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(71) Applicant *(for all designated States except US)*: **DOW GLOBAL TECHNOLOGIES LLC** [US/US]; 2040 Dow Center, Midland, MI 48674 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **PADILLA-ACEVEDO, Angela I.** [CO/US]; Apt. # 1524, 514 That Way, Lake Jackson, TX 77566 (US). **VALETTE, Ludovic** [FR/US]; 708 Oleander, Lake Jackson, TX 77566 (US). **MULLINS, Michael J.** [US/US]; 2217 Sheridan Street, Houston, TX 77030 (US). **VERGHESE, Kandathil E.** [IN/US]; 305 Rosemary Lane, Lake Jackson, TX 77566 (US). **WILSON, Mark B.** [US/US]; 217 Lexington, Clute, TX 77531 (US).

(74) Agent: **PRIETO, Joe**; The Dow Chemical Company, Intellectual Property, P. O. Box 1967, Midland, Michigan 48641-1967 (US).

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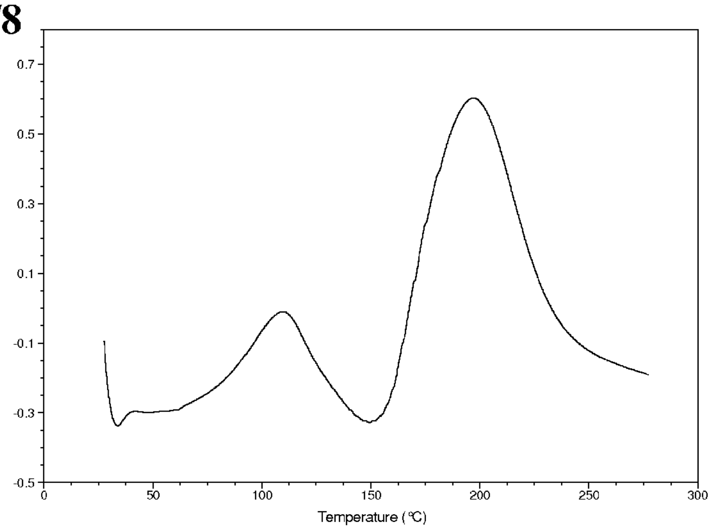

(57) Abstract: A solvent-free curable epoxy resin composition including (a) at least one divinylarene dioxide; and (b) at least one hardener; wherein the solvent-free curable epoxy resin composition is substantially free of solvent and has at least two exotherm peaks and wherein the exothermic peak difference of the two exotherm peaks is sufficient to allow the curable solvent-free epoxy resin composition of being B-staged.

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CURABLE RESIN COMPOSITIONS

FIELD

The present invention relates to a curable resin composition for use in various processes. More specifically, the present invention relates to a B-stageable, solvent-free divinylarene dioxide curable resin composition for use in processes such as for example manufacturing prepregs and laminates.

BACKGROUND

Typically, printed circuit boards are prepared by stacking a plurality of prepregs in various arrangements, followed by pressing at high temperatures (e.g. greater than 170 °C). The prepregs consist of a partially cured curable resin coated onto fiber reinforcement, typically glass. A “partially cured” curable resin is known in the art as a “B-staged” resin. This partial curing or “B-staging,” raises the glass transition temperature (Tg) of the thermoset above ambient temperature (20 °C to 30 °C); whereby the Tg can be from 30 °C to 100 °C so that the prepregs can be rolled up without sticking. When the prepregs are stacked, pressed, and heated to achieve final cure the resin can flow to consolidate the layers before final cure (typically, final cure occurs when the Tg of the composition does not vary by more than 5 °C as measured by differential scanning calorimetry).

The ability to B-stage a resin is essential to the process of manufacturing printed circuit boards. A B-staged resin is a resin which has a portion of its curable moieties reacted for example, anywhere from 1 mol % to 95 mol %, of the resin’s curable moieties; and wherein the “gel point” of the resin has not been reached. (The “gel point” is defined as the point at which a liquid formulation begins to exhibit elastic properties and increased viscosity). The “gel point” of a curable resin is the point along the cure profile at which an infinite network forms. Although further cure can occur, the resin will no longer flow. A B-staged resin can melt and flow during subsequent processing and further heating. During this latter process, called “C-staging” or “final cure”, the resulting thermoset is crosslinked beyond the gel point and will no longer flow. At this C-stage, for example, typically more than 90 mol % of the curable moieties of the resin have reacted.

Typically, a resin formulation used to make prepregs is dissolved in a solvent. This resulting solvent solution is called a “varnish” or “dope”. The solvent is required in a resin formulation because the solvent is used to reduce the viscosity of the resin formulation, for example, below 1 Pa·s such that good fiber wetting (impregnation of the fibers with the resin without the presence of "dry spots" on the fiber) is achieved. When the wetting of the fibers is adequate, the resultant prepregs made from the resin formulation are void-free and the surface of the prepregs is smooth.

After a fiber reinforcement is wetted with a varnish, the wetted fiber reinforcement is usually passed through a ventilated oven to both evaporate the solvent and partially cure (B-stage) the resin. With known processes, it is critical to control the extent of cure during B-staging. For example, if insufficient cure is achieved (e.g., < 20 mol % of the resin's curable moieties are reacted), the resin will flow too much such that the resin does not impregnate the fiber successfully, and instead the resin flows straight through the fibers, leaving the fibers dry during final cure. For example, for the preparation of electrical laminates, the dryness of the fibers is such that the fibers have less than 40 wt % resin at the B-stage. Thus, a part to be pressed having a low resin/fiber ratio, causes the pressed parts to be too thin and valuable resin is lost. For example, in the preparation of electrical laminates, if more than 10 % of the resin is forced beyond the edge of a fiber reinforcement such as a reinforcing fabric, the resin is considered to have too much flow.

On the other hand, if too much cure occurs during B-staging (i.e., the resin is at or past its gel point), the layers of parts to be pressed will not flow together during pressing, which (i) causes poor adhesion between plies (e.g., the plies easily come apart, and no flow of resin is apparent during the curing, and the laminate is not "transparent"); and (ii) causes voids to be formed in the cured product.

As aforementioned, a formulation used to prepare a prepreg material, includes the use of a solvent in the formulation. A significant part of the cost of preparation of prepregs is related to the cost of the solvent, the cost of the energy needed to evaporate the solvent from the prepregs, and the cost of the energy needed to incinerate the solvent vapors before the vapors are released into the environment. Therefore, a formulation and process for making prepregs that do not use a solvent (i.e., a solventless or solvent-free formulation and process) would be beneficial to the industry.

Solvent-free methods for making prepregs have heretofore been described, but none of the known solvent-free methods offer a combination of (i) the use of a low initial resin viscosity (e.g., <10,000 cP mPa-s), and (ii) the ability to B-stage prepregs. Therefore, there continues to be a need for B-staging curable resins for prepreg production in a multistage process without the use of solvent in the B-stageable formulation.

Current B-staging processes include promoting polymerization reaction of part of the resin starting material and suspending the polymerization reaction at an appropriate B-stage. For instance, a polymer composition which is formed in a first stage of curing by combining a base molecule and a linker molecule, results in a prepolymer which still has to be further cured in a second, third or further curing stage. A notable drawback to this process is lack of reproducibility to consistently reach the same B-stage or the same degree of polymerization, especially when a radical polymerization step is required in an overall curing process.

