

**METHODS OF PREPARING ACTIVE CHROMIUM/ALUMINA CATALYSTS VIA
TREATMENT WITH SULFATE AND POLYMERS PRODUCED USING THE
CHROMIUM/ALUMINA CATALYSTS**

5 CROSS-REFERENCE TO RELATED APPLICATIONS

 This application claims priority to U.S. Patent Application Serial No. 10/829,850
entitled "Methods of Preparing Active Chromium/alumina Catalysts Via Treatment With
Sulfate" and U.S. Patent Application Serial No. 10/829,844 entitled "Polymers Having Low
Levels of Long Chain Branching and Methods of Making the Same," both of which were filed
10 on April 22, 2004 and are incorporated by reference herein in their entirety.

 FIELD OF THE INVENTION

 The present invention generally relates to catalysts for polymerizing olefins, and more
particularly to methods of preparing active catalysts by treating a chromium-based catalyst
having an alumina support with sulfate. The present invention generally further relates to
15 polymers, and more particularly to polymers having relatively low levels of long chain
branching and methods of making the same using sulfate treated chromium-based catalysts
having alumina supports.

 BACKGROUND OF THE INVENTION

 Supported chromium oxide catalysts are commonly employed to prepare polyolefins
20 having desirable characteristics. Various supports for chromium oxide catalysts have been
disclosed in the art. The particular support used for the chromium oxide strongly affects the
properties of the polymer being formed. Silica supports have primarily been used due to their
ability to form highly active polymerization catalysts. However, silica supports do not provide
for the production of ultra high molecular weight polymers when hexavalent chromium is
25 formed during the catalyst activation, which often occurs. Aluminum phosphate supports are
similar to silica supports in that they form highly active catalysts. However like the silica
supports, they also do not have the ability to produce very high molecular weight polymers.
Further, the polymers produced using the aluminum phosphate supports tend to contain
relatively high amounts of long chain branching, which is not always a desirable property

during processing of the polymer. A need therefore exists to develop a method for producing polyolefins having less long chain branching and higher molecular weights.

While the possibility of using alumina supports for chromium oxide catalysts has been described in the art, such supports typically are not used. Alumina supports desirably have relatively high surface areas and are very porous; however, chromium oxide catalysts supported by alumina are not sufficiently active to be considered commercially viable. The activity of such catalysts can be improved by adding fluoride to the alumina support. It is believed that the fluoride replaces surface hydroxide groups, which are believed to interfere with polymerization. Unfortunately, the addition of too much fluoride tends to sinter the alumina, resulting in the deactivation of the catalysts. A need therefore exists to develop a method for increasing the activity of chromium catalysts supported by alumina without being concerned that the alumina might be sintered.

SUMMARY OF THE INVENTION

According to an embodiment, methods of preparing a polymerization catalyst include contacting a support comprising alumina with a sulfating agent and with chromium. In an embodiment in which the chromium is provided from a chromium compound such as chromium oxide, the support can be calcined to activate the catalyst after loading the sulfating agent and the chromium on the support. Alternatively, the sulfating agent can be loaded on the support while calcining it. In another embodiment in which the chromium is provided from an organochromium compound, the support can be calcined after contacting it with the sulfating agent and before contacting it with the organochromium compound.

In an embodiment, catalyst compositions for polymerizing olefins comprise chromium and a sulfate treated alumina support. The catalyst compositions have an activity for ethylene polymerization that is at least 25% greater than an activity of the same catalyst without sulfate. Further, they have a surface area greater than 100 m²/g and a pore volume greater than 0.8 cc/g. As an aspect of the present invention, a resin made using a catalyst as described herein is also advantageously provided.

Methods of producing a polymer include contacting at least one olefin with a catalyst prepared by contacting a support comprising alumina with a sulfating agent and with chromium. Polymer compositions produced in this manner can exhibit relatively low levels of long chain branching. Such low levels of long chain branching are indicated by the high weight-average molecular weight (M_w) values combined with the low zero shear viscosity (E_o) values of the polymers. In an embodiment, polymer compositions with polydispersity index values (i.e., M_w/M_n) in a range of from 6 to 15 have M_w values greater than 300,000 g/mol and E_o values less than 1×10^6 Pa.s. The low levels of long chain branching are also indicated by the narrow rheological breadths combined with the high M_w values of the polymer compositions. In an embodiment, the polymer compositions have rheological breadths greater than 0.25. The high M_w values combined with the low relaxation times of the polymers further indicate the low chain branching of the polymers. In an embodiment, polymer compositions have relaxation times less than 10 seconds.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts a graph illustrating the activity of a chromium/alumina catalyst treated with sulfate as a function of the amount of ammonium sulfate added to the catalyst.

Figure 2 depicts the molecular weight distributions of polyethylene resins formed using a chromium/alumina catalyst treated with sulfate.

Figure 3 depicts the molecular weight distributions of polyethylene resins formed using chromium/alumina catalysts treated with sulfate and not treated with sulfate.

Figure 4 depicts an Arnett plot showing the linearity of polyethylene resins formed using chromium/alumina catalysts treated with sulfate and not treated with sulfate.

Figure 5 depicts the molecular weight distributions of polyethylene resins formed using chromium/alumina catalysts treated with different amounts of ammonium sulfate.

Figure 6 depicts the molecular weight distributions of polyethylene resins formed using organochromium/alumina catalysts treated with sulfate.

Figures 7 and 8 depict the molecular weight distributions of polyethylene resins formed using chromium/alumina catalysts, some of which were treated with varying amounts of phosphate, fluoride, and sulfate.

Figure 9 depicts an Arnett plot of molecular weight distributions of polyethylene resins formed using chromium/aluminophosphate catalysts treated with sulfate and not treated with sulfate.

DETAILED DESCRIPTION OF THE INVENTION

A chromium-based catalyst having an alumina (Al_2O_3) support can be treated with sulfate (i.e., sulfate anions) to enhance the activity of the catalyst, making its use in the production of polymers commercially viable. The alumina support primarily comprises alumina. In particular, the amount of alumina present in the support is at least 50% by weight of the total support. The alumina support can be made using methods known in the art. Examples of such methods include: reacting sodium aluminate, which is basic, with aluminum sulfate, which is acidic; neutralizing an aluminum salt with a base such as ammonia or ammonia hydroxide; performing flame hydrolysis of an aluminum compound; or performing hydrolysis of an organic solution of an aluminum compound by, e.g., adding water to an alcohol solution of aluminum isopropoxide ($\text{Al}(\text{OC}_3\text{H}_7)_3$). Examples of sources of alumina include a crystalline form and a hydrated form of alumina. More specific examples include aluminum hydroxide ($\text{Al}(\text{OH})_3$), boehmite (AlOOH) and gamma alumina (Al_2O_3). The alumina support can also contain minority amounts of other materials that can be added for various reasons, such as fluoride, phosphate, silica, magnesia, boria, or titania. These materials can be added in the form of cogellation or by surface treatment. Optionally, the alumina support can be calcined prior to any treatment by, e.g., heating in air at a temperature in a range of from 300°C to 900°C or from 500°C to 800°C.

