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(54) **VISCOSITY-MODIFIED LACTIDE POLYMER COMPOSITION AND PROCESS FOR MANUFACTURE THEREOF**

LACTID POLYMER ZUSAMMENSETZUNG MIT MODIFIZIERTER VISKOSITÄT UND VERFAHREN ZU SEINER HERSTELLUNG

COMPOSITION POLYMERE DE LACTIDE A VISCOSITE MODIFIEE ET PROCEDE DE FABRICATION

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Description

[0001] The present invention relates to selected lactide polymer compositions and processes for manufacturing such compositions.

Background of the Invention

[0002] The present disclosure concerns ongoing efforts in developing lactide polymers useable in preferred manners. U.S. Patent 5,142,023 discloses, generally, a continuous process for the manufacture of lactide polymers from lactic acid. Selected polymers according to U.S. Patent 5,142,023 have physical properties suitable for replacing petrochemical-based polymers for packaging, paper-coating and other applications. Related processes for generating purified lactide and creating polymers therefrom are disclosed in U.S. Patents 5,247,058, 5,247,059 and 5,274,073.

[0003] Generally, commercial exploitation of polymers utilizing processes such as those disclosed in the above patents can involve conversion of raw material monomers into polymer beads, resins, or other pelletized or powdered products. The polymer in this form would then be sold to end users who would extrude, blow-mold, cast films, blow films, foam, thermoform, injection-mold, fiber-spin or otherwise convert the polymer at elevated temperatures, to form useful articles. The above processes (and related processes) are collectively referred to herein as "melt-processing". Polymers produced by processes such as those disclosed in the above patents ., and which are to be sold commercially as beads, resins, powders or other non-finished solid forms, are herein generally referred to collectively as polymer resins. These polymer resins, if biodegradable, can help alleviate the environmental stress due to disposal of items such as packaging materials, coated paper products, films, single use diapers and the like.

[0004] Lactide polymers are subject to unwanted degradation during melt processing via a number of pathways. These pathways include hydrolysis and other side reactions, which, for example, result in lactide formation and decreased molecular weight of the polymer. Furthermore, as processing temperatures are increased (especially to above about 230°C), lactide polymer degradation is substantially and undesirably accelerated. Accordingly, even if a relatively melt-stable lactide polymer can be produced, it would be generally desirable to provide a lactide polymer or resin formulation that can be processed into useful articles at reduced temperatures (i.e., especially and preferably at no more than about 180°C).

[0005] During certain melt processing operations, linear polymers such as linear polylactide exhibit certain undesired flow properties, such as necking. For example, if polylactide is extruded as a film onto a moving substrate, the film of polylactide being directed onto the substrate will tend to neck under the tensional forces caused by the moving substrate. By "necking" in this context it is meant that the width of the film will tend to narrow as the film is pulled or stretched. This leads to problems with control of the process and problems with maintaining consistency in film thickness, etc. Specifically, in comparison to polypropylene or polyethylene, linear polylactides (PLA) typically exhibit substantially more problem necking and less melt strength. Linear polymers, such as PLA, also tend to exhibit hydrodynamic instability or draw resonance at high draw ratios. This draw resonance can cause a periodic variation in a coating width and/or gauge, for example, and can lead to rupture of the polymer web.

[0006] Moreover, in a coating application or blown film production the polymer must withstand various forces such as acceleration in going from the die to the substrate in a coating application or the gas pressure that causes stretching in a blown film. The ability to withstand these forces is referred to as "melt-strength". There has been a need for lactide polymer formulations that will have improved melt-strength.

Summary of the Invention

[0007] Polylactide polymer compositions with improved melt-strength and rheplogy and methods for making the same are disclosed in the attached claims. The methods include providing in the polylactide polymer composition, polylactide polymer molecules which have been modified, relative to linear non-substituted polylactide, to provide increased molecular interaction among polylactide backbone chains in the composition. The polymer composition can (and preferably will) have at least one of the following, relative to linear non-substituted polylactide: an increased weight average molecular weight, increased branching and/or increased bridging. Preferably, the polymer has a number average molecular weight from about 10,000 (and more preferably at least 50,000) to about 300,000.

[0008] In addition, the preferred polymer compositions preferably have a residual monomer concentration of zero to about 2 percent by weight; and a water concentration of zero to about 2000 parts per million. The polymer should preferably have a weight average molecular weight from about 100,000 to about 1,200,000.

[0009] In many useful and preferred applications, the method will involve providing modified polylactide polymer molecules having sufficient molecular interaction to produce a polymer composition having a polydispersity of at least about 2.5. One manner in which this molecular interaction can be provided is generating bridging between polylactide molecules through free radical reaction. Such bridging can, for example, be generated by using a molar ratio of free

radical initiator to polymer within a range of 0.01:1 to 10:1.

[0010] Certain applications of the invention are directed toward compositions comprising: a polylactide based polymer composition having a number average molecular weight of at least 10,000 (and preferably at least 50,000); and preferably a polydispersity of at least 2.5. Preferably, the polymer has a weight average molecular weight of at least about 100,000 and not greater than about 1,200,000.

[0011] It is an advantage to the present invention that improved polylactide polymer compositions can be made from a lactide mixture which has not been recrystallized from a solvent. That is, the lactide mixture may include initiators such as small amounts of water or lactic acid therein, yet improved polymer compositions according to the present invention (for example, those having a number average of molecular weight of at least 50,000) will still result. Preferred methods disclosed herein for accomplishing this involves reacting the lactide mixture which has not been recrystallized from a solvent (or a polymer resulting from a lactide mixture which has not been recrystallized from a solvent) with a non-initiating lactide reactant containing at least two epoxide groups. An alternate method useable to accomplish the desired result, disclosed herein, is using radical reactions to generate linking, or the introduction of a cross-linkable group into the polymer molecules. Also, chain extenders can be used. Variations of these approaches, and others, will be apparent from the detailed description below.

Brief Description of the Drawings

[0012]

Fig. 1 is a schematic representation of a preferred process for the manufacture of a melt-stable lactide polymer.

Fig. 2 is a graph of the natural log of a linear lactide polymer's intrinsic viscosity with respect to the natural log of the polymer's molecular weight.

Fig. 3 is a graph of the apparent shear viscosity of three PLA polymers with respect to the apparent shear rate at a temperature of 175 degrees Celsius.

Fig. 4 is a graph of the apparent shear viscosity of two PLA polymers with respect to the apparent shear rate at 175 degrees Celsius.

Detailed Description of the Invention

[0013] The present invention concerns methods of improving polylactide polymers with respect to rheology (melt flow) and melt strength characteristics. In particular the invention concerns improvements in the rheology and/or melt strength of the molten polymer which tend to lessen propensities to "neck" or exhibit similar phenomena. The invention preferably concerns accomplishment of such improvements without undesirably affecting other preferred characteristics of preferred polylactide polymers including, for example: compostability and/or biodegradability characteristics; melt stable characteristics; and the characteristic of being able to be raised sufficiently above t_g (glass transition temperature or softening point) for accomplishment of a fluid material of appropriate flow characteristics for processing, without reaching temperatures at which substantial or undesirable levels of degradation begins to occur.

[0014] The improved processing features achievable in some applications of the present invention include lower temperature processing, lower power consumption and pressure, and increased melt strength and improved melt flow characteristics. The polymers of the present invention may be melt processed into films, sheets, coatings for paper, blow molded articles, fibers, foam, foamed articles, thermoformed articles, injection molded articles, non-woven fabrics and the like. These articles may thereafter be components of various commercial articles, such as films for diapers.

Rheology

[0015] In general, the rheology characteristics of a resin or polymer are its viscosity or flow characteristics. For polymers such as polylactide (PLA), i.e. thermoplastic polymers, rheology or flow characteristics are used in reference to the characteristics exhibited by the polymer once the temperature of the polymer is raised above t_g (or melting point if a crystalline polymer is involved). Generally, the concern is with respect to the flow characteristics of the polymer once it has been raised to a sufficient temperature that viscosity is reduced to a point where various melt processing steps are feasible.

[0016] Typically, for polylactide polymers (PLA) melt processing is feasible when the shear viscosity of the resin has been reduced to at least about 10,000 Pa-s (Pascal-seconds), and typically to within a range of about 1 Pa-s to about 1,000 Pa-s. For typical polylactide polymers such as those described in U.S. Patent 5,142,023 to Gruber et al., t_g is about 50°C to about 65°C, and the materials are typically heated to about 160°C to about 200°C for processing.

[0017] With respect to rheology of linear polymers, various characterizations are typically made with respect to viscosity. Typically the term "viscosity" is used to characterize the melt flow characteristics of (or the flowability of) the

polymer. With respect to these melt flow characteristics, two types of viscosity are generally considered important. One of these is shear viscosity, which generally relates to evaluations of capillary flow, i.e. how much of the molten polymer can flow through a capillary tube within a given period of time, etc. For example, in the paper coating industry, shear viscosity is used to indicate the force which will be needed to push the polymer through an extruder die. A higher shear viscosity indicates that a larger force is required to push the polymer resin through processing equipment, such as an extruder die, and a lower shear viscosity indicates that a lower force is required to push the polymer through processing equipment.

[0018] The other type of viscosity characteristic which is important is related to extensional viscosity. Extensional viscosity refers to viscosity in the absence of shear, and generally relates to the resistance of the polymer to flow when pulled or drawn. A higher extensional viscosity indicates that the resin is very resistant to flow when pulled or drawn, and a lower extensional viscosity indicates that the resin is not very resistant to flow when pulled or drawn.

[0019] Extensional viscosity is particularly important with respect to melt processing and the characteristic of necking. Change in extensional viscosity at increasing strain rate, and the time-dependent response of the polymer in extensional flow, can also be important with respect to melt processing operations. Collectively these define the extensional viscosity characteristics. A difficulty with conventional polylactides is that they are prone to neck, because of poor extensional viscosity characteristics.

[0020] Development of desireable polymers for melt processing requires, in part, development of a desireable balance of extensional viscosity characteristics and shear viscosity. If the extensional viscosity is not only increased, but the shear viscosity is also increased substantially, the characteristics of the polymer melt may be affected such that it is no longer desirable for melt processing. For example, if both the extensional and shear viscosities are substantially increased by increasing molecular weight, a lactide polymer resin may not flow sufficiently readily through conventional processing equipment (at conventional processing temperatures) to be widely acceptable. If the temperature in the processing equipment is increased to compensate for this lack of flowability, undesirable degradation of the polymer may be accelerated during polymer production or melt processing. Also, for example, if both extensional and shear viscosities are substantially decreased by decreasing molecular weight, a lactide polymer resin may require less force to flow readily through the conventional processing equipment, but the resin will be more prone to neck.

[0021] In addition, a higher molecular weight (i.e., above a critical molecular weight) lactide polymer is preferred, because the physical properties such as modulus, tensile strength, percentage elongation at break, impact strength, flexural modulus, and flexural strength remain relatively constant when the lactide polymer is above a threshold molecular weight. The lower limit of molecular weight of the preferred polymer compositions of the present invention is preferably set at a point above this threshold in order to result in a lactide polymer with more predictable physical properties upon melt-processing. In general, this critical "lower" number average molecular weight is at least about 10,000 (and preferably at least 50,000), and a preferable "lower" weight average molecular weight is at least about 100,000.

[0022] The practical upper limit of the molecular weight is based upon a practical upper limit of workable viscosity (viscosity generally increases with increased molecular weight). In order to melt-process a very high molecular weight lactide polymer, the melt-processing temperature must be increased to reduce the viscosity of the polymer. As the processing temperature is increased, however, undesirable degradation of the lactide polymer is accelerated.

[0023] The exact upper limit on molecular weight may vary depending on the particular melt-processing application since required viscosities vary, and residence time within the melt-processing equipment also varies. Thus, the degree of degradation, for a given polymer, in each type of processing system will also be expected to vary. It is believed that one could readily determine the suitable molecular weight upper limit for meeting the viscosity and degradation requirements in any selected application, however. Generally, the number average molecular weight of the preferred polymer will not be greater than about 300,000 and the weight average molecular weight will not be greater than about 1,200,000.

The Linear Nature of PLA

[0024] In general, poor extensional viscosity characteristics and rheology characteristics which lead to significant amounts of necking, are characteristics of linear polymers, and PLA is a linear polymer. Approaches to improving PLA, according to the present invention, generally concern methods of increasing interaction between the long polymer chains of individual molecules sufficiently to improve rheology, while at the same time not introducing so much interaction that other characteristics such as compostability, biodegradability, and melt-processability, are undesirably affected. Thus, an improved or modified polylactide polymer, in accord with the present invention, is one in which the interaction between the long polymer chains of individual molecules is increased such that rheology is improved, without substantially undesirably affecting compostability, biodegradability, and melt-processability of the polymer. In general, the methods described herein concern modifications that can be made during polymer resin formation. Thus, initially, a brief consideration of the formation of linear PLA is presented.