For example, in the aerospace and sporting goods industry, where prepregs are typically made with carbon fibers, a solventless process is used which involves using a hot-melt technique in order to impregnate the fibers with resin. The thickness of the prepreg is finely controlled by using calender rollers. No solvent is used in this process as structural composites made using these prepregs needs to be below a certain void content such as typically, < 1%. The prepreg produced in this manner undergoes very little cure (e.g., < 30% of the reactive moieties) during the prepregging process. The level of tack is controlled primarily by controlling the viscosity of the starting formulation at the prepregging temperature and the storage temperature. The main disadvantage of this type of prepreg is the need to transport the prepreg in refrigerated or cryogenic containers in order to prevent the tacky prepreg from undergoing further cure. Continued cure results in a loss of tackiness as well as causes issues during the subsequent laminate cure. In addition, once the prepreg needs to be used, the prepreg has to be warmed up back up to ambient temperature which adds additional work (and cost) to the process cycle. Most often these prepregs are stacked in specific stacking sequences depending on the design requirements for a specific use; and are cured in an autoclave under heat and pressure. It would therefore be ideal to provide a resin composition that can be used to form a tacky prepreg that is stable at ambient temperature. Typically, a storage stable resin composition includes a B-stageable material that will not continue to significantly crosslink during storage so as to facilitate shipping at ambient temperature.

SUMMARY

One embodiment of the present invention is directed to a solventless composition having a low viscosity (e.g., < 10,000 mPa-s when measured at 25 °C).

Another embodiment of the present invention includes a solventless composition having a cure mechanism that proceeds in two stages, wherein the two stages have substantially different rates. This "de-coupling reaction solventless composition" of the present invention allows for some prepreg process variation without a substantial variation in the final pressed parts.

Still another embodiment of the present invention is directed to a solventless process for preparing prepregs and laminates. The present invention provides the industry with a "more practical approach" to preparing compositions useful for prepreg and laminates.

Yet another embodiment of the present invention is directed to a B-stageable, low viscosity, solvent-free curable epoxy resin composition including a mixture of (a) at least one divinylarene dioxide; and (b) at least one hardener; wherein the solventless curable epoxy resin composition is solvent-free and has at least two exotherm peaks and wherein the exothermic peak difference of the two exotherm peaks is sufficient to allow the solventless curable epoxy resin composition of being B-staged.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention may be illustrated by, but not limited thereto, the drawings herein wherein:

Figure 1 is a thermogram *via* differential scanning calorimetry (DSC) of an example of a solventless composition of the present invention starting with a mixture of divinylbenzene dioxide (DVBDO), diethylene triamine (DETA), and diethyltoluenediamine (DETDA).

Figure 2 is a thermogram *via* DSC of an example of a solventless composition of the present invention starting with a mixture of DVBDO, DETA, and DETDA which has been preheated to 110 °C for 1 hour.

Figure 3 is a thermogram *via* DSC of an example of a solventless composition of the present invention starting with a mixture of DVBDO, DETA and DETDA which has been preheated to 110 °C for 1 hour and heated to 210 °C for 2 hours.

Figure 4 is a thermogram *via* DSC of an example of a solventless composition of the present invention starting with a mixture of DVBDO, bisphenol A and DETDA.

Figure 5 is a thermogram *via* DSC of an example of a solventless composition of the present invention starting with a mixture of DVBDO, DETA, bisphenol A, and a catalyst.

Figure 6 a rheology curve of the viscosity at B-staging of an example of a solventless composition of the present invention starting with a mixture of DVBDO, DETA and DETDA.

Figure 7 is a portion of the rheology curve of Figure 6 showing the first 30 minutes of the curve.

Figure A is a rheology curve of the viscosity at B-staging of an example of a composition starting with a mixture of XZ92530, XZ92535 and 2-phenyl imidazole.

DESCRIPTION

"A-stage" with reference to describing a composition herein, refers to a composition, when prepared, is at an initial point where no reaction has taken place.

"B –stage" with reference to describing a composition, refers to a point where a first reaction of a composition has taken place or for example when a first reaction between an epoxide resin and at least one hardener is complete.

"A-to-B–stage" with reference to describing a composition herein, refers to pre-pregging, or partial curing a curable composition before reaching gellation of the composition.

"B-stageable" with reference to describing a composition herein, refers to a composition that is capable of being B-staged, i.e., a composition that can be put through a prepregging or partial curing process to form a B-stage composition.

"C–stage" with reference to describing a composition herein, refers to a point where all reactions in a composition have reached completion. For example, at this point most of the epoxides present in a curable composition are consumed.

"B-to-C–stage" with reference to describing a composition herein, refers to fully curing a curable composition leading to gellation and to the formation of a cross-linked thermoset.

A "dual-cure technology" or a "dual-cure composition" refers to a composition containing two distinct curing reactions (or "two distinct chemical reactions") that occur at different temperatures. In the present invention, the temperature difference is characterized by the difference between peak exotherms in a differential scanning calorimeter scan. For example, the composition of the present invention is capable of undergoing a B-staging reaction and a C-staging reaction, wherein the B-staging reaction and the C-staging reaction are two distinct chemical reactions.

"Thermally decoupled" herein refers to the ability of a dual-cure composition to be B-staged by heating to a temperature at which only one of two curing reactions occurs.

"Solventless" (also referred to as "solvent-free", "substantially free of solvent" or "absence of solvent") with reference to describing a composition herein means a composition having substantially no solvent concentration or a solvent is absent in the composition except for a possible non-significant amount or trace amount of solvent being present. For example, a "solventless" composition may include a solvent concentration in the composition of less than 2 % of a low-boiling (<150 °C at 1 bar) of a non-reacting component. In addition, a solventless composition may include one or more solutes or components in which the components of the mixture are dissolved.

A "solvent" includes a substance different from the components of the mixture of components making up the curable resin composition of the present invention.

In its broadest scope, the present invention includes a solventless curable (also referred to as thermosetting or crosslinkable) resin composition (also referred to as a system, mixture, or formulation) including (a) at least one divinylarene dioxide; and (b) at least one hardener, wherein the at least one hardener may include for example a first and/or second hardener; and wherein the resin composition comprises a substantial absence of solvent. Optionally, the solventless composition may include (c) at least one other epoxy resin other than and different from the divinylarene dioxide.

In general, the solventless composition of the present invention includes (i) (a)) at least one divinylarene dioxide; and (b) at least one hardener; (ii) (a) at least one divinylarene dioxide; (b) at least one hardener; and (c) at least one epoxy resin other than the divinylarene dioxide; or (iii) (a) at least one divinylarene dioxide; (b) two or more hardeners; and (c) at least one epoxy resin other than the divinylarene dioxide.

