more preferably a Ziegler-Natta catalyst comprising the product of reaction of:

- a) a solid catalyst component comprising a Ti compound and an electron donor compound ED supported on MgCl_2 ;
- b) an organo-Al compound; and optionally
- c) an external electron donor compound ED_{ext} .

Preferably in component a) the ED/Ti molar ratio ranges from 1.5 to 3.5 and the Mg/Ti molar ratio is higher than 5.5, in particular from 6 to 80.

Among suitable titanium compounds are the tetrahalides or the compounds of formula $\text{TiX}_n(\text{OR}^1)_{4-n}$, where $0 \leq n \leq 3$, X is halogen, preferably chlorine, and R^1 is C_1 - C_{10} hydrocarbon group. The titanium tetrachloride is the preferred compound.

The ED compound is generally selected from alcohol, ketones, amines, amides, nitriles, alkoxysilanes, aliphatic ethers, and esters of aliphatic carboxylic acids.

Preferably the ED compound is selected among, amides, esters and alkoxysilanes.

Excellent results have been obtained with the use of esters which are thus particularly preferred as ED compound. Specific examples of esters are the alkyl esters of C_1 - C_{20} aliphatic carboxylic acids and in particular C_1 - C_8 alkyl esters of aliphatic mono carboxylic acids such as ethylacetate, methyl formiate, ethylformiate, methylacetate, propylacetate, i-propylacetate, n-butylacetate, i-butylacetate. Moreover, are also preferred the aliphatic ethers and particularly the C_2 - C_{20} aliphatic ethers, such as tetrahydrofurane (THF) or dioxane.

In the said solid catalyst component the MgCl_2 is the basic support, even if minor amount of additional carriers can be used. The MgCl_2 can be used as such or obtained from Mg compounds used as precursors that can be transformed into MgCl_2 by the reaction with halogenating compounds. Particularly preferred is the use of MgCl_2 in active form which is widely known from the patent literature as a support for Ziegler-Natta catalysts. Patents USP 4,298,718 and USP 4,495,338 were the first to describe the use of these compounds in Ziegler-Natta catalysis. It is known from these patents that the magnesium dihalides in active

form used as support or co-support in components of catalysts for the polymerization of olefins are characterized by X-ray spectra in which the most intense diffraction line that appears in the ASTM-card reference of the spectrum of the non-active halide is diminished in intensity and broadened. In the X-ray spectra of preferred magnesium dihalides in active form said most intense line is diminished in intensity and replaced by a halo whose maximum intensity is displaced towards lower angles relative to that of the most intense line. Particularly suitable for the preparation of the polyethylene composition of the present invention are the catalysts wherein the solid catalyst component a) is obtained by first contacting the titanium compound with the MgCl_2 , or a precursor Mg compound, optionally in the presence of an inert medium, thus preparing an intermediate product a') containing a titanium compound supported on MgCl_2 , which intermediate product a') is then contacted with the ED compound which is added to the reaction mixture alone or in a mixture with other compounds in which it represents the main component, optionally in the presence of an inert medium.

With the term "main component" we intend that the said ED compound must be the main component in terms of molar amount, with respect to the other possible compounds excluded inert solvents or diluents used to handle the contact mixture. The ED treated product can then be subject to washings with the proper solvents in order to recover the final product. If needed, the treatment with the ED compound desired can be repeated one or more times.

As previously mentioned, a precursor of MgCl_2 can be used as starting essential Mg compound. This can be selected for example among Mg compound of formula MgR'_2 where the R' groups can be independently C1-C20 hydrocarbon groups optionally substituted, OR groups, OCOR groups, chlorine, in which R is a C1-C20 hydrocarbon groups optionally substituted, with the obvious proviso that the R' groups are not simultaneously chlorine. Also suitable as precursors are the Lewis adducts between MgCl_2 and suitable Lewis bases. A particular and preferred class being constituted by the $\text{MgCl}_2 (\text{R}''\text{OH})_m$ adducts in which R'' groups are C1-C20 hydrocarbon groups, preferably C1-C10 alkyl groups, and m is from 0.1 to 6, preferably from 0.5 to 3 and more preferably from 0.5 to 2. Adducts of this type can generally be obtained by mixing alcohol and MgCl_2 in the presence of an inert hydrocarbon immiscible with the adduct, operating under stirring conditions at the melting temperature of the adduct (100-130°C). Then, the emulsion is quickly quenched, thereby causing the solidification of the adduct in form of spherical particles. Representative methods for the preparation of these spherical adducts are reported for example in USP 4,469,648, USP

4,399,054, and WO98/44009. Another useable method for the spherulization is the spray cooling described for example in USP 5,100,849 and 4,829,034.

Particularly interesting are the $\text{MgCl}_2 \cdot (\text{EtOH})_m$ adducts in which m is from 0.15 to 1.7 obtained subjecting the adducts with a higher alcohol content to a thermal dealcoholation process carried out in nitrogen flow at temperatures comprised between 50 and 150°C until the alcohol content is reduced to the above value. A process of this type is described in EP 395083.

The dealcoholation can also be carried out chemically by contacting the adduct with compounds capable to react with the alcohol groups.