In a first embodiment, the chromium and the sulfate can be loaded on the alumina support before subjecting the support to a final calcination step for activating the catalyst. In this case, the chromium can be loaded before the sulfate, after the sulfate, or concurrently with the sulfate. The support can also be subjected to an initial calcination step to dehydrate it prior to further treatment with sulfate and chromium. This step converts hydrated forms of alumina

precursors, such as $\text{Al}(\text{OH})_3$ and AlOOH , to less hydrated forms. The initial calcining step can be accomplished by heating the support in an oxidizing, reducing, or inert atmosphere, which can be dry or can contain substantial amounts of humidity. Such initial dehydration can be carried out at a temperature ranging from 150°C to 900°C ; alternatively, from 200°C to 800°C ; 5 or alternatively, from 300°C to 700°C . The dehydration step can last for a duration of from a few minutes to 24 hours. After the initial dehydration step, the support can be given a sulfate and chromium treatment, followed by the final calcination or activation step.

Alternatively, the sulfate can be loaded on the alumina support during the calcination step and after loading the chromium. The chromium can be loaded on the support using 10 incipient wetness impregnation with a solution in which a chromium compound is dissolved. The chromium compound can be one or more compounds suitable for conversion to the hexavalent state of chromium. Examples of suitable chromium compounds include tertiary butyl chromate in a hydrocarbon liquid, chromium trioxide in water, chromium acetate in water, chromium nitrate in alcohol, or combinations thereof. The chromium is added in an amount 15 sufficient to ensure that the final catalyst contains a desired level of chromium.

The sulfate can be loaded on the support by contacting it with a sulfating agent. As used herein, "sulfating agent" is defined as a material capable of providing a sulfate ion to an alumina support, wherein the sulfating agent can be in the form of a solution, a gas, or combinations thereof. When the sulfating agent is a solution, it can be applied to the support via incipient 20 wetness impregnation. When the sulfating agent is a gas such as SO_3 , it can be introduced to a vessel in which the support is positioned during the calcination of the support. Examples of sulfating agents include: SO_3 gas; H_2SO_4 in water or an organic liquid such as an alcohol; aqueous solutions comprising at least one of the following compounds: $(\text{NH}_4)_2\text{SO}_4$, $\text{Al}_2(\text{SO}_4)_3$, CuSO_4 , ZnSO_4 , $\text{KAl}(\text{SO}_4)_2$, ZrOSO_4 , TiOSO_4 , MgSO_4 , $(\text{NH}_4)\text{HSO}_4$, NaHSO_4 , $(\text{NH}_4)\text{HSO}_3$, 25 CaSO_4 and $\text{Cr}_2(\text{SO}_4)_3$, and combinations thereof. Sulfur containing materials that are capable of further oxidation to sulfate during the calcination step can also serve as the sulfating agent. Examples of such sulfur containing materials include sulfite salts, sulfurous acid, organic sulfides, sulfoxides, and SO_2 . Additional examples of sulfating agents include sulfur halides such as thionyl chloride and sulfuryl chloride.

In a second embodiment in which the chromium compound is an organochromium compound, the sulfate is loaded on the alumina support before performing a calcination step to activate the support, followed by treating the support anhydrously with the organochromium compound. No further calcination of the organochromium compound is required to activate the catalyst. Examples of suitable organochromium compounds include zerovalent compounds such as pi bonded chromium complexes, for example, dicumene chromium and dibenzene chromium. Pi bonded chromium complexes are described in U.S. Patent No. 3,976,632, which is incorporated by reference herein in its entirety. Other examples include divalent and trivalent organochromium compounds such as chromocene (bis(cyclopentadienyl)chromium (II)), and substituted derivatives thereof in which the cyclopentadienyl rings contain one or more substituents, chromium diallyl and triallyl, bis(2,4 dimethyl pentdienyl) chromium, and amidochromium compounds. Additional examples of organochromium compounds can be found in U.S. Patent Nos. 4,806,513, 4,690,990, 4,803,253, and 5,200,379, which are incorporated by reference herein in their entirety.

In the two embodiments described above, the calcination step for activating the catalyst is performed by heating it in an oxidizing atmosphere, for example, in the presence of oxygen (O_2), at a temperature in a range of from 200°C to 1,000°C; alternatively, from 300°C to 800°C; or alternatively, from 400°C to 700°C. The calcining treatment can also involve reducing or other steps, such as treatment with carbon monoxide, hydrogen, or haliding agents. In the first embodiment, at least a portion of the chromium compound is converted to the hexavalent state as a result of being calcined. A substantial portion of the sulfate remains on the support during the calcination step in both embodiments, resulting in an increase in the activity of the chromium-based catalyst. Without intending to be limited by theory, it is believed that the sulfate bonds with aluminum and replaces hydroxide groups at the surface of the support that hinder the activity of the catalyst. The sulfate also provides greater acidity to the chromium active sites. In addition, the introduction of the sulfate to the support causes little or no sintering of the alumina such that its relatively high surface area and porosity only decline by small amounts.

The activated catalyst formed in the two embodiments described above optionally can be reduced. In an embodiment, the support is reduced by heating it in the presence of carbon

monoxide at a temperature in the range of from 100°C to 900°C; alternatively, from 200°C to 500°C; or alternatively, from 300°C to 400°C.

Catalyst compositions for polymerizing olefins can be formed in the manner described above. Such catalyst compositions can include chromium and aluminum sulfate on an alumina support. The chromium is present in such catalyst compositions in an amount of from 0.01% to 10%; alternatively, from 0.1% to 10%; alternatively, from 0.5% to 5%; or alternatively, from 0.8% to 3%, all percentages being by total weight of the final catalyst composition. The sulfate is present in an amount of from 1% to 50%; alternatively, from 5% to 40%; or alternatively, from 10% to 30%, all percentages being by total weight of the final catalyst composition. In an embodiment, a catalyst composition is formed that has an activity at least 25% greater than the activity of the same catalyst composition (based on the weight of the alumina support) without sulfate treatment, where the catalyst compositions are run under control conditions to polymerize olefins. In another embodiment, the catalyst composition has an activity more than 25%; alternatively, more than 50%; or alternatively, more than 100%, greater than the activity of the same catalyst composition without sulfate treatment. Also, in an embodiment, the catalyst composition has a surface area greater than 50 m²/g; alternatively, greater than 100 m²/g; or alternatively, greater than 200 m²/g. Further, in an embodiment, the catalyst composition has a pore volume greater than 0.5 cc; alternatively, greater than 0.8 cc; or alternatively, greater than 1 cc.

As an aspect of the present invention, a resin made using a catalyst as described herein is also advantageously provided. The catalyst can be made in accordance with any of the methods described herein.