For example, in one embodiment, the solventless composition may include the following components: (a) at least one divinylarene dioxide; (b1) at least a first hardener, and (b2) at least a second hardener; and (c) optionally, at least one epoxy resin other than the divinylarene dioxide

In addition, the present invention is directed to a solventless B-stageable, low viscosity epoxy curable resin composition that exhibits at least two distinct exotherm peaks representing at least two distinct chemical reactions, as measured by DSC; wherein the exothermic peak difference of the two exotherm peaks is sufficient to allow the solventless curable epoxy resin composition of being B-staged. In other words, the present invention includes a solventless curable composition that exhibits two different curing mechanisms as shown by the at least two distinct exotherm peaks and the exothermic peak difference of the two exotherm peaks, as measured by DSC.

The two curing mechanisms are essentially two separate epoxy-hardener reactions which take place at two different temperatures – a first low curing temperature (T_1) and a second high curing temperature (T_2), wherein the low temperature T_1 is not equal to the high temperature T_2 and wherein the high temperature T_2 is higher than the low temperature T_1. The low temperature curing reaction at temperature T_1 enables a convenient way to produce a stable prepreg (B-stage), whereas the high temperature curing reaction at temperature T_2 can be useful for the final cure to produce a thermoset network (C-stage).

The exothermic peak difference of the two exotherm peaks exhibited by the solventless composition, may include, for example, exotherms separated by an exothermic peak difference of at least greater than or equal to (≥) 20 °C in one embodiment; at least ≥ 30 °C in another embodiment; and at least ≥ 40 °C in still another embodiment, when measured with a heating rate of 10 °C/minute; and wherein the solventless composition has an initial viscosity of less than 100,000 mPa-s when measured at the processing temperature of the solventless B-stageable composition.

As aforementioned, the present invention provides a solventless curable composition capable of producing a prepreg or a B-staged material which comprises a first composition with a lower curing temperature T_1 and a second composition with a higher curing temperature T_2, where $T_1 \neq T_2$ and $T_2 > T_1$. The "B-stageable curable resin composition" (or "dual-cure formulation") exhibits two distinct ranges of reaction – a first reaction that takes place at a low temperature and a second reaction that takes place at a high temperature. In the present invention, the reactions are "thermally decoupled" by conducting the B-stage prepregging at a lower temperature independently from a final cure taking place at a higher temperature. The ability to thermally decouple the solventless composition results in improved processability of the composition including the use of a wider range of processing conditions such as longer running times in a treater during prepreg manufacturing (running time can be for example ≥ 30 minutes).

In one embodiment, the temperature range where the two different curing mechanisms (the low and high temperature reactions) take place may range generally from 25 °C to 300 °C (temperature ranges measured by DSC). In another embodiment, the range for the exotherm peak separation of the two reactions taking place may be between 30 °C and 150 °C.

Generally, T_1 is greater than or equal to 10 °C and less than T_2 in one embodiment. In another embodiment, T_2 may range between 0 °C and 180 °C; between 10 °C and 150 °C in still another embodiment; and between 20 °C and 120 °C in yet another embodiment.

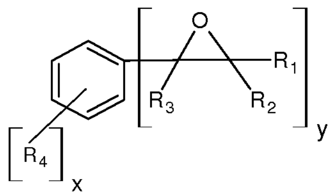
Generally, T_2 is greater than 20 °C and less than 300 °C in one embodiment. In another embodiment, T_2 may range between 80 °C and less than 300 °C; between 120 °C and 250 °C in still another embodiment; and between 150 °C and 200 °C in yet another embodiment.

The solventless dual-cure composition of the present invention that exhibits a decoupling of reactions at two different temperatures may include a dual-cure composition that exhibits a shoulder or an overlap in the partition of exotherms at the A-stage as shown in a DSC scan. In spite of this overlap of exotherm peaks, the reactions are “thermally decoupled” by conducting the B-stage prepregging at a lower temperature independently from a final cure taking place at a higher temperature.

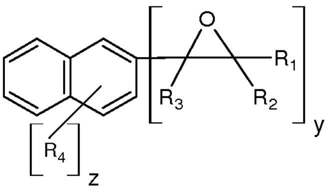
The solventless B-stageable curable resin composition of the present invention advantageously allows the composition to be B-staged *via* “thermal decoupling” of the reactions taking place at two separate and different temperatures T_1 and T_2. Also, advantageously the prepreg is stable after holding for long periods of time at T_1 without the resin reaching gellation (for example, the prepreg may remain stable for ≥ 5 minutes in one embodiment; ≥ 10 minutes in another embodiment; ≥ 20 minutes in still another embodiment; and ≥ 30 minutes in yet another embodiment). These advantageous results of the present invention solventless compositions are an improvement over conventional formulations because conventional formulations can turn from a low viscosity liquid to a gel within minutes such as described in R. B. Roller, *Rheology of Curing Thermoset: A Review*, Polymer Eng. & Sci., 1986, 26 (6), pp. 432-440. Conventional formulations work well for curing processes in which the monomers are converted to a finished part in one step, such as for castings and potting. However, conventional formulations are not suitable for processes that require a B-staged intermediate.

In preparing the solventless curable resin composition of the present invention, the composition may include at least one or more divinylarene dioxide epoxy resins as component (a). For example, the epoxy resin useful as component (a) includes at least one divinylarene dioxide; or two or more different divinylarene dioxides. The divinylarene dioxide useful in the present invention may comprise, for example, any substituted or unsubstituted arene nucleus bearing one or more vinyl groups in any ring position. For example, the arene portion of the divinylarene dioxide may consist of benzene, substituted benzenes, (substituted) ring-annulated benzenes or homologously bonded (substituted) benzenes, or mixtures thereof. The divinylbenzene portion of the divinylarene dioxide may be *ortho*, *meta*, or *para* isomers or any mixture thereof. Additional substituents may consist of H_2O_2-resistant groups including saturated alkyl, aryl, halogen, nitro, isocyanate, or RO– (where R may be a saturated alkyl or aryl). Ring-annulated benzenes may consist of naphthlalene, tetrahydronaphthalene. Homologously bonded (substituted) benzenes may consist of biphenyl, diphenylether.

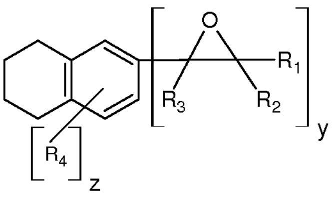
The divinylarene dioxide used for preparing the compositions of the present invention may be illustrated generally by general chemical Structures I-IV as follows:



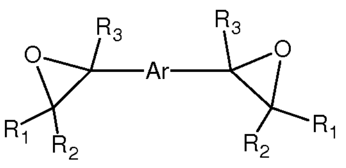
Structure I



Structure II



Structure III



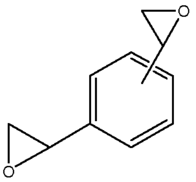
Structure IV

In the above Structures I, II, III, and IV of the divinylarene dioxide comonomer of the present invention, each R_1, R_2, R_3 and R_4 individually may be hydrogen, an alkyl, cycloalkyl, an aryl or an aralkyl group; or a H_2O_2-resistant group including for example a halogen, a nitro, an isocyanate, or an RO group, wherein R may be an alkyl, aryl or aralkyl; x may be an integer of 0 to 4; y may be an integer greater than or equal to 2; x+y may be an integer less than or equal to 6; z may be an integer of 0 to 6; and z+y may be an integer less than or equal to 8; and Ar is an arene fragment including for example, 1,3-phenylene group. In addition, R4 can be a reactive group(s) including epoxide, isocyanate, or any reactive group and Z can be an integer from 0 to 6 depending on the substitution pattern.