Generally these dealcoholated adducts are also characterized by a porosity (measured by mercury method) due to pores with radius up to 0.1 μm ranging from 0.15 to 2.5 cm^3/g preferably from 0.25 to 1.5 cm^3/g .

It is preferred that the dealcoholation reaction is carried out simultaneously with the step of reaction involving the use of a titanium compound. Accordingly, these adducts are reacted with the $\text{TiX}_n(\text{OR}^1)_{4-n}$ compound (or possibly mixtures thereof) mentioned above which is preferably titanium tetrachloride. The reaction with the Ti compound can be carried out by suspending the adduct in TiCl_4 (generally cold). The mixture is heated up to temperatures ranging from 80-130°C and kept at this temperature for 0.5-2 hours. The treatment with the titanium compound can be carried out one or more times. Preferably it is repeated twice. It can also be carried out in the presence of an electron donor compound as those mentioned above. At the end of the process the solid is recovered by separation of the suspension via the conventional methods (such as settling and removing of the liquid, filtration, centrifugation) and can be subject to washings with solvents. Although the washings are typically carried out with inert hydrocarbon liquids, it is also possible to use more polar solvents (having for example a higher dielectric constant) such as halogenated hydrocarbons.

As mentioned above, the intermediate product is then brought into contact with the ED compound under conditions able to fix on the solid an effective amount of donor. Due to the high versatility of this method, the amount of donor used can widely vary. As an example, it can be used in molar ratio with respect to the Ti content in the intermediate product ranging from 0.5 to 20 and preferably from 1 to 10. Although not strictly required the contact is typically carried out in a liquid medium such as a liquid hydrocarbon. The temperature at which the contact takes place can vary depending on the nature of the reagents. Generally it is comprised in the range from -10° to 150°C and preferably from 0° to 120°C. It is plane that

temperatures causing the decomposition or degradation of any specific reagents should be avoided even if they fall within the generally suitable range. Also the time of the treatment can vary in dependence of other conditions such as nature of the reagents, temperature, concentration etc. As a general indication this contact step can last from 10 minutes to 10 hours more frequently from 0.5 to 5 hours. If desired, in order to further increase the final donor content, this step can be repeated one or more times. At the end of this step the solid is recovered by separation of the suspension via the conventional methods (such as settling and removing of the liquid, filtration, centrifugation) and can be subject to washings with solvents. Although the washings are typically carried out with inert hydrocarbon liquids, it is also possible to use more polar solvents (having for example a higher dielectric constant) such as halogenated or oxygenated hydrocarbons.

As previously mentioned, the said solid catalyst component is converted into catalysts for the polymerization of olefins by reacting it, according to known methods, with an organometallic compound of group 1, 2 or 13 of the Periodic Table of elements, in particular with an Al-alkyl compound.

The alkyl-Al compound is preferably chosen among the trialkyl aluminum compounds such as for example triethylaluminum, triisobutylaluminum, tri-n-butylaluminum, tri-n-hexylaluminum, tri-n-octylaluminum. It is also possible to use alkylaluminum halides, alkylaluminum hydrides or alkylaluminum sesquichlorides such as AlEt_2Cl and $\text{Al}_2\text{Et}_3\text{Cl}_3$ optionally in mixture with said trialkyl aluminum compounds.

The external electron donor compound ED_{ext} optionally used to prepare the said Ziegler-Natta catalysts can be equal to or different from the ED used in the solid catalyst component a). Preferably it is selected from the group consisting of ethers, esters, amines, ketones, nitriles, silanes and their mixtures. In particular it can advantageously be selected from the C2-C20 aliphatic ethers and in particulars cyclic ethers preferably having 3-5 carbon atoms such as tetrahydrofuran and dioxane.

Specific examples of the above described Ziegler-Natta catalysts and of methods for their preparation are provided in WO2004106388. However, the therein described prepolymerization of the solid catalyst component containing the Ti compound and the electron donor compound ED (solid catalyst component a)) is not comprised in the preferred embodiments according to the present invention.

In particular, the polyethylene composition of the present invention is obtainable by a process wherein all the polymerization steps are carried out in the presence of the said catalyst.

In fact it has been found that by using the above described polymerization catalyst, the polyethylene composition of the present invention can be prepared in a process comprising the following steps, in any mutual order:

- a) polymerizing ethylene, optionally together with one or more comonomers, in a gas-phase reactor in the presence of hydrogen;
- b) copolymerizing ethylene with one or more comonomers in another gas-phase reactor in the presence of an amount of hydrogen less than step a);

where in at least one of said gas-phase reactors the growing polymer particles flow upward through a first polymerization zone (riser) under fast fluidization or transport conditions, leave said riser and enter a second polymerization zone (downcomer) through which they flow downward under the action of gravity, leave said downcomer and are reintroduced into the riser, thus establishing a circulation of polymer between said two polymerization zones.

In the first polymerization zone (riser), fast fluidization conditions are established by feeding a gas mixture comprising one or more olefins (ethylene and comonomers) at a velocity higher than the transport velocity of the polymer particles. The velocity of said gas mixture is preferably comprised between 0.5 and 15 m/s, more preferably between 0.8 and 5 m/s. The terms "transport velocity" and "fast fluidization conditions" are well known in the art; for a definition thereof, see, for example, "D. Geldart, Gas Fluidisation Technology, page 155 et seq. , J. Wiley & Sons Ltd. , 1986".

