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(54) **Title:** BIOMODAL HIGH-DENSITY POLYETHYLENE RESINS AND COMPOSITIONS WITH IMPROVED PROPERTIES AND METHODS OF MAKING AND USING THE SAME

(57) **Abstract:** The present disclosure is related to bimodal high-density polyethylene polymer compositions with increased high melt strength and good processability comprising a base resin which has a density of about 945 kg/m³ to about 955 kg/m³, and comprises an ethylene polymer (A) having a density of at least about 968 kg/m³, in an amount ranging from 45% to 55% by weight and an ethylene polymer (B) having a density lower than the density of polymer (A) wherein said composition has a complex viscosity at a shear rate of 0,01 rad/s ranging from about 200 to about 450 kPa.s and a complex viscosity at a shear rate of 100 rad/s ranging from about 1900 to about 2500 Pa.s. The present disclosure also relates to methods of making, and using the present compositions, and to articles made from there composition, and preferably to pipes and fittings.

BIMODAL HIGH-DENSITY POLYETHYLENE RESINS AND COMPOSITIONS WITH IMPROVED PROPERTIES AND METHODS OF MAKING AND USING THE SAME

This application claims priority to U.S. Provisional Application No. 5 61/631,209 filed on December 29, 2011, the disclosure of which is expressly incorporated herein by reference in its entirety.

The present disclosure relates to polyethylene resins, more particularly those suitable for use as pipes, pipe attachments or fittings, and processes for producing such resins. The present disclosure also relates to the use of polyethylene 10 compounds comprising such resins for the manufacture of pipes or pipe fittings, and to such fittings themselves.

For many high density polyethylene (HDPE) applications, polyethylene with enhanced toughness, strength and environmental stress cracking resistance (ESCR) is desirable. In the context of manufacturing of large diameter thick wall pipe, melt 15 strength of the polymer is also desirable. Increased melt strength helps prevent having the polymer material flow downward due to the effects of gravity. Materials that sag produce pipe with thicker pipe walls on the bottom of the pipe and thinner wall distribution on top of the pipe. Pipe industry standards set limits of maximum allowable variation in wall thickness. Thus, use of polymers with high sagging 20 characteristics can result in producing pipes that are not compliant or unable to meet certain standards. An increase of the melt strength of the polymer, and in turn a reduction in sagging, can be accomplished by long chain branching in the polymer. The long branching prevents the material from sagging as the material exits the pipe extruder, before it enters the vacuum cooling tank.

25 The present disclosure is also directed to compositions with good resistance to sagging. The disclosure is also directed to composition suitable to applications in which higher low shear melt strength of the polymer melt would be beneficial including blow molding, extruded sheet and film applications. In one embodiment the compositions of the present disclosure are used for the manufacture of pipes and 30 fittings. Polyethylene resins are known for the production of pipes and fittings. Pipe resins require high stiffness (creep rupture strength), combined with a high

resistance against slow crack growth as well as resistance to rapid crack propagation yielding impact toughness. Polyethylene pipes are widely used as they are lightweight and can be easily assembled by fusion welding. Polyethylene pipes also have a good flexibility and impact resistance, and are corrosion free. However
5 unless they are reinforced, they are limited in their hydrostatic resistance by the inherent low yield strength of polyethylene. It is generally accepted that the higher the density of the polyethylene, the higher will be the long term hydrostatic strength. ISO 9080, ISO 12162, ASTM D883 and ASTM D3350 describe the classifications of pipes according to the PE100 and PE4710 specifications.

10 One requirement for such pipes is to have very good long term strength as measured by the "Minimum Required Strength" (MRS) rating. Extrapolation according to ISO 9080 shows that they have an extrapolated 20°C / 50 years stress at a lower prediction level (97.5% confidence level ~"LPL") of at least 8 and 10 MPa; such resins have an MRS rating of MRS 8 or MRS 10 and are known as PESO and
15 PE100 resins respectively. Another requirement for such pipes is to have very good long term strength as represented by the Hydrostatic Design Basis (HDB). Extrapolation according to ASTM D2837 shows that they have a 23°C/100,000 hour intercept of at least 1530 psi. Such resins would have an HDB rating of 1600 psi and are known as PE3608 or PE4710 resins depending on other short term material
20 characteristics such as density and stress crack resistance. In one embodiment, the present disclosure is directed to pipes manufactured with the polyethylene compositions and resins of the present disclosure. In one embodiment, the pipes made with the compositions and resins of the present disclosure meet PE 100 specifications. In one embodiment, pipes made with the composition and resins of
25 the present disclosure meet PE 4710 specifications. These are polyethylene resins which when used for the formation of pipes of specific dimensions, survive a long term pressure test at different temperatures for a period of 10,000 hours. The density of the current basic powder used in the production of a PE100 or PE4710 compound ranges from about 0.945 g/cm³ to about 0.955 g/cm³, preferably from about 0.947 to
30 0.951 g/cm³, and preferably is about 949 g/cm³. In certain embodiment, the polyethylene resins contain conventional amounts of black pigments and exhibit densities ranging from about 0.958 to about 0.961 g/cm³.

in one embodiment, the present disclosure is also directed to polymer compositions with good resistance to sagging. In one embodiment, the compositions and resins of the present disclosure could be used for applications where melt strength of high-density polyethylene is important, including blow molding, extruded sheet, and film applications. In another embodiment, this disclosure is also directed to pipes manufactured with the polyethylene composition and resin of the present disclosure and having a diameter greater than 24 inches and a wall thickness greater than 2 ½ inches. Large diameter thick pipes generally require high-density polyethylene (HDPE) with high melt strength. High melt strength polymer can be provided by the long chain branching in the polymer that prevents the material from sagging as the material exits the pipe extruder, before it enters the vacuum cooling tank. High-density polyethylene resins with poor melt strength sag, begin to flow downward due to the effects of gravity, producing pipe with non-uniform wall distributions. Materials that sag produce pipe with thicker pipe walls on the bottom of the pipe and thinner wall distribution on top of the pipe. Pipe industry standards set limits of maximum allowable variation in wall thickness. Low sag behavior for most pipe extrusion applications can be predicted by a material's complex viscosity measured at a frequency of 0.01 rad/s at a temperature of 190 °C ($\eta^*_{0.01}$). Examples of pipes with low sag behaviour, but poor mechanical properties have been discussed in the art WO 08006487, EP - 1 137707 and EP-B- 1655333. The compositions of the present disclosure exhibit excellent mechanical properties such as stress crack resistance, creep resistance and resistance to rapid crack propagation.

In another embodiment, the present disclosure is related to pipe having very high environmental stress crack resistance (PE100-RC). Pipe with these characteristics is suitable for pipe laying techniques such as sandless installations, or when the pipe is in contact with aggressive mediums such as detergents. For example, the German PAS 1075 (Public Application Scheme for sandless pipe installation) requires the following properties for pipes to be labelled PE100-RC (for Resistant to Cracks): FNCT > 8 760 h at 80°C under 4 MPa in 2% Arkopal N100, Point loading test > 8 760 h at 80°C under 4 MPa in 2% Arkopal NiOO, and NPT > 8 760 h at 80°C [176°F], 9.2 bar. The compositions of the present disclosure fulfil

the requirements for the PE100-RC classification. Pipes with good mechanical properties are known in the art, for example in WO 08006487, and EP-1985660,

In one embodiment of the present disclosure, reticulation is used to improve the melt strength of the polymer compositions while retaining good processability and good mechanical properties. In one embodiment, reticulation of the polymer with the addition of peroxide is used to achieve the properties of the present composition. Methods for increasing the melt strength of HDPE compositions by the use of thermally decomposable initiators such as peroxides have been discussed in the art. U.S. Patent No. 4390,666, WO 08/006487, WO 9747682, WO 2011/090846, U.S. Patent No. 4,390,666, WO 2008/083276, WO 2009/091730, U.S. Patent Publication No. 2007/0048472, WO 2006/036348, EP1969018, U.S. Patent Publication No. 2008/0161526 and U.S. Publication No. 2011/0174413. In one aspect, the present disclosure is also directed to processes and methods to manufacture a bimodal high-density polyethylene pipe resin with improved melt-strength while maintaining processability and retaining the properties characteristic of PE 100 and USPE 4710 materials.

Processability of a polymer composition can be characterized by its viscosity at a given shear stress that would be experienced during pipe extrusion. This processability can be predicted by viscosity measurements such as complex viscosity at 100 rad/s (η^*_{100}) for pipe extrusion and/or a melt index test such as HLMI. Processability for most pipe extrusion applications can be predicted by a material's complex viscosity measured at a frequency of 100 rad/s at a temperature of 190 °C. The processability can be directly measured on pipe extrusion equipment by throughput and amperage load required to produce a given pipe size.