In one embodiment, the divinylarene dioxide used in the present invention may be produced, for example, by the process described in U.S. Patent Provisional Application Serial No. 61/141457, filed December 30, 2008, by Marks et al. The divinylarene dioxide compositions that are useful in the present invention are also disclosed in, for example, U.S. Patent No. 2,924,580.

In another embodiment, the divinylarene dioxide useful in the present invention may comprise, for example, divinylbenzene dioxide, divinylnaphthalene dioxide, divinylbiphenyl dioxide, divinyldiphenylether dioxide, and mixtures thereof.

In a preferred embodiment of the present invention, the divinylarene dioxide used in the epoxy resin composition may be for example divinylbenzene dioxide (DVBDO). Most preferably, the divinylarene dioxide component that is useful in the present invention includes, for example, a divinylbenzene dioxide as illustrated by the following chemical formula of Structure V:

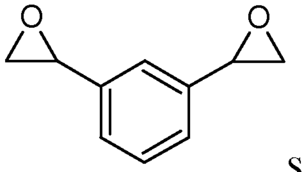


Structure V

The chemical formula of the above DVBDO compound may be as follows: $C_{10}H_{10}O_2$; the molecular weight of the DVBDO is 162.2; and the elemental analysis of the DVBDO is: C, 74.06; H, 6.21; and O, 19.73 with an epoxide equivalent weight of 81 g/mol.

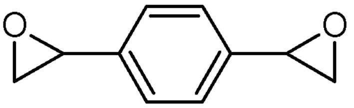
Divinylarene dioxides, particularly those derived from divinylbenzene such as for example divinylbenzene dioxide (DVBDO), are class of diepoxides which have a relatively low liquid viscosity but a higher rigidity and crosslink density than conventional epoxy resins.

Structure VI below illustrates an embodiment of a preferred chemical structure of the DVBDO useful in the present invention:



Structure VI

Structure VII below illustrates another embodiment of a preferred chemical structure of the DVBDO useful in the present invention:



Structure VII

When DVBDO is prepared by the processes known in the art, it is possible to obtain one of three possible isomers: *ortho*, *meta*, and *para*. Accordingly, the present invention includes a DVBDO illustrated by any one of the above Structures individually or as a mixture thereof. Structures VI and VII above show the *meta* (1,3-DVBDO) isomer and the *para* (1,4-DVBDO) isomer of DVBDO, respectively. The *ortho* isomer is rare; and usually DVBDO is mostly produced generally in a range of from 9:1 to 1:9 ratio of *meta* (Structure VI) to *para* (Structure VII) isomers. The present invention preferably includes as one embodiment a range of from 6:1 to 1:6 ratio of Structure VI to Structure VII, and in other embodiments the ratio of Structure VI to Structure VII may be from 4:1 to 1:4 or from 2:1 to 1:2.

In yet another embodiment of the present invention, the divinylarene dioxide may contain quantities (such as for example less than 20 wt %) of substituted arenes. The amount and structure of the substituted arenes depend on the process used in the preparation of the divinylarene precursor to the divinylarene dioxide. For example, divinylbenzene prepared by the dehydrogenation of diethylbenzene (DEB) may contain quantities of ethylvinylbenzene (EVB) and DEB. Upon reaction with hydrogen peroxide, EVB produces ethylvinylbenzene monoxide while DEB remains unchanged. The presence of these compounds can increase the epoxide equivalent weight of the divinylarene dioxide to a value greater than that of the pure compound but can be utilized at levels of 0 to 99 % of the epoxy resin portion.

In one embodiment, the divinylarene dioxide, for example DVBDO, useful in the present invention comprises a low viscosity liquid epoxy resin. The viscosity of the divinylarene dioxide used in the present invention ranges generally from 0.001 Pa s to 0.1 Pa s, preferably from 0.01 Pa s to 0.05 Pa s, and more preferably from 0.01 Pa s to 0.025 Pa s, at 25 °C.

The concentration of the divinylarene oxide used in the solventless compositions of the present invention as the epoxy component may range generally from 0.5 weight percent (wt %) to 100 wt%, preferably, from 1 wt % to 99 wt %, more preferably from 2 wt % to 98 wt %, and even more preferably from 5 wt % to 95 wt % depending on the fractions of the other ingredients in the reaction product composition.

One advantageous property of the divinylarene dioxide useful in the present invention is its rigidity. The rigidity property of the divinylarene dioxide is measured by a calculated number of rotational degrees of freedom of the dioxide excluding side chains using the method of Bicerano described in *Prediction of Polymer Properties*, Dekker, New York, 1993. The rigidity of the divinylarene dioxide used in the present invention may range generally from 6 to 10, preferably from 6 to 9, and more preferably from 6 to 8 rotational degrees of freedom.

The concentration of the divinylbenzene dioxide useful for making the composition will depend on the other ingredients added to the composition, however in general, the concentration of the DVBDO is between 1 wt % to 99 wt %, preferably between 5 wt % to 90 wt %, and most preferably between 7 wt % to 60 wt % based on the weight of the total composition.

In one embodiment of the solventless composition of the present invention, divinylbenzene dioxide as the epoxy resin component is used in a concentration of 20 wt % to 80 wt % based on the weight of the total reaction product composition.

In a broad scope of the present invention, at least one hardener is used in the solventless composition of the present invention and in one embodiment two or more hardeners (also referred to as curing agents or cross-linkers) are used in the composition of the present invention. For example, at least a first hardener, component (b1), and at least a second hardener, component (b2), may be used in the composition. Both the first hardener and the second hardener may be any hardener known in the art which is appropriate for curing epoxy resins, with the proviso that the first hardener is different from the second hardener.

The hardeners of choice used in the present invention may depend on the application requirements. Generally, the first and/or second hardeners useful in the present invention may be selected from, for example, but are not limited to, dicyandiamide, substituted guanidines, phenolic, amino, benzoxazine, anhydrides, amido amines, polyamides, polyamines, aromatic amines, carbodiimides, polyesters, polyisocyanates, polymercaptans, urea formaldehyde and melamine formaldehyde resins, and mixtures thereof.

In one embodiment, at least one hardener, component (b), may include one or more of aliphatic amines such as ethanolamine, ethylenediamine, diethylenetriamine (DETA), triethyleneaminetetramine (TETA), 1-(o-tolyl)-biguanide, dicyandiamide, amine-terminated polyols, aromatic amines such as methylenedianiline (MDA), toluenediamine (TDA), diethyltoluenediamine (DETDA), diaminodiphenylsulfone (DADS), polyphenols such as bisphenol A, bisphenol F, 1,1-bis(4-hydroxyphenyl)-ethane, hydroquinone, resorcinol, catechol, tetrabromobisphenol A, novolacs such as phenol novolac, bisphenol A novolac, hydroquinone novolac, resorcinol novolac, naphthol novolac, mercaptans such as mercaptan-terminated polysulfide polymers, Capcure (trademark of Cognis) hardeners, anhydrides such as phthalic anhydride, trimellitic anhydride, nadic methyl anhydride, methyl tetrahydrophthalic anhydride, methyl hexahydrophthalic anhydride; and mixtures thereof.