In the second polymerization zone (downcomer), the polymer particles flow under the action of gravity in a densified form, so that high values of density of the solid are reached (mass of polymer per volume of reactor), which approach the bulk density of the polymer.

In other words, the polymer flows vertically down through the downcomer in a plug flow (packed flow mode), so that only small quantities of gas are entrained between the polymer particles.

Such process allows to obtain from step a) an ethylene polymer with a molecular weight lower than the ethylene copolymer obtained from step b).

Preferably, the polymerization of ethylene to produce a relatively low molecular weight ethylene polymer (step a) is performed upstream the copolymerization of ethylene with a comonomer to produce a relatively high molecular weight ethylene copolymer (step b). To

this aim, in step a) a gaseous mixture comprising ethylene, hydrogen and an inert gas is fed to a first gas-phase reactor, preferably a gas-phase fluidized bed reactor. The polymerization is carried out in the presence of the previously described Ziegler-Natta catalyst. Preferably, no comonomer is fed to said first gas phase reactor and a highly crystalline ethylene homopolymer is obtained in step a). However, a minimal amount of comonomer may be fed with the proviso that the degree of copolymerization in step a) is limited so that the density of the ethylene polymer obtained in step a) is not less than 0.960 g/cm^3 .

Hydrogen is fed in an amount depending on the specific catalyst used and, in any case, suitable to obtain in step a) an ethylene polymer with a melt flow index MIE from 50 to 200 g/10 min. In order to obtain the above MIE range, in step a) the hydrogen/ethylene molar ratio is indicatively from 1 to 3, the amount of ethylene monomer being from 5 to 30 % by volume, preferably from 5 to 20 % by volume, based on the total volume of gas present in the polymerization reactor. The remaining portion of the feeding mixture is represented by inert gases and one or more comonomers, if any. Inert gases which are necessary to dissipate the heat generated by the polymerization reaction are conveniently selected from nitrogen or saturated hydrocarbons, the most preferred being propane.

The operating temperature in the reactor of step a) is selected between 50 and 120°C , preferably between 65 and 100°C , while the operating pressure is between 0.5 and 10 MPa, preferably between 2.0 and 3.5 MPa.

In a preferred embodiment, the ethylene polymer obtained in step a) represents from 40 to 60% by weight of the total ethylene polymer produced in the overall process, i. e. in the first and second serially connected reactors.

The ethylene polymer coming from step a) and the entrained gas are then passed through a solid/gas separation step, in order to prevent the gaseous mixture coming from the first polymerization reactor from entering the reactor of step b) (second gas-phase polymerization reactor). Said gaseous mixture can be recycled back to the first polymerization reactor, while the separated ethylene polymer is fed to the reactor of step b). A suitable point of feeding of the polymer into the second reactor is on the connecting part between the downcomer and the riser, wherein the solid concentration is particularly low, so that the flow conditions are not negatively affected.

The operating temperature in step b) is in the range of 65 to 95°C , and the pressure is in the range of 1.5 to 4.0 MPa. The second gas-phase reactor is aimed to produce a relatively high molecular weight ethylene copolymer by copolymerizing ethylene with one or more

comonomers. Furthermore, in order to broaden the molecular weight distribution of the final ethylene polymer, the reactor of step b) can be conveniently operated by establishing different conditions of monomers and hydrogen concentration within the riser and the downcomer.

To this purpose, in step b) the gas mixture entraining the polymer particles and coming from the riser can be partially or totally prevented from entering the downcomer, so to obtain two different gas composition zones. This can be achieved by feeding a gas and/or a liquid mixture into the downcomer through a line placed at a suitable point of the downcomer, preferably in the upper part thereof. Said gas and/or liquid mixture should have a suitable composition, different from that of the gas mixture present in the riser. The flow of said gas and/or liquid mixture can be regulated so that an upward flow of gas counter-current to the flow of the polymer particles is generated, particularly at the top thereof, acting as a barrier to the gas mixture entrained among the polymer particles coming from the riser. In particular, it is advantageous to feed a mixture with low content of hydrogen in order to produce the higher molecular weight polymer fraction in the downcomer. One or more comonomers can be fed to the downcomer of step b), optionally together with ethylene, propane or other inert gases.

The hydrogen/ethylene molar ratio in the downcomer of step b) is comprised between 0.005 and 0.2, the ethylene concentration being comprised from 1 to 20%, preferably 3- 10%, by volume, the comonomer concentration being comprised from 0.2 to 1.5 % by volume, based on the total volume of gas present in said downcomer. The rest is propane or similar inert gases. Since a very low molar concentration of hydrogen is present in the downcomer, by carrying out the process of the present invention is possible to bond a relatively high amount of comonomer to the high molecular weight polyethylene fraction.

The polymer particles coming from the downcomer are reintroduced in the riser of step b).

Since the polymer particles keep reacting and no more comonomer is fed to the riser, the concentration of said comonomer drops to a range of 0.1 to 1% by volume, based on the total volume of gas present in said riser. In practice, the comonomer content is controlled in order to obtain the desired density of the final polyethylene. In the riser of step b) the hydrogen/ethylene molar ratio is in the range of 0.02 to 0.2, the ethylene concentration being comprised between 5 and 15 % by volume based on the total volume of gas present in said riser. The rest is propane or other inert gases.