[0025] In general, linear (unsubstituted) PLA is formed from ring opening polymerization of the cyclic dimeric ester of lactic acid, i.e. lactide. This is described, for example, in U.S. Patent 5,247,059 to Gruber et al. While the precise nature of the polymerization is not fully understood, in general it appears to concern chain propagation in the following manner. An initiator having a group containing an active moiety (such as a -OH group) therein is provided and mixed with the lactide. The initiator may comprise, for example, water, an alcohol, lactic acid, amines or other materials. The "active moiety group" reacts with one of the carbonyl groups of the cyclic dimer, to open the ring. Each ring opening results in the generation of an active -OH group on the end of the polymer backbone. The newly generated active -OH group can react with another lactide molecule, to ring open. Chain propagation thus occurs in a linear fashion. The length of the chains, i.e. the molecular weight of the resulting polymer, will in part depend upon the number of active -OH groups initially provided; and the rate of reaction and length of time allowed. If each initiator has only one or two, active -OH group(s) thereon, in general, the resultant polymer will be a linear polymer with one or two hydroxyl terminated ends. In general, as more equivalents of initiator are provided, the molecular weight of the resulting polymer will be lower. That is, in general, molecular weight is inversely proportional to the number of initiators.

Approaches to Generating Interaction Between Long Polymer Chains

[0026] As indicated above, generally, improving extensional viscosity characteristics in a linear polymer can be accomplished by providing interaction between the long polymer backbones. Providing interaction between the long polymer backbones, typically, can be accomplished by increasing the weight average molecular weight of the lactide polymer melt, providing branching within the lactide polymer, and/or providing bridging in the lactide polymer. In this context, "bridging" refers to bonding between long polymer PLA-based chains. The term "branching" refers to either providing pendent groups from a linear PLA-based polymer chains or providing long polymer segments joined to one another through a residue. The term "PLA-based polymer chains" refers to polymer chains in which the majority of repeat polymer units or residues are unsubstituted lactic acid or lactide residues. Preferably they comprise at least 50% by weight residues from lactic acid or lactide. Providing branching and/or bridging in the lactide polymer can lead to a less linear polymer.

Introduction of Branching Into the Polymer Backbone

[0027] A method to improve the rheological properties of PLA is through introduction of branching into the polymer backbone. In particular, the introduction of branching into the polymer backbone produces less linear polylactide molecules. It is believed that less linear polylactide molecules exhibit improved rheological properties because the molecular entanglements last longer due to decreased ability to move by reptation (diffusion). Reduced neck-in is one property improved with the less linear polymer's improved rheological behavior.

[0028] Generally, as illustrated in Fig. 2, linear polylactide polymers exhibit a characteristic curve of intrinsic viscosity with respect to polymer molecular weight. As branching or other molecular interaction is introduced into the PLA, the resulting curve of intrinsic viscosity versus molecular weight deviates significantly from the graph of intrinsic viscosity versus molecular weight of a linear lactide polymer. This deviation is an indication that branching or other molecular interaction has occurred.

[0029] Introducing sufficient branching into a linear polylactide to generate improved rheology may be accomplished by means of non-initiating lactide reactants containing at least two epoxide groups, such as an epoxidized hydrocarbon or an epoxidized oil, to form a branched (i.e. less linear) polylactide polymer.

[0030] The term "linear polylactide" as used herein refers to a linear non-substituted polylactide polymer, such as those disclosed in U.S. Patents 5,142,023, 5,247,058 and 5,247,059 to Gruber et al. The term "polylactide polymer" as used herein refers to a polymer in which the majority of repeat units in the polymer chains are lactic acid based or lactide based residues. For example, after removing additives such as fillers and plasticizers using methods known in the art, such as extraction and filtration, a polymer sample is hydrolyzed or saponified. Typically, a polylactide polymer, after removing additives, will yield 50% or more, by weight, of lactic acid residues.

Providing Bridging Between the Polymer Backbones

[0031] Another way in which interaction between the polymer chains can be increased is to introduce bridging between polymer backbones. This bridging can be introduced subsequent to polymer formation. Bridging will generally improve the extensional viscosity characteristics of the PLA by providing a small amount of cross-linking between the long backbones and thus creating resistance to stretch or pull during polymer melt processing. Long backbone chains which have been bridged together, generally, form a new less linear polylactide molecule.

[0032] Any of a variety of means can be used to determine the presence of branching of, or bridging between, polymer chains. The following is an example of one technique. Control samples of dried and devolatilized linear polylactide are

prepared. The molecular weights of the test samples should be within the range of the molecular weights of the controls. The samples are then dissolved in a solvent. This solvent should be the same solvent that is used as a mobile phase for the gel permeation chromatography (GPC). The intrinsic viscosity of each sample is determined at the same temperature and in the same solvent as the GPC is run. Using GPC, the molecular weights of the samples should be determined relative to a standard, such as polystyrene. Either weight average molecular weight or viscosity average molecular weight is used.

[0033] Based upon the GPC results, a plot of the natural log of intrinsic viscosity (in deciliters per gram) versus the natural log of molecular weight should be made. In addition, a regression line should be made for the control samples. This regression line is made by measuring the molecular weight and intrinsic viscosity of several (i.e. at least 3 and preferably at least 7) linear polylactide samples and plotting the results. These control samples should provide a range of molecular weights sufficient to accommodate the test samples as plotted on the same chart as the regression line.

[0034] Various techniques are available for providing bridging in the linear lactide polymer and thus converting it into a less linear lactide polymer. For example, free radical generating peroxides can be used to cleave substituents from the polylactide backbones, generating a polymer radical that can bond with another polymer radical.

Some Specific Means of Increasing Molecular Interaction

[0035] The following discusses some more specific means of increasing molecular interaction between polylactide polymer backbones. In general, control of the amount of interaction between the long polymer chains is desirable for maintaining a melt-stable, workable, compostable and/or biodegradable material. In evaluating possible specific methods for improving rheological properties, while at the same time retaining other preferred characteristics of melt stable polylactides, a number of approaches to increasing interaction between long polymer chains of polylactide have been evaluated.

[0036] The principal approaches can be divided into two types. The first type of approach involves reacting a radical generating moiety with a group contained in a polylactide polymer chain such that the residual polylactide chain becomes a radical that can react with another residual polylactide chain. Thus, two residual polylactide chains can bond or link to one another. A variation of this approach involves using a radical generating moiety to link to a reactant having either a bulky organic group therein (for branching) or a functional group therein that can be later reacted to cause bridging, to the polymer. An example of this latter would be maleic anhydride.

[0037] The second principal approach involves including a moiety other than unsubstituted lactide in some of the polylactide chains, i.e. a reactant containing at least two epoxide groups.

[0038] The following discussion is a detailed description of specific types of radical generators, initiating reactants, non-initiating lactide reactants, and combination reactants that can be used in accord with the present invention.

Generating Interaction Between Linear Polymer Molecules Using Free Radical Reaction

[0039] This approach to generating small amounts of bonding between linear polylactide molecules was generally characterized above. The following scenario will provide a greater understanding of this technique. Consider a mixture of polylactide polymer materials. If a free radical initiator is provided in the mixture, the initiator will, upon activation, generate free radicals. Among the possibilities of follow-up reaction, is that various free radicals from the initiator will react with carbon-hydrogen bonds in different polymer molecules, for example removing a hydrogen atom from each and generating, in the remaining or residual polymer molecule, a free radical. This reaction is believed to most likely (statistically) take place at one of the tertiary carbons in the polymer backbone.

[0040] The polymer has now become a free radical or a free radical residue of a polylactide polymer. Among the reactions of which it is capable, is reaction with yet another polymer molecule, which has been converted to a polymer radical by the same process. Reaction with the other polymer radical would generate a bond between the two polymer molecules. It will be understood that in general such a polymer free radical reaction is statistically unfavored. However, it need only occur to a small extent for sufficient linear polymer linking (bridging) to occur, to increase molecular interaction, and thus enhance rheology characteristics.

[0041] This mechanism for providing interaction among polylactide polymer chains, although useful, does have some drawbacks. For example, there is potential for gel formation. More specifically, if too much initiator is used there may be so much interaction among the residual polymer chains that the polymer gels and loses much of its flowability characteristics. Processing a polymer with poor flowability characteristics can be difficult and costly. Therefore, polymer gelling is discouraged.

[0042] The radical generator, preferably, is added during or after polylactide formation. Combining the radical generator with the polylactide after polymerization adds a step to the polymer processing. However, the reaction rate of this process is typically so fast that very little additional processing time is typically needed.

[0043] Another example of a drawback of this mechanism is that byproducts can be produced. Because there is no

precise control over what the radicals generated during this process will react with, there are typically several types of byproducts that result from this reaction process. These byproducts may have to be separated from the resulting polylactide polymer prior to melt-processing the polymer.

[0044] An advantage of this mechanism for generating interaction among polylactide chains is that many radical generators are inexpensive and readily available. In addition, many break down to byproducts which are readily removed, for example, by devolatilization. Also, the extent of bonding is so small that the biodegradability or compostability of the polylactide polymer is not significantly lost.

[0045] A variety of free radical initiators may be utilized to generate interaction between linear polymer molecules according to this technique. In general, any radical initiator that readily removes a moiety, such as hydrogen, from a polylactide chain to form a residual polylactide free radical (which can then react with another residual polylactide free radical) can be used in accord with the present invention. A wide variety of peroxide radical initiators are known and can be used. Peroxide initiators useable in accord with the present invention include: 2,5-dimethyl-2,5-di(t-butylperoxy) 3-hexyne; 2,5-dimethyl-2,5-di(t-butylperoxy) hexane; 2,5-dimethyl-2,5-di(t-amylperoxy) hexane; 4-(t-butylperoxy)-4-methyl-2-pentanol; Bis(t-butylperoxyisopropyl) benzene; Dicumyl peroxide; Ethyl 3,3-bis(t-butylperoxy) butyrate; Ethyl 3,3-bis(t-amylperoxy) butyrate; and, Dibenzoyl peroxide. Commercial products such as Lupersol 130; Lupersol 101; t-amyl 101; Lupersol D-240; Luperox 802; Luperox 500; Lupersol 233; Lupersol 533; and, Lucidol 78, available from ELF Atochem of Philadelphia, PA are useable. A preferred radical initiator is ethyl 3,3-di-(t-butylperoxy)-butyrate), preferably as Luperco 233-XL (available from ELF Atochm, as a 40% concentration of the peroxide in a $CaCO_3$ carrier). A preferred addition technique is to compound the peroxide into the PLA using a twin screw extruder.

[0046] In general, to achieve a sufficient interaction among polymer chains to improve rheology (extensional viscosity characteristics) in a manner sufficient to inhibit necking or the like, a relatively large amount of initiator will be needed. Typically, if molar ratios of initiator to polymer of about 0.01:1 to 10:1 (more preferably 0.05/1 to 3/1) are used, a sufficient amount of polymer interaction will occur to achieve improvement in rheology. In such circumstances (as has been observed) the number average molecular weight of the polymer increases by only about ten percent, whereas the weight average molecular weight increases about twenty percent or more. Molar ratios of initiator to polymer of above about 10:1 are believed likely to cause excessive gelling in typical systems.

Providing Non-initiating Lactide Reactants

[0047] Another approach to increasing molecular interaction involves utilizing non-initiating lactide reactants to generate interaction between long polymer chains. This technique is advantageous because it does not involve the addition of initiating reactants into the prepolymer or polymerizing mixture. Thus, it is well adapted to application in processing using polylactide mixtures which have not been purified by recrystallization from a solvent.

[0048] In general, a non-initiating lactide reactant is a material which, when reacted with lactic acid, lactide or polylactide, reacts with an active -OH in the polylactide but which cannot, by itself and before reaction with the lactic acid, lactide or polylactide, initiate propagation. For example, for propagations involving lactide ring opening to form polylactides, epoxy compounds are non-initiating lactide reactants. In particular, when the active -OH group of a lactide or polylactide molecule reacts with the epoxy group contained in a non-initiating lactide reactant, the oxirane ring opens and provides a new -OH group for further reaction with lactides (i.e. chain propagation). However, for each oxirane group only one reactive -OH group (for propagation) is formed from a reaction with the lactic acid or lactide polymer. Thus, the oxirane ring does not initiate polymer formation but rather merely becomes incorporated into the polymer chain and will permit chain propagation to continue.