In another embodiment wherein the solventless curable composition of the present invention contains two different hardeners, i.e. wherein the first hardener does not equal the second hardener, the first hardener, component (b1), may include for example DETA, amino ethyl piperazine (AEP), Jeffamine EDR 176, amine terminated polybutadiene (ATPB), and mixtures thereof. In this embodiment, the second hardener, component (b2), may include DETDA, 1-(o-tolyl)-biguanide, bisphenol A, a hardener available commercially as Rezicure 3000, and mixtures thereof.

In the solventless curable composition of the present invention containing two different hardeners, i.e. wherein the first hardener does not equal the second hardener, the molar ratio of hardeners used in the composition may range generally from 0.01 wt % to 100 wt % in one embodiment; and from 100 wt % to 0.01 wt % in another embodiment, based on the weight of the composition ingredients.

In preparing the solventless curable resin composition of the present invention, the composition may include, as an optional component, one or more epoxy resins well known in the art, in combination with the divinylarene dioxide component described above. Epoxy resins are those compounds containing at least one vicinal epoxy group. The epoxy resin may be saturated or unsaturated, aliphatic, cycloaliphatic, aromatic or heterocyclic and may be substituted. The epoxy resin may also be monomeric or polymeric. The epoxy resin useful in the present invention may be selected from any known epoxy resins in the art. An extensive enumeration of epoxy resins useful in the present invention is found in Lee, H. and Neville, K., *Handbook of Epoxy Resins*, McGraw-Hill Book Company, New York, 1967, Chapter 2, pages 257-307.

The epoxy resins, used in embodiments disclosed herein with component (a) of the present invention, may vary and include conventional and commercially available epoxy resins, which may be used alone or in combinations of two or more. In choosing epoxy resins for the solventless compositions disclosed herein, consideration should not only be given to properties of the final product, but also to viscosity and other properties that may influence the processing of the resin composition.

For example, in one embodiment of the present invention, the composition may include a four-component system, for example, a composition comprising two different epoxides, wherein at least one of the epoxides is a divinylarene dioxide, and two different hardeners. For example, the composition may include a divinylarene dioxide as the first epoxy resin in combination with a conventional liquid epoxy resin as the second epoxy resin. In another embodiment, a liquid epoxy resin, other than D.E.R 383, such as DEN 438, may be used to decrease the amount of divinylarene oxide needed for the composition.

In another embodiment, the epoxy resin or resins used with divinylarene dioxide of the composition may be selected from epoxy resins that have a dual role of being a reactant and a reactive diluent. By the using this type of epoxy resin, the present invention composition addresses the problems of prior art compositions requiring a solvent. The present invention composition does not require a solvent and therefore a solvent-removal process to remove the solvent from the composition is also not required during the preparation of the varnish to the final stage when the end thermoset is obtained.

Particularly suitable epoxy resins known to the skilled artisan useful in the present invention are based on reaction products of polyfunctional alcohols, phenols, cycloaliphatic carboxylic acids, aromatic amines, or aminophenols with epichlorohydrin. A few non-limiting embodiments include, for example, bisphenol A diglycidyl ether, bisphenol F diglycidyl ether, resorcinol diglycidyl ether, and triglycidyl ethers of para-aminophenols. Other suitable epoxy resins known to the skilled worker include reaction products of epichlorohydrin with o-cresol and, respectively, phenol novolacs. It is also possible to use a mixture of two or more epoxy resins.

The epoxy resin useful in the present invention for the preparation of the epoxy resin composition may be selected from commercially available products. For example, D.E.R.® 331, D.E.R.332, D.E.R. 334, D.E.R. 580, D.E.N.® 431, D.E.N. 438, D.E.R. 736, or D.E.R. 732 available from The Dow Chemical Company may be used. As an illustration of the present invention, the epoxy resin component (a) may be a liquid epoxy resin, D.E.R. 383 (diglycidyl ether of bisphenol A) having an epoxide equivalent weight of 175-185, a viscosity of 9.5 Pa-s and a density of 1.16 g/cc. Other commercial epoxy resins that can be used for the epoxy resin component can be D.E.R. 330, D.E.R. 354, or D.E.R. 332.

Other suitable epoxy resins useful as component (b) are disclosed in, for example, U.S. Patent Nos. 3,018,262.7,163,973, 6,887,574, 6,632,893, 6,242,083, 7,037,958, 6,572,971, 6,153,719, and 5,405,688, PCT Publication WO 2006/052727; U.S. Patent Application Publication Nos. 20060293172, 20050171237, 2007/0221890 A1.

The solventless curable resin composition of the present invention may include at least one catalyst to facilitate the reaction of the epoxy resin compound with the hardener. The catalyst useful as an optional component in the composition of the present invention may include catalysts well known in the art, such as for example, catalyst compounds containing amine, phosphine, heterocyclic nitrogen, ammonium, phosphonium, arsonium, sulfonium moieties, and any combination thereof. Some non-limiting examples of the catalyst of the present invention may include, for example, ethyltriphenyl-phosphonium; benzyltrimethylammonium chloride; heterocyclic nitrogen-containing catalysts described in U.S. Patent No. 4,925,901; imidazoles; triethylamine; and any combination thereof.

The selection of the catalyst useful in the present invention is not limited to any particular catalyst; and commonly used catalysts for epoxy compositions can be used. Also, the addition of a catalyst to the solventless composition of the present invention may depend on the composition prepared. For example, the catalyst may include tertiary amines, imidazoles, organo-phosphines, acid salts, and mixtures thereof.

In one embodiment, the catalyst may include tertiary amines such as, for example, triethylamine, tripropylamine, tributylamine, benzyldimethylamine, 2-methylimidazole, 1-benzyl-2-methyl imidazole, 2-phenyl imidazole, mixtures thereof.

The concentration of the optional catalyst used in the present invention may be less than 10 wt %; and generally from 0.01 wt % to 10 wt % in one embodiment, from 0.1 wt % to 5 wt % in another embodiment, from 0.2 wt % to 3 wt % in still another embodiment, and from 0.5 wt % to 2 wt % in yet another embodiment. Lower concentrations of catalyst typically do not provide sufficient catalytic effect, resulting in too slow reactivity of the compositions. Higher concentrations of catalyst typically result in too high reactivity of the compositions.

In one embodiment, the composition of the present invention will not typically contain a catalyst; however, when the curable composition of the present invention includes a catalyst as a component, the catalyst may be an organic acid catalyst; a Lewis acid catalyst; a polymer supported (polymeric beads) Lewis acid catalyst; or mixtures thereof.

A filler may be added to the present solventless composition to improve thermomechanical properties such as modulus, fracture toughness, and CTE of the cured product. For example, the solventless composition may include one or more optional functional or non-functional fillers such as for example, fused silica, natural silica, synthetic silica, natural aluminum oxide, synthetic aluminum oxide, hollow fillers, aluminum trihydroxide, aluminum hydroxide oxide, boron nitride, silicon carbide, mica, aluminum powder, zinc oxide, silver, graphite, aluminum nitride, mullite, gold, carbon, carbon nanotubes, graphene, glass fibers/sheets, carbon fibers, or other organic or inorganic particulate filler, either added into the composition in their end state or formed *in-situ*. Silica, whether fused, natural or synthetic, is a one preferred embodiment of a filler used in the composition of the present invention.