A polymer composition can be formed by polymerizing at least one monomer in the presence of the foregoing sulfate treated chromium-based catalyst having an alumina support. Examples of suitable monomers include mono-olefins containing 2 to 8 carbon atoms per molecule such as ethylene, propylene, 1-butene, 1-pentene, 1-hexene, and 1-octene. The chromium-based catalyst is particularly suitable for producing polyethylene homopolymers and copolymers of ethylene and mono-olefins containing 3 to 8 carbon atoms per molecules. Any polymerization reactor known in the art that is capable of polymerizing olefin monomers to produce the homopolymers or copolymers described herein also can be used. Such reactors can

comprise slurry reactors, gas-phase reactors, solution reactors or any combination thereof. Gas phase reactors can comprise fluidized bed reactors or tubular reactors. Slurry reactors can comprise vertical loops or horizontal loops. Solution reactors can comprise stirred tank or autoclave reactors. Such reactors can be combined into multiple reactor systems operated in parallel or in series. The catalyst also can be used to produce ethylene polymers in a particle form process as disclosed in U.S. Patent Nos. 3,624,063, 5,565,175, and 6,239,235, which are incorporated by reference herein in their entirety. If desired, hydrogen (H₂) also can be introduced to the reaction zone to reduce the molecular weight of the polymer formed. The amount of catalyst present in the reaction zone can range from 0.001% to 1% by weight of all materials in the reaction zone.

In an embodiment, a slurry polymerization process is employed in which the catalyst is suspended in an inert organic medium and agitated to maintain it in suspension throughout the polymerization process. The organic medium can, e.g., be a paraffin, a cycloparaffin, or an aromatic. For the production of ethylene polymers, the slurry polymerization process can be carried out in a reaction zone at a temperature of from 50°C to 110°C and at a pressure in the range of from 100 psia to 700 psia or higher. At least one monomer is placed in the liquid phase of the slurry in which the catalyst is suspended, thus providing for contact between the monomer and the catalyst. The activity and the productivity of the catalyst are relatively high. As used herein, the activity refers to the grams of polymer produced per gram of solid catalyst charged per hour, and the productivity refers to the grams of polymer produced per gram of solid catalyst charged.

In one embodiment, the monomer also can be contacted with a cocatalyst in addition to the chromium-based catalyst. The cocatalyst can be contacted with the catalyst either before or after entry into the reaction zone. For example, the catalyst and cocatalyst can each be fed independently into a mixing vessel ahead of the reactor where they are allowed to pre-contact each other in a hydrocarbon solvent for a period of from 1 minute to 10 hours at temperatures ranging from -20°C to 100°C. After this duration, the contacted catalyst and cocatalyst are both fed to the reaction zone. Since each feed stream can be measured and controlled independently, pre-contacting the catalyst and the cocatalyst provides a method of continuously controlling the composition of the catalyst and thereby the properties of the polymer produced. Alternatively,

some or all of the catalyst and cocatalyst can also be fed directly into the reaction zone where they contact each other for the first time in the presence of the monomer. Examples of suitable cocatalysts include organoaluminum compounds such as triethylaluminum, organoboron compounds such as triethylboron, tri-n-butylborane, and tripropylborane, and combinations thereof. Other suitable organoaluminum compounds include aluminum alkyls such as R_3^4Al , R_2^4AlX , and R^4AlX_2 compounds where R^4 is a 1 to 12 carbon atom hydrocarbyl radical and X is a halogen such as chlorine. The cocatalyst can, for example, be triethylaluminum chloride or diethylaluminum chloride. Other suitable organoboron compounds include trialkyl boron compounds, particularly those having alkyl groups of 1 to 12 carbon atoms or 2 to 5 carbon atoms, triaryl boron compounds such as triphenylborane, alkyl boron alkoxides such as $B(C_2H_5)_2OC_2H_5$ and halogenated alkyl boron compounds such as $BC_2H_2Cl_2$. Alkyls of lithium, magnesium, zinc, and other metals and organohydrosilanes can also be used as a cocatalyst. The cocatalyst can be premixed with the catalyst, or alternatively it can be introduced into the reaction zone as a separate stream. The amount of cocatalyst present in the reaction zone can be in the range of from 0.2 to 25 or from 0.2 to 10 parts per million by weight based on the weight of the solvent or diluent in systems employing such solvent or diluent. When no solvent or diluent is used, the catalyst can be impregnated with the cocatalyst in an amount that provides for a cocatalyst to chromium mole ratio in the range of from 0.1:1 to 100:1; alternatively, from 0.5:1 to 50:1; or alternatively, from 1:1 to 10:1.

In another embodiment, the monomer can be contacted with another catalyst simultaneously with the sulfated chromium-based catalyst and the cocatalyst if one is used. For example, the sulfated chromium-based catalyst can be used in conjunction with a Ziegler-Natta catalyst to produce a bimodal polymer in a single reactor using one set of polymerization conditions. Suitable Ziegler-Natta catalyst are disclosed in U.S. Patent Nos. 5,275,992, 5,237,025, 5,244,990, 5,179,178, 4,855,271, 5,179,178, 5,275,992, and 4,607,019, each of which is incorporated by reference herein in its entirety. The sulfated chromium/alumina catalyst also can be used with another chromium-based catalyst such as a chromium/silica catalyst. A bimodal polymer has both relatively high and low molecular weight distributions and thus exhibits physical properties characteristic of both such as stress crack resistance and good processability.

Polymers such as polyethylene homopolymers and copolymers of ethylene with other mono-olefins can be produced in the manner described above to have unique properties. For instance, the polymers exhibit relatively low levels of long chain branching. Such low levels of long chain branching are indicated by the narrow rheological breadths combined with the high M_w values of the polymers. Rheological breadth refers to the breadth of the transition region between Newtonian and power-law type shear rate for a polymer or the frequency dependence of the viscosity of the polymer. The rheological breadth is a function of the relaxation time distribution of a polymer resin, which in turn is a function of the resin molecular structure or architecture. Assuming the Cox-Merz rule, the rheological breadth can be calculated by fitting flow curves generated in linear-viscoelastic dynamic oscillatory frequency sweep experiments with a modified Carreau-Yasuda (CY) model, which is represented by the following equation:

$$E = E_o \left[1 + (T_\xi \dot{\gamma})^a \right]^{\frac{n-1}{a}}$$

where

E = viscosity (Pa·s)

$\dot{\gamma}$ = shear rate (1/s)

a = rheological breadth parameter

T_ξ = relaxation time (s) [describes the location in time of the transition region]

E_o = zero shear viscosity (Pa·s) [defines the Newtonian plateau]

n = power law constant [defines the final slope of the high shear rate region]

To facilitate model fitting, the power law constant is held at a constant value. Details of the significance and interpretation of the CY model and derived parameters can be found in: C. A. Hieber and H. H. Chiang, *Rheol. Acta*, 28, 321 (1989); C.A. Hieber and H.H. Chiang, *Polym. Eng. Sci.*, 32, 931 (1992); and R. B. Bird, R. C. Armstrong and O. Hassager, *Dynamics of Polymeric Liquids, Volume 1, Fluid Mechanics*, 2nd Edition, John Wiley & Sons (1987), each of which is incorporated by reference herein in its entirety. In particular, the polymers have high “a” parameter values greater than 0.25; alternatively, greater than 0.30; or alternatively, greater than 0.35, indicating the narrowness of their rheological breadths. The polymers exhibit a narrow rheological breadth even when the polymers have low high load melt index (HLMI)

values. The HLMI represents the rate of flow of a molten resin through an orifice of 0.0825 inch diameter when subjected to a force of 21,600 grams at 190°C. The HLMI values are determined in accordance with ASTM D1238 condition E. The polymers have HLMI values less than 5 g/10 min; alternatively, less than 3 g/10 min; or alternatively, less than 2 g/10 min.