[0049] If the non-initiating lactide reactant molecule includes two non-initiating reactive groups, such as epoxy groups thereon, it can be used to link long polymer chains together (i.e., the residue of the non-initiating lactide reactant molecule becomes a bridge). The bridge can be longer if the active groups are at the ends of a hydrocarbon chain, for example. Similarly, if a non-initiating lactide reactant includes three or more non-initiating reactive groups then the result can be a polymer molecule having numerous long polylactide chains extending in different directions. In general, the use of non-initiating lactide reactants leads to a polymer with improved melt flow properties and preferred characteristics with respect to processing phenomena, such as necking.

[0050] A variety of materials are useable to generate improved polylactide polymers with respect to melt flow properties, through reaction with non-initiating lactide reactants. Useful non-initiating lactide reactants include, for example, copolymerizing agents having two or more epoxy groups per molecule, such as many epoxidized oils.

[0051] When copolymerizing agents having two or more epoxy groups per molecule are added to the prepolymer mixture before or during polymerization, a less linear polymer can result when compared to non-copolymerized lactide polymers.

[0052] Useful copolymerizing agents or non-initiating lactide reactants having epoxide groups include epoxidized fats and oils of many kinds. In particular, when lactide is copolymerized with an epoxidized oil, it is believed that the oxirane rings of the epoxidized oil react with either terminal alcohol groups or terminal acid groups of the lactide polymer

during reaction to form a less linear lactide polymer compared to a non-copolymerized lactide polymer.

[0053] Preferably, epoxidized: fatty acids, glycerides, diglycerides, triglycerides and mixtures thereof, are used a copolymerizing agents. More preferably, epoxidized: animal fats, animal oils, vegetable fats, vegetable oils, monoglycerides, diglycerides, triglycerides, free fatty acids and derivatives thereof are used. Most preferably, epoxidized vegetable oils such as epoxidized linseed oil, epoxidized soybean oil and mixtures thereof are used. Additional useful epoxidized oils may include epoxidized: cottonseed oil, ground nut oil, soybean oil, sunflower oil, rape seed oil or cannola oil, sesame seed oil, olive oil, corn oil, safflower oil, peanut oil, sesame oil, hemp oil, tung oil, neat's food oil, whale oil, fish oil, castor oil, and tall oil.

[0054] Epoxidized linseed oil has been used as a copolymerizing agent with great success. In particular, an epoxidized linseed oil known as Flexol® Plasticizer LOE (commercially available from Union Carbide Corporation) is a preferred copolymerizing agent of the present invention.

[0055] It is interesting that epoxidized linseed oil is marketed as a plasticizer, however the T_g of the resultant polymer is fairly constant, which indicates little plasticizing effect at the levels tested. An advantage associated with copolymerizing agents such as epoxidized linseed oil, is they can act as a lubricant during processing without the resultant polymer having a greasy texture.

[0056] Epoxidized soybean oil, for example, Paraplex® G-62, commercially available from C.P. Hall Corp., is also a preferred copolymerizing agent for the present invention.

[0057] It has been found that die processability characteristics can be improved with use of compositions and methods of the present invention. In particular, it has been found that, when processing polymers of the present invention while holding temperature, molecular weight, polymer flow rate and plasticizer concentration constant, there can be a reduction in die pressure when compared with linear non-functionalized polylactide polymers of comparable weight average molecular weight. This advantageous reduction in die pressure has been found to be most evident when using non-initiating lactide reactants, such as epoxides, to promote molecular interaction in accord with the present invention.

[0058] Coating operations, for example, can be conducted more efficiently with use of a polymer that contributes to improved die processability characteristics, such as reduced die pressure. This reduction can save energy and reduce equipment wear. Preferably, in accord with the present invention, a polymer is prepared such that it can be processed with a die pressure that has been reduced at least 10% when compared with linear non-functionalized PLA of comparable weight average molecular weight that is processed under similar conditions. More preferably, the polymer is prepared such that there has been at least a 15% die pressure reduction and most preferably, there has been at least a 20% die pressure reduction. In general, a preferred polymer in accord with the present invention is prepared such that it can be processed with a die pressure that has been reduced with respect to a linear polylactide of comparable weight average molecular weight which is melt processed under the same conditions. This die pressure reduction is illustrated below in Examples 9 and 13.

[0059] Regardless of what type copolymerizing agent (i.e. non-initiating lactide reactant) is used, the amount of copolymerizing agent added to the prepolymer mixture can vary with the specific application. Generally, if the amount of copolymerizing agent (i.e. non-initiating lactide reactant) added to the prepolymer or polymerizing mixture is insubstantial, then the melt flow properties of the resulting polymer will not be improved. Moreover, if too much copolymerizing agent (i.e. non-initiating lactide reactant) is added to the prepolymer or polymerizing mixture then the reaction can lead to very high molecular weight polymers and/or gels. In general, the amount of copolymerizing agent will vary with the desired molecular weight and polydispersity index of the resulting polymer. A practical lower limit on the copolymerizing agent is to have at least 1 equivalent (equivalents = moles of functionality) of copolymerizing agent for every 20 moles of polymer. More preferably, the copolymerizing agent is present at a level of at least 1 equivalent of copolymerizing agent for every 10 moles of polymer. Most preferably, the copolymerizing agent is present at a level of at least 1 equivalent of copolymerizing agent for every 5 moles of polymer.

[0060] A practical upper limit on the copolymerizing agent is determined based on the following conservative estimate of a theoretical gel point (TGP). The TGP, in equivalents of copolymerizing agent per mole of polymer, is estimated as:

$$TGP = f/f\text{-}1$$

where f is the functionality of the copolymerizing agent. The concentration of copolymerizing agent is preferably less than 5 x TGP, more preferably less than 2 x TGP, and most preferably less than 1 x TGP. The moles of polymer can be estimated beforehand from the total moles of initiator, as determined, for example, by gel permeation chromatography.

[0061] For f=1 the TGP goes to infinity, as gelation cannot occur. For this case, the maximum amount of copolymerizing agent is preferably less than 50%; and more preferably less than 10% of the polymer weight.

[0062] Preferably, the copolymerizing agent is biodegradable, or forms a biodegradable residue in the polymer, so that combinations of the lactide and copolymerizing agent (i.e. non-initiating lactide reactant) can also be biodegradable.

[0063] Any of the compounds and/or methods described in this section can be combined in order to form a viscosity modified polylactide polymer. For example, more than one type of non-initiating lactide reactant can be added to the prepolymer mixture in order to form a polymer that contains residues of more than one type of non-initiating lactide reactant. Chemically different types of non-initiating lactide reactants can be combined and added to the prepolymer mixture (e.g. both a reactant containing a cyclic ester and a reactant containing an epoxide can be used). In addition, both non-initiating lactide reactants and initiating reactants can be added to the prepolymer mixture.

Preparation of Improved Melt Stable Lactide Polymers

[0064] In general, lactide polymers according to the present invention are manufactured from the polymerization of lactide. Except for the improvements defined herein with respect to interacting long polymer chains for rheology improvement, general techniques for preparation of lactide polymers according to the present invention are disclosed in U.S. Patents 5,142,023 and 5,247,059 to Gruber et al. Thus, the techniques described herein are well adapted for use in continuous processing and are not limited to use in batch processing. These techniques may be applied, with modifications as described herein, to obtain improved polymers according to the present invention.

[0065] In general, various techniques outlined above for generating interaction among linear polymers can be characterized as practiced in at least one of three, general manners: by providing a reactant or initiator in the prepolymer mixture prior to polymerization; providing a reactant or initiator during lactide polymerization, or possibly by providing a reactant or initiator after lactide polymerization. An example of the first type of modification is the general technique of providing an initiating reactant in the prepolymer mixture. An example of the second technique is providing a non-initiating lactide reactant in the lactide mixture during polymerization. An example of the third technique is utilization of a free radical initiator to create polymer radicals which react to generate bonding between polymer molecules, after polymerization.

[0066] The lactide polymer composition may include other polymeric species which can, for example, be incorporated through melt blending. Examples of other polymers which could be blended include, but are not limited to, poly(hydroxybutyrate); poly(hydroxybutyrate-co-hydroxy valerate); poly(vinyl alcohol); poly(caprolactone); and, poly(glycolide). Preferably, the blended polymer is biodegradable, compostable, and made from annually renewable resources.

Polymer Composition

[0067] Preferred lactide polymer compositions of the present invention comprise a mixture of polylactide polymer chains having a number average molecular weight from about 10,000 to about 300,000. More preferably, the number average molecular weight is at least 50,000. In still more preferred compositions, the number average molecular weight ranges from about 50,000 to about 150,000. In general, physical properties such as modulus, tensile strength, percentage elongation at break, impact strength, flexural modulus, and flexural strength remain statistically constant when the lactide polymer samples are above a threshold molecular weight. The lower limit of molecular weight of the polymer compositions of the present invention is preferably above about 50,000 in order to result in a lactide polymer with predictable physical properties upon melt-processing. There typically is a practical upper limit on molecular weight based on increased viscosity with increased molecular weight. In order to melt-process a high molecular weight lactide polymer, the melt-processing temperature should be increased to reduce the viscosity of the polymer. The exact upper limit on molecular weight should be determined for each melt-processing application in that required viscosities vary and residence time within the melt-processing equipment will also vary. Thus, the degree of degradation in each type of processing system will also vary. It is believed that one could determine the suitable molecular weight upper limit for meeting the viscosity and degradation requirements in any application.

[0068] Preferably, the polymer is prepared to have a weight average molecular weight of at least about 100,000 and not greater than 1,200,000. The melt-stable lactide polymer compositions in a preferred embodiment are dependent on the desired crystalline state of the product. For a semi-crystalline product the polymer compositions are the reaction product of polymerizing a lactide mixture comprising about 15% by weight or less of meso and D-lactide, with the balance L-lactide. More preferably, the reaction mixture will contain less than 6% by weight of meso and D-lactide, with a balance of L-lactide. For an amorphous product, the polymer compositions are generally the reaction product of polymerizing a lactide mixture comprising about 6% by weight or more of meso-and D-lactide, with a balance of L-lactide. More preferably, the reaction mixture will contain more than about 9% but less than about 50% by weight of meso-and D-lactide, with the balance L-lactide. The optical composition disclosed includes the benefit of utilizing meso-lactide as disclosed by Gruber et al. in U.S. Patent No. 5,338,822.

[0069] In accord with the present invention, the prepolymer mixture (i.e. lactide monomer) may contain additional cyclic ester monomers along with lactide. For example, dioxanones (such as p-dioxanone), laciones (such as ∈-caprolactone or 4-valerolactone), dioxan(dione)s (such as glycolide or tetramethyl 1,4-dioxan-2,5-dione), or ester-amides (such as morpholine-2,5-dione).

[0070] The residual monomer concentration (if any) in the preferred melt-stable lactide polymer composition is less than about 2 percent by weight. In a preferred composition the concentration of residual lactide monomer in the polymer is less than about 1 percent by weight and more preferably less than about 0.5 percent by weight. It has been found that the monomer should not be used as a plasticizing agent in the resin of the present invention due to significant fouling or plating out problems in processing equipment. It is believed that, typically, low levels of monomer concentration do not plasticize the final polymer.

[0071] The water concentration (if any) within the melt-stable lactide polymer composition preferably is less than about 2,000 parts-per-million. More preferably, this concentration is less than about 1000 parts-per-million and most preferably less than 500 parts-per-million. The polymer melt-stability is significantly affected by moisture content. Thus, the melt-stable polymer should have the water removed prior to melt-processing. It is recognized that water concentration may be reduced prior to processing the polymerized lactide to a resin. Thus, moisture control could be accomplished by packaging such resins in a way which prevents moisture from contacting the already-dry resin. Alternatively, the moisture content may be reduced at the melt-processor's facility just prior to the melt-processing step in a dryer. It has been found that the presence of water can cause excessive loss of molecular weight which may affect the physical properties of the melt-processed polymer.