The complex viscosity at 100 **rad/s** (η^*_{100}) most closely represents the shear rate imparted on the material during pipe extrusion. Viscosity is predictive of processability, i.e. extrusion energy demand and ultimately throughput. Within the context of the present disclosure, the complex viscosity at 100 rad/s (η^*_{100}) may also be referred to as the processability viscosity. A polymer composition with a lower processability viscosity value would be easier to process, or require less energy or amperage to achieve the same throughput (lbs/hour), when compared to a

composition with a high processability viscosity value. If a material's processability
viscosity is too high, or the material is too viscous, the energy required to achieve a
desired throughput rate may be outside of the capability of the extrusion equipment.
In this case the total throughput for that resin would be the limiting factor, and
5 extrusion rates would have to be decreased until the energy demand of the line is
within the equipment's capability. For pipe extrusion resins, a resin with good
processability are generally expected to have a complex viscosity at 100 rad/s
ranging from about 1,900 to about 2,600 Pa.s

In a first aspect, the present disclosure provides a bimodal high-density
10 polyethylene polymer composition comprising a base resin which has a density of
about 945 kg/m³ to about 955 kg/m³, preferably 946 kg/m³ to 951 kg/m³, most
preferably 947 kg/m³ to 951 kg/m³ and comprises an ethylene polymer (A) having a
density of at least 968 kg/m³, preferably above 970 kg/m³, most preferably above
971 kg/m³ in an amount ranging from about 45 to about 55% by weight, preferably
15 from about 47 to about 53% by weight, preferably from about 48 to about 52% by
weight, most preferably from about 49.5 to about 51.5% by weight, and an ethylene
polymer (B) having a density lower than the density of polymer A, wherein said
composition has a complex viscosity at a shear rate of 0.01 rad/s ranging from about
200 to about 450 kPa.s, preferably from about 220 to about 450 kPa.s, most
20 preferably from about 220 to about 420 kPa.s and a complex viscosity at a shear rate
of 100 rad/s ranging from about 1900 Pa.s to about 2600 Pa.s, preferably from about
2000 to about 2500 Pa.s, most preferably from about 2100 to about 2450 Pa.s.

The melt index MI₅ of the polyethylene composition is preferably from about
0.1 to about 0.5 g/10 min, preferably from 0.20 to 0.45 g/10 min, most preferably
25 from 0.2 - 0.4 g/10 min. For the purposes of the present disclosure, melt flow
Indices HLMI, MI₅ and MI_{3/4} are measured according to ISO 1133 at a temperature of
190 °C under loads of 21.6 kg, 5 kg and 2.16 kg respectively.

The shear thinning index SHI is the ratio of the viscosity of the polyethylene
composition at different shear stresses. In the present disclosure, the shear stresses at
30 2.7 kPa and 210 kPa are used for calculating the SHI_{2.7/210} which may be considered
as a measure of the broadness of the molecular weight distribution. The SHI_{2.7/210} of

the composition preferably ranges from about 60 to about 115, preferably from about 65 to 105, most preferably from about 75 to 95.

The composition preferably has a $G'(G'' \approx 3000)$ (Pa) ranging from about 1600 to about 2500, preferably from about 1650 to about 2400, most preferably
5 from about 1700 to about 2200.

The composition preferably has a complex viscosity at a constant shear stress of 747 Pa (η^{*747}) preferably from about 400 kPa.s to about 1300 kPa.s, preferably from 500 to 900 kPa.s, and most preferably from 550 to 900 kPa.s. In one embodiment, the composition has a η^{*747} viscosity ranging from about 650 to about
10 900 kPa.s.

The composition preferably has a zero shear viscosity (η^{*0}) preferably greater than about 500 kPa.s, preferably greater than 650 kPa.s, and most preferably greater than 800 kPa.s. In one embodiment, the composition has a η^{*0} viscosity ranging from about 800 to about 1,200 kPa.s.

15 The base resin may optionally further comprise a small prepolymerization fraction in an amount of 5% or less based on total polyethylene. Alternatively or additionally it may further comprise a fraction of very high molecular weight polymer, having a weight average molecular weight higher than the weight average molecular weight components (A), (B) or the prepolymer, in an amount of 5 wt% or
20 less based on total polyethylene.

It is generally preferred that the ratio of polymer (A) to polymer (B) in the base resin is between 45:55 and 55:45, more preferably between 47:53 and 53:47, and most preferably between 48:52 and 52:48, regardless of the presence or otherwise of any additional polyethylene fractions.

25 The form of the molecular weight distribution curve, i.e. the appearance of the graph of the polymer weight fraction as function of its molecular weight, of a multimodal polyethylene such as the base resin will show two or more maxima or at least be distinctly broadened in comparison with the curves for the individual fractions. For example, if a polymer is produced in a sequential multistage process

utilising reactors coupled in series with different conditions in each reactor, each of the polymer fractions produced in the different reactors will have its own molecular weight distribution and weight average molecular weight. The molecular weight distribution curve of such a polymer comprises the sum of the individual curves of the fractions, typically yielding a curve for the multimodal polymer having a substantially single peak or two or more distinct maxima. A "substantially single peak" may not follow a Gaussian distribution, may be broader than a Gaussian distribution would indicate, or have a flatter peak than a Gaussian distribution. Some substantially singular peaks may have a tail on either side of the peak. In some embodiments it may be possible to mathematically resolve a "substantially single peak" in a molecular weight distribution curve into two or more components by various methods.

It is particularly preferred that ethylene polymer (A) is a homopolymer, and the ethylene polymer (B) is a copolymer of ethylene and a C₄-C₈ alpha-olefin.

As used within this disclosure, the term "homopolymer" is understood to denote an ethylene polymer composed essentially of monomer units derived from ethylene and substantially devoid of monomer units derived from other olefins, which corresponds to a comonomer content of less than about 0.15 mol%. The term "copolymer of ethylene and a C₄-C₈ alpha-olefin" is understood to denote a copolymer comprising monomer units derived from ethylene and monomer units derived from a C₄-C₈ alpha-olefin and, optionally, from at least one other alpha-olefin. The C₄-C₈ alpha-olefin can be selected from olefinically unsaturated monomers comprising from 4 to 8 carbon atoms, such as, for example, 1-butene, 1-pentene, 1-hexene, 3-methyl-1-butene, 3- and 4-methyl-1-pentenes and 1-octene. Preferred alpha-olefins are 1-butene, 1-hexene and 1-octene and more particularly 1-hexene. More preferred comonomers are C₆-C₈ alpha-olefins, the most preferred comonomer is 1-hexene.

The other alpha-olefin which may also be present additional to the C₄-C₈ alpha-olefin is preferably selected from olefinically unsaturated monomers comprising from 3 to 8 carbon atoms, such as, for example, propylene, 1-butene, 1-pentene, 3-methyl-1-butene, 3- and 4-methyl-1-pentenes, 1-hexene and 1-octene.

The content in the composition of monomer units derived from C₄-C₈ alpha-olefin, hereinafter called comonomer content is preferably from about 0.3 to 0.65 mol%, preferably from about 0.4 to 0.65 mol%, and most preferably from about 0.4 to 0.6 mol%. The content in copolymer (B) of monomer units derived from C₄-C₈ alpha-olefin is generally at least 0.6 mol%, in particular at least 0.8 mol%. The comonomer content of copolymer (B) is usually at most 1.5 mol%, preferably at most 1.1 mol%.

In one embodiment of the present disclosure, polymer (A) has an MI₂ ranging from about 200 to 600. In one embodiment of the present disclosure polymer (A) has an MI₂ ranging from about 300 to 500 g/10 min. In one embodiment, the density of polymer (A) preferably ranges from about 968 kg/m³ to 975 kg/m³. The density of polymer (A) more preferably ranges from about 970 kg/m³ to 974 kg/m³, and from 971 to 974 kg/m³. The density of copolymer (B) preferably ranges from about 915 kg/m³ to 935 kg/m³, and from about 920 kg/m³ to about 930 kg/m³.

If polymers (A) and (B) are made separately and then blended, it is possible to measure directly the melt index, density and comonomer content of both polymers. However, if the multimodal polymer is made in a multistage process in which one polymer is made prior to the other and then the second polymer is made in the presence of the first polymer, the melt index, density and comonomer content of the second polymer cannot be measured, and instead for the purposes of this disclosure they are defined as follows:

The melt index of the second polymer is defined as that measured for the second polymer when made separately under the same polymerization conditions as used to make the multimodal base resin. In other words, the second polymer is made separately using the same catalyst and under the same polymerization conditions as those employed in the second reactor of the multimodal polymerization, and its melt index is then measured. The density of the second polymer is defined as being that calculated from the relationship: density (resin) = wt%(1)*density(1) + wt%(2)*density(2) where (1) and (2) are respectively the first and second polymers.