- 5 The low levels of long chain branching of the polymers are also indicated by the high weight-average molecular weight (M_w) values combined with the low zero shear viscosity (E_o) values of the polymers. In particular, the polymers have M_w 's greater than 300,000 grams/mole (g/mol); alternatively, greater than 400,000 g/mol; or alternatively, greater than 500,000 g/mol. Also, they have E_o values less than 5×10^6 Pa·s, less than 1×10^6 Pa·s, or less than 5×10^5 Pa·s.
- 10 The high M_w values combined with the low relaxation times (T_ℓ) of the polymers further indicate the low chain branching of the polymers. In particular, the polymers have relaxation times less than 10 seconds; alternatively, less than 7 seconds; or alternatively, less than 5 seconds. The polymers further have high tan delta values. Tan delta is the ratio of the loss modulus to the elastic modulus measured at a particular frequency on an oscillating viscometer
- 15 as described above. In particular, the polymers have tan delta values, measured at 0.1 radians/second (very low shear rates), greater than 1.5; alternatively, greater than 1.7; or alternatively, greater than 1.9 when the M_w is above 300,000 g/mol.

- In addition, polyethylene resins produced using the sulfate treated chromium/alumina catalyst are unique in their molecular weight distributions. The molecular weight distribution
- 20 (MWD) can be described by a parameter known as the polydispersity index (PDI), which indicates the breadth of the molecular weight distribution and is equivalent to the weight-average molecular weight of a polymer divided by the number-average molecular weight of the polymer (i.e., M_w/M_n). In particular, the polyethylene resins have PDI values greater than 4; alternatively, greater than 6; alternatively, greater than 8; or alternatively, greater than 10.
- 25 Surprisingly, the PDI values of such polyethylene resins also are often less than 20; alternatively, less than 17; alternatively, less than 15; or alternatively, even less than 12. In an embodiment, the polyethylene resins have PDI values in the range of from 6 to 15. Further, the M_z (z-average molecular weight)/ M_w ratios of the polymer compositions are less than 10; alternatively, less than 6; or alternatively, less than 5 and thus indicate a relatively high tail in
- 30 the MWD.

Throughout the specification, the molecular weights and molecular weight distributions are obtained using gel permeation chromatography (GPC). The GPC is performed using a Waters 150 CV gel permeation chromatograph with trichlorobenzene (TCB) as the solvent, with a flow rate of 1 milliliter/minute at a temperature of 140°C. 2,6-Di-*t*-butyl-4-methylphenol (BHT) at a concentration of 1.0 gram per liter is used as a stabilizer in the TCB. An injection
5 volume of 220 liters is used with a nominal polymer concentration of 0.3 gram/liter at room temperature. Dissolution of the sample in stabilized TCB is carried out by heating at 160-170°C for 20 hours with occasional, gentle agitation. The gel permeation chromatograph includes two Waters HT-6E columns (7.8 mm×300 mm). The columns were calibrated with a broad linear
10 polyethylene standard (Chevron Phillips Chemical Company Marlex® BHB 5003) for which the molecular weight has been determined.

Polymer resins having the previously described properties can be formed into articles of manufacture or end use articles using techniques known in the art such as extrusion, blow molding, injection molding, fiber spinning, thermoforming, and casting. For example, a
15 polymer resin can be extruded into a sheet, which is then thermoformed into an end use article such as a container, a cup, a tray, a pallet, a toy, or a component of another product. Examples of other end use articles into which the polymer resins can be formed include pipes, films, bottles, fibers, and so forth. Additional end use articles would be apparent to those skilled in the art.

20

EXAMPLES

The invention having been generally described, the following examples are given as particular embodiments of the invention and to demonstrate the practice and advantages thereof. It is understood that the examples are given by way of illustration and are not intended to limit the specification or the claims to follow in any manner.

25

EXAMPLE 1

The following procedure was repeated 3 times to form 3 different catalyst samples (samples 1, 2, and 3). An alumina support (alumina "A") purchased from W.R. Grace Company was calcined in nitrogen at 600°C in preparation for its use as a catalyst support. The

support had a surface area of 280 m²/g and a pore volume of 1.5 cc/g. The alumina support was then impregnated with various amounts of ammonium sulfate in aqueous solution as shown in Table 1 below, followed by drying the support in a vacuum oven at 100°C for 10 hours. The support was then impregnated with a methanolic solution of Cr(NO₃)₃ to incorporate chromium therein, followed by drying it in a vacuum oven at 100°C for 10 hours. The resulting catalyst precursor was then activated by calcination in dry air for 3 hours at 600°C.

Table 1 shows several physical properties of the activated catalyst samples and the compositions of the catalyst samples. Table 1 further provides the weight percent of sulfate added to each alumina support and the weight percent of sulfate actually found by X-ray fluorescence analysis in each catalyst sample after the calcination step, all weight percentages being by total weight of the catalyst. Based on the results depicted in Table 1, all or a substantial portion of the sulfate added to the support was retained on the catalyst during the calcination. For samples 1 and 2, the amount of sulfate measured after calcining was slightly larger than the actual amount of sulfate added. This additional amount of sulfate can be explained by the observance that the base alumina initially contained 1.7% sulfate residue as Na₂SO₄ by weight of the support as a result of its preparation. It was also observed that the weight of the alumina support increased significantly due to the adsorption of the sulfate. However, adding sulfate to the support did not contribute additional surface area to the support. A "Quantachrome Autosorb-6 Nitrogen Pore Size Distribution Instrument" was used to determine the surface area and pore volume of the supports. This instrument was acquired from the Quantachrome Corporation of Syosset, N.Y.

The measured surface area and pore volume, expressed per gram of the finished catalyst, are also shown in Table 1. In addition, the measured surface area and pore volume were corrected for the additional weight of the sulfate as shown in Table 1 and are also expressed in Table 1 per gram of the original alumina support. In view of these corrected values, surface area and pore volume did not significantly decline as the amount of sulfate added was increased. Rather, they surprisingly stayed about the same.

Table 1							
Catalyst Sample	Amount of $(\text{NH}_4)_2\text{SO}_4$ Added, grams/100 g of Al_2O_3	Amount of SO_4 Added, wt. %	Amount of SO_4 Measured, wt. %	Measured Pore Volume, cc/g	Measured Surface Area, m^2/g	Corrected Surface Area, m^2/g	Corrected Pore Volume, cc/g
Alumina A	0	0	1.7	1.45	300	300	1.45
1	10	6.78	8.7	1.356	195.5	214	1.49
2	20	12.70	14.28	1.296	285.2	333	1.51
3	40	22.54	19.35	1.173	164.5	204	1.45

EXAMPLE 2

Catalyst samples (samples 4-9) were prepared in the same manner as described in Example 1 with different amounts of sulfate except that catalyst sample 4 contained no sulfate. The amount of sulfate added to each catalyst sample and the weight percent of hexavalent chromium (Cr VI) contained in each sample by total weight of the sample are shown in Table 2 below.