[0072] In preferred compositions of the present invention, a stabilizing agent of a type and in an amount sufficient to reduce yellowing and molecular weight loss is included in the melt-stable composition. Stabilizing agents useful in the present polymer compositions comprise antioxidants and/or water scavengers. Preferred antioxidants are phosphite-containing compounds, hindered phenolic compounds or other phenolic compounds. Useful antioxidants include such compounds as trialkyl phosphates, mixed alkyl/aryl phosphates, alkylated aryl phosphates, sterically hindered aryl phosphates, aliphatic spirocyclic phosphates, sterically hindered phenyl spirocyclics, sterically hindered bisphosphonites, hydroxyphenyl propionates, hydroxy benzyls, alkylidene bisphenols, alkyl phenols, aromatic amines, thioethers, hindered amines, hydroquinones and mixtures thereof. Commercially-available stabilizing agents have been tested and fall within the scope of the present lactide polymer composition. Biodegradable antioxidants are preferred.

[0073] In the manufacture of the lactide polymer compositions of the present invention, the reaction to polymerize lactide is typically catalyzed. Many catalysts have been cited in literature for use in the ring-opening polymerization of lactones. These include but are not limited to: $SnCl_2$, $SnBr_2$, $SnCl_4$, $SnBr_4$, aluminum alkoxides, tin alkoxides, zinc alkoxides, SnO, PbO, Sn (2-ethyl hexanoates), Sb (2-ethyl hexanoates), Bi (2-ethyl hexanoates), Na (2-ethyl hexanoates) (sometimes called octets), Ca stearates, Mg stearates, Zn stearates, and tetraphenyltin. Applicants have also tested several catalysts for polymerization of lactide at 180°C which include: tin(II) bis(2-ethyl hexanoate) [T-9, Atochem], dibutyltin diacetate [Fascat 4200®, Atochem], butyltin tris(2-ethyl hexanoate) [Fascat 9102®, Atochem], hydrated monobutyltin oxide [Fascat 9100®, Atochem], antimony triacetate [S-21, Atochem], and antimony tris(ethylene glycoxide) [S-24, Atochem]. Of these catalysts, tin(II) bis(2-ethyl hexanoate), butyltin tris(2-ethyl hexanoate) and dibutyltin diacetate appear to be most effective.

[0074] It has been found that the use of catalysts to polymerize lactide significantly affects the stability of the resin product. It appears the catalyst as incorporated into the polymer also is effective at catalyzing the reverse depolymerization reaction. To minimize this negative effect, in preferred compositions, the residual catalyst level in the resin is present in a molar ratio of monomer-to-catalyst greater than 3,000:1, preferably greater than 5,000:1 and most preferably greater than 10,000:1. It is believed that a ratio of 20,000:1 may be used, but polymerization will be slow. It has been found that when catalyst level is controlled within these parameters, catalytic activity is sufficient to polymerize the lactide while sufficiently low to enable melt-processing without adverse effect when coupled with low residual monomer levels and low water concentration as described above in polymers of number average molecular weight between 10,000 to about 300,000. It is believed in most applications the addition of a stabilizing agent may be unnecessary if catalyst level is optimized.

[0075] If the lactide polymer composition is used as a coating, as detailed in pending U.S. Patent No. 5,475,080 which is a continuation in part of U.S. Patent No. 5,338,822, a plasticizer may be included in the polymer formulation in order to improve the coating quality of the polymer. More particularly, plasticizers reduce the glass transition temperature of poly(lactide), which aides in processing and coating the polymer at lower temperatures and may improve flexibility and reduce cracking tendencies of the coated product.

[0076] Selection of a plasticizing agent requires screening of many potential compounds and consideration of several criteria. For use in a biodegradable coating the preferred plasticizer is to be biodegradable, non-toxic, compatible with the resin and relatively nonvolatile.

[0077] Plasticizers in the general classes of alkyl or aliphatic esters, ether, and multi-functional esters and/or ethers are preferred. These include alkyl phosphate esters, dialkylether diesters, tricarboxylic esters, epoxidized oils and esters, polyesters, polyglycol diesters, alkyl alkylether diesters, aliphatic diesters, alkylether monoesters, citrate esters, dicarboxylic esters, vegetable oils and their derivatives, and esters of glycerine. Most preferred plasticizers are tricarboxylic esters, citrate esters, esters of glycerine and dicarboxylic esters. These esters are anticipated to be biodegrad-

able. Plasticizers containing aromatic functionality or halogens are not preferred because of their possible negative impact on the environment.

[0078] For example, appropriate non-toxic character is exhibited by triethyl citrate, acetyltriethyl citrate, tri-n-butyl citrate, acetyltri-n-butyl citrate, acetyltri-n-hexyl citrate, n-butyryltri-n-hexyl citrate and dioctyl adipate.

[0079] The resulting polylactide should also exhibit reduced neck-in when compared with linear non-functionalized polylactide of a comparable molecular weight. In order to determine whether the neck-in of the polylactide is reduced, any method well known in the art can be used. The following method is useable. A polylactide polymer film is extruded under the following conditions. An extruder with a suitable film die, for example, a one-inch (2.54 mm) extruder with a six-inch (15.24 cm) film die and chill roll stack, is used. The extruder is set at conditions suitable to produce an extrusion cast film using a linear polymer with a number average molecular weight comparable to the test polymer. The number average molecular weight of the linear polylactide should be within 20% of the less linear polylactide test sample. Typical die temperatures for polylactide are 160°C to about 180°C. The extruder speed and take up roll speed are adjusted to produce a film of about 0.5 (12.2 μm) to about 3.0 mil (73,2 μm) thickness. The neck-in is determined as the die width minus the finished film width. The test polymer should be run at the same conditions as the linear control polymer, and the test sample's neck-in should be determined in the same manner. The neck-in ratio is the neck-in of the test sample (modified) polymer divided by the neck-in for the linear control polymer. Improvement of significance has occurred if a neck-in ratio of less than about 0.8 is obtained. Preferred improvement has resulted if the neck-in ratio is less than about 0.4.

Melt-Stable Lactide Polymer Process

[0080] The process for the manufacture of a melt-stable lactide polymer comprises the steps of first providing a purified lactide mixture, such as that produced in the process disclosed by Gruber et al. in U.S. Patents 5,247,059 and 5,244,073, although the source of lactide is not critical to the process of the present invention.

[0081] The lactide mixture is polymerized to form a lactide polymer or polylactide with some residual unreacted monomer in the presence of a catalyst means for catalyzing the polymerization of lactide to form polylactide. Catalysts suitable for such polymerization have been listed previously. The concentration of catalysts utilized may be optimized as discussed previously.

[0082] In a preferred embodiment, a stabilizing agent as disclosed above, which may be an antioxidant and/or a water scavenger is added to the lactide polymer. It is recognized that such stabilizing agents may be added simultaneously with or prior to the polymerization of the lactide to form the lactide polymer. The stabilizing agent may also be added subsequent to polymerization.

[0083] The lactide polymer is then devolatilized to remove unreacted monomer which may also be a by-product of decomposition reactions or the equilibrium-driven depolymerization of polylactide. Any residual water which may be present in the polymer would also be removed during devolatilization, although it is recognized that a separate drying step may be utilized to reduce the water concentration to less than about 1,000 parts-per-million. The devolatilization of the lactide polymer may take place in any known devolatilization process. The key to selection of a process is operation at an elevated temperature and usually under conditions of vacuum to allow separation of the volatile components from the polymer. Such processes include a stirred tank devolatilization or a melt-extrusion process which includes a devolatilization chamber and the like.

[0084] In a preferred process for manufacture of a melt-stable lactide polymer composition, the process also includes the step of adding a molecular weight control agent to the lactide prior to catalyzing the polymerization of the lactide. Molecular weight control agents include active hydrogen-bearing compounds, such as lactic acid, esters of lactic acid, alcohols, amines, glycols, diols and triols which function as chain-initiating agents. Such molecular weight control agents are added in sufficient quantity to control the number average molecular weight of the polylactide to between about 10,000 and about 300,000.

[0085] Next referring to Figure 1 which illustrates a preferred process for producing a melt-stable lactide polymer composition. A mixture of lactides enters a mixing vessel (3) through a pipeline (1). A catalyst for polymerizing lactide is also added through a pipeline (13). Within mixing vessel (3) a stabilizing agent may be added through a pipeline (2). A water scavenger may also be added through the pipeline (2). The stabilized lactide mixture is fed through a pipeline (4) to a polymerization process (5) which may be conducted at temperatures greater than 160°C. The polymerized lactide or lactide polymer leaves the polymerization process through a pipeline (6). The stream is fed to a second mixing vessel (8) within which a stabilizing agent and/or catalyst deactivating agent may be added through a pipeline (7). The stabilized lactide polymer composition is then fed to a devolatilization process (10) through a pipeline (9). Volatile components leave the devolatilization process through a pipeline (11) and the devolatilized lactide polymer composition leaves the devolatilization process (10) in a pipeline (12). The devolatilized lactide composition is fed to a resin-finishing process (14). Within the resin-finishing process the polymer is solidified and processed to form a pelletized or granular resin or bead. Applicants recognize the polymer may be solidified and processed to form resin

or bead first, followed by devolatilization. The resin is then fed to a drying process (16) by conveyance means (15). Within the drying process (16) moisture is removed as a vapor through pipeline (17). The dried lactide polymer resin leaves the drying process (16) by a conveyance means (18) and is fed to a melt-processing apparatus (19). Within the melt-processing apparatus (19) the resin is converted to a useful article as disclosed above. The useful article leaves the melt-processing apparatus (19) through a conveyance means (20). The process illustrated in Fig. 1 can be readily conducted as a continuous process.

[0086] The various agents (for example, radical initiators, non-initiating reactants or initiating reactants) useable to provide the improved polymers as discussed herein may be added at various points in the process. For example, at mixing vessel 3, in the polymerization reactor, at vessel 8, in devolatilize 10, or in subsequent processing steps.

[0087] One example of a useful article, is a coated paper article. A typical method of coating paper, as disclosed in US-A 5 475 080, is by extruding a melt through a die onto a moving substrate. After the coating process, the paper may be calendared to improve surface properties such as smoothness and gloss. In the calendaring process, the coated paper passes through alternating hard and soft rolls which reform the surface, often producing a gloss while smoothing or leveling surface face contours.

EXAMPLES

[0088] Examples 1 through 10 and 16-18 disclose methods and compositions utilizing a non-initiating lactide reactant . Examples 11-15 disclose methods and compositions utilizing peroxides and free radical reaction, as previously discussed. In the examples, Mn = number average molecular weight as determined by gel permeation chromatography (GPC); Mw = weight average molecular weight by GPC. Mz is the sum of the product of the number of molecules of a molecular weight times the cube of that molecular weight, divided by the sum of the number of molecules of a molecular weight times the square of that molecular weight.

Example 1

Copolymerization of Lactide with Epoxidized Soybean Oil and Epoxidized Tall Oil

[0089] Epoxidized soybean oil (FLEXOL® EPO, commercially available from Union Carbide) and epoxidized tall oil (FLEXOL® EP8, commercially available from Union Carbide) were separately copolymerized with lactide. A phosphite based process stabilizer (Weston TNPP, commercially available from General Electric) was added to the lactide at 0.4 weight percent. Catalyst (2-Ethylhexanoic acid, tin(II) salt from Aldrich Co., Milwaukee, WI) in a tetrahydrofuran carrier was added in a molar ratio 1 part catalyst/10,000 parts lactide. Mixtures of the molten lactide, epoxidized oil, stabilizer, and catalyst were sealed in vials and polymerized at 180°C for 2.5 hours. The samples were then dissolved in chloroform and analyzed by gel permeation chromatography using a refractive index detector and Ultrastyragel® IR column from Waters Chromatography to determine weight average and number average molecular weights for the resulting copolymer resins. The system temperature was 35°C and the GPC column was calibrated against poly(styrene) standards. The results of these tests appear in Table 1.

Table 1

Sample	Weight Average Mol. Weight	% Conversion
control poly(lactide)	240,000	71
copolymerized with 1.0 wt% epoxidized soybean oil	400,000	96
copolymerized with 1.5 wt% epoxidized tall oil	178,000	96

[0090] The results for the epoxidized soybean oil show a significant increase in the weight average molecular weight, indicative of a coupling or crosslinking mechanism during the copolymerization. This is attributed to the multiple oxirane functionality contained in most of the epoxidized soybean oil molecules (an average of about 4.6 oxirane oxygens/molecule). The epoxidized tall oil copolymer does not show an increase in weight average molecular weight, presumably because each of the tall oil molecules contain an average of only about 1 oxirane group. The results for both the epoxidized tall oil and the epoxidized soybean oil show an increase in reaction rate for the copolymerization, achieving 96% conversion of the monomers, while the control reaction only exhibited 71% conversion.