The comonomer content of the second polymer is defined as being that calculated from the relationship: comonomer content (resin) = wt%(1)*comonomer content (1) + wt%(2)*comonomer content (2) where (1) and (2) are respectively the first and second polymers.

5 If the multimodal polymer is made with a "multiple catalyst system" such as a bimetallic catalyst, it is possible to make both polymers (A) and (B) in the same reactor. In such a case it is not possible to measure directly the properties of either polymer (A) or polymer (B). Therefore in this case the properties of both polymers (A) and (B) are defined as being those obtained when the respective polymers are
10 prepared separately using the individual catalysts of the "multiple catalyst system", and under the same polymerization conditions as those employed for making the multimodal polymer.

In one embodiment, the multimodal composition of the present disclosure comprises a base resin having a density ranging from about 947 to about 951 kg/m³,
15 and comprising an ethylene polymer (A) having a density of at least 971 kg/m³ in an amount ranging from about 48 to about 52 wt%, an ethylene polymer (B) having a density of about 920 to about 930 kg/m³ in an amount ranging from about 52 to about 48 wt%, and said composition having a comonomer content of ranging from about 0.30 to about 0.65 mol% a G'(G'' = 3000) (Pa) between 1700 and 2200 Pa., a
20 complex viscosity at a shear rate of 100 rad/sec ranging from about 2100 to about 2450 Pa.s, a complex viscosity at a shear rate of 0.01 rad/s ranging from about 220 to about 420 kPa.s.

In other embodiments, the polymer compositions may comprise additional components without departing from the scope of the present disclosure. In particular,
25 the composition may contain conventional additives in an amount of up to about 10 wt%, preferably up to about 5 wt% and more preferably up to about 3 wt% based on the total weight of the composition. Such additives include stabilizers (antioxidizing agents and/or anti-UV agents), antistatic agents and processing aids, as well as pigments. The composition may also contain up to 10 wt.% of another polyolefin,
30 preferably another polyethylene.

As used in the present disclosure, "multiple catalyst system" refers to a composition, mixture or system including at least two different catalyst compounds, each having the same or a different metal group, including a "dual catalyst," e.g., a bimetallic catalyst. Use of a multiple catalyst system enables the multimodal product to be made in a single reactor. Each different catalyst compound of the multiple catalyst system may reside on a single support particle, in which case a dual (bimetallic) catalyst is considered to be a supported catalyst. However, the term bimetallic catalyst also broadly includes a system or mixture in which one of the catalysis resides on one collection of support particles, and another catalyst resides on another collection of support particles. Preferably, in that latter instance, the two supported catalysts are introduced to a single reactor, either simultaneously or sequentially, and polymerization is conducted in the presence of the bimetallic catalyst system, i.e., the two collections of supported catalysts. Alternatively, the multiple catalyst system includes a mixture of unsupported catalysts in slurry or solution form.

In one embodiment according to the present disclosure, the multimodal polyethylene base resin is preferably obtained by a multistage ethylene polymerization, typically using a series of reactors. A multistage process is a polymerization process in which a polymer comprising two or more fractions is produced by producing at least two polymer fraction(s) in separate reaction stages, usually with different reaction conditions in each stage, in the presence of the reaction product of the previous stage. The polymerization reactions used in each stage may involve conventional ethylene homopolymerization or copolymerization reactions, e.g. gas-phase, slurry phase, liquid phase polymerizations, using conventional reactors, e.g. loop reactors, gas phase reactors, batch reactors etc.

It is preferred that the polymer (A) is produced in the first reactor, and that polymer (B) is produced in a subsequent reactor. However this order may be reversed. If the base resin includes a prepolymer, this is made in a reactor preceding the first reactor. It is preferred that all reactors are slurry reactors, in particular slurry loop reactors. In one embodiment, the preferred multistage polymerization process includes in a first reactor, ethylene is polymerized in slurry in a first mixture

comprising a diluent, hydrogen, a catalyst based on a transition metal and a cocatalyst, so as to form from 30 to 70% by weight with respect to the total weight of the composition of an ethylene homopolymer (A); said first mixture is withdrawn from said reactor and is subjected to a reduction in pressure, so as to degas at least a portion of the hydrogen to form an at least partially degassed mixture, and said at least partially degassed mixture, together with ethylene and a C₄-C₈ alpha-olefin and, optionally, at least one other alpha-olefin, are introduced into a subsequent reactor and the slurry polymerization is carried out therein in order to form from 30 to 70% by weight, with respect to the total weight of the composition, of a copolymer of ethylene and of C₄-C₈ alpha-olefin.

In one embodiment, a low-molecular weight (LMW) ethylene polymer component (A) is made in a first reactor and a high-molecular weight (HMW) ethylene polymer component (B) is added in a second reactor. Within the context of this disclosure the terms "LMW ethylene polymer component (A)", "ethylene polymer component (A)" or "LMW ethylene component" may be used interchangeably. Similarly, within the context of this disclosure the terms "HMW ethylene polymer component (B)", "ethylene polymer component (B)" or "HMW ethylene component" may also be used interchangeably. The mass ratio of LMW ethylene polymer component (A) to the final bimodal HDPE polymer is in an amount ranging from 45% to 55% by weight, preferably from 47 to 53% by weight, preferably from 48 to 52% by weight, and most preferably from 49.5 to 51.5% by weight. In one embodiment, the polymerization occurs in both reactors in the presence of hydrogen, and the ratio of molar hydrogen concentration in the first reactor to molar hydrogen concentration in the second reactor is from 250:1 to 350:1.

The disclosure also provides a process for obtaining a pipe or a pipe fitting, comprising the steps of polymerising ethylene and optionally comonomer, compounding the polyethylene composition, and then extruding or injection moulding the composition to form an article. In most embodiments according to the present disclosure, the step of polymerising ethylene preferably forms a multimodal polyethylene.

The catalyst employed in the polymerization process to produce the polyethylene base resins used in the compositions of the disclosure may be any catalyst(s) suitable for preparing such polyethylenes. If the polyethylene is bimodal, it is preferred that the same catalyst produces both the high and low molecular weight fractions. For example, the catalyst may be a Ziegler-Natta catalyst or a metallocene catalyst. Preferably the catalyst is a Ziegler-Natta catalyst.

In the case of a Ziegler-Natta catalyst, the catalyst used comprises at least one transition metal. Transition metal means a metal of groups 4, 5 or 6 of the Periodic Table of elements (CRC Handbook of Chemistry and Physics, 75th edition, 1994-95). The transition metal is preferably titanium and/or zirconium. A catalyst comprising not only the transition metal but also magnesium is preferably utilized. Good results have been obtained with catalysts comprising: from 5 to 30%, preferably from 6 to 22%, most preferably 8 to 18% by weight of transition metal, from 0.5 to 20%, preferably from 2 to 18%, most preferably 4 to 15% by weight of magnesium, from 20 to 70%, preferably from 30 to 65%, most preferably 40 to 60% by weight of halogen, such as chlorine, from 0.1 to 10%, preferably from 0.2 to 8%, most preferably 0.5 to 5% by weight of aluminium; the balance generally consisting of elements arising from products used for their manufacture, such as carbon, hydrogen and oxygen. These catalysts are preferably obtained by coprecipitation of at least one transition metal composition and a magnesium composition by means of a halogenated organoaluminium composition. Such catalysts have been described in U.S. Patent Nos. 3,901,863; 4,292,200 and 4,617,360. The catalyst is preferably introduced only into the first polymerization reactor, i.e. there is no introduction of fresh catalyst into the further polymerization reactor. The amount of catalyst introduced into the first reactor is generally adjusted to obtain an amount of at least 0.5 mg of transition metal per litre of diluent. The amount of catalyst usually does not exceed 100 mg of transition metal per litre of diluent.

In one embodiment, a preferred catalysts contain 8 to 18% by weight of transition metal, 4 to 15% by weight of magnesium, 40 to 60% by weight of chlorine and 0.5 to 5% by weight of aluminium, and have a residual organic radical content in the precipitated catalyst of less than 35 wt%. These catalysts are also obtained by

coprecipitation of at least one transition metal compound and a magnesium compound by means of a halogenated organoaluminium compound, but with a ratio of transition metal to magnesium of no more than about 1:1. For additional discussion in these catalyst see EP-B-2021385 which is incorporated herein in its entirety.

A preferred catalytic system for use in the process of the present disclosure comprises a catalytic solid comprising magnesium, at least one transition metal selected from the group consisting of titanium and zirconium and a halogen, prepared by successively reacting, in a first step (i) at least one magnesium compound (M) chosen from oxygen-containing organic magnesium compounds with at least one compound (T) selected from the group consisting of oxygen-containing organic tetravalent titanium and zirconium compounds, until a liquid complex is obtained; treating, in a second step, the complex obtained in the first step with a halogen-containing aluminic compound of formula ALR_nX_{3-n} , in which R is a hydrocarbon radical comprising up to 20 carbon atoms, X is a halogen and n is less than 3, and an organometallic compound of a metal chosen from lithium, magnesium, zinc, aluminium or tin.