A polymerization run using each catalyst sample was made in a 2.2 liter steel reactor equipped with a marine stirrer rotating at 400 rpm. A steel jacket containing boiling methanol with a connection to a steel condenser surrounded the reactor. The boiling point of the methanol was controlled by varying nitrogen pressure applied to the condenser and jacket, which permitted precise temperature control to within half a degree centigrade, with the help of electronic control instruments. A small amount (0.04 to 0.10 grams) of the catalyst sample was first charged under nitrogen to the dry reactor. Next 1.2 liter of isobutane liquid was charged to the reactor, and the reactor was heated up to 95°C. Triethylboron (TEB) cocatalyst was added in a heptane solution midway during the isobutane addition. The amount of TEB cocatalyst added was equal to 8 ppm of the isobutane diluent by weight. Finally, ethylene was added to the reactor to equal a fixed pressure of 550 psig (3792 kPa), which was maintained during the experiment. The stirring was allowed to continue for one hour, and the activity was noted by recording the flow of ethylene into the reactor to maintain the set pressure.

After the allotted time, the ethylene flow was stopped and the reactor slowly depressurized and opened to recover a granular polymer powder. In all cases the reactor was

clean with no indication of any wall scale, coating, or other forms of fouling. The polymer powder was then removed and weighed. Activity was specified as grams of polymer produced per gram of solid catalyst charged per hour.

The results of these polymerization runs are shown in Table 2 below. The HLMI of the polymer resin recovered from each run was determined in accordance with ASTM D1238. All of the polymers had an HLMI of zero. To compensate for the sulfate weight gain, the activity was corrected and is thus expressed as grams of polymer produced per gram of the original alumina support per hour. In most cases, adding sulfate to the catalyst increased the activity of the catalyst. The activity of these catalysts is plotted against sulfate loading in Figure 1.

10

Run No.	Catalyst Sample No.	Amount of (NH ₄) ₂ SO ₄ added, grams per 100 g Al ₂ O ₃	Amount of Cr VI, wt. %	Catalyst Charged, g	Polymer Yield, g	Run Time, min	Activity, g/g Al ₂ O ₃ /h	Corrected Activity, g/g Al ₂ O ₃ /h
1	4	0		0.0303	48	30	3168	3168
2	5	5		0.058	119	31	3971	4115
3	6	10	0.3286	0.0458	141	35	5278	5661
4	6	10	0.3286	0.044	131	34	5254	5636
5	6	10	0.3286	0.0458	141	35	5278	5661
6	6	10	0.3286	0.044	131	34	5254	5636
7	7	20		0.0605	142	30	4694	5377
8	7	20	0.2295	0.0533	158	30	5929	6791
9	7	20		0.0605	142	30	4694	5377
10	8	20		0.1235	246	20	5976	6845
11	8	20		0.0497	112	34	3977	4555
12	8	20		0.0384	87	31	4385	5023
13	9	40	0.1046	0.0652	131	39	3091	3990
14	9	40	0.1046	0.0711	123	31	3348	4322

EXAMPLE 3

A catalyst treated with 20 parts of ammonium sulfate per 100 parts by weight of alumina was made according to the procedure described in Example 1. The catalyst contained 2 % Cr by weight of the alumina. It was calcined at 600°C for activation, and then it was used to polymerize ethylene at 95°C and 550 psig, (3792 kPa) according to the procedure described above, with the exception of two changes. First, two of the runs were performed using 8 ppm of triethylaluminum (TEA) as the cocatalyst, and two runs were performed using 8 ppm of

triethylboron (TEB) as the cocatalyst. Second, 50 psig (345 kPa) of H₂ was added to the autoclave after isobutane addition but before ethylene addition. This was done during each run to decrease the molecular weight of the polyethylene resin formed in each run. Despite the large amount of hydrogen added, the polyethylene resins still had HLMI values of zero. Figure 2 illustrates the molecular weight distributions of the polyethylene resins produced in those runs. As can be seen in Figure 2, the molecular weight distributions of the polyethylene resins were moderately broad, and their M_w values were very high. In fact, the average M_w was over 1 million, which is surprising considering the large amount of H₂ present. Despite this high M_w, there is a lack of high M_w tail, as can be seen from the sharp decline in the molecular weight distribution curve at high M_w. This can also be seen by lower M_z/M_w ratios, which also measures breadth but are more sensitive to the high side of the distribution.

Figure 3 compares the molecular weight distribution of one of the foregoing polymers formed using the sulfate treated Cr/alumina catalyst (treated with 14% SO₄ by weight of the catalyst) and the TEB cocatalyst to the MWD of a polymer formed using a Cr/alumina catalyst containing no sulfate but otherwise prepared, activated, and run identically. Figure 3 again illustrates the narrowing effect of the sulfate on the MWD.

EXAMPLE 4

Catalysts treated with 0 to 40 parts ammonium sulfate per 100 parts alumina by weight were made as previously described in Example 1. These catalysts contained 2% Cr by weight of the alumina and were calcined at 600°C for activation. These catalysts were then allowed to polymerize ethylene at 95°C and 550 psig (3792 kPa) as previously described, except that 175 psig (1207 kPa) of hydrogen gas was added to decrease the molecular weight of the polymer formed. The cocatalyst used was 8 ppm by weight (based on the isobutane diluent) of a mixture of 3 parts TEB and 1 part TEA.

As shown in Table 3 below, various properties of the polyethylene resin produced in each run were determined at 190°C. GPC was employed to determine the MW, MN, and MZ values for each polyethylene resin. The zero shear viscosity (E₀), relaxation time (T_ξ), rheological breadth parameter (a), and the tan delta of each polyethylene resin were determined as described above. Two HLMI values are provided: the first one was determined using the

aforementioned ASTM method and the second one was calculated using the rheology of the polymer. The melt index (MI), which represents the rate of flow of a molten resin through an orifice of 0.0825 inch diameter when subjected to a force of 2,160 grams at 190°C, was determined in accordance with ASTM D1238.

5 As shown in Table 3, despite the large amount of H₂ added, the polyethylene resins had low HLMI values, which indicate that they had high molecular weights. Further, as the amount of sulfate increased, the HLMI dropped, indicating that the presence of the sulfate caused the molecular weights to increase. The measured molecular weights also increased as the amount of sulfate increased. Despite the high molecular weights, the polydispersity index
10 values (M_w/M_n) of the polyethylene resins were surprisingly narrow, with M_w/M_n values ranging from 8 to 13. The resins also unexpectedly exhibited M_z/M_w values of around 4. The M_z/M_w is another measure of molecular weight breadth, which is particularly sensitive to the highest molecular weight components of the distribution.

A distinctive feature of the polymer resins was their low degree of long chain branching,
15 as indicated by several of the results in Table 3. The HLMI/MI ratio values were much lower than those of polymers produced by other chromium-based catalysts at such high M_w . Despite having M_w values in the range of 300,000 to over 500,000 g/mol, the relaxation times of the resins were only 2 to 6 seconds, which is also unique for polymers in general, and especially for polymers produced by chromium-based catalysts. The resins also exhibited high tan delta
20 (measured at 0.1 rad/sec) values and rheological breadth parameters unprecedented by other chromium-based catalysts. In each case, the addition of sulfate caused those values to go up, indicating a decrease in long chain branching. In fact, the catalyst containing the largest amount of sulfate produced a polyethylene resin having a M_w of over half a million and a rheological breadth parameter of 0.38. A parameter of 0.38 is above that expected from even a Ziegler-
25 Natta catalyst at the same M_w . The high tan delta values exhibited by the polyethylene resins also indicate that the resins were essentially linear.