The surface of the fillers may optionally be treated to improve filler and polymer interaction. For example, the fillers utilized in the present invention may optionally be surface treated either before incorporation into the solventless composition, or *in-situ,* during the compounding of the composition. Examples of surface treatments include fatty acids, silane coupling agents, titanates, zirconates or silazane compounds.

The acceptable particle size of the filler material generally may range from nano to conventional micro size. For example, the particle size of the filler may be in the range of from 0.0005 μm to 500 μm, preferably from 0.100 μm to 100 μm, and more preferably from 0.01 μm to 30 μm.

Acceptable filler morphologies include, but are not limited to, platelet, fibrous, spherical, needle, amorphous or any combination thereof. Fillers with different size and different shape may be combined to have a synergistic effect on coefficient of thermal expansion, modulus, electrical and / or heat conductivity.

Filler loadings useful in the present invention may vary. The concentration of the filler is generally from 0 wt % to 99 wt % in one embodiment, from 0.1 wt % to 95 wt % in another embodiment, from 10 wt % to 90 wt % in still another embodiment, and from 50 wt % to 80 wt % in yet another embodiment, based on the weight of the solids in the composition. Volumetric loadings of the fillers can range from 0 vol % to 90 vol % in one embodiment, from 0.1 vol % to 90 vol % in another embodiment, from 0.1 vol % to 85 vol % in still another embodiment, from 0.1 vol % to 85 vol % in yet another embodiment, from 1 vol % to 85 vol % in yet one other embodiment and from 1 vol % to 70 vol % in still one more embodiment, depending on the desired properties.

It is well-known that high filler loadings required in conventional epoxy-based compositions provide many technical challenges, such as greatly increasing the viscosity of the underfill compositions, reducing the flowability of the compositions between an electronic component and a substrate, and requiring higher application temperatures. The ever shrinking pitch size of solder bumps and bonding pads compounds this difficulty. It has been found that the present underfill compositions exhibit low viscosity and excellent flowability even with relatively high filler loadings. Specifically, the present invention provides a composition including a divinylarene diepoxide, a hardener, and a filler, wherein the composition has a viscosity of from 0.005 Pa-s to 100 Pa-s at 25 °C when the filler is present in an amount of 1 vol % to 70 vol %, based on the total volume of the composition. Preferably, the composition has a viscosity of from 0.01 Pa-s to 25 Pa-s at 25 °C, and more preferably from 0.01 Pa-s to 10 Pa-s at 25 °C, when the filler is present in an amount of 1 vol % to 70 vol %. In a particularly preferred embodiment, the composition has a viscosity of from 0.005 Pa-s to 1 Pa-s at 25 °C when the filler is present in an amount of 50 vol % to 70 vol%. It is preferred that in such composition the divinylarene diepoxide is divinylbenzene dioxide. A further advantage of the present underfill composition is that they can be applied at or near room temperature, which is significantly lower than conventional underfill compositions.

The compositions of the present invention advantageously may use a wide array of hardeners and the composition allows more choices of fillers, such as nano fillers, than conventional compositions, thus the formulating options of the present compositions are broadened. The present compositions also have low (for example, less than 5 ppm) to no total halides. In addition, because the present compositions also allow high filler loading, the compositions can achieve lower CTE (for example less than 30 ppm/°C below the Tg) or better thermal conductivity (for example, greater than 1.0 W/mK) at the same flow rate during application or better flow rate at same CTE or heat conductivity.

Other optional components that may be useful in the present invention are components normally used in resin compositions known to those skilled in the art. For example, the optional components may comprise compounds that can be added to the solventless composition to enhance application properties (e.g. surface tension modifiers or flow aids), reliability properties (e.g. adhesion promoters) the reaction rate, the selectivity of the reaction, and/or the catalyst lifetime.

An assortment of additives may be added to the solventless composition of the present invention including for example, flame retardants, toughening agents, diluents; stabilizers; plasticizers; catalyst de-activators; halogen containing or halogen free flame retardants; a synergist to improve the performance of the flame extinguishing ability such magnesium hydroxide, zinc borate, or metalocenes; and mixtures thereof.

The concentration of the additives used in the present invention may range generally from 0 wt % to 90 wt % in one embodiment, from 0.01 wt % to 80 wt % in another embodiment, from 0.1 wt % to 70 wt % in still another embodiment, and from 0.5 wt % to 60 wt % in yet another embodiment.

In another embodiment, the concentration of the additives used in the present invention may range generally from 15 wt % to 12 wt %, from 12 wt % to 10 wt % in another embodiment, from 10 wt % to 8 wt % in still another embodiment, and from 8 wt % to 6 wt % in yet another embodiment.

In one embodiment, when the curable composition of the present invention includes other additives as a component, the additive may be, for example, a flame retardant and fillers that provide flame retardancy; a toughening agent; at least one reinforcement material such as glass fibers or carbon fibers; a filler such as talc, calcium carbonate, silica or alumina; a thermally and/or electrically conductive material such as silver, graphite, carbon nanotubes, or boron nitride; and mixtures thereof. When a flame retardant is used in the composition, the cure thermoset can show a high level of flame retardancy characterized by UL94 V-2 ranking in one embodiment, a UL94 V-1 ranking in another embodiment, and a UL94 V-0 ranking in still another embodiment.

In one embodiment, a composition may contain a latent catalyst to lower the activation energy for the reaction of the second hardener with the second epoxide accompanied by the required decoupling of the reactions. “Activation energy” is the minimum amount of energy required to initiate a reaction.

In another embodiment, a composition of the present invention may be prepared with the appropriate compounds such that the composition is capable of providing a tacky prepreg at ambient temperature and then is capable of being stored stable at ambient temperature until such time the composition is cured into a laminate at an elevated temperature.

In a preferred embodiment, the composition of the present invention includes at least one reinforcement material to form a prepreg and/or a laminate. The reinforcement material can include for example glass fibers, carbon fibers, or mixtures thereof.

In the process of preparing a laminate one or more prepregs produced in accordance with the present invention are stacked followed by heat pressing the stack of prepregs to form a laminate.

In one embodiment, the solventless composition of the present invention may include a three-component composition, for example, a composition comprising a divinylarene dioxide, an epoxide different from the divinylarene dioxide, and a hardener. For example, the composition may include a divinylarene dioxide component (a); and a hardener component (b); and (c) an epoxy resin different from the divinylarene dioxide, wherein the epoxy resin component (c) may comprise for example any of the optional epoxy resins described above

In another embodiment, the composition of the present invention may include a three-component composition, for example, a composition comprising a divinylarene dioxide and two different hardeners. For example, the composition may include a divinylarene dioxide component (a); and a hardener component (b) comprising (b1) a first hardener and (b2) a second hardener, wherein the first hardener and the second hardener each separately and individually may comprise for example two different hardeners selected from the hardeners described above; and an epoxide different from the divinylarene dioxide.