The preparation of the solid catalytic complex comprises the step (ii), the main function of which is to reduce the valency of the transition metal and simultaneously additionally halogenate, if necessary, the magnesium compound and/or the transition metal compound: thus most of the alkoxy groups still present in the magnesium compound and/or in the transition metal compound are substituted by halogens, such that the liquid complex obtained after step (i) is transformed in a catalytically active solid. The reduction and possible further halogenation are performed simultaneously using the halogen-containing aluminic compound which thus acts as a reductive halogenating agent. The treatment using the halogen-containing aluminic compound in step (ii) of the preparation of the catalytic solid may be carried out by any suitable known means, and preferably by gradually adding the halogen-containing organoaluminium compound to the liquid complex obtained in step (i). The temperature at which step (ii) is performed should not exceed 60 °C, temperatures of no more than 50 °C being the most advantageous.

The preferred temperature range is 25-50 °C, with the most preferable range being 30-50 °C. The co-catalyst utilized in the process is preferably an organoaluminum compound. Unhalogenated organoaluminum compounds of formula AlR_3 in which R represents an alkyl grouping having from 1 to 8 carbon atoms are preferred. In one embodiment, triethylaluminum and triisobutylaluminum are preferred.

In one embodiment, the multistage polymerization process described above for producing the composition of the disclosure utilizes a Ziegler-Natta catalyst. In such a case the polymerization temperature is generally from 20 to 130°C, preferably at least 60°C, and generally it does not exceed 115°C. The total pressure at which the process is effected is in general from 0.1 MPa to 10 MPa. In the first polymerization reactor, the total pressure is preferably at least 2.5 MPa. Preferably, it does not exceed 5 MPa. In the further polymerization reactor, the total pressure is preferably at least 1.3 MPa. Preferably, it does not exceed 4.3 MPa.

The period of polymerization in the first reactor and in the further reactor is in general at least 20 minutes, preferably at least 30 minutes. The period of polymerization generally does not exceed 5 hours, and preferably it does not exceed 3 hours. In this process, a slurry comprising the resin of the disclosure is collected at the outlet of the further polymerization reactor. The composition may be separated from the suspension by any known means. Usually, the suspension is subjected to a pressure expansion (final expansion) to eliminate the diluent, the ethylene, the α -olefin and any hydrogen from the composition.

In one embodiment, the material modified by a decomposable thermal initiators such as a peroxide according to the present disclosure can be used in the production of thick wall pipe within those industry standards, while still meeting or exceeding PE100 and PE4710 standards, and while maintaining good processability.

In one embodiment, polymer compositions according to the present disclosure are reticulated, usually in a post-production compounding step. The polymer composition can be reticulated using a decomposable thermal initiators. The bimodal resin flake produced on the reactor or reactors acts as the base material

to be modified. This material is fed to the extrusion equipment along with the additive package and the decomposable thermal initiators. The extrusion equipment melts the HDPE flake and disperses the additives and the decomposable thermal initiators. Consistency of polymer and additive feed determines how well the polymer/additive/decomposable thermal initiators mixture is dispersed. The temperature and residence time in the mixing and extruder cause the decomposable thermal initiators to react with the base polymer.

In one embodiment, cross-linking of the polymer is done using decomposable thermal initiators. The cross-linking of the polymer is controlled by addition of the initiator in powder or liquid form in the pre-mix of additives fed in the extruder, simultaneously with polyethylene powder. The decomposable thermal initiator may be added as a neat compound or may alternatively be dispersed in another polymer as a masterbatch, typically polyethylene or polypropylene. The type of initiator is selected according to its half time life curve versus temperature

Decomposable thermal initiators are known in the art, such as azobisisobutyronitrile (AIBN), peroxy compound such as diacyl peroxides, acetyl alkylsulfonyl peroxides, dialkyl peroxydicarbonates, tert-alkylperoxyesters, OO-tert-alkyl O-allyl monoperoxy carbonates, di(tert-alkylperoxy)ketals, di(tert-alkyl)peroxides, tert-alkyl hydroperoxides, and ketone peroxides, redox initiators, and the like.

In one embodiment, preferred peroxy compounds comprise diacylperoxides such as dibenzoyl peroxide BPO, di(2,4-dichlorobenzoyl) peroxide, diacetyl peroxide, dilauroyl peroxide, didecanoyl peroxide, diisononoyl peroxide and succinic acid peroxide; peroxy esters such as di-tert-butyl diperoxyphthalate, tert-butyl perbenzoate, tert-butyl peracetate, tert-amyl perbenzoate, 2,5-di(benzoylperoxy)-2,5-dimethylhexane, tert-butyl peroxy maleic acid, tert-butyl peroxyisobutyrate, tert-butyl peroxyethylhexanoate(tert-butyl peroxoate), tert-amyl peroxoate, 2,5-di(2-ethylhexylperoxy)-2,5-dimethylhexane, tert-butyl peroxy pivalate, tert-amyl peroxy pivalate, tert-butyl peroxyneodecanoate, tert-amyl peroxyneodecanoate, a-cumyl peroxyneodecanoate; diperoxyketals, such as ethyl-3,3-di(tert-butylperoxy)butyrate, ethyl 3,3-di(tert-amylperoxy)-butyrate, di-tert-butyl 4,4,

-di(tert-butylperoxy)valerate, 2,2-di(tert-butylperoxy)butane, 1,1-di(tert-butylperoxy)cyclohexane, 1,1-di(tert-butylperoxy)-3,3,5-trimethylcyclohexane, and 1,1-di(tert-amylperoxy)cyclohexane; dialkylperoxides, such as 2,5(tert-butylperoxy)-2,5-dimethyl-3-hexyne, di-tert-butyl peroxide, tert-butylcumyl peroxide, 2,5-di(tert-butylperoxy)-2,5-dimethylhexane, *o*-*o*'-di(tert-butylperoxy)-1,3- and 1,4-diisopropylbenzene, and dieumylperoxide; peroxydicarbonates such as di-*n*-propyl peroxydicarbonate, diisopropyl peroxydicarbonate, dicetyl peroxydicarbonate, di-*sec*-butyl peroxydicarbonate, di(2-ethylhexyl)peroxydicarbonate, and di(4-tert-butylcyclohexyl)peroxydicarbonate; and tert-alkylhydroperoxides such as tert-butyl hydroperoxide, tert-amyl hydroperoxide, cumene hydroperoxide, 2,5-dihydroxyperoxy-2,5-dimethylhexane, pinane hydroperoxide, para-menthane hydroperoxide, and diisopropylbenzene hydroperoxide.

In some embodiments of the present disclosure peroxy initiators are selected from: 2,5-dimethyl-2,5-di(tert-butylperoxy)hexyne-3; 2,5-dimethyl-2,5-di(tert-butylperoxy)hexane; di-tert-butyl peroxide; 1,3,1,4-di-tert-butylperoxyisopropylbenzene; tert-butylcumylperoxide; dieumylperoxide; 3,3,6,6,9,9-hexamethyl-1,2,4,5-tetracyclotnonane; 4,4-di-tert-butylperoxy-*n*-butylvalerate; 1,1-di-tert-butylperoxycyclohexane; tert-butylperoxybenzoate; dibenzoyl peroxide; di(2,4-dichlorobenzoyl)peroxide; di(*p*-chlorobenzoyl)peroxide; 2,2-di(tert-butylperoxy)butane; ethyl-3,3-bis(tert-butylperoxy)butyrate. In one embodiment, the compositions and resins according to the present disclosure are treated with 2,5-dimethyl-2,5-di(tert-butylperoxy)hexane and bis(tert-butylperoxyisopropyl)benzene.

In a preferred embodiment of the present disclosure the polymer is treated with 2,5-dimethyl-2,5-di(tert-butylperoxy)hexane, commercially available under the names Trigonox 101 and Pergaprop Hx 7,5 PP, adhered to a PP flake surface at a 7.5 wt% concentration. In some embodiments, the amount of neat peroxy initiator used in the cross-linking process ranges from about 50 ppm to about 150 ppm by weight, and preferably from about 50 ppm to about 100 ppm by weight. Preferably the amount of peroxide is sufficient to ensure that the resulting polyethylene composition has the desired complex viscosity at low shear rate ($\eta_{0.01}^*$). The amount

of peroxy initiator required to obtain the desired value depends partly on the melt strength of the original unreticulated polyethylene as well as on the type of peroxide used and on the compounding conditions, more specifically the melt temperature and extruder residence time as these factors will influence the reticulation efficiency.