Table 3					
Run Number	1	2	3	4	5
Amount of (NH ₄) ₂ SO ₄ Added, g/100 g Al ₂ O ₃	0	10	20	20	40
HLMI, g/10 min	4.7	2.96	2.55	2.07	0.277
Cr (VI), wt. %	1.8	0.3286	0.4389	0.2295	0.1046
Mn/1000, kg/mol	4.4	24.33	26.27	32.2	65.03
Mw/1000, kg/mol	459	328.6	301.7	367.83	521.14
Mz/1000, kg/mol	3600	1361.49	1265.41	1548.55	2295.61
Mw/Mn	105	13.503	11.487	11.422	8.014
Mz/Mw	7.8	4.14	4.19	4.21	4.40
Zero Shear Viscosity, Pa·s	8.1 E+6	4.88E+05	4.45E+5	6.82E+05	1.38E+6
Relaxation Time, s	137	2.12	1.83	3.14	5.52
Rheological Breadth Parameter, a	0.2749	0.2962	0.3027	0.30	0.3846
MI, g/10 min	0.008	0.049	0.0495	0.0334	0.0099
HLMI, g/10 min	0.92	2.18	2.11	1.50	0.32
HLMI/MI	115	45	43	45	33
Tan delta @ 0.1/s	0.853	1.841	1.917	1.705	1.562

Another indication of the effect of sulfate in decreasing long chain branching can be seen in Figure 4, which is called an "Arnett" plot. Additional disclosure regarding the Arnett plot can be found in Long Chain Branching in Polyethylene from the Phillips Chromium Catalyst, M. P. McDaniel,* D. C. Rohlfing, and E. A. Benham, Polymer Reaction Engineering Vol. 11, No. 2, pp. 105–135, 2003, which is incorporated by reference herein in its entirety. When the log of the zero shear melt viscosity is plotted against the log of the weight average molecular weight, linear polymers fall on the Arnett reference line, which is also shown in Figure 3. Thus, the farther off this line a point falls, the more long chain branching it contains. The two curve lines represent 1 branch in 10⁶ and 10⁵ carbons. Thus, one can see that the more sulfate added, the closer the points come to the linear reference line.

Figure 5 shows the molecular weight distribution of some of the polymers in Table 3. One can see that as sulfate is added to the catalyst, the molecular weight distribution narrows, eliminating especially the low molecular weight end of the curve.

EXAMPLE 5

The following run was performed twice and demonstrates the use of an organochromium compound with the sulfated alumina support. Alumina A from W.R. Grace

was again obtained and impregnated with an aqueous solution of ammonium sulfate to incipient wetness. The total amount of ammonium sulfate added was equivalent to 20 wt.% based on the weight of the alumina (calculated as Al_2O_3). After being dried in a vacuum oven for 12 hours, this powder was then calcined in dry air for 3 hours at 600°C. 10 grams of the calcined sulfated alumina was then slurried in 100 mL of dry heptane, to which was injected dicumene chromium (0) slowly over 1 minute, in an amount chosen to yield 1% Cr (calculated as the metal) by weight based on the weight of the calcined sulfated alumina. The dicumene chromium was quickly adsorbed onto the support, as indicated by the color migration from the heptane liquid to the support. After adsorption at room temperature, the remaining heptane was evaporated off with gentle heat (~40°C).

Exactly 0.1513 gram of the catalyst described above was then added to the reactor described above, followed by 1.2 liters of isobutane, 20 psi hydrogen, and then 550 psig (3792 kPa) ethylene. Each polymerization run was made at 100°C for 70 minutes, and yielded 74 grams of polyethylene. The melt index obtained for each sample was 32.9. The MWD's for the two runs are shown in Figure 6. In each run, a very broad MWD was obtained having a M_N of 1730, a M_W of 116,000, and a M_Z of 2,912,000.

EXAMPLE 6

The following runs demonstrate the use of sulfate to modify the molecular weight distribution on an aluminophosphate catalyst. Alumina A having a surface area of 300 m^2/g and a pore volume of 1.5 cc/g was obtained from W.R. Grace. It was calcined in flowing dry nitrogen at 600°C for 1 hour. At this point some of the alumina was treated with sulfate and the rest was not. The alumina to be sulfated was then impregnated to incipient wetness with water containing sulfuric acid in an amount equivalent to 7.3% by weight of the dry alumina to be used (calculated as Al_2O_3). The damp powder was then dried at 110°C for 8 hours and again calcined in nitrogen at 600°C for an hour.

Then samples of both sulfated and non-sulfated aluminas were slurried in methanol to which ammonium bifluoride, phosphoric acid and chromium nitrate were added sequentially. A final drying at 100°C for 8 hours under vacuum removed excess methanol. These catalysts contained 2% Cr by weight of the catalyst. The amounts of phosphate and fluoride added are

listed in Tables 4 and 5 below. Each catalyst was then activated by calcination in flowing dry air at 400 to 750 °C as shown in the tables. Polymerization runs were made at 95°C by the same procedures described above. Triethylaluminum or triethylboron cocatalyst was used, along with 50 psig (345 kPa) H₂. Ethylene was supplied on demand at 550 psig (3792 kPa) for 60 minutes.

The properties of the polymers produced are shown in Tables 4 and 5. One can see in Table 4 that both the M_w/M_n and M_z/M_w values were narrowed by the addition of sulfate. To see this effect one must perform the polymerizations at the same activation temperature (600°C), with the same cocatalyst (TEA vs. TEB) and at the same level of phosphate, since each of these variables contributes to the breadth of the molecular weight distribution. When that comparison is made one can see that sulfate does have the effect of narrowing the molecular weight distribution by diminishing both the high and low molecular weight tails. Thus, both the M_w/M_n and M_z/M_w values are lower for the sulfated samples. Figures 7 and 8 show the molecular weight distribution curves, which make this effect abundantly clear. Figure 9 shows an Arnett plot of this same data, which demonstrates that the sulfate tends to make the polymer more linear. In each series (TEA and TEB), the addition of sulfate causes the points to move closer to the Arnett line, indicating increasing linearity.

TABLE 4												
Run #	P/Al	%F	%SO ₄	Act. Temp	Co-Catalyst	Activity	HLMI	M _n /1000	M _w /1000	M _z /1000	M _w /M _n	M _z /M _w
SULFATED												
1	0.10	2	7.3	400°C	TEB	1683	8.0	10.68	391.8	2741.9	36.7	7.0
2	0.10	2	7.3	400°C	TEA	1341	0.2	32.08	479	2236.3	14.9	4.7
3	0.10	2	7.3	600°C	TEB	959	6.5	12.14	397	2512	32.7	6.3
4	0.10	2	7.3	600°C	TEA	520	0.3	26.64	701.28	2721.5	26.3	3.9
5	0.10	2	7.3	750°C	TEB	1636	22.3	4.79	307.51	2469.8	64.2	8.0
6	0.10	2	7.3	750°C	TEA	1668	0.6	31.67	478.14	2233.7	15.1	4.7
NOT SULFATED												
7	0	0	0	600°C	TEB	1074	4.7	4.39	459.08	3603.43	104.6	7.8
8	0.11	2	0	600°C	TEB	1636	50.5	6.09	202.77	2956.45	33.3	14.6
9	0.11	2	0	600°C	TEA	882	4.5	5.01	398.17	3768.54	79.5	9.5
10	0	0	0	600°C	TEA	559	0.7	6.25	720.12	5221.44	115.2	7.3
11	0	2	0	600°C	TEA	634	0.0	7.79	887.56	3932.04	113.9	4.4
12	0	10	0	600°C	TEA	205	0.3	8.47	756.55	3809.53	89.3	5.0
13	0.04	2.7	0	600°C	TEA	1168	0.3	5.86	670.59	3690.24	114.4	5.5
14	0.04	2.7	0	600°C	TEA	1406	0.6	7.98	626.58	3688.54	78.5	5.9