In still another embodiment, the composition of the present invention may include a four-component composition, for example, a composition comprising a divinylarene dioxide, an epoxide different from the divinylarene dioxide, and two different hardeners. For example, the composition may include a divinylarene dioxide component (a); a hardener component (b) comprising (b1) a first hardener and (b2) a second hardener, wherein the first hardener and the second hardener each separately and individually may comprise for example two different hardeners selected from the hardeners described above; and (c) an epoxy resin different from the divinylarene dioxide, wherein the epoxy resin component (c) may comprise for example any of the optional epoxy resins described above.

In the embodiment wherein at least two hardeners (a first hardener and a second hardener) are used, the molar ratio of the first hardener to the second hardener may be from 0.001 to 1000. In the curable composition of the present invention containing two different hardeners, i.e. wherein the first hardener does not equal the second hardener, the molar ratio of hardeners used in the composition may range generally from 0.01 wt % to 100 wt % in one embodiment; and from 100 wt % to 0.01 wt % in another embodiment, based on the weight of the composition ingredients.

In the embodiment wherein at least two epoxy resins are used, such as for example, wherein the composition includes a divinylarene dioxide as the first epoxy resin in combination with bisphenol A diglycidyl ether or epoxy novolac as the second epoxy resin; the viscosity of at least one of the epoxy resins used may be between 1 mPa-s and 100,000 mPa-s, between 5 mPa-s and 50,000 mPa-s in another embodiment, between 10 mPa-s and 10,000 mPa-s in still another embodiment, and between 10 mPa-s and 1,000 mPa-s in yet another embodiment, at ambient temperature.

In general, the process for preparing the solventless curable epoxy resin composition of the present invention includes for example (i) admixing or blending (a) at least one divinylarene dioxide; and (b) at least one hardener; (ii) admixing or blending (a) at least one divinylarene dioxide; and (b) two or more hardeners; or (iii) admixing or blending (a) at least one divinylarene dioxide; (b) two or more hardeners; and (c) at least one epoxy resin different from the divinylarene dioxide. For example, in one embodiment, the composition may include (a) at least one divinylarene dioxide; (b1) at least a first hardener, and (b2) at least a second hardener.

In preparing the solventless composition of the present invention, various optional compounds may be added to the composition, such as for example, a solvent, a cure catalyst: and/or other ingredients as needed. For example, the preparation of the solventless curable epoxy resin composition of the present invention is achieved by blending with or without vacuum in a Ross PD Mixer (Charles Ross), divinylbenzene dioxide, a hardener, a filler, a catalyst, and optionally any other desirable additives. Any of the above-mentioned optional assorted composition additives, for example an additional epoxy resin, may also be added to the composition during the mixing or prior to the mixing to form the composition.

All the components of the solventless curable epoxy resin composition are typically mixed and dispersed at a temperature enabling the preparation of an effective epoxy resin composition having the desired balance of properties for prepregs and laminates applications. For example, the mixing temperature used in the present invention may be generally at or below the B-staging temperature. In one embodiment, the temperature of mixing may be at least 10 °C below the B-staging temperature, and 20 °C below the B-staging temperature in another embodiment. In still another embodiment, the temperature during the mixing of all components may be generally from 20 °C to 100 °C and from 25 °C to 90 °C in yet another embodiment. Lower mixing temperatures help to minimize reaction of the resin and hardener components to maximize the pot life of the composition.

In one embodiment wherein at least two hardeners are used in the composition, the components are mixed at ambient temperature. For example, when the composition is solvent free, and a solid first hardener is used, the solid compound may first be dissolved in the epoxy used, below curing temperature, and then the solution may be cooled to ambient temperature. In this embodiment, a second hardener that may start reacting at ambient temperature may be added to the solution containing the dissolved first hardener.

Generally, the solventless curable composition of the present invention advantageously has no solvent present in the composition or the composition has very little amount of solvent which is present because the solvent is introduced into the composition with the other compounds used in the composition. As aforementioned, “solventless” with reference to describing a composition herein means a composition having substantially no solvent concentration or a solvent is absent in the composition except for a possible non-significant amount or trace amount of solvent being present. Accordingly, a “solventless” composition may include a non-detrimental amount of solvent concentration in the composition; however, the solvent concentration is less than 10 percent by weight in one embodiment; less than 5 weight percent in another embodiment; less than 2 weight percent in still another embodiment; less than 1 weight percent in yet another embodiment; and less than 100 ppm in still one other embodiment.

Generally, the solventless curable composition of the present invention advantageously has a low viscosity. By "low viscosity" with reference to the solventless curable composition of the present invention, it is meant that the composition has a viscosity of less than 100,000 mPa-s under processing conditions of the B-stageable composition in one embodiment; and less than 50,000 mPa-s under processing conditions of the B-stageable composition in another embodiment. For example, the viscosity of the curable composition of the present invention generally may be in the range of from 10 mPa-s to less than 100,000 mPa-s in one embodiment; from 100 mPa-s to less than 50,000 mPa-s in another embodiment; from 100 mPa-s to 10,000 mPa-s in still another embodiment; from 100 mPa-s to less than 5,000 mPa-s in yet another embodiment; from 100 mPa-s to less than 2,000 mPa-s in still one other embodiment; and from 100 mPa-s to less than 1,000 mPa-s in yet one other embodiment; wherein the viscosity is measured under the processing conditions of the B-stageable composition such as for example at ambient temperature.

The solventless B-stageable curable resin composition of the present invention generally is processed *via* thermal cure. For example, the curing of the solventless curable composition may be carried out at a predetermined temperature and for a predetermined period of time sufficient to partially cure the composition with the first hardener to produce a B-staged material. For example, the temperature of partially curing the composition may be generally from 0 °C to 180 °C in one embodiment; from 10 °C to 150 °C in another embodiment; and from 20 °C to 120 °C in still another embodiment; and the partial curing time may be chosen between 1 minute to 24 hours in one embodiment, between 2 minutes to 2 hours in another embodiment, and between 3 minutes to 1 hour in still another embodiment. After the first partial curing of the composition, a B-staged material is formed.

In another embodiment, the partial curing of the solventless curable composition may be carried out at a predetermined temperature of for example, generally from ambient temperature to 100 °C in one embodiment; from 25 °C to 50 °C in another embodiment; and from 25 °C to 100 °C in still another embodiment. The predetermined period of time to partially cure the solventless composition may be chosen between 10 minutes to a few days in one embodiment, between 20 minutes to 48 hours in another embodiment, between 30 minutes to 2 hours in still another embodiment; and between 30 minutes to 1 hour in yet another embodiment. After the first partial curing of the composition, a B-staged material is formed.

In one embodiment a B-staged material is produced by partially curing a solventless composition of the present invention wherein the curable moieties (e.g., epoxy functionalities) of the resin composition have been consumed, i.e. have been reacted. For example, generally from 1 mol % to 95 mol % of the resin's curable moieties have reacted in one embodiment, from 10 mol % to 80 mol % of the resin's curable moieties have reacted in another embodiment, and from 20 mol % to 70 mol % of the resin's curable moieties have reacted in still another embodiment.

In one preferred embodiment, a B-staged material is prepared from the composition of the present invention by partially curing a curable epoxy resin composition. For example, B-staging the composition includes partially curing the composition such that from 10 percent to 80 percent of the epoxy functionalities of the curable epoxy resin composition are consumed.