Example 2

Examples of Epoxidized Linseed Oil as a Copolymerizing Agent

[0091] A copolymerized poly(lactide) was produced by adding epoxidized linseed oil to a continuous pilot plant polymerization of lactide in the same manner described in Example 1. This was accomplished by adding a solution of TNPP and epoxidized linseed oil (FLEXOL® Plasticizer LOE from Union Carbide), in a ratio of 1:2 by weight, at a rate of 10 gm/hr to the continuous polymerization such that the weight ratio of epoxidized oil to lactide was 0.55. Lactic acid was processed into lactide in a continuous pilot scale reactor, purified by distillation, and fed to a continuous polymerization reactor system. The polymerization system consisted of a 1-gallon (3.8 l) and a 5-gallon (19 l) reactor in series. The reactors are continuous feed, stirred tank reactors. The lactide feed rate was 1.1 kg/hr, the catalyst, tin (II) bis (2-ethyl hexanoate) (T-9 from Atochem) was added at a rate of 0.03 weight percent. A phosphite process stabilizer (Weston TNPP® from General Electric) was added at a rate of 0.3 weight percent. Reactor temperatures were 190°C to 200°C. The resulting polymer pellets were bagged every eight hours and labelled as samples I-VII. The pellets were dried and collected for GPC analysis. Total run time was 52 hours generating 60 kilograms material.

GPC results after drying:

[0092]

Table 2

Example	Time	Mn	Mw	PDI
start	zero	89000	220000	2.5
I	0-8 hours	79000	307000	2.9
II	8-16 hours	50000	296000	5.0
III	16-24 hours	72200	323000	4.4
IV	24-32 hours	80900	339000	4.2
V	32-40 hours	81500	316000	3.9
VI	40-48 hours	76200	303000	4.0
VII	48-52 hours	81600	319000	4.0

[0093] The resulting material was then subjected to a devolatilization process to remove the residual amount of unreacted monomer lactide. After devolatilization, samples III-VII were combined and used in further testing. Molecular weights of the combined fractions after devolatilization were: Mn-75,000 Mw-325000 PDI-4.3 and a residual lactide level of less than 0.5 percent as recorded by a GPC.

Example 3

Example of Vial Polymerizations with Epoxidized Oil, Showing Effect on Rate of Polymerization

[0094] Tin(II) bis (2-ethylhexanoate) commercially available as 2-ethylhexanoic acid, tin(II) salt from Aldrich Chemical Company, and epoxidized linseed oil (FLEXOL® Plasticizer LOE from Union Carbide) were placed into a vial. A molten mixture of 90% L-lactide and 10% D,L-lactide, with 0.4% by weight of a stabilizer (Weston TNPP), was then added to the vial. An identical set was made up without the epoxidized oil. In each case the final catalyst concentration was 1 part catalyst per 5000 parts lactide and the epoxidized oil was 1% by weight of the final reaction mixture. The solutions were sealed and placed in an oil bath at 180°C. Samples were pulled over time and analyzed by GPC for molecular weight and extent of lactide conversion.

[0095] The experiment was repeated, except that the catalyst and the epoxidized oil were added to the molten lactide before it was placed in the respective vials.

[0096] The results of both experiments are shown in Tables 3 and 4 respectively. The epoxidized oil resulted in an increase in the polymerization reaction rate in each study. The weight average molecular weight and PDI (polydispersion index) are also higher.

Table 3

Sample	Time (min.)	% Conversion	Mn	Mw	PDI
Control	15	10	6800	7800	1.12
	30	16	39100	40600	1.04
	45	48	30400	40100	1.32
	60	73	48900	77800	1.59
	90	78	54000	86200	1.60
With 1% epoxidized oil	15	12	7800	8800	1.12
	30	69	57100	115000	2.01
	45	74	50500	112000	2.22
	60	80	67300	123000	1.82
	90	93	78400	176000	2.25

Table 4

	Time (min.)	% Conversion	Mn	Mw	PDI
Control	15	0	-----	------	----
	30	8	5400	5700	1.05
	45	18	14500	16500	1.14
	60	28	26400	29000	1.10
	90	45	26900	29000	1.15
With 1% epoxidized oil	15	11	7500	8800	1.17
	30	32	24700	29700	1.22
	45	57	31300	44000	1.40
	60	69	50300	71000	1.41
	90	84	53500	96400	1.80

Example 4

Cast Film at Typical Extrusion Temperatures

[0097] Films of a control polymer and a copolymer of the present invention were extruded. The conditions and the results follow:

Extruder

[0098] Equipment: Killion 1" extruder 30/1 L/D rate with a 6" (15.24 cm) cast sheet displaced about 1/2 inch (1.27 cm) from a three stack chill roll. The following were the temperatures (°C):

Zone 1	Zone 2	Zone 3	Zone 4	Adapter	Die	Melt	Chill Roll
148.9	165.6	176.7	176.7	16.3	165.6	171.1	37.8

Table 5

Cast film results: Base PLA (Mn = 70,000; Mw = 215,000)						
Power (amps)	Screw Speed (rpm)	Press (psi, bar)	Take Off Setting	Thickness (mils, nm)	Width (inches, cm)	Neck-in (inches , cm)
12.5	40	3840 (268.8)	2.0	17.0 (0.4)	5.125 (13.0)	0.875 (2.2)
12.5	40	3840 (268.8)	4.0	8.0 (0.2)	4.625 (11.7)	1.375 (3.5)
12.5	40	3840 (268.8)	6.0	5.5 (0.14)	4.375 (11.1)	1.625 (4.1)
12.5	40	3840 (268.8)	8.0	4.0 (0.1)	4.250 (10.8)	1.75 (4.4)
12.5	40	3840 (268.8)	10.0	2.5 (0.06)	4.0 (10.2)	2.0 (5.1)
12.0	30	3610 (252.7)	10.0	1.5 (0.04)	4.0 (10.2)	2.0 (5.1)
11.5	20	3380 (236.6)	10.0	1.0 (0.03)	3.75 (9.5)	2.25 (5.7)
11.5	10	2850 (199.5)	10.0	0.7 (0.02)	3.75 (9.5)	2.25 (5.7)

Table 6

PLA w/epoxidized linseed oil (Mn = 75,000; Mw = 325,000)						
Power (amps)	Screw Speed (rpm)	Press (psi, bar)	Take Off Setting	Thickness (mils, nm)	Width (inches, cm)	Neck-in (inches, cm)
5.5	40	1950 (136.5)	2.0	12.0 (0.3)	5.0 (12.7)	1.0 (2.54)
5.0	40	1950 (136.5)	4.0	8.5 (0.2)	5.0 (12.7)	1.0 (2.54)
5.0	40	1950 (136.5)	6.0	5.5 (0.14)	4.75 (12.1)	1.25 (3.18)
5.0	40	1950 (136.5)	8.0	4.0 (0.10)	4.75 (12.1)	1.25 (3.18)
5.0	40	1950 (136.5)	10.0	3.5 (0.09)	4.75 (12.1)	1.25 (3.18)
5.0	30	1650 (115.5)	10.0	2.0 (0.05)	4.75 (12.1)	1.25 (3.18)
5.0	20	1250 (87.5)	10.0	1.0 (0.03)	4.75 (12.1)	1.25 (3.18)
4.5	10	880 (61.6)	10.0	0.5 (0.01)	4.75 (12.1)	1.25 (3.18)

[0099] The results show that poly(lactide) copolymerized with epoxidized linseed oil processes at lower power consumption and pressure, and generates a polymer with reduced neck-in.

Example 5

Cast Film at Reduced Extrusion Temperatures

[0100] Separate films made from a poly(lactide) control polymer and from the copolymer of the present invention described in Example 2 were extruded under various conditions. The resulting films were then evaluated using standard measuring techniques. The extruding conditions and the data gathered from this evaluation are set forth below:

Extruder Temperatures (°C) of:							
Zone 1	Zone 2	Zone 3	Zone 4	Adapter	Die	Melt	Chill Roll
140.6°C	146.1	151.7	151.7	151.7	151.7	151.7	37.8

Table 7

Cast film results: PLA w/epoxidized linseed oil						
Power (amps)	Screw Speed (rpm)	Press (psi, bar)	Take Off Setting	Thickness (mils, nm)	Width (inches, cm)	Neck-in (inches, cm)
10.5	40	3470 (243)	2.0	10.0 (0.25)	5.125 (13.0)	0.875 (2.2)

Table 7 (continued)

Cast film results: PLA w/epoxidized linseed oil						
Power (amps)	Screw Speed (rpm)	Press (psi, bar)	Take Off Setting	Thickness (mils, nm)	Width (inches, cm)	Neck-in (inches, cm)
10.0	40	3470 (243)	4.0	6.0 (0.15)	5.125 (13.0)	0.875 (2.2)
10.0	40	3470 (243)	6.0	4.0 (0.10)	5.125 (13.0)	0.875 (2.2)
10.0	40	3470 (243)	8.0	3.5 (0.09)	5.0 (12.7)	1.0 (2.5)
10.0	10	3470 (243)	10.0	2.5 (0.06)	5.0 (12.7)	1.0 (2.5)
7.5	30	3250 (228)	10.0	1.5 (0.04)	5.0 (12.7)	1.0 (2.5)
6.0	20	2720 (190)	10.0	0.7 (0.02)	5.0 (12.7)	1.0 (2.5)
6.0	10	2000 (140)	10.0	0.5 (0.01)	5.125 (13.0)	0.875 (2.2)
2.5	4.5	1450 (102)	10.0	0.25 (0.006)	5.25 (13.3)	0.75 (1.9)
2.5	1.0	920 (64)	10.0	0.1 (0.003)	5.25 (13.3)	0.75 (1.9)

[0101] Under similar extrusion temperatures, the control poly(lactide) could not run because the power consumption exceeded maximum levels (>15 amps). The results show that poly(lactide) polymerized with epoxidized linseed oil has the benefit of processing at lower temperatures and generates a polymer with increased melt strength, less neck-in and a film of lower thickness.

Example 6

Blown Film of Base Poly(lactide) with Epoxidized Linseed Oil

[0102] A copolymer of lactide with epoxidized linseed oil was prepared in the manner described in Example 2 and was blown into a 8 inch (20.32 cm) width film at thickness from 3.0 to 0.5 mils (76,2 - 13 μm). The blown film line consisted of a Killion tower connected to a Killion 1" (2.54 cm) extruder 30:1 L/D ratio equipped with a 2.25 inch (5.7 cm) blown film die. Distance from the die to the towers nip roll was 2.5 feet (75 cm).

Table 8

Extruder Temperatures (°C) :							
Zone 1	Zone 2	Zone 3	Zone 4	Adapter	Die	Melt	Chill Roll
148.9	160	165.6	162.8	154.4	154.4	154.4	160

[0103] Operation of the blown film line was very smooth.

Example 7 (comparative)

Use of Hydroxyl Initiators and Effect on Molecular Weight

[0104] L-lactide was melted under nitrogen and catalyst [tin (II) bis 2-ethylhexanoate, 1:5000 molar ratio of tin to lactide] was added. Initiator was added at the rate of 1:500 molar basis, initiator to lactide. The samples were polymerized at 80°C for 2 hours. Samples were then ground and devolatilized at 125°C and 10 mmHg pressure overnight. Samples were reground, dissolved in chloroform, and analyzed by gel permeation chromatography (GPC) against polystyrene standards. The results are shown below:

Initiator	Mn	Mw	PDI
Dodecanol	54,800	113,000	2.06
2-EHMPD	55,400	95,000	1.72
Dipentaerythritol	56,400	93,600	1.66

2-EHMPD is 2-ethyl-2-(hydroxy methyl)-1,3-propane diol. The number average molecular weights are consistent with the expected values for adding hydroxyl initiators. The low PDI (PDI < 2) are consistent with the most probable distri-

bution for multi-functional initiators. The PDI are lower than the PDI of about 2.0 which is typically seen for vial polymerization of lactide.

Example 8

Lactide/Epoxidized Soybean Oil Copolymerization

[0105] Lactide was copolymerized with epoxidized soybean oil in a continuous pilot line. The feed contained 0.25 weight percent epoxidized soybean oil [Paraplex G-62; C.P. Hall], 0.1 weight % PNPG process stabilizer [Weston], and 0.03 weight percent catalyst (tin II) bis (2-ethyl hexanoate). Two back-mixed reactors in series (1 gallon (3.8 l) and 5 gallon (19 l)) were used. The reaction temperature was about 215°C, and the reactors were about 75% full.