5 The optimal peroxide loading level will vary based on the material's starting melt strength and the type of organic peroxide used. Materials with low shear viscosities lower than 200,000 Pa.s generally do not to have the melt strength capable of producing thick wall pipe with wall distributions within industry specifications. In one embodiment, the load of peroxide is controlled to obtain
10 material which exhibits low shear viscosities at 0.01 rad/s no greater than about 450,000 Pa.s. In one embodiment, the preferred amount of peroxide used is below 150 by weight. It is possible to produce thick wall pipe with materials that have low shear viscosities greater than 450,000 Pa.s, but the increased low shear viscosity of the material would not produce additional advantage, the use of additional
15 peroxide may become cost prohibitive, cause end product processing issues (such as decrease in throughput and undesirable surface imperfections), and could cause physical property degradation. Examples of possible processing issues associated with use of higher levels of peroxide include the presence of excess gels in the material, causing rough surfaces and weak spots in the pipe that could lead to early
20 pipe failures under pressure.

The polyethylene powder produced in a polymerization process such as that disclosed above is fed to the extrusion equipment along with the additive package and the peroxide. The extrusion equipment melts the powder and disperses any additives and the peroxide. The peroxide must be well dispersed within the polymer
25 melt, at temperatures hot enough and residence times long enough to fully initiate the peroxide and allow the consequent radical chain reactions to occur to a sufficient extent to produce the desired effect. The peroxide must be well dispersed within the polymer melt, at temperatures hot enough and residence times long enough to fully
30 initiate the peroxide and allow the consequent radical chain reactions to occur to a sufficient extent to produce the desired effect of increased melt strength and retained

processability. The additive feeding hardware must be able to feed a consistent amount of peroxide, to give a consistent (homogeneous) modified product.

If a peroxide carrier with a particle size more similar to the other additives that are being added to the HDPE melt could be used, the additives could all be
5 combined into a larger tote bin, allowing the additive feeder to feed at higher rates with less variability to produce better control of organic peroxide addition rates. Also the type of peroxide used and the carrier used to transport the peroxide could be changed (liquid, PP flake, HDPE flake). The organic peroxide and its carrier could be replaced with functional alternatives. If available, a HDPE flake or pellet
10 could be used as a carrier for the peroxide, a neat liquid peroxide could be used, as well as other forms of the desired peroxide. Other organic peroxides that could be used include dicumyl peroxide, tert-butylperoxyisopropylbenzene, and 1,3-bis(tert-butylperoxy)isopropane, and others. Such replacement materials, while not changing the basic disclosure,
15 would result in the possible need for a re-calculation in target peroxide concentrations and other reactive extrusion conditions, such as residence time needed to achieve proper mixing.

Tighter controls and better peroxide addition methods may improve the properties of the compositions according to the present disclosure. Extrusion
20 temperature and residence time allow the peroxide to fully react once added to the base resin flake. Temperatures must be high enough and the peroxide must remain in contact with the polymer for long enough for the long chain branching to occur. The peroxide used can be added as either a solid or a liquid.

The extrusion equipment could also be replaced or altered to use many
25 different types of commercially available polymer extrusion equipment. The extrusion equipment used must be capable of providing sufficient heating, residence time, and shear (work) being imparted on the polymer.

If the extrusion temperature is too high, the peroxide could be consumed before being able to be well dispersed in the polymer matrix, especially if it were to
30 come in contact with a hot surface before being mixed with the polymer. The

peroxide reaction would begin, but not react with the polymer chains. The desired melt strength increase would not be achieved in the polymer. If this were to occur, reduced long chain branching would occur and the low shear viscosity of the bulk HDPE material would not be sufficient. Extrusion temperatures may impact the
5 reticulation process. In one embodiment, the reticulation according to the present disclosure is carried at a temperature lower than about 320 °C. In one embodiment, the reticulation according to the present disclosure is carried at a temperature lower than about 280 °C (550 °F). The minimum residence time at a certain temperature depends on the half life of the peroxide at that temperature. The half life at a given
10 temperature will vary with type of peroxide used.

Compositions made according to some embodiments of the present disclosure can be mixed with the usual processing additives for polyolefins, such as stabilizers (antioxidizing agents and/or anti-UV agents), antistatic agents and processing aids, as well as pigments.

15 Pipes made from the compositions according to some embodiments of the disclosure preferably have one or more of the following properties an MRS 10 rating or better as defined by standard ISO/TR.9080 or a PE4710 listing per ASTM D883 and ASTM D3350.

Unless otherwise specified, all numbers expressing quantities of ingredients,
20 reaction conditions, and other properties or parameters used in the specification and claims are to be understood as being modified in all instances by the term "about." All numerical ranges herein include all numerical values and ranges of all numerical values within the recited range of numerical values. By way of non-limiting illustration, concrete examples of certain embodiments of the present disclosure are
25 given below.

EXAMPLES

Testing methods

Melt Index

Melt indexes were determined according to ISO 1133 or ASTM D1238 and the
5 results are indicated in g/10 min, but **both** tests will give substantially the same
results. For polyethylenes a temperature of 190 °C is applied, MI₂ is determined
under a load of 2.16 kg, MI₅ is determined under a load of 5 kg and HLM₁ is
determined under a load of 21.6 kg.

Density

10 Density of the polyethylene was measured according to ISO 1183-1 (Method
A) and the sample plaque was prepared according to ASTM D4703 (Condition C)
where it was cooled under pressure at a cooling rate of 15 °C/min from 190° C to 40
°C.

Comonomer content

15 The C₄-C₈ alpha-olefin content is measured by ¹³C NMR according to the
method described in J. C. Randall, JMS-Rev. Macromol. Chem. Phys., C29(2&3), p.
201-317 (1989). The content of units derived from C₄-C₈ alpha-olefin is calculated
from the measurements of the integrals of the lines characteristic of that particular
C₄-C₈ alpha-olefin in comparison with the integral of the line characteristic of the
20 units derived from ethylene (30 ppm). A polymer composed essentially of monomer
units derived from ethylene and a single C₄-C₈ alpha-olefin is particularly preferred.

Environmental stress crack resistance (ESCR)

Environmental stress crack resistance (ESCR) is determined by Notched Pipe
Test (NPT). The notched pipe test was performed according to ISO 13479: 1997 on
25 a pipe of diameter 110mm and thickness 10mm (SDR 11). The test was run at 80 °C
at a pressure of 9.2 bar.

Stress crack resistance (PENT)

Another method to measure environmental stress crack resistance is the Pennsylvania Notched Tensile Test (PENT), ASTM D1473. PENT is the North American accepted standard by which pipe resins are tested to classify their ESCR performance. A molded plaque is given a specified depth notch with a razor and tested at 80°C under 2,4 MPa stress to accelerate the stress cracking failure mode of a material. The time in which the specimen fails, breaks completely or elongates over a certain length, is used for its ESCR classification. A PE4710 by definition must not fail before 500 hours. Materials described in this patent would test over 10,000 hours without failure and be considered high performance materials.

Resistance to rapid crack propagation (RCP)

Resistance to rapid propagation of cracks (RCP) is measured according to method S4 described in ISO standard 13477. The critical temperature was determined on a pipe of diameter 110 mm and thickness 10 mm (SDR 11) at a constant pressure of 5 bar. The critical temperature is defined as the lowest crack-arrest temperature above the highest crack propagation temperature; the lower the critical temperature, the better the resistance to rapid crack propagating.

Creep resistance

Creep resistance is measured according to ISO 1167 on a pipe of diameter 50 mm and thickness 3 mm (SDR 17) pipes to determine the lifetime prior to failure at a temperature of 20°C and 80°C and a stress of between 5 and 13 MPa.

Dynamic rheology at constant shear rate

Dynamic rheological measurements to determine the complex viscosities η^* as a function of shear rate are carried out, according to ASTM D 4440, on a dynamic rheometer (e.g., ARES), such as a Rheometrics, Ares model 5 rotational rheometer, with 25 mm diameter parallel plates in a dynamic mode under an inert atmosphere. For all experiments, the rheometer has been thermally stabilised at 190 °C for at least 30 minutes before inserting the appropriately stabilized (with antioxidant

additives), compression-molded sample onto the parallel plates. The plates are then closed with a positive normal force registered on the meter to ensure good contact. After about 5 minutes at 190 °C, the plates are lightly compressed and the surplus polymer at the circumference of the plates is trimmed. A further 10 minutes is allowed for thermal stability and for the normal force to decrease back to zero. That is, all measurements are carried out after the samples have been equilibrated at 190 °C for about 15 minutes and are run under full nitrogen blanketing.