More details on the above described polymerization process are provided in WO9412568.

The following examples are given to illustrate, without limiting, the present invention.

Unless differently stated, the following test methods are used to determine the properties reported in the detailed description and in the examples.

- **Density**

Determined according to ISO 1183 at 23°C.

- **Molecular Weight Distribution Determination**

The determination of the molar mass distributions and the means M_n , M_w and M_w/M_n derived therefrom was carried out by high-temperature gel permeation chromatography using a method described in ISO 16014-1, -2, -4, issues of 2003. The specifics according to the mentioned ISO standards are as follows: Solvent 1,2,4-trichlorobenzene (TCB), temperature of apparatus and solutions 135°C and as concentration detector a PolymerChar (Valencia, Paterna 46980, Spain) IR-4 infrared detector, capable for use with TCB. A WATERS Alliance 2000 equipped with the following pre-column SHODEX UT-G and separation columns SHODEX UT 806 M (3x) and SHODEX UT 807 (Showa Denko Europe GmbH, Konrad-Zuse-Platz 4, 81829 Muenchen, Germany) connected in series was used. The solvent was vacuum distilled under Nitrogen and was stabilized with 0.025% by weight of 2,6-di-tert-butyl-4-methylphenol. The flowrate used was 1 ml/min, the injection was 500 µl and polymer concentration was in the range of 0.01% < conc. < 0.05% w/w. The molecular weight calibration was established by using monodisperse polystyrene (PS) standards from Polymer Laboratories (now Agilent Technologies, Herrenberger Str. 130, 71034 Boeblingen, Germany)) in the range from 580g/mol up to 11600000g/mol and additionally with Hexadecane. The calibration curve was then adapted to Polyethylene (PE) by means of the Universal Calibration method (Benoit H., Rempp P. and Grubisic Z., & in J. Polymer Sci., Phys. Ed., 5, 753(1967)). The Mark-Houwink parameters used herefore were for PS: $k_{PS} = 0.000121 \text{ dl/g}$, $\alpha_{PS} = 0.706$ and for PE $k_{PE} = 0.000406 \text{ dl/g}$, $\alpha_{PE} = 0.725$, valid in TCB at 135°C. Data recording, calibration and calculation was carried out using NTGPC_Control_V6.02.03 and NTGPC_V6.4.24 (hs GmbH, Hauptstraße 36, D-55437 Ober-Hilbersheim, Germany) respectively.

- **Shear-induced crystallization test**

This method is utilized to determine the onset time of shear-induced crystallization (SIC) of the polymer, $t_{\text{onset, SIC}}$. Samples are melt-pressed at 210 °C, 4 min, under 200 bar in a lab press to 1mm thick-plaques. Disc specimens are cut-out with a diameter of

25 mm. The samples are inserted in the plate-plate oscillatory-shear rheometer. A Physica MCR 301 rotational rheometer from AntonPaar is used.

The sample is then molten inside the test-geometry at 190 °C for 4 min, cooled down with ~10K/min to the test temperature, $T = 125$ °C, and annealed for 5 min. Consequently, steady-shear under constant shear rate is applied and the shear viscosity is monitored as a function of time. The experiment is repeated applying each time a different shear-rate ranging from 0.05 to 0.5 s^{-1} . The onset time for SIC, $t_{onset,SIC}$, is taken at the point where the viscosity has increased at 50% of its steady-state value $\eta@125^{\circ}C$. The steady-state value is the average of the steady-shear melt viscosity measured at the specific temperature.

The plot of $\log t_{onset,SIC}$ vs. \log shear-rate provides a linear function (of type $y=Ax+B$) which is extrapolated to a shear rate of 1000 s^{-1} (process-relevant) to determine the value of $t_{onset,SIC}@1000$.

The SIC Index is then calculated according to the following relation:

$$SIC\ Index = (t_{onset,SIC}@1000 \times t_{onset,quiescent}) / (HLMI \times 100)$$

The $t_{onset, quiescent}$ (in sec) is the crystallization onset at temperature of 125 °C under quiescent conditions, i.e. no shear, measured in isothermal mode in a differential-scanning-calorimetry apparatus, DSC, as hereinafter explained.

HLMI is the melt flow index (g/10min) measured at $T = 190$ °C with 21.6 kg load, according to ISO 1133.

The same protocol is described in the following documents.

- I. Vittorias, *Correlation among structure, processing and product properties*, Würzburger Tage 2010, Wolfgang Kunze TA Instruments, Germany.

- Wo DL, Tanner RI (2010), *The impact of blue organic and inorganic pigments on the crystallization and rheological properties of isotactic polypropylene*, Rheol. Acta 49, 75.

Derakhshandeh M., Hatzikiriakos S. G., *Flow-induced crystallization of high-density polyethylene: the effects of shear and uniaxial extension*, Rheol. Acta, 51, 315-327, 2012.