[0106] The copolymer had a number average molecular weight of about 70,000 and a weight average molecular weight of about 210,000, giving a PDI of about 3.0. Under similar conditions, but without the epoxidized oil, the pilot line produced poly(lactide) with a PDI of 2.1-2.5 and comparable number average molecular weight.

Example 9

Neck-in on Cast Film Using Epoxidized Soybean Oil Modified PLA

[0107] A performance comparison for extruding a cast sheet was made using normal, linear poly(lactide) and the less linear poly(lactide) copolymerized with epoxidized soybean oil) from Example 8. The test was conducted using a 1" (2.54 cm) Killion extruder with 30/1 L/D connected to a 6" (15.24 cm) cast sheet die. The die was approximately 1/2 inch (1.27 cm) from a three roll chill stack. The extruder die temperature was 345°F (173.9 °C) and the chill roll was 100°F (37.8°C). The following table presents the measured power usage, die pressure, and film neck-in (die width - minimum sheet width) for base poly(lactide) and the modified polymer. The take-off setting was held constant.

Screw Speed (rpm)	Base Poly(lactide) Approx Thick (mil)μm	Power (amps)	Press (psi)bar	Neck-in (inches)cm	Power (amps)	Modified Poly(lactide) Press (psi)bar	Neck-in (inches)cm	Neck-in ratio
40	3 (76.2)	15	1260 (88)	1.75 (4.4)	8	785 (55)	0.7 (1.8)	0.40
30	2 (50.8)	12.5	1090 (76)	1.75 (4.4)	8	650 (46)	0.9 (2.3)	0.51
20	1.5 (38.1)	12.5	860 (60)	1.75 (4.4)	7.5	510 (36)	1.0 (2.5)	0.57
10	0.8 (20.3)	10.5	560 (39)	2.0 (5.1)	6.0	300 (21)	1.0 (2.5)	0.50
5	0.5 (12.7)	7.0	280 (20)	3.25 (8.3)	6.0	190 (13)	1.25 (3.2)	0.38

The modified polymer shows benefits, at all screw speeds, of reduced power consumption, reduced die pressure, and reduced neck-in.

Example 10

Curtain Coating with Epoxidized Soybean Oil Modified PLA

[0108] A comparison of linear poly(lactide) and modified poly(lactide) copolymer from Example 8 was made on an extrusion curtain coating line. The linear poly(lactide) had a number average molecular weight of 95,000 with a PDI of 2.34, and the modified polymer had a number average molecular weight of 70,000 and PDI of 3.08.

[0109] The extrusion curtain coating line consisted of a 1.5" (3.81 cm) extruder with a 24:1 L/D, connected to a vertical 13" (33 cm) coat hanger die. The extruder was run with a die temperature of 425°F (218.3°C). The polymer was coated onto 15 pound (6.8 kg) basis weight kraft paper at a speed of 150 feet (45m) per minute. The die was held 3" (7.62 cm) above the substrate. The polymer through-put was varied using the screw speed of the extruder to produce coatings of various thicknesses. The table below shows the power consumption, coating thickness, and amount of neck-in (die width - minimum coating width) at various screw speeds.

Linear Poly(lactide)

Screw Speed (rpm)	Power (amps	Thick (mil)μm)	Neck-in (inch)cm)
90	15	1.5 (38	4 (10.1)
60	12	1.0 (25)	5 (12.7)
45	12	0.6 (15)	5 (12.7)
30	10	0.4 (10)	5 (12.7)

Modified Poly(lactide)

Power (amps)	Thick (mil)μ)	Neck-in (inch)cm)
10	1.5 (38)	1.0 (2.54)
5	1.0 (25)	1.5 (3.8)
4	0.5 (13)	2.0 (5.0)
4	0.4 (10)	2.0 (5.0)

The linear polymer exhibited a very uneven coating action, with the edge of the coating weaving in and out to make a coating of uneven width. Both materials showed excellent adhesion to the paper and produced coatings free of tears or gels.

Example 11

Peroxide Treatment of Plasticized Poly(Lactide)

[0110] Poly(lactide) with 10.5 weight percent acetyl tri-n-butyl citrate as a plasticizer was blended with 0.25% and 0.5% dicumyl peroxide. The peroxide was misted onto the pellets as a 50% solution in acetone, followed by vacuum drying at room temperature for 3 hours to remove the acetone. The pellets were then injection molded at 180 C with a hold time of 4.5 minutes. Molecular weights were determined by GPC. Gel content was determined as the residue remaining after dissolving at 1% in refluxing acetone for 3 hours and filtering. The table below shows the change in molecular weight profile after treatment. The increase in high molecular weight components is consistent with bridging due to peroxide induced crosslinking.

	Control	0.25% treated	0.50% treated
Mn	64,000	87,000	82,000
Mw	170,000	326,000	456,000
Mz	376,000	1,162,000	1,184,000
PDI	2.65	3.73	5.49
% gel	0.0%	1.5%	2.1%

The 0.25% treated sample was slightly hazy, the 0.5% treated sample was dull and hazy. Material properties of glass transition temperature, melting point, annealed percent crystallinity, break stress, modulus, and heat distortion temperature were unchanged.

Example 12

Peroxide Treatment/Neck-in on Cast Films

[0111] Poly(lactide) pellets were coated with 0.2 weight percent of either Lupersol 101 or Lupersol TBEC (ELF Atochem) and processed in an extruder to make an extrusion cast film using a 6" (15.24 cm) die. The die temperature of the extruder was 335°F (168.3°C) with a residence time of about 4 minutes. The table below presents molecular weight distributions as determined by GPC and gel content as measured by acetone insolubles.

	Base	TBEC Modified	101 Modified
Mn	66,900	74,400	67,600
Mw	161,000	200,000	184,000
Mz	306,000	423,000	376,000
PDI	2.40	2.69	2.73
% gel	0.0%	1.0%	0.0%

All films were clear (non-hazy).
The neck-in was determined as the die width minus the film width.

Thick		Neck-in and neck-in ratio			
(mil μm)	Base	TBEC	(ratio)	101	(ratio)
0.5 (13)	2.5	1.2 (3.0)	0.48	1.2 (3.0)	0.48
1.0 (25)	2.4	1.2 (3.0)	0.50	1.2 (3.0)	0.50

Example 13

Peroxide Treatment/Neck-in on Cast Films

[0112] A blend of plasticizer (acetyl tri-n-butyl citrate) and peroxide (ethyl 3,3-bis-(t-butylperoxy)-butyrate) (commercially available is Luperco 233XL from ELF Atochem was compounded with poly(lactide) and 4 weight % Celite Super Floss (Celite) diatomaceous earth using a Leistritz twin screw extruder. The material was pelletized and dried, with molecular weights as shown below.

Sample	% peroxide	% plasticizer	Mn	Mw	PDI
1	0.0	0.0	77,000	165,000	2.13
2	0.10	20	86,500	197,000	2.28
3	0.25	15	81,800	219,000	2.68
4	0.50	20	72,300	261,000	3.61
5	1.00	15	61,400	243,000	3.96
6	1.00	20	71,800	275,000	3.83

The increase in high molecular weight components, as seen in the Mw and the PDI, with increasing peroxide level is clearly evident.

[0113] Samples were tested for neck-in under extrusion cast film conditions using a 6" (15.24 cm) extrusion die. The neck-in is measured as the width of the die (6" (15.24 cm)) minus actual sheet width (inches (cm)). The following values were obtained as a function of extruder screw speed.

Screw Speed	Thick (mil) (μm)	Film 1	Neck-in (inches) (cm) Film 3	Film 4	Film 6	Neck-in ratio Film 3	Film 4	Film 6
40	3.0 (76.2)	1.96 (5.0)	1.28 (3.3)	0.50 (1.3)	0.41 (1.0)	0.65	0.26	0.21
30	2.0 (50.8)	2.06 (5.2)	1.15 (2.9)	0.50 (1.3)	0.34 (0.9)	0.56	0.24	0.17
20	1.5 (38.1)	2.13 (5.4)	1.31 (3.3)	0.56 (1.4)	0.25 (0.6)	0.61	0.26	0.26
10	0.8 (20.3)	2.35 (6.0)	1.19 (3.0)	0.38 (1.0)	0.51 (1.3)	0.16		
5	0.4 (10.4)	2.90 (7.4)	1.19 (3.0)	0.31 (0.8)	0.41 (1.0)	0.11		

Increasing peroxide clearly reduced neck-in at all screw speeds.

[0114] The following amps and die pressure were measured at various screw speeds. Melt temperature for all tests was 165-172°C.

Amps during sheet extrusion:					
Screw Speed	**Amps**				
(rpm)	Film 1	Film 3	Film 4	Film 5	Film 6
40	14.5	7	4.5	7	3.5
30	14	6.5	4	5.5	3
20	13	6	3.2	3.5	2.8
10	11	5	2.8	3	
5	8.5	3	2		

Die pressure during sheet extrusion:					
Screw Speed	**Die Pressure (psi bar)**				
(rpm)	Film 1	Film 3	Film 4	Film 5	Film 6
40	1150 (80.5)	800 (56)	720 (50.4)	920 (64.4)	730 (51.1)
30	970 (67.9)	680 (47.6)	640 (44.8)	770 (53.9)	600 (42)
20	770 (53.9)	560 (39.2)	530 (37.1)	630 (44.1)	480 (33.6)
10	495 (34.7)	400 (28)	380 (26.6)	490 (34.3)	
5	310 (21.7)	300 (21)	270 (18.9)		

The large drop in amps and die pressure between film 1 and the others is presumably due to the addition of plasticizer in the other formulations. To see the effect of peroxide, we compare films 3 and 5 (0.25% and 1%) peroxide at constant 15% plasticizer) and films 4 and 6 (0.50% and 1% peroxide at constant 20% plasticizer). The peroxide seems to have caused a slight decrease in amperage but uncertain (possible increase) effect on die pressure.

Example 14

Peroxide Treatment/Blown Film Results

[0115] Samples 3, 4, 5, and 6 from Example 13 were blown into 2 mil (50 μm) film using a Killion extruder with a 2.25" (5.7 cm) blown film die and a Killion tower. The materials formed blown films with less difficulty than linear poly (lactide). Film properties from tensile and trouser tear test results are shown below. The tensile test is provided in ASTM D882 and the trouser tear test is exemplified by ASTM D1938.

Sample	% elong. at yield	% elong. break	tensile break energy (in-lb)	tear break energy (in-lb)
3	6.7	10	1.4 (0.16 Nm)	0.30 (0.033 Nm)
5	3.6	4	1.2 (0.13 Nm)	0.28 (0.031 Nm)
6	8.1	368	70.4 (7.86 Nm)	0.15 (0.017 Nm)
4	11.5	491	78.0 (8.70 Nm)	0.23 (0.026 Nm)

Example 15

Effect of Peroxide Treatment on Shear Viscosity as Determined by Capillary Rheometry

[0116] A series of polymers, with 15% plasticizer and various levels of peroxide (Luperco 233XL), prepared in a manner similar to those in Example 13 were tested using a capillary viscometer at a temperature of 175°C. The viscosity data are shown in the table below.

Material	Shear rate	Apparent Shear Viscosity (Pa-S)		
		500/sec	1000/sec	5000/sec
0.1% peroxide		198	95	26
0.25% peroxide		258	118	33
1.0% peroxide		267	123	39

The data show that at increasing levels of peroxide the apparent shear viscosity increases. This is consistent with increased molecular weight due to bridging.

Example 16

Intrinsic Viscosity vs. Molecular Weight Data

[0117] A series of linear non-functionalized poly(lactide) samples were prepared using vial polymerizations with lactic acid added as a molecular weight control agent. These samples were dried and devolatilized, then dissolved in chloroform for GPC molecular weight determination (relative to polystyrene standards) and for intrinsic viscosity (IV). Both the GPC and the intrinsic viscosity were carried out at 35°C. The intrinsic viscosity measurements were made at three or more concentration points and extrapolated to zero concentration, following standard procedure.

[0118] A branched poly(lactide) copolymer with epoxidized linseed oil, from Example 2, was also tested in this manner.

[0119] The results are shown in Figure 2, where ln(IV) is plotted vs ln(apparent weight average mol weight). (I.V. is measured in deciliters/gram.) For typical poly(lactide), with a PDI of about 2, all the points are expected to fall on a single line, determined by the Mark-Houwink constants. A branched polymer, with sufficiently long arms, is expected to have a smaller radius of gyration and exhibit a lower intrinsic viscosity at a given molecular weight. The figure shows intrinsic viscosity relative to apparent molecular weight, which in this case is equivalent to GPC retention time and therefore to hydrodynamic volume. It can be shown that a branched polymer, because of its smaller radius of gyration, has a higher molecular weight and lower IV at a given hydrodynamic volume. The point for the modified polymer is an example of this.