Two strain sweep (SS) experiments are initially carried out at 190 °C to **determine the linear viscoelastic** strain that would generate a torque signal which is greater than 10% of the lower scale of the transducer, over the full frequency (e.g. 0.01 to 100 rad/s) range. The first SS experiment is carried out with a low applied frequency of 0.1 rad/s. This test is used to determine the sensitivity of the torque at low frequency. The second SS experiment is carried out with a high applied frequency of 100 rad/s. This is to ensure that the selected applied strain is well within the linear viscoelastic region of the polymer so that the oscillatory rheological measurements do not induce structural changes to the polymer during testing. In addition, a time sweep (TS) experiment is carried out with a low applied frequency of 0.1 rad/s at the selected strain (as determined by the SS experiments) to check the stability of the sample during testing.

The frequency sweep (FS) experiment was then carried out at 190°C using the above appropriately selected strain level between dynamic frequencies range of 10^{-2} to 100 rad/s, under nitrogen. The **dynamic** rheological data thus measured were then analysed using the rheometer software (viz., Rheometrics RHIGS V4.4 or Orchestrator Software) to determine the melt elastic modulus G' ($G''=3000$) at a reference melt viscous modulus (G'') value of $G''=3000$ Pa. If necessary, the values were obtained by interpolation between the available data points using the Rheometrics software.

The term "Storage modulus", $G'(\omega)$, also known as "elastic modulus", which is a **function** of the applied oscillating frequency, ω , is defined as the stress in phase with the strain in a sinusoidal deformation divided by the strain; while the term

"Viscous modulus", $G''(\omega)$, also known as "loss modulus", which is also a function of the applied oscillating frequency, ω , is defined as the stress 90 degrees out of phase with the strain divided by the strain. Both these moduli, and the others linear viscoelastic, dynamic rheological parameters, are well known within the skill in the art, for example, as discussed by G. Marin in "Oscillatory Rheometry", Chapter 10 of the book on Rheological Measurement, edited by A.A. Collyer and D.W. Clegg, Elsevier, 1988.

Melt rheology at constant shear stress

The rheological properties of a material at a low shear rates were measured to better understand the material as it sags under gravitation forces. A constant stress test was used to determine the complex viscosity η^* at low shear stress. The experiments were conducted using an ARES G2 manufactured by TA Instruments. In this transient experiment, the sample was placed under a low shear stress where the viscosity was no longer shear stress dependent. In this region at very low shear stresses, the shear rate is also expected to be very low, much lower than the complex viscosity measured at 0.01 rad/s, and the viscosity in the region is expected to be shear rate independent. The compliance is a function of shear stress and time and defined as the ratio of time dependent strain over a constant stress. The experiments were conducted at low shear stress values where the creep compliance becomes independent of shear stress and linear with time allowing the determination of zero shear viscosity. The inverse slope of the compliance plot can be defined as the material's zero shear viscosity and can be seen in Table 1. The experiments were carried out at 190 °C under nitrogen using a 25 mm diameter parallel plate. The distance between the parallel plates during the experiment was 1.7 mm \pm 1%. Stress control loop parameters were run and calculated prior to the test using a strain amplitude determined in the linear viscoelastic region. A total time of 6 minutes was used to condition the sample and transducer. A low shear stress of 747 Pa is then applied to the sample and maintained for 1800 seconds. After this time the viscosity of the sample is measured. The zero shear viscosity is determined from the time dependent creep compliance,

Preparation of black composition

The **manufacture** of a base resin I comprising ethylene polymers was carried out in suspension in **isobutane** in two loop reactors, **connected** in series and
5 separated by a device which makes it possible continuously to carry out the reduction in pressure. Isobutane, ethylene, hydrogen, triethylaluminium and the catalyst were continuously introduced into the first loop reactor and the polymerization of ethylene was **carried** out in this mixture in order to form the homopolymer (A). This mixture, additionally comprising the homopolymer (A), was
10 continuously withdrawn from the said reactor and was subjected to a reduction in pressure, to remove at least a portion of the hydrogen. The resulting mixture, at least partially degassed of hydrogen, was then continuously introduced into a second polymerization reactor, at the same time as ethylene, 1-hexene, isobutane and hydrogen, and the polymerization of the ethylene and of the hexene was carried out
15 therein in order to form the ethylene/1-hexene copolymer (B). The suspension comprising the **composition** comprising ethylene polymers was continuously withdrawn from the second reactor and this suspension was subjected to a final reduction in pressure, so as to flash the isobutane and the reactants present (ethylene, hexene and hydrogen) and to recover the composition in the form of a dry powder,
20 which was subsequently treated in a purge column in order to remove most of the process components trapped in the polymer particles. Catalysts were used as described in EP-B-2021385. The other polymerization conditions and copolymer properties are presented in Table 1.

Additives were incorporated to the powder particles and subsequently
25 intensively mixed together prior to feeding the compounding equipment, a conventional twin screw extruder. The additives included at least one acid neutralizer like calcium stearate or zinc stearate in an amount between 500 and 2000 ppm or a mixture of both, and at least one process antioxidant like Irgafos 168 in an amount between 500 and 2500 ppm and at least one thermal antioxidant like
30 irganox 1010 in an amount between 500 and 2500 ppm. Small quantities of processing aid, such as SOLEF 11010/1001, may also be added. The additives also

include Carbon Black in an amount of 2.0 - 2.4 wt%. A thermal decomposition agent, 2,5-dimethyl-2,5-di(tert-butylperoxy)hexane (DHBP) is optionally incorporated in the feed via a 7.5 wt% master batch in polypropylene.

This mixture of flake/additives/peroxide enters the mixing section of the extruder where the material is heated, melted, and mixed together. The time the material spends in the mixing and extrusion sections is considered the reaction's residence time. The other pelletization conditions and properties of the pelletized resin are specified in Table 2.

Table 1

Polymerization conditions and properties for base polymer I

EXAMPLE	I
Reactor 1	
C2 (mol%)	1.75
H2/C2 (mol/mol%)	42.1
T (°C)	95
Residence time (h)	2.17
wt % (A)	49
MI ₂ (g/10min) [*]	400
Density (kg/m ³)	973
Reactor 2	
C2 (mol%)	2.61
C6/C2 (mol/mol%)	137.3
H2/C2 (mol/mol%)	0.71
T (°C)	85
Residence time (h)	0.87
Final composition (base resin)	
MI ₅ (g/10min) [*]	0.31
Density (kg/m ³)	948.5
Comonomer content (mol%)	0.60

^{*} Measured according to ISO1133

Table 2
Pelletisation condition and properties of pelletised resins

EXAMPLE	C1	2	3	4
Pelletisation conditions				
DHBP7.5%IC5	0	400	700	1000
Peroxide amount (ppm MB)	0	30	53	75
Peroxide amount (ppm pure)	0	30	53	75
Carbon black content [wt%]	2.2	2.1	2.2	2.2
Total specific energy [kWh/t]	278	278	279	280
Max melt temperature [°C]	312	313	314	312
Properties polymer composition (after pelletisation - black compound)				
MI ₅ (g/10min)**	0.29	0.26	0.25	0.24
HLMI (g/10min)**	8.5	9.2	9.8	9.5
HLMI/MI ₅	29	35	38	40
Density (kg/m ³)	959.9	959.2	959.8	959.0
G'(G'' = 3000) (Pa)	1,276	1,664	1,927	2,096
$\eta^*_{0.01}$ (Pa.s)	185,778	215,823	257,745	299,653
η^*_{100} (Pa.s)	2,504	2,382	2,396	2,401
SHI 2.7 / 210 (-)	44	61	76	96
η^* at G* = 2.7 kPa (Pa.s)	150,519	197,229	255,503	311,613
η^*_{747} (kPa.s)	280	446	647	889
NPT 80°C - 9.2bar on 110SDR11 pipes (h)	> 8 800	> 8 800	> 8 800	> 8 800
RCP S4 Critical Temperature on 110SDR11 pipes (°C)	-17.5	-27.5		-17.5
creep at 20°C / 12.4 MPa (h)		2,269	688	803
creep at 20°C / 12.1 MPa (h)	2,632	3,080	2,139	3,066
creep at 20°C / 11.8 MPa (h)	> 7,200	> 7,200	> 7,200	> 7,200
creep at 80°C / 5.7 MPa (h)	207	490	1,236	4,066
creep at 80°C / 5.5 MPa (h)	> 7,800	> 7,800	> 7,800	> 7,800

** measured according to ISO1133

Preparation of natural composition

The manufacture of a base resin II was carried out as described for base resin I above. Polymerization conditions and copolymer properties are presented in Table 3.

5 2,5-Dimethyl-2,5-di(tert-butylperoxy)hexane (DFIBP) was incorporated to the powder particles and subsequently intensively mixed together prior in a Farrel FCM mixer. The balance of the additive formulation (primary antioxidant, etc.) is added via a separate feeder at the same location. This mixture of
flake/additives/peroxide enters the mixer where the material is heated, melted, and
10 mixed together. A polymer ribbon then leaves the mixer through the orifice and is fed to the extruder. The material is conveyed to the die where it is then pelletized. The processing time in the mixer and the extruder is defined as the residence time.