- Isothermal DSC

The $t_{onset,quiescent}$, the onset time when no deformation is applied at 125 °C, is determined by the iso-DSC (isothermal Differential Scanning Calorimetry) method. It is measured at 125 °C in a TA Instruments Q2000 DSC apparatus. The determination

of the $t_{\text{onset,quiescent}}$ is performed utilizing the commercially available software TA Universal Analysis 2000. The sample preparation and set-up follows the DIN EN ISO 11357-1:2009 and ISO 11357-3:1999.

- **Melt flow index**

Determined according to ISO 1133 at 190°C with the specified load.

- **Long Chain Branching index (LCB)**

The LCB index corresponds to the branching factor g' , measured for a molecular weight of 10^6 g/mol. The branching factor g' , which allows determining long-chain branches at high Mw, was measured by Gel Permeation Chromatography (GPC) coupled with Multi-Angle Laser-Light Scattering (MALLS), as described in the following. The parameter g' is the ratio of the measured mean square radius of gyration to that of a linear polymer having the same molecular weight. Linear molecules show g' of 1, while values less than 1 indicate the presence of LCB. Values of g' as a function of mol. weight, M , were calculated from the equation:

$$g'(M) = \langle Rg^2 \rangle_{\text{sample},M} / \langle Rg^2 \rangle_{\text{linear ref.},M}$$

where $\langle Rg^2 \rangle_{,M}$ is the root-mean-square radius of gyration for the fraction of mol. weight M .

The radius of gyration for each fraction eluted from the GPC (as described above but with a flow-rate of 0.6 ml/min and a column packed with 30µm particles) is measured by analyzing the light scattering at the different angles. Therefore, from this MALLS setup it is possible to determine mol. weight M and $\langle Rg^2 \rangle_{\text{sample},M}$ and to define a g' at a measured $M = 10^6$ g/mol. The $\langle Rg^2 \rangle_{\text{linear ref.},M}$ is calculated by the established relation between radius-of-gyration and molecular weight for a linear polymer in solution (Zimm and Stockmayer WH 1949)) and confirmed by measuring a linear PE reference with the same apparatus and methodology described.

The same protocol is described in the following documents.

Zimm BH, Stockmayer WH (1949) *The dimensions of chain molecules containing branches and rings*. J Chem Phys 17

Rubinstein M., Colby RH. (2003), *Polymer Physics*, Oxford University Press

- **Comonomer content**

The comonomer content is determined by means of IR in accordance with ASTM D 6248 98, using an FT-IR spectrometer Tensor 27 from Bruker, calibrated with a

chemometric model for determining ethyl- or butyl- side-chains in PE for butene or hexene as comonomer, respectively.

- **Environmental stress cracking resistance according to full notch creep test (FNCT)**

The environmental stress cracking resistance of polymer samples is determined in accordance to international standard ISO 16770 (FNCT) in aqueous surfactant solution. From the polymer sample a compression moulded 10 mm thick sheet has been prepared. The bars with squared cross section (10x10x100 mm) are notched using a razor blade on four sides perpendicularly to the stress direction. A notching device described in M. Fleissner in Kunststoffe 77 (1987), pp. 45 is used for the sharp notch with a depth of 1.6 mm. The load applied is calculated from tensile force divided by the initial ligament area. Ligament area is the remaining area = total cross-section area of specimen minus the notch area. For FNCT specimen: $10 \times 10 \text{ mm}^2 - 4 \text{ times of trapezoid notch area} = 46.24 \text{ mm}^2$ (the remaining cross-section for the failure process / crack propagation). The test specimen is loaded with standard condition suggested by the ISO 16770 with constant load of 5 MPa at 90°C in an aqueous solution of 2% by weight of ARKOPAL N100 and 5% of anionic surfactant GENAPOL Paste. Time until rupture of test specimen is detected.

- **Charpy aFM**

Fracture toughness determination by an internal method on test bars measuring 10 x 10 x 80 mm which had been sawn out of a compression molded sheet with a thickness of 10 mm. Six of these test bars are notched in the center using a razor blade in the notching device mentioned above for FNCT. The notch depth is 1.6 mm. The measurement is carried out substantially in accordance with the Charpy measurement method in accordance with ISO 179-1, with modified test specimens and modified impact geometry (distance between supports). All test specimens are conditioned to the measurement temperature of 0°C over a period of from 2 to 3 hours. A test specimen is then placed without delay onto the support of a pendulum impact tester in accordance with ISO 179-1. The distance between the supports is 60 mm. The drop of the 2 J hammer is triggered, with the drop angle being set to 160°, the pendulum length to 225 mm and the impact velocity to 2.93 m/s. The fracture toughness value is expressed in kJ/m² and is given by the quotient of the impact energy consumed and the initial cross-

sectional area at the notch, aFM. Only values for complete fracture and hinge fracture can be used here as the basis for a common meaning (see suggestion by ISO 179-1).

Examples 1- 4 and Comparative Example 1

- Process Setup

In Example 1 the process of the invention was carried out under continuous conditions in a plant comprising two serially connected gas-phase reactors, as shown in Figure 1.

Comparative Example 1 is carried out in the same plant under continuous conditions as well.

Example 1

- The solid catalyst component was prepared as described in Example 13 of WO2004106388. The AcOEt/Ti molar ratio was of 8.