TABLE 5												
Run #	P/AI	%F	%SO ₄	Act. Temp	Co-Catalyst	Activity	HLMI	M _n /1000	M _w /1000	M _z /1000	M _w /M _n	M _z /M _w
SULFATED												
15	0.10	2	7.3	400°C	TEB	1683	8.0	10.68	391.8	2741.9	36.7	7.0
16	0.10	2	7.3	400°C	TEA	1341	0.2	32.08	479	2236.3	14.9	4.7
17	0.10	2	7.3	600°C	TEB	959	6.5	12.14	397	2512	32.7	6.3
18	0.10	2	7.3	600°C	TEA	520	0.3	26.64	701.28	2721.5	26.3	3.9
19	0.10	2	7.3	750°C	TEB	1636	22.3	4.79	307.51	2469.8	64.2	8.0
20	0.10	2	7.3	750°C	TEA	1668	0.6	31.67	478.14	2233.7	15.1	4.7
NOT SULFATED												
21	0	0	0	600°C	TEB	1074	4.7	4.39	459.08	3603.43	104.6	7.8
22	0.11	2	0	600°C	TEB	1636	50.5	6.09	202.77	2956.45	33.3	14.6
23	0.11	2	0	600°C	TEA	882	4.5	5.01	398.17	3768.54	79.5	9.5
24	0	0	0	600°C	TEA	559	0.7	6.25	720.12	5221.44	115.2	7.3
25	0	2	0	600°C	TEA	634	0.0	7.79	887.56	3932.04	113.9	4.4
26	0	10	0	600°C	TEA	205	0.3	8.47	756.55	3809.53	89.3	5.0
27	0.04	2.7	0	600°C	TEA	1168	0.3	5.86	670.59	3690.24	114.4	5.5
28	0.04	2.7	0	600°C	TEA	1406	0.6	7.98	626.58	3688.54	78.5	5.9

While preferred embodiments of the invention have been shown and described, modifications thereof can be made by one skilled in the art without departing from the spirit and teachings of the invention. The embodiments described herein are exemplary only, and are not intended to be limiting. Many variations and modifications of the invention disclosed herein are possible and are within the scope of the invention. Use of the term "optionally" with respect to any element of a claim is intended to mean that the subject element is required, or alternatively, is not required. Both alternatives are intended to be within the scope of the claim.

Accordingly, the scope of protection is not limited by the description set out above but is only limited by the claims which follow, that scope including all equivalents of the subject matter of the claims. Each and every claim is incorporated into the specification as an embodiment of the present invention. Thus, the claims are a further description and are an addition to the preferred embodiments of the present invention. The discussion of a reference herein is not an admission that it is prior art to the present invention, especially any reference that may have a publication date after the priority date of this application. The disclosures of all patents, patent applications, and publications cited herein are hereby incorporated by reference, to the extent that they provide exemplary, procedural or other details supplementary to those set forth herein.

What is claimed:

1. A method of increasing polymerization activity of a chromium catalyst comprising an alumina support comprising contacting the support with a sulfating agent.
2. A method of preparing a polymerization catalyst comprising contacting a support comprising alumina with a sulfating agent and with chromium.
3. The method of claim 2, wherein the chromium is present in the catalyst in an amount of from 0.1% to 10% by total weight of the catalyst.
4. The method of claim 2, wherein sulfate is present in the catalyst in an amount of from 1% to 50% by total weight of the catalyst.
5. The method of claim 2, further comprising calcining the support.
6. The method of claim 5, wherein the calcining is performed by heating the support in an oxidizing atmosphere at a temperature in a range of from 200°C to 1,000°C.
7. The method of claim 5, wherein the calcining is performed by heating the support in an oxidizing atmosphere at a temperature in a range of from 300°C to 800°C.
8. The method of claim 5, wherein the calcining is performed by heating the support in an oxidizing atmosphere at a temperature in a range of from 400°C to 700°C.
9. The method of claim 5, wherein the support is contacted with the sulfating agent before the calcining.
10. The method of claim 5, wherein the support is contacted with the sulfating agent during the calcining.
11. The method of claim 5, wherein the support is contacted with the chromium before the calcining.
12. The method of claim 5, further comprising reducing the support.

13. The method of claim 5, further comprising reducing the support in the presence of carbon monoxide at a temperature in a range of from 200°C to 800°C.
14. The method of claim 2, wherein the sulfating agent comprises $(\text{NH}_4)_2\text{SO}_4$, H_2SO_4 , $\text{Al}_2(\text{SO}_4)_3$, CuSO_4 , $\text{Cr}_2(\text{SO}_4)_3$, MgSO_4 , ZrOSO_4 , TiOSO_4 , $(\text{NH}_4)\text{HSO}_4$, NaHSO_4 ,
5 $(\text{NH}_4)\text{HSO}_3$, CaSO_4 , $\text{Cr}_2(\text{SO}_4)_3$, SO_3 , SO_2 , $\text{KAl}(\text{SO}_4)_2$, ZnSO_4 , ZrOSO_4 , sulfurous acid, organic sulfides, sulfur halides, or combinations thereof.
15. The method of claim 2, wherein the catalyst further comprises phosphate, silica, fluoride, magnesia, titania, boria, or combinations thereof.
16. The method of claim 2, wherein the chromium is provided from tertiary butyl
10 chromate, chromium trioxide, chromium acetate, chromium nitrate, or combinations thereof.
17. The method of claim 2, wherein the chromium is provided from an organochromium compound.
18. The method of claim 17, further comprising calcining the support after contacting the
15 support with the sulfating agent and before contacting the support with the chromium.
19. The method of claim 17, wherein the organochromium compound comprises dicumene chromium, dibenzene chromium, bis(cyclopentadienyl)chromium (II) and substituted derivatives thereof, amidochromium compounds, or combinations thereof.
20. The method of claim 2, wherein an activity of the catalyst is at least 25% greater than
20 can be obtained from a same catalyst without sulfate.
21. A catalyst made by the method of claim 2.
22. A catalyst composition for polymerizing olefins, comprising chromium and a sulfate treated alumina support.
23. The catalyst composition of claim 22 having an activity for ethylene polymerization
25 that is at least 25% greater than an activity of a same catalyst without sulfate.