[0120] Each of the linear poly(lactides) falls within 0.07 units of the ln(IV) vs ln (apparent weight average mol weight) line. The modified polymer is 0.5 units lower than predicted by that line. According to the test described above, this is an example of a poly(lactide) with long chain branching and thus increased molecular interaction.

Example 17

Comparison of Copolymerized Epoxidized Oil with Blending of Epoxidized Oil

[0121] Polymer samples of base poly(lactide), base poly(lactide) compounded in an extruder with 0.2% and 0.5% epoxidized soybean oil (ESO), and a copolymer of poly(lactide) with about 0.3% epoxidized soybean oil were tested for apparent shear viscosity using a capillary viscometer. Molecular weight data, determined by gel permeation chromatography, are shown below.

Sample	Mn	Mw	PDI
Base poly(lactide)	76,000	176,000	2.3
Base+ 0.2% ESO	70,000	158,000	2.3
Base + 0.5% ESO	66,000	151,000	2.3
Copolymer	50,000	213,000	4.8

Results of the capillary viscosity testing at 175°C are shown in Figures 3 and 4. The copolymer is seen to have a dramatically lower apparent shear viscosity. The lower shear viscosity at higher weight average molecular weight is surprising, but is consistent with the reduced die pressure observed when processing the epoxidized oil copolymers in Examples 4 and 9.

Example 18

Screw Sticking Evaluation

[0122] An injection molding machine was set at 350°F (176.7°C) and the screw was filled with a test polymer. The test polymer was allowed to sit in the screw for 2 minutes and then it was extruded at 500 psi (35 bar). The actual rpm of the screw was monitored as the material was extruded. In the absence of sticking, a maximum of 150 rpm was achieved. For base poly(lactide) (or linear non-functionalized polylactide) these conditions can result in a screw which will not turn at all, due to sticking. The following table presents the results of testing the polymers from Example 17.

Sample	Screw speed (rpm)
Base poly(lactide)	5-15
Base + 0.2% ESO	2-15
Base + 0.5% ESO	1-15
Copolymer of lactide/ESO	135-152

The table shows that, when processing the copolymer, the injection molder screw developed the full rpm -- indicating less tendency to stick. This is a surprising and significant processing benefit of the epoxidized oil copolymer. This benefit is not obtained from a simple mixture of base poly(lactide) and epoxidized oil.

Claims

1. A method of producing a polylactide polymer composition, said method including the step of generating bridging between polylactide molecules by free radical reaction or generating branching by forming the polylactide molecules in a procedure including a reactant containing at least two epoxide groups.

2. A method according to claim 1, comprising producing a polylactide polymer composition having a polydispersity index of at least 2.5.

3. A method according to claim 1 or 2, comprising producing a polymer having a number average molecular weight from 50,000 to 300,000.

4. A method according to claim 1 or 2, comprising producing a polymer having a weight average molecular weight from 100,000 to 1,200,000.

5. A method according to claim 1, wherein said step of generating bridging between polylactide molecules by free radical reaction comprises providing a molar ratio of free radical initiator to polymer within the range of 0.01: to 10:1.

6. A method according to claim 1, wherein the step of generating branching by forming the polylactide molecules in a procedure including a reactant containing et least two epoxide groups includes the step of forming polylactide molecules in a procedure including a reactant in addition to unsubstituted lactic acid or lactide, said reactant containing at least two epoxide groups, which reactant does not initiate lactide chain formation.

7. Polymer composition obtainable by the process of any of the claims 1-6.

8. Polymer composition comprising the reaction product of a mixture comprising

   a) lactide material comprising lactide, polylactide or a mixture thereof,
   b) 0.1 to 10 wt % of a copolymerizing agent comprising an epoxidized material containing two or more epoxy groups per molecule.

9. Polymer composition according to claim 8, wherein said copolymerizing agent comprises epoxidized linseed oil or epoxidized soybean oil.

10. Polymer composition according to claim 9, having a polydispersity index of at least 4.0.

11. Polymer composition according to claim 9, having a weight average molecular weight of at least 296,000.

12. Polymer composition according to claim 8, having a polydispersity index of at least 2.9.

13. A film, a coated paper, a non-woven fabric or an injection molded article prepared from the polymer of claim 7.

14. A film, a diaper, a sheet, a coated paper, a non-woven fabric, a thermo-formed article, a blow-molded article or an injection molded article prepared from the polymer of claim 8.

Patentansprüche

1. Verfahren zum Herstellen einer Polylactidpolymer-Zusammensetzung, mit dem Schritt des Erzeugens einer Überbrückung zwischen Polylactid-Molekülen durch eine radikalische Reaktion oder des Erzeugens einer Verzweigung durch Bilden der Polylactid-Moleküle in einem Prozess mit einem Reaktanten mit mindestens zwei Epoxidgruppen.

2. Verfahren nach Anspruch 1, mit dem Schritt des Herstellens einer Polylactidpolymer-Zusammensetzung mit einem Polydispersitäts-Index von mindestens 2,5.

3. Verfahren nach Anspruch 1 oder 2, mit dem Schritt des Herstellens eines Polymers mit einem zahlenmäßigen Mittelwert des Molekulargewichts von 50.000 bis 300.000.

4. Verfahren nach Anspruch 1 oder 2, mit dem Schritt des Herstellens eines Polymers mit einem gewichtsbezogenen Mittelwert des Molekulargewichts von 100.000 bis 1.200.000.

5. Verfahren nach Anspruch 1, bel dem der Schritt des Erzeugens einer Überbrückung zwischen Polylactid-Molekülen durch eine radikalische Reaktion das Herstellen eines Molverhältnisses von Radikalinitiator zu Polymer in einem Bereich von 0,01: bis 10:1 umfasst.

6. Verfahren nach Anspruch 1, bei dem der Schritt des Erzeugens einer Verzweigung durch Bilden der Polylactid-Moleküle in einem Prozess mit einem Reaktanten mit mindestens zwei Epoxidgruppen den Schritt des Bildens von Polylactid-Molekülen in einem Verfahren umfasst, bei dem ein Reaktant zusätzlich zu nicht substituierter Milchsäure oder Lactid verwendet wird, wobei der Reaktant mindestes zwei Epoxidgruppen aufweist und der Reaktant keine Lactidkettenbildung initiiert.

7. Polymer-Zusammensetzung, die durch das Verfahren nach Ansprüchen 1-6 erhalten wird.

8. Polymer-Zusammensetzung mit dem Reaktionsprodukt einer Mischung, die aufweist:

a) Lactidmaterial mit Lactid, Polylactid oder einer Mischung daraus,
b) 0,1 bis 10 Gewichtsprozent eines Copolymerisationsmittels mit einem epoxydierten Material mit zwei oder mehr Epoxidgruppen pro Molekül.

9. Polymer-Zusammensetzung nach Anspruch 8, bei der das Copolymerisationsmittel epoxydiertes Leinöl oder epoxydiertes Sojabohnenöl enthält.

10. Polymer-Zusammensetzung nach Anspruch 9, mit einem Polydispersitäts-Index von mindestens 4,0.

11. Polymer-Zusammensetzung nach Anspruch 9, mit einem gewichtsbezogenen Mittelwert des Molekulargewichts von mindestens 296.000.

12. Polymer-Zusammensetzung nach Anspruch 8, mit einem Polydispersitäts-Index von mindestens 2,9.

13. Film, beschichtetes Papier, Faservlies oder Spritzgussartikel gebildet aus dem Polymer nach Anspruch 7.

14. Film, Windel, Folie, beschichtetes Papier, Faservlies, warmgeformter Artikel, Blasformartikel oder Spritzgussartikel gebildet aus dem Polymer nach Anspruch 8.

Revendications

1. Procédé de fabrication d'une composition polymère de polylactide, ledit procédé comprenant l'étape consistant à générer un pont entre les molécules de polylactide par réaction de radicaux libres ou consistant à générer une ramification en formant les molécules de polylactide dans un mode opératoire comprenant un réactif contenant au moins deux groupes époxyde.

2. Procédé selon la revendication 1, comprenant la fabrication d'une composition polymère de polylactide ayant un indice de polydispersité d'au moins 2,5.

3. Procédé selon la revendication 1 ou 2, comprenant la préparation d'un polymère ayant une masse moléculaire moyenne en nombre comprise entre 50 000 et 300 000.

4. Procédé selon la revendication 1 ou la revendication 2, comprenant la production d'un polymère ayant une masse moléculaire moyenne en poids comprise entre 100 000 et 1 200 000.

5. Procédé selon la revendication 1, dans lequel ladite étape consistant à générer un pont entre les molécules de polylactide par une réaction de radicaux libres comprend l'établissement d'un rapport molaire amorceur de radicaux libres/polymère compris dans la plage allant de 0,01:1 à 10:1.

6. Procédé selon la revendication 1, dans lequel l'étape consistant à générer une ramification en formant les molécules de polylactide dans un mode opératoire comprenant un réactif contenant au moins deux groupes époxyde comprend l'étape consistant à former les molécules de polylactide dans un mode opératoire comprenant un réactif en plus de l'acide lactique ou du lactide non substitué, ledit réactif contenant au moins deux groupes époxyde, lequel réactif n'amorce pas la formation de la chaîne de lactides.

7. Composition polymère pouvant être obtenue par le mode opératoire selon l'une quelconque des revendications 1 à 6.

8. Composition polymère comprenant le produit réactionnel d'un mélange comprenant :

   a) une substance à base de lactide, comprenant du lactide, du polylactide ou un mélange de ceux-ci,
   b) de 0,1 à 10 % en poids d'un agent de compolymérisation comprenant une substance époxydée contenant deux groupes époxyde ou plus par molécule.

9. Composition polymère selon la revendication 8, dans laquelle ledit agent de copolymérisation comprend de l'huile de lin époxydée ou de l'huile de soja époxydée.

10. Composition polymère selon la revendication 9, ayant un indice de polydispersité d'au moins 4,0.

11. Composition polymère selon la revendication 9, ayant une masse moléculaire moyenne en poids d'au moins 296 000.

12. Composition polymère selon la revendication 8, ayant un indice de polydispersité d'au moins 2,9.

13. Film, papier couché, tissu non tissé ou article moulé par injection préparé à partir du polymère selon la revendication 7.

14. Film, couche-culotte, feuille, papier couché, tissu non tissé, article thermoformé, article moulé par soufflage ou article moulé par injection préparé à partir du polymère selon la revendication 8.

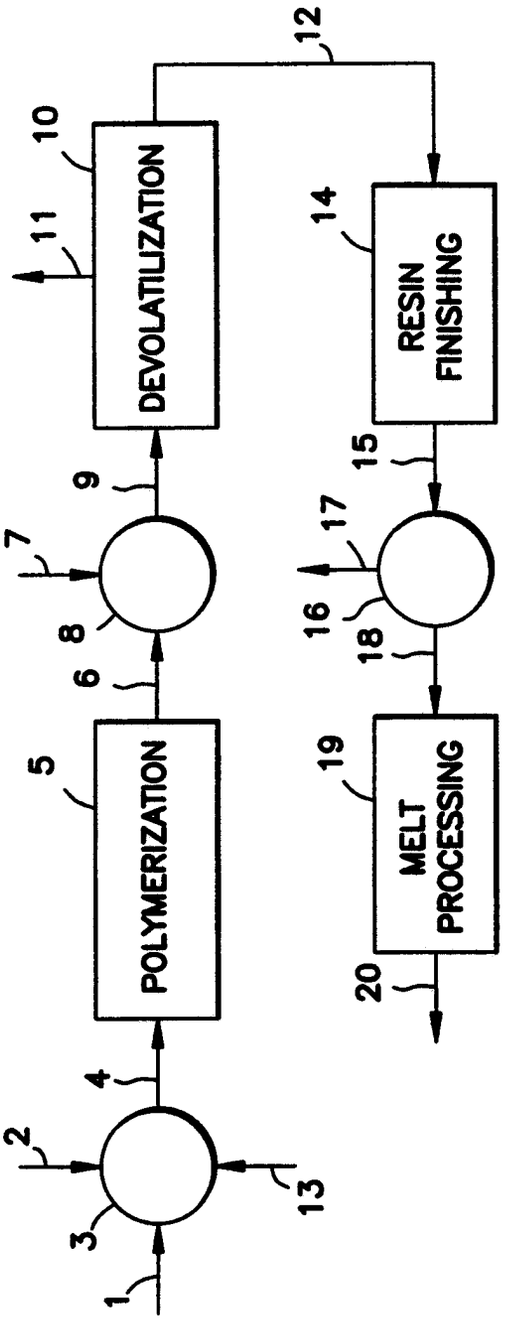
1
2
3
4
5
POLYMERIZATION
6
7
8
9
10
DEVOLATILIZATION
11
12
13
14
RESIN FINISHING
15
16
17
18
19
MELT PROCESSING
20