- Polymerization

7 g/h of the solid catalyst component prepared as described above were fed, using 5 kg/h of liquid propane, to a precontacting apparatus, in which also a mixture of triisobutylaluminum (TIBA) and diethylaluminum chloride (DEAC) as well tetrahydrofuran (THF) were dosed. The weight ratio between TIBA and DEAC was 7:1. The weight ratio between aluminum alkyl and solid catalyst component was 10:1. The weight ratio between aluminum alkyl and THF was 70. The precontacting step was carried out under stirring at 50°C with a total residence time of 70 minutes.

The catalyst enters the first gas-phase polymerization reactor 1 of Fig. 1 via line 10. In the first reactor ethylene was polymerized using H₂ as molecular weight regulator and in the presence of propane as inert diluent. 35 kg/h of ethylene and 62 g/h of hydrogen were fed to the first reactor via line 9. No comonomer was fed to the first reactor.

The polymerization was carried out at a temperature of 75 °C and at a pressure of 2.5 MPa. The polymer obtained in the first reactor was discontinuously discharged via line 11, separated from the gas into the gas/solid separator 12, and reintroduced into the second gas-phase reactor via line 14.

The polymer produced in the first reactor had a melt index MIE of about 90 g/10 min and a density of 0.968 kg/dm³.

The second reactor was operated under polymerization conditions of about 80 °C, and a pressure of 2.5 MPa. 16 kg/h of ethylene and 1.2 kg/h of 1-hexene were introduced in the downcomer 33 of the second reactor via line 46. 5 kg/h of propane, 17.5 kg/h of ethylene and 1.0 g/h of hydrogen were fed through line 45 into the recycling system.

In order to broaden the molecular weight distribution of the final ethylene polymer, the second reactor was operated by establishing different conditions of monomers and hydrogen concentration within the riser 32 and the downcomer 33. This is achieved by feeding via line 52, 150 kg/h of a liquid stream (liquid barrier) into the upper part of the downcomer 33. Said liquid stream has a composition different from that of the gas mixture present in the riser. Said different concentrations of monomers and hydrogen within the riser, the downcomer of the second reactor and the composition of the liquid barrier are indicated in Table 1. The liquid stream of line 52 comes from the condensation step in the condenser 49, at working conditions of 60°C and 2.5 MPa, wherein a part of the recycle stream is cooled and partially condensed. As shown in the figure, a separating vessel and a pump are placed, in the order, downstream the condenser 49. The final polymer was discontinuously discharged via line 54.

The polymerization process in the second reactor produced relatively high molecular weight polyethylene fractions. In Table 1 the properties of the final product are specified. It can be seen that the melt index of the final product is decreased as compared to the ethylene resin produced in the first reactor, showing the formation of high molecular weight fractions in the second reactor.

The first reactor produced around 53 % by weight (split wt %) of the total amount of the final polyethylene resin produced by both first and second reactors. At the same time, the obtained polymer is endowed with a relatively broad molecular weight distribution as witnessed by a ratio MIF/MIP equal to 33.

Example 2

The process of the invention was carried out with the same setup and the same polymerization catalyst of Example 1. Also the process conditions and consequently the obtained polymer properties of the first reactor were the same.

The second reactor was operated under polymerization conditions of about 80 °C, and a pressure of 2.5 MPa. 16 kg/h of ethylene and 1.5 kg/h of 1-hexene were introduced in the downcomer of the second reactor via line 46. 5 kg/h of propane, 20.0 kg/h of ethylene and 0.5 g/h of hydrogen were fed through line 45 into the recycling system.

In order to broaden again the molecular weight distribution of the final ethylene polymer, the second reactor was operated by establishing different conditions of monomers and hydrogen concentration within the riser 32 and the downcomer 33. Again 150 kg/h of barrier liquid were fed via line 52. The gas compositions of the riser, the downcomer and the liquid barrier

are indicated in Table 1. The liquid stream of line 52 comes from the condensation step in the condenser 49, at working conditions of 57°C and 2.5 MPa, wherein a part of the recycle stream is cooled and partially condensed.

The first reactor produced around 50.7 % by weight (split wt %) of the total amount of the final polyethylene resin produced by both first and second reactors. At the same time, the obtained polymer is endowed with a relatively broad molecular weight distribution as witnessed by a ratio MIF/MIP equal to 34.

Example 3

The process of the invention was carried out with the same setup and the same polymerization catalyst of Example 1. Also the process conditions and consequently the obtained polymer properties of the first reactor were the same.

The second reactor was operated under polymerization conditions of about 80 °C, and a pressure of 2.5 MPa. 18 kg/h of ethylene and 1.6 kg/h of 1-hexene were introduced in the downcomer of the second reactor via line 46. 5 kg/h of propane, 16.0 kg/h of ethylene and 1.7 g/h of hydrogen were fed through line 45 into the recycling system.

In order to broaden again the molecular weight distribution of the final ethylene polymer, the second reactor was operated by establishing different conditions of monomers and hydrogen concentration within the riser 32 and the downcomer 33. 300 kg/h of barrier liquid were fed via line 52. The gas compositions of the riser, the downcomer and the liquid barrier are indicated in Table 1. The liquid stream of line 52 comes from the condensation step in the condenser 49, at working conditions of 60°C and 2.5 MPa, wherein a part of the recycle stream is cooled and partially condensed.