Table 4 presents data for reticulated samples and non-reticulated samples. These predictive rheological tools show no statistically significant difference in
15 processing parameters while a significant shift in low shear viscosity is present. To confirm the predictive measurement for processability and to show that no loss in processability was experienced comparisons of pipe extrusion measurements of processability are shown in the Table 4. Furthermore, the predictive measurement for melt strength was examined and confirmed by the pipe extrusion data offered for
20 reticulated and non-reticulated samples. The wall thickness improvements and similar processability show that a peroxide modified resin will exhibit improved melt strength with no loss of processability as expected from predictive rheological results.

Table 3
Polymerization conditions and properties for base polymer II

EXAMPLE	II
Reactor 1	
C2 (mol%)	3.3
H2/C2 (mol/mol%)	47
T (°C)	96
wt % (A)	49.5
MI ₂ (g/10min)*	400
Density (kg/m ³)	972
Reactor 2	
C2 (mol%)	3.0
C6/C2 (mol/mol%)	130
H2/C2 (mol/mol%)	0.17
T (°C)	85
Final composition (base resin)	
MI ₅ (g/10min)*	0.30
Density (kg/m ³)	949

* Measured according to ASTM D1238

5

Table 4

Example	C5	6	7	8
Pelletization conditions				
Peroxide amount (ppm pure)	0	75	92	130
Properties polymer composition (after pelletization – natural compound)				
MI ₅ (g/10min)**	0.26	0.26	0.19	0.22
HLMI (g/10min)**	7.3	8.4	7.0	7.2
HLMI/MI ₅	27.6	32.6	36.6	32.9
Density (kg/m ³)	948.4	949.0	948.9	949.7
G'(G'' = 3000) (Pa)	1,248	1,851	1,985	
G'(G'' = 5000) (Pa)	2,370	3,378	3,834	
$\eta^*_{0.01}$ (Pa.s)	187,073	261,190	364,960	428,436
η^*_{100} (Pa.s)	2304	2272	2,403	2,330
Zero Shear Viscosity (η_0) (Pa.s)	426,112	876,962	1,295,824	3,028,376
SHI 2.7/210	39	91	115	
η^* at G* = 2.7 kPa (kPa.s)	168.3	257.8	399.9	
η^*_{747} (kPa.s)			1,296	
PENT Failure Time (h)	>10,000		>7,900	>10,000
Pipe Extrusion Data				
Typical Throughput Rates (lb/hr)**	1,885	1,500	1,750	2,351
Extruder Load (%)	70	83	77	73
Pipe Size	28'' DR 11	24'' DR 5	30'' DR9	48'' DR 17
Wall Thickness Limitation (inches)	2 1/4''	4.5''	3.33'' - 4'' or higher	2.82'' - 3.5'' or higher

* Measured according to ASTM D1238

** Dependent on extruder capability, extruder size, pipe size and downstream cooling constraints.

5 Other embodiments will be apparent to those skilled in the art from consideration of the specification and practice of the present disclosure. It is intended that the specification and examples be considered as exemplary only, with a true scope and spirit of the invention being indicated by the following claims.

WHAT IS CLAIMED IS:

1. A bimodal high-density polyethylene polymer composition comprising a base resin which has a density of about 945 kg/m³ to about 955 kg/m³, preferably 946 to 951 kg/m³, most preferably 947 to 951, and comprises an ethylene polymer (A) having a density of at least about 968 kg/m³, preferably above 970, most preferably above 971 in an amount ranging from about 45% to about 55% by weight, preferably between 47 and 53% by weight, preferably between 48 and 52% by weight, most preferably between 49.5 and 51.5%, by weight and an ethylene polymer (B) having a density lower than the density of polymer (A), wherein said composition has a complex viscosity at a shear rate of 0.01 rad/s ranging from about 200 to about 450 kPa.s, preferably between 220 and 450 kPa.s, most preferably between 220 and 420 kPa.s and a complex viscosity at a shear rate of 100 rad/s ranging from about 1900 to about 2600 Pa.s, preferably from 2000 to 2500 Pa.s, most preferably from 2100 to 2450 Pa.s,
2. The polymer composition according to claim 1, wherein the composition exhibits a viscosity at a constant shear stress of 747 Pa (11*747) ranging from about 400 kPa.s to about 1300 kPa.s, preferably from 500 to 900 kPa.s, more preferably from 550 to 900 kPa.s, most preferably from 650 to 900 kPa.s.
3. The polymer composition according to any preceding claim, wherein the composition has a G'(G'' = 3000) (Pa) ranging from about 1600 to about 2500, preferably 1650 to 2400, most preferably between 1700 and 2200.
4. The polymer composition according to any preceding claim, wherein the composition exhibits a melt index MI₅ ranging from about 0.1 to about 0.5 g/10 min, preferably 0.2 to 0.45 g/10 min, most preferably 0.2 to 0.4 g/10 min.

5. The polymer composition according to any preceding claim, wherein the composition has a comonomer content ranging from about 0.3 to about 0.65 mol%, preferably 0.4 to 0.65 mol%, most preferably 0.4 to 0.6 mol%.
6. The polymer composition according to any preceding claim, wherein the ratio of ethylene polymer (A) to polymer ethylene (B) in the base resin is from about 45:55 to about 55:45, preferably from about 47:53 to about 53:47, most preferably from about 48:52 to about 52:48.
7. The polymer composition according to any preceding claim, wherein the composition exhibits a complex viscosity at a constant shear stress of 747 Pa (η^*_{747}) preferably from about 400 kPa.s to about 1300 kPa.s, preferably from 500 to 900 kPa.s, and most preferably from 550 to 900 kPa.s.
8. The polymer composition according to any preceding claim, wherein the composition exhibits a melt index MIS ranging from about 0.1 to about 0.5 g/10 min as measured according to ISO 1133.
9. The polymer composition according to any preceding claim, wherein the base resin has a density ranging from about 947 to about 951 kg/m³, and comprises an ethylene polymer (A) having a density of at least 971 kg/m³ in an amount ranging from about 48 to about 52 wt%, an ethylene polymer (B) having a density of about 920 to about 930 kg/m³ in an amount ranging from about 52 to about 48 wt%, and wherein the composition has a comonomer content of ranging from about 0.4 - 0.6 mol%, a G' ($G'' = 3000$) (Pa) between 1700 and 2200 Pa, a complex viscosity at a shear rate of 100 rad/sec ranging from about 2100 to about 2450 Pa.s, and a complex viscosity at a shear rate 0.01 rad/s ranging from about 220 to about 420 kPa.s.

10. The polymer composition according to any preceding claim, further comprising peroxide in an amount ranging from about 50 ppm to about 150 ppm.
11. The polymer composition according to claim 10, wherein the peroxide is present in an amount ranging from about 30 ppm to about 100 ppm, preferably ranging from about 40 ppm to about 100 ppm, most preferably ranging from about 50 ppm to about 80 ppm.
12. The polymer composition according to any preceding claim, which when made into a pipe has an MRS rating of 10 or better or an HDB of 1600 psi at 23 °C or better.
13. The polymer composition according to any preceding claim, wherein the composition meets the PE 100 specification.
14. The polymer composition according to any preceding claim, wherein the composition meets the PE 4710 specification.
15. The polymer composition according to claim 12 in the form of a pipe
16. The polymer composition according to claim 13 in the form of a pipe

17. The polymer **composition** according to any preceding claim, which when made into a pipe, wherein the composition has a resistance to stress cracking of greater than about 8,760 h, preferably greater than 9,000 h, most preferably greater than 10,000 h as measured by notch pipe test according to ISO 13479: 1997

18. The polymer composition according to any preceding claim, which when made into a pipe exhibits PENT Failure Time (h) of greater than about 500 hours.

19. The polymer composition according to any preceding claim, which when made into a pipe exhibits PENT failure Time (h) of greater than about 2,000 hours,

20. The polymer **composition** according to any preceding claim, which when made into a pipe exhibits PENT failure Time (h) of greater than about 10,000 hours.

21. The polymer composition according to any preceding claim, wherein the composition meets the PE 4710 specification.

22. A process for producing a bimodal high-density polyethylene composition with improved high-melt strength comprising:

preparing a bimodal high-density polyethylene base resin comprising an ethylene polymer (A) having a density of at least about 968 kg/m³ in an amount ranging from about 45% to about 55% by weight, and an ethylene polymer (B) having a density lower than the density of polymer A, wherein the composition has a density of about 945 kg/m³ to about 951 kg/m³;

feeding the high-density polyethylene polymer composition into an extrusion device;

feeding peroxide in an amount ranging from about 50 ppm to about 150 ppm

over the weight of the resin into the extrusion device; and

mixing the polymer composition and the peroxide in the extrusion device until substantially homogeneous,

wherein the resulting composition exhibits a complex viscosity at a shear rate of 0.01 rad/s ranging from about 200 to about 450 kPa.s, and a complex viscosity at a shear rate of 100 rad/s ranging from about 1900 to about 2600 Pa.s.