FIG. 1

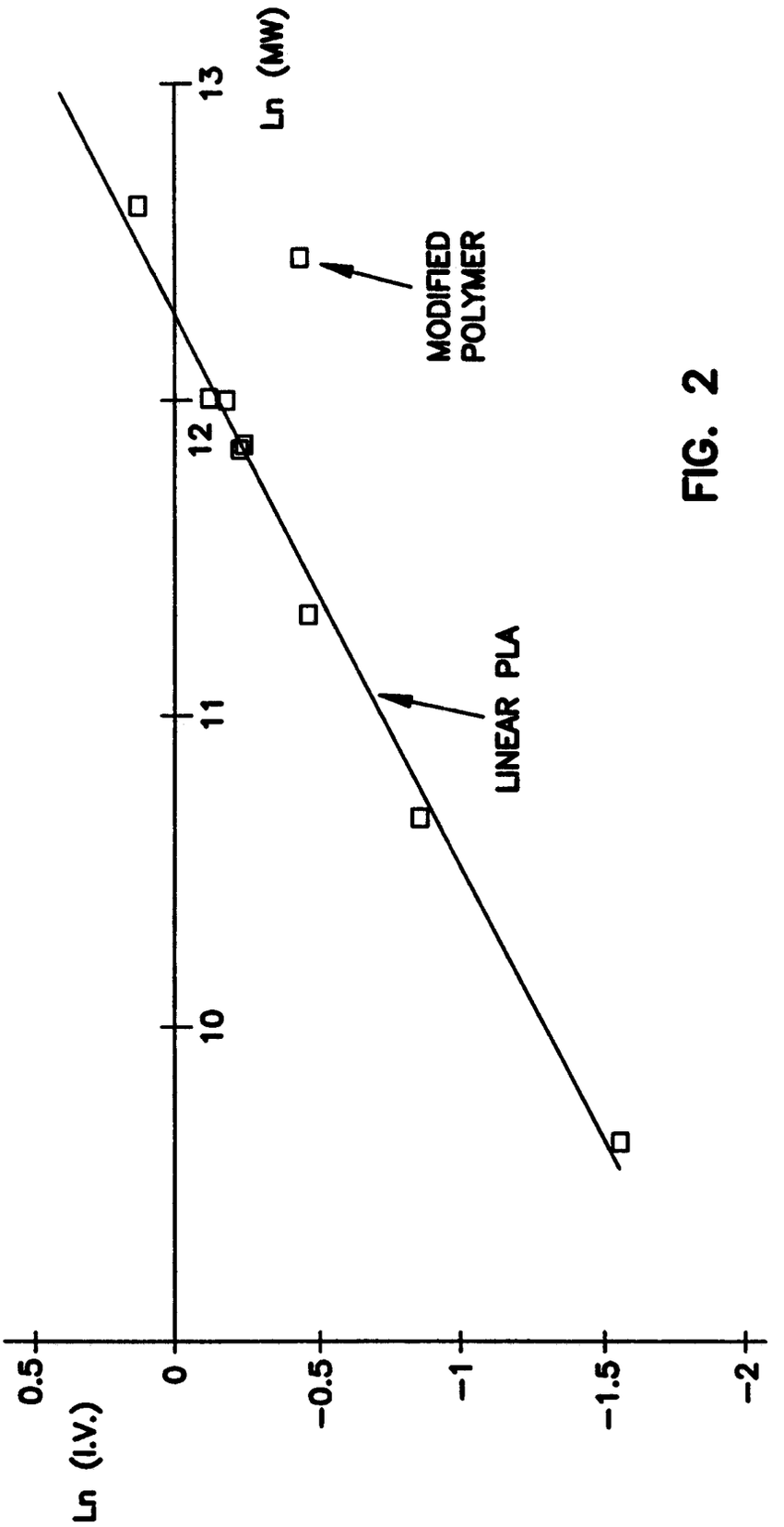

FIG. 2

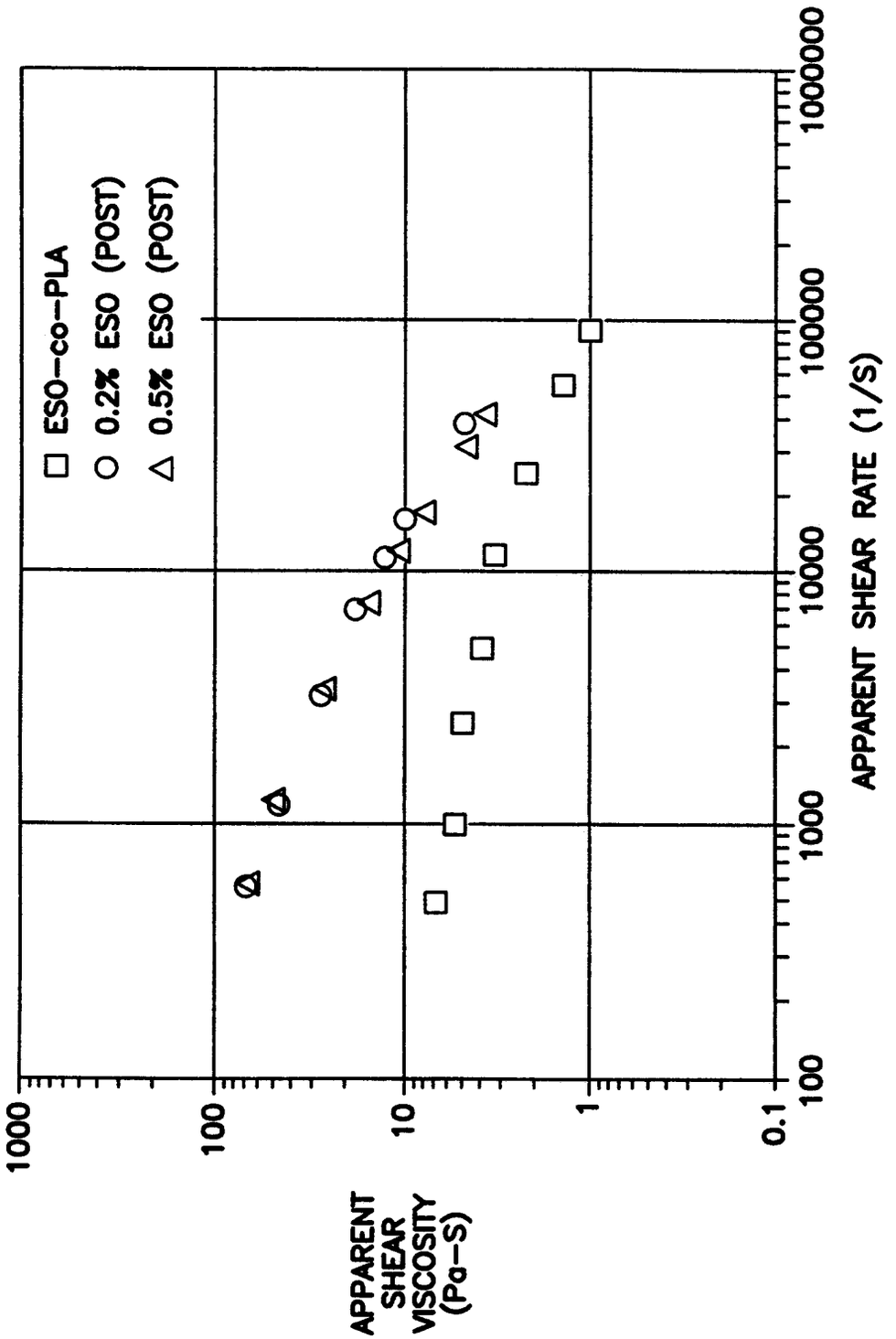
ESO-co-PLA
0.2% ESO (POST)
0.5% ESO (POST)
APPARENT SHEAR VISCOSITY (Pa-S)
1000
100
10
1
0.1
100
1000
10000
100000
1000000
APPARENT SHEAR RATE (1/S)

FIG. 3

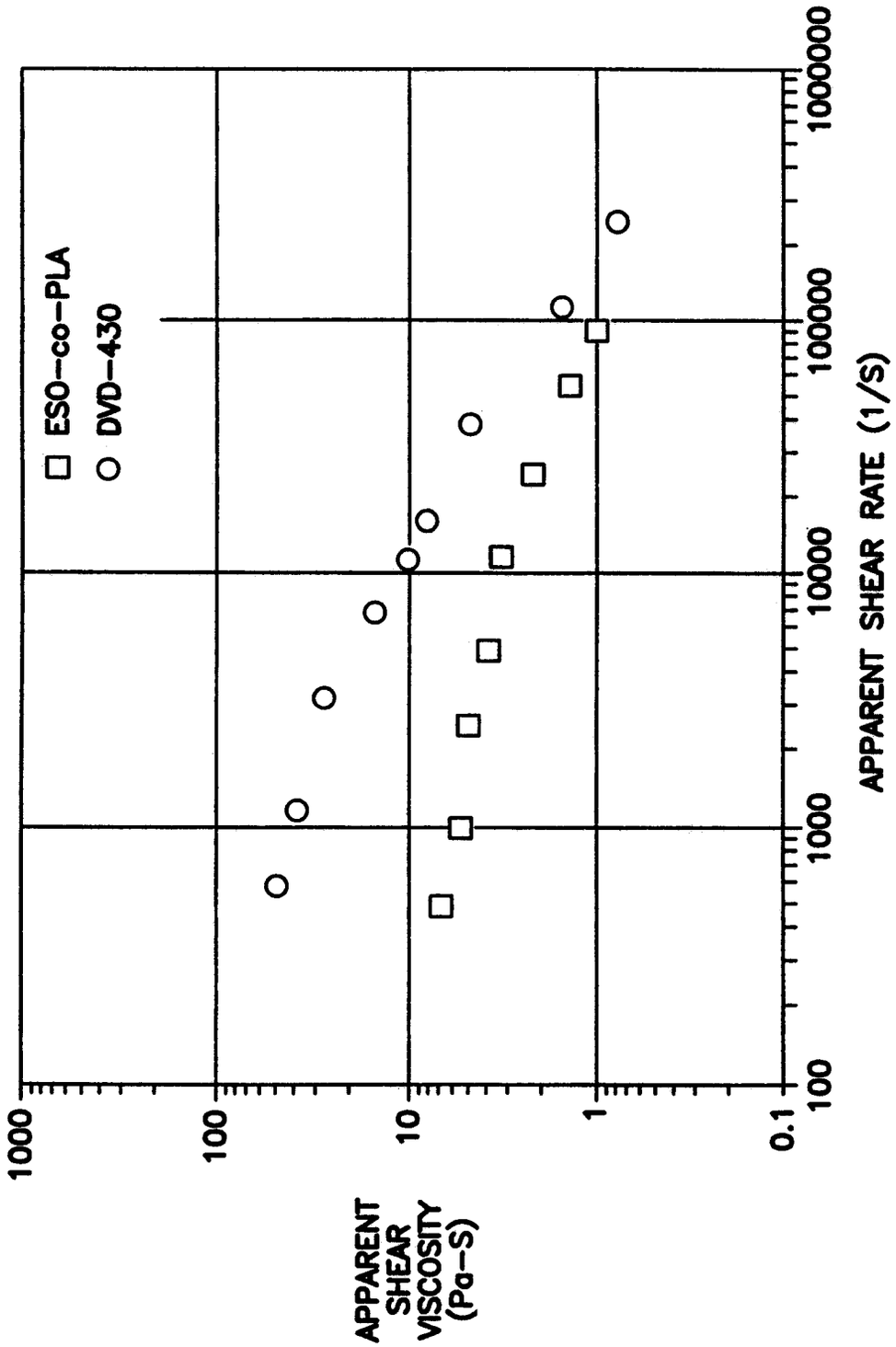
ESO-co-PLA
DVD-430
APPARENT SHEAR VISCOSITY (Pa-S)
1000
100
10
1
0.1
APPARENT SHEAR RATE (1/S)
100
1000
10000
100000
1000000

FIG. 4