The first reactor produced around 53.8 % by weight (split wt %) of the total amount of the final polyethylene resin produced by both first and second reactors. At the same time, the obtained polymer is endowed with a relatively broad molecular weight distribution as witnessed by a ratio MIF/MIP equal to 34.

Example 4

The process of the invention was carried out with the same setup and the same polymerization catalyst of Example 1. Also the process conditions and consequently the obtained polymer properties of the first reactor were the same.

The second reactor was operated under polymerization conditions of about 80 °C, and a pressure of 2.5 MPa. 20 kg/h of ethylene and 1.35 kg/h of 1-hexene were introduced in the

downcomer of the second reactor via line 46. 5 kg/h of propane, 31.0 kg/h of ethylene and 0.7 g/h of hydrogen were fed through line 45 into the recycling system.

In order to broaden again the molecular weight distribution of the final ethylene polymer, the second reactor was operated by establishing different conditions of monomers and hydrogen concentration within the riser 32 and the downcomer 33. 150 kg/h of barrier liquid were fed via line 52. The gas compositions of the riser, the downcomer and the liquid barrier are indicated in Table 1. The liquid stream of line 52 comes from the condensation step in the condenser 49, at working conditions of 56°C and 2.5 MPa, wherein a part of the recycle stream is cooled and partially condensed.

The first reactor produced around 50.3 % by weight (split wt %) of the total amount of the final polyethylene resin produced by both first and second reactors. At the same time, the obtained polymer is endowed with a relatively broad molecular weight distribution as witnessed by a ratio MIF/MIP equal to 33.

Comparative Example 1

The polymerization was carried out using the same setup of Example 1, but the polymerization catalyst was the same as used in example 6 of WO2005019280.

8 g/h of the solid catalyst component prepared as described above were fed, using 5 kg/h of liquid propane, to a precontacting apparatus, in which triethylaluminum (TEA) as well tetrahydrofuran (THF) were dosed. The weight ratio between aluminum alkyl and solid catalyst component was 5:1. The weight ratio between aluminum alkyl and THF was 44. The precontacting step was carried out under stirring at 50°C with a total residence time of 70 minutes.

The catalyst enters the first gas-phase polymerization reactor 1 of Fig. 1 via line 10. In the first reactor ethylene was polymerized using H₂ as molecular weight regulator and in the presence of propane as inert diluent. 40 kg/h of ethylene and 75 g/h of hydrogen were fed to the first reactor via line 9. No comonomer was fed to the first reactor.

The polymerization was carried out at a temperature of 80 °C and at a pressure of 2.4 MPa. The polymer obtained in the first reactor was discontinuously discharged via line 11, separated from the gas into the gas/solid separator 12, and reintroduced into the second gas-phase reactor via line 14.

The polymer produced in the first reactor had a melt index MIE of about 100 g/10 min and a density of 0.968 kg/dm³.

The second reactor was operated under polymerization conditions of about 80 °C, and a pressure of 2.1 MPa. 12 kg/h of ethylene and 1.5 kg/h of 1-hexene were introduced in the downcomer 33 of the second reactor via line 46. 5 kg/h of propane, 26.5 kg/h of ethylene and 1.2 g/h of hydrogen were fed through line 45 into the recycling system.

In order to broaden the molecular weight distribution of the final ethylene polymer, the second reactor was operated by establishing different conditions of monomers and hydrogen concentration within the riser 32 and the downcomer 33. This is achieved by feeding via line 52, 200 kg/h of a liquid stream (liquid barrier) into the upper part of the downcomer 33. Said liquid stream has a composition different from that of the gas mixture present in the riser. Said different concentrations of monomers and hydrogen within the riser, the downcomer of the second reactor and the composition of the liquid barrier are indicated in Table 1. The liquid stream of line 52 comes from the condensation step in the condenser 49, at working conditions of 53°C and 2.1 MPa, wherein a part of the recycle stream is cooled and partially condensed. As shown in the figure, a separating vessel and a pump are placed, in the order, downstream the condenser 49. The final polymer was discontinuously discharged via line 54.

The polymerization process in the second reactor produced relatively high molecular weight polyethylene fractions. In Table 1 the properties of the final product are specified. It can be seen that the melt index of the final product is decreased as compared to the ethylene resin produced in the first reactor, showing the formation of high molecular weight fractions in the second reactor.

The first reactor produced around 50 % by weight (split wt %) of the total amount of the final polyethylene resin produced by both first and second reactors. At the same time, the obtained polymer is endowed with a relatively broad molecular weight distribution as witnessed by a ratio MIF/MIP equal to 38.8