24. The catalyst composition of claim 22 having a surface area of greater than 100 m²/g.
25. The catalyst composition of claim 22 having a pore volume of greater than 0.8 cc/g.
26. The catalyst composition of claim 22, wherein the chromium is present in an amount of from 0.1 % to 10 % by total weight of the catalyst composition.
- 5 27. The catalyst composition of claim 22, wherein the sulfate is present in an amount of from 1 % to 50 % by total weight of the catalyst.
28. The catalyst composition of claim 22, wherein the sulfate is a derivative of (NH₄)₂SO₄, H₂SO₄, Al₂(SO₄)₃, CuSO₄, Cr₂(SO₄)₃, MgSO₄, KAl(SO₄)₂, ZnSO₄, ZrOSO₄, TiOSO₄, (NH₄)HSO₄, NaHSO₄, (NH₄)HSO₃, CaSO₄, Cr₂(SO₄)₃, SO₃, SO₂, sulfurous acid,
10 organic sulfides, sulfur halides, or combinations thereof.
29. The catalyst composition of claim 22, wherein the support comprises surface bonded sulfate ions.
30. The catalyst composition of claim 22, wherein the support further comprises phosphate, silica, fluoride, magnesia, titania, boria, or combinations thereof.
- 15 31. The catalyst composition of claim 22, wherein the chromium is a derivative of tertiary butyl chromate, chromium trioxide, chromium acetate, chromium nitrate, or combinations thereof.
32. The catalyst composition of claim 22, wherein the chromium is a derivative of an organochromium compound.
- 20 33. The catalyst composition of claim 32, wherein the organochromium compound comprises dicumene chromium, dibenzene chromium, bis(cyclopentadienyl)chromium (II) and substituted derivatives thereof, amidochromium compounds, or combinations thereof.
34. A sulfate-treated, chromium-based polymerization catalyst having an alumina support.

35. A method of using the catalyst of any one of claims 21, 22, or 34 in an olefin polymerization reaction.
36. A method of producing a polymer comprising contacting at least one olefin with a catalyst prepared by contacting a support comprising alumina with a sulfating agent
5 and with chromium.
37. The method of claim 36, further comprising contacting the olefin with a cocatalyst.
38. The method of claim 37, wherein the cocatalyst comprises an alkylaluminum, alkylboron, alkyl zinc, alkyl magnesium, alkyl lithium, an organohydrosilane, or combinations thereof.
- 10 39. The method of claim 36, further comprising contacting the olefin with another catalyst simultaneously with said contacting the olefin with the catalyst.
40. The method of claim 39, wherein the another catalyst comprises a Ziegler Natta catalyst.
41. A polymer composition having a PDI in a range of from 6 to 15, a M_w greater than
15 300,000 g/mol, and an E_o less than 1×10^6 Pa·s.
42. The polymer composition of claim 41, wherein the E_o is less than 5×10^5 Pa·s.
43. The polymer composition of claim 41, wherein the M_w is greater than 400,000 g/mol.
44. The polymer composition of claim 43, wherein the E_o is less than 5×10^5 Pa·s.
45. The polymer composition of claim 41, comprising polyethylene, copolymers of
20 polyethylene with mono-olefins having from 3 to 8 carbon atoms, or combinations thereof.
46. A polymer composition having a PDI in a range of from 6 to 15, a M_w greater than 500,000 g/mol, and an E_o less than 5×10^6 Pa·s.

47. The polymer composition of claim 46, comprising polyethylene, copolymers of polyethylene with mono-olefins having from 3 to 8 carbon atoms, or combinations thereof.
48. A polymer composition having a PDI in a range of from 6 to 15, a M_w greater than 300,000 g/mol and a relaxation time less than 10 seconds.
49. The polymer composition of claim 48, wherein the relaxation time is less than 5 seconds.
50. The polymer composition of claim 48, wherein the M_w is greater than 400,000 g/mol.
51. The polymer composition of claim 49, wherein the M_w is greater than 400,000 g/mol.
52. The polymer composition of claim 48, wherein the M_w is greater than 500,000 g/mol.
53. The polymer composition of claim 48, comprising polyethylene, copolymers of polyethylene with mono-olefins having from 3 to 8 carbon atoms, or combinations thereof.
54. A polymer composition having a PDI in a range of from 6 to 15, a M_w greater than 300,000 g/mol, and a rheological breadth parameter greater than 0.25.
55. The polymer composition of claim 54, wherein the M_w is greater than 500,000 g/mol.
56. The polymer composition of claim 54, wherein the rheological breadth parameter is greater than 0.30.
57. The polymer composition of claim 56, wherein the M_w is greater than 500,000 g/mol.
58. The polymer composition of claim 54, wherein the rheological breadth is greater than 0.35.
59. The polymer composition of claim 58, wherein the M_w is greater than 500,000 g/mol.

60. The polymer composition of claim 54, comprising polyethylene, copolymers of polyethylene with mono-olefins having from 3 to 8 carbon atoms, or combinations thereof.
- 5 61. A polymer composition made using a chromium-based catalyst, the polymer composition having a HLMI less than 100 g/10 min and a rheological breadth parameter greater than 0.25.
62. The polymer composition of claim 61, wherein the rheological breadth is greater than 0.30.
- 10 63. The polymer composition of claim 61, wherein the rheological breadth parameter is greater than 0.35.
64. The polymer composition of claim 61, wherein the chromium-based catalyst is prepared by contacting a support comprising alumina with a sulfating agent and with chromium.
- 15 65. The polymer composition of claim 61, comprising polyethylene, copolymers of polyethylene with mono-olefins having from 3 to 8 carbon atoms, or combinations thereof.
66. A polymer composition comprising polyethylene and having a PDI in a range of from 6 to 15, a HLMI less than 5 g/10 min, and an E_0 less than 1×10^6 Pa·s.
67. The polymer composition of claim 66, wherein the E_0 is less than 5×10^5 Pa·s. .
- 20 68. The polymer composition of claim 66, wherein the HLMI is less than 3 g/10 min.
69. The polymer composition of claim 67, wherein the HLMI is less than 3 g/10 min.
70. The polymer composition of claim 66 being made by a method comprising contacting ethylene with a catalyst prepared by contacting a support comprising alumina with a sulfating agent and with chromium.

71. The polymer composition of claim 66, wherein the polyethylene comprises copolymers of polyethylene with mono-olefins having from 3 to 8 carbon atoms.
72. A polymer composition comprising polyethylene and having a PDI in a range of from 6 to 15, a HLMI less than 2 g/10 min, and an E_o less than 5×10^6 Pa.s.
- 5 73. The polymer composition of claim 72, wherein the E_o is less than 1×10^6 Pa.s.
74. The polymer composition of claim 72, wherein the E_o is less than 5×10^5 Pa.s.
75. The polymer composition of claim 72, wherein the polyethylene comprises copolymers of polyethylene with mono-olefins having from 3 to 8 carbon atoms.
76. Use of the polymer composition of any one of claims 41, 48, 54, 66, or 72.
- 10 77. An article of manufacture comprising the polymer composition of any one of claims 41, 48, 54, 66, or 72.
78. The article of manufacture of claim 77 having a PDI equal to or greater than 8.
79. The article of manufacture of claim 77, comprising an extruded article, an injection molded article, a thermoformed article, a fiber, a cast article, or combinations thereof.
- 15 80. A polymer produced by a method as defined in any one of claims 36 to 40.
81. A resin made using a catalyst as defined in any one of claims 21 to 34.