23. The process according to claim 22, wherein the base polymer composition comprises ethylene polymer (A) in an amount ranging from about 45% to 55% by weight, preferably between 47 and 53% by weight, preferably between 48 and 52% by weight, most preferably between 49.5 and 51.5% by weight.

24. The process according to claims 22-23, wherein the peroxide is organic peroxide.

25. The process according to claim 24, wherein the organic peroxide is selected from the group consisting of 2,5 Dimethyl 2,5 Di(tert-butylperoxyl)hexane, dicumyl peroxide, tert-butylcumyl peroxide, 1,3-1,4 Bis(tert-butylperoxyisopropyl)benzene, and 2,5 Dimethyl 2,5 Di(tert-butylperoxy)hexane.

26. The process according to claim 25, wherein the organic peroxide is 2,5 Dimethyl 2,5 Di(tert-butylperoxyl)hexane.

27. The process according to claims 22-26, wherein a carrier is used to deliver the peroxide to the extrusion device.

28. The process according to claim 27, wherein the carrier of the peroxide is selected from the group consisting of a liquid, polypropylene flake, polypropylene pellet, high-density polyethylene flake and high-density polyethylene pellet.

29. The process according to claim 18, wherein polyethylene polymers (A) and (B) are prepared separately and subsequently blended to produce the base polymer composition.

30. A process for producing a bimodal high-density polyethylene (HDPE) composition with improved high-melt strength comprising:

preparing a bimodal HDPE polymer flake comprising a low molecular weight (LMW) ethylene polymer component (A) and a high molecular weight (HMW) ethylene polymer component (B) in a multiple reactor cascade process, wherein the polymerization is carried out in the presence of hydrogen, and wherein the ratio of molar hydrogen concentration in the reactor producing the LMW component (A) to the molar hydrogen concentration in the reactor producing the HMW component (B) ranges from about 250:1 to about 350:1;

feeding the HDPE polymer flake into an extrusion device;

feeding a reactive agent into the extrusion device; and

mixing the bimodal HDPE polymer flake and the active agent in the extrusion device until homogeneous.

31. The process according to claim 30, wherein reactive agent is mixed with the bimodal HDPE polymer flake in the extrusion device at temperatures up to about 550 °F (288 °C) until homogeneous for increasing long chain branching within the HDPE composition while maintaining processability of the HDPE composition.

32. The process according to claims 30-31, wherein the processability is measured by a shear thinning index at 2.7 kPa and 210 kPa from about 60 to about 115, a complex viscosity at 100 rads/s ranging from about 1,900 Pa.s to 2,600 Pa.s, and a high load melt index ranging from about 6 to 11 g/10 min.

33. A process for producing a bimodal high-density polyethylene (HDPE) composition with improved high-melt strength comprising:

preparing a bimodal HDPE base polymer flake comprising a low molecular weight (LMW) ethylene polymer component (A) and a high molecular weight (HMW) ethylene polymer component (B) in a multiple reactor cascade process, wherein the polymerization is carried out in the presence of hydrogen, and wherein the ratio of molar hydrogen concentration in the reactor producing the LMW component (A) to the molar hydrogen concentration in the reactor producing the HMW component (B) ranges from about 250:1 to about 350:1,

feeding the HDPE polymer flake into an extrusion device;

feeding a thermal decomposition agent into the extrusion device; and

mixing the bimodal HDPE polymer flake and the reactive agent in the extrusion device until homogeneous.

34. The process according to claim 33, wherein HMW polymer component is polymerized in the presence of 1-butene, 1-hexene, or 1-octene.
35. The process according to claims 33-34, wherein the mass ratio of the LMW component (A) to the bimodal composition ranges from about 49,5 % to about 51.5 %.
36. The process according to claim 33, wherein the thermal decomposition agent is peroxide
37. The process according to claim 36, wherein the peroxide is organic peroxide.
38. The process according to claim 37, wherein the organic peroxide is selected from the group consisting of 2,5 Dimethyl 2,5 Di(tert-butylperoxyl)hexane, dicumyl peroxide, tert-butylcumyl peroxide, 2,9,3-29,4 Bis(tert-butylperoxyisopropyl)benzene, and 2,5 Dimethyl 2,5 Di(tert-butylperoxyl)hexane.
39. The process according to claims 33-38, wherein the organic peroxide is fed into the extrusion device in an amount ranging from about 50 ppm to about 150 ppm.
40. The process according to claim 39, wherein a carrier is used to deliver the peroxide to the extrusion device.

41. The process according to claim 40, wherein the carrier of the peroxide is selected from the group consisting of a liquid, polypropylene flake, polypropylene pellet, HDPE flake and HDPE pellet.
42. The process according to claim 41, wherein the LMW component (A) is made in a first reactor and the HMW component (B) is added in a second reactor.
43. The process according to claim 33-42, wherein the composition exhibits a complex viscosity at 0.01 rad/s ranging from about 200 kPa.s to about 450 kPa.s.
44. The process according to claim 33-43, wherein the composition exhibits a complex viscosity at 100 rad/s ranging from about 1,900 Pa.s to about 2,600 Pa.s.
45. The process according to claim 33-44, wherein the composition exhibits a melt index MI5 ranging from about 0.1 to about 0.5 g/10 min.
46. The process according to claim 33-45, wherein the composition exhibits a density ranging from about 945 kg/m³ to about 955 kg/m³.
47. The process according to claims 33-46, wherein the degree of homogenization of the base polymer composition with the reactive agent is achieved through a consistent feed of reactive agent into the extruder.

48. A bimodal high density polyethylene composition made according to the process in claims 32-46, wherein the composition exhibits improved melt strength and substantially similar processability to that of the base polymer,

49. The composition according to claim 48, wherein the composition exhibits a low shear complex viscosity at 0.01 rad/s ranging from about 200 kPa.s to about 450 kPa.s,

50. The composition according to claims 49, wherein the composition exhibits a complex viscosity at 100 rad/s ranging from about 1,900 Pa.s to about 2,600 Pa.s.

51. The composition according claims 48-50, wherein the composition exhibits a complex viscosity at a constant shear stress of 747 Pa (η^*_{747}) preferably from about 400 kPa.s to about 1300 kPa.s, preferably from 500 to 900 kPa.s, and most preferably from 550 to 900 kPa.s.

52. The composition according to claim 51, wherein the composition exhibits a melt index MI_5 ranging from about 0.1 to about 0.5 g/10 min.

53. The composition according to claim 52, wherein the composition exhibits a density ranging from about 945 kg/m³ to about 955 kg/m³.

54. A high-density polyethylene polymer pipe made with a composition according to claims 48-53,

55. The pipe according to claim 54, wherein the pipe meets PE100 specifications.
56. The pipe according to claim 54, wherein the pipe meets PE4710 specifications.
57. The pipe according to claim 54, wherein the pipe exhibits PENT Failure Time (h) of greater than about 500 hours.
58. The pipe according to claim 57, wherein the pipe exhibits PENT failure Time (h) of greater than about 2,000 hours.
59. The pipe according to claim 58, wherein the pipe exhibits PENT failure Time (h) of greater than about 10,000 hours.
60. A process for producing a biniodal high-density polyethylene (HDPE) composition with improved high-melt strength for making a large diameter pipe comprising:
- preparing a biniodal HDPE polymer flake comprising a low molecular (LMW) ethylene homopolymer component and a high molecular weight (HMW) ethylene polymer component in a multiple reactor cascade process, the HMW component having a higher molecular weight average than the LMW component;
 - feeding the HDPE polymer flake into an extrusion device;

introducing a thermal decomposition agent continuously into the extrusion device; and

mixing the thermal decomposition agent within the bimodal HDPE polymer flake in the extrusion device at temperatures up to 550 °F (288 °C) until homogeneous for increasing long chain branching within the HDPE composition while maintaining processability of the HDPE composition, wherein processability is measured by a shear thinning index at 2.7 kPa and 210 kPa from about 60 to about 115, a complex viscosity at 100 rads/s ranging from about 1,900 Pa.s to 2,500 Pa.s, a complex viscosity at 0.01 rad/s ranging from about 200 kPa.s to about 450 kPa.s and a high load melt index ranging from about 6 to 11 g/10 min.

61. The composition according claim 60, wherein the composition exhibits a complex viscosity at a constant shear stress of 747 Pa (η^*_{747}) preferably from about 400 kPa.s to about 1300 kPa.s, preferably from 500 to 900 kPa.s, and most preferably from 550 to 900 kPa.s.