Table 1

	Ex. 1	Ex. 2	Ex. 3	Ex. 4	Comp. 1
Operative conditions first reactor					
H ₂ /C ₂ H ₄ Molar ratio	2.4	1.9	1.9	2.0	1.7
C ₂ H ₄ %	13.5	13.2	15.1	15.4	14
Split (wt%)	53.0	50.7	53.8	50.3	50
Operative conditions second reactor					
H ₂ /C ₂ H ₄ Molar ratio riser	0.028	0.017	0.056	0.020	0.038
C ₂ H ₄ % riser	5.8	8.1	6.6	10.9	15
C ₆ H ₁₂ riser	0.09	0.85	0.76	0.58	1.2
H ₂ /C ₂ H ₄ Molar ratio downer	0.039	0.026	0.025	0.030	0.04
C ₂ H ₄ % downer	2.3	3.2	1.6	3.8	5.4
C ₆ H ₁₂ downer	0.90	0.94	0.99	0.63	2.2
H ₂ /C ₂ H ₄ Molar ratio barrier	0.005	0.005	0.010	0.005	0.01
C ₂ H ₄ % barrier	3.9	5.7	4.1	8.0	6.5
C ₆ H ₁₂ barrier	0.80	1.13	1.28	0.81	2.7
Final Polymer properties					
MIP [5 kg] (g/10 min.)	0.29	0.20	0.32	0.18	0.21
MIF [21.6 kg] (g/10 min.)	9.6	6.8	11	5.9	8.15
MIF/MIP	33	34	34	33	38.8
Density (g/cm ³)	0.9515	0.9484	0.9495	0.9508	0.9487
Mw [g/mol]	3.4E+5	3.7E+5	3.5E+5	3.2E+5	3.6E+5
Mz [g/mol]	2E+6	1.8E+6	2.3E+6	1.3E+6	5.0E+6
Mw/Mn	35	31	38	38	52
LCB	0.96	0.9	0.9	0.9	0.69
Comonomer (C ₆ H ₁₂) content IR [%]	1.4	1.6	1.7	1.2	1.6
SIC index	1.2	1.8	1.4	2.1	1.9
FNCT 5 MPa/90°C (hours)**	214	358	121	>1000	93
Charpy aFM, T = 0°C [kJ/m ²]	12.9	16.7	13.0	17.2	8.9

Notes : C₂H₄ = ethylene; C₄H₈ = butene; C₆H₁₂ = hexene; ** aqueous solution of 5% Genapol Paste and 2% Arkopal N100

The embodiments of the present invention for which an exclusive property or privilege is claimed are defined as follows:

1. A polyethylene composition having the following features:
 - 1) density from 0.945 to 0.955 g/cm³, determined according to ISO 1183 at 23°C;
 - 2) ratio MIF/MIP from 31 to 45, where MIF is the melt flow index at 190°C with a load of 21.60 kg, and MIP is the melt flow index at 190°C with a load of 5 kg, both determined according to ISO 1133;
 - 3) SIC Index from 1.0 to 2.5;
 - 4) Long Chain Branching index equal to or greater than 0.85;
 wherein the SIC Index is the Shear-Induced Crystallization Index, determined according to the following relation:

$$\text{SIC Index} = (t_{\text{onset, SIC@1000}} \times t_{\text{onset, quiescent}}) / (\text{HLMI} \times 100)$$
 where $t_{\text{onset, SIC@1000}}$ is measured in seconds and is the time required for crystallization onset under shear rate of 1000 s⁻¹, the $t_{\text{onset, quiescent}}$ is measured in seconds and is the crystallization onset time at temperature of 125°C under no shear, determined in isothermal mode by differential scanning calorimetry; HLMI is the melt flow index determined at 190°C with a load of 21.6 kg, according to ISO 1133.
2. The polyethylene composition of claim 1, comprising one or more ethylene copolymers.
3. The polyethylene composition of claim 2, containing 1 – 3% by weight of one or more comonomers.
4. The polyethylene composition of claim 3, wherein the one or more comonomers present in the ethylene copolymers are selected from olefins having formula CH₂=CHR wherein R is an alkyl radical, linear or branched, having from 1 to 10 carbon atoms.
5. The polyethylene composition of claim 1 or 2, obtained by using a Ziegler-Natta polymerization catalyst.

6. The polyethylene composition of claim 1, having at least one of the following additional features:
 - Mw equal to or greater than 250000 g/mol;
 - MIP: 0.05 – 0.5 g/10 min.;
 - MIF: 1 – 15 g/10 min.;
 - Mw/Mn: 25 – 45.
7. The polyethylene composition of claim 1, comprising:
 - A) 40 – 60 % by weight of an ethylene homopolymer or copolymer with density equal to or greater than 0.960 g/cm³ and melt flow index MIE at 190°C with a load of 2.16 kg, according to ISO 1133, of 50 – 200 g/10 min.;
 - B) 40 – 60 % by weight of an ethylene copolymer having a MIE value lower than the MIE value of A).
8. Manufactured articles comprising the polyethylene composition of claim 1.
9. Manufactured articles according to claim 8, in form of pipes.
10. Process for preparing the polyethylene composition of claim 1, wherein all the polymerization steps are carried out in the presence of a Ziegler-Natta polymerization catalyst supported on MgCl₂.
11. The process of claim 10, comprising the following steps, in any mutual order:
 - a) polymerizing ethylene, optionally together with one or more comonomers, in a gas-phase reactor in the presence of hydrogen;
 - b) copolymerizing ethylene with one or more comonomers in another gas-phase reactor in the presence of an amount of hydrogen less than step a);

where in at least one of said gas-phase reactors the growing polymer particles flow upward through a first polymerization zone under fast fluidization or transport conditions, leave said riser and enter a second polymerization zone through which they flow downward under the action of gravity, leave said second polymerization zone and are reintroduced into the first polymerization zone, thus establishing a circulation of polymer between said two polymerization zones.