The continued curing of the solventless curable composition may be carried out at a predetermined temperature and for a predetermined period of time sufficient to completely cure the composition with the second hardener. For example, the temperature of second curing step of the composition may be generally from 80 °C to 300 °C in one embodiment; from 120 °C to 250 °C in another embodiment; and from 150 °C to 200 °C in still another embodiment; and the complete curing time may be chosen between 1 minute to 24 hours in one embodiment, between 2 minutes to 6 hours in another embodiment, and between 5 minutes to 2 hours in still another embodiment.

At the C-stage of a solventless resin composition of the present invention, generally more than 70 mol % of the curable moieties of the resin composition have been reacted in one embodiment, more than 80 mol % of the curable moieties have reacted in another embodiment, and more than 90 mol % of the curable moieties of the resin have reacted.

In another embodiment, the continued curing of the solventless curable composition may be carried out at a predetermined temperature of for example, generally from 50 °C to 220 °C in one embodiment; from 50 °C to 150 °C in another embodiment;

and from 100 °C to 150 °C in still another embodiment. In addition, predetermined period of time to completely cure the solventless composition may be chosen between 5 minutes to 4 hour in one embodiment, between 10 minutes to 2 hours in another embodiment, and between 30 minutes to 1 hour in still another embodiment.

As an illustration of one embodiment of the solventless composition of the present invention, the divinylarene dioxide used in the solventless composition may be a divinylbenzene dioxide (DVBDO). The DVBDO may be used as the sole resin in the composition of the present invention to form the epoxy matrix in the final composition; or the DVBDO resin may be used in combination with an epoxy resin such as any of the aforementioned optional conventional epoxy resins for example diglycidyl ether of bisphenol A or epoxy novolac to prepare the final composition. For example an epoxy resin may be used as an additive diluent. The use of DVBDO imparts improved properties to the curable composition and the final cured product over conventional glycidyl ether, glycidyl ester or glycidyl amine epoxy resins. The DVBDO's unique combination of low viscosity in the uncured state, and high Tg after cure due to the rigid DVBDO molecular structure and increase in cross-linking density, enables a formulator to apply new composition strategies.

In another embodiment, the solventless composition may include DVBDO and at least two different hardeners, wherein the composition is capable of being B-staged. In this embodiment, each of the two different hardeners contain an amine functionality; and wherein the exotherm peak difference (measured by DSC with a heating rate of 10 °C /minute) can be ≥ 10 °C in one embodiment, ≥ 20 °C in another embodiment, ≥ 30 °C in still another embodiment, and ≥ 60 °C in yet another embodiment.

In still another embodiment, the solventless composition may include DVBDO and at least two different hardeners wherein one of the hardeners contains an amine functionality and the other hardener contains a phenol functionality; and wherein the peak exotherm peak difference can be ≥ 10 °C in one embodiment, ≥ 20 °C in another embodiment, ≥ 30 °C still another embodiment, and at least ≥ 40 °C in yet another embodiment, when measured by DSC with a heating rate of 10 °C/minute.

In one embodiment of the present invention includes at least one hardener, component (b), includes at least a first hardener and at least a second hardener different from the first hardener; wherein the curable resin composition undergoes at least two different curing mechanisms which take place at two different temperatures – one curing mechanism or reaction occurring at a first temperature comprising a low curing temperature

T_1 and another curing mechanism occurring at a second temperature comprising a high curing temperature T_2, wherein T_1 is not the same as T_2 and T_2 is greater than T_1; such that the solventless curable resin composition exhibits two distinct exotherms. In this embodiment, the two distinct exotherms are sufficient to allow the solventless curable resin composition of being B-staged at least once at the first low temperature. In addition, the first and second hardeners have an exotherm peak difference separated by at least greater than or equal to (≥)10 °C in one embodiment; ≥ 20 °C in another embodiment; and ≥ 30 °C in still another embodiment, as measured by DSC with a heating rate of 10 °C/minute.

In general, the solventless curable resin composition has an initial viscosity of less than 10,000 mPa-s in one embodiment, < 5,000 mPa-s in another embodiment, < 2,000 mPa-s in still another embodiment, and < 1,000 mPa-s in yet another embodiment when measured at ambient temperature.

The exotherm peak difference when measured by differential scanning calorimetry with a heating rate of 10 °C/minute, of the solventless composition of the present invention, is at least greater than or equal to 30 °C in one embodiment; and greater than or equal to 40 °C in another embodiment. The exotherm peak difference when measured by differential scanning calorimetry with a heating rate of 10 °C/minute, of the solventless composition of the present invention, is from 20 °C to 180 °C in one embodiment; from 30 °C to 150 °C in another embodiment; and from 80 °C to 100 °C in still another embodiment.

In one preferred embodiment, the present invention provides a solventless curable composition that is capable of producing a prepreg or a B-staged material comprised of a first composition with a low first curing temperature T_1 and a second composition with a high second curing temperature T_2, where T_1 is different than T_2 and T_2 is greater than T_1. In the present invention, a "B-stageable curable resin composition" or "dual-cure composition" refers to a composition containing two distinct ranges of reaction. That is, a reaction that takes place at a low temperature and a reaction that takes place at a high temperature. In the present invention composition, the reactions are "thermally decoupled" by conducting the B-stage prepregging at a lower temperature independently from a final cure taking place at a higher temperature. This results in improved processability including a wider range of processing conditions such as longer (where running time can be ≥ 30 minutes) running times in a treater during prepreg manufacturing.

In one embodiment, the temperature range where the two different curing mechanisms (the low and high temperature reactions) take place may range generally from 25 °C to 300 °C (temperature ranges measured by DSC). In another embodiment, the range for the exotherm peak separation of the two reactions taking place may be between 30 °C and 150 °C.

In one preferred embodiment, the Tg of the B-staged material produced from the composition of the present invention can be at least 30 °C; and the Tg of the C-staged material produced from the composition of the present invention can be at least 50 °C.

With reference to Figures 1-3, there is shown graphical illustrations of the stages of a solventless composition of the present invention beginning with the A-stage of the composition going to the B-stage of the composition, and the B-stage of the composition going to the C-stage. Figure 1 shows the characterization of the composition at the A-stage *via* DSC. Figure 1 shows that at the A-stage two distinct ranges of reactions are present in the composition. At the B-stage, the spectra show the decoupling of the reactions *via* completion of the low temperature reaction during the A-stage to the B-stage reaction. The C-stage shows the formation of the thermoset network.

With reference to Figure 1-3 again, there is shown a graphical illustration of a composition of the present invention of the characterization of the stages of the present invention *via* DSC. The first thermogram was conducted on a mixture of an epoxy (DVBDO) with two hardeners DETA and DETDA (it represents a typical mixture in the A-stage) that is heated at a rate of 10 °C/minute from 30 °C to 275 °C. The thermogram shows two exotherms at distinct temperatures, the low temperature exotherm with a peak at $T_1 = 111$ °C and the high temperature exotherm with a peak at $T_2 = 196$ °C. The 2nd thermogram is a similar temperature scan, but the sample has been preheated at 110 °C for 60 minutes to represent a typical B-stage material. Only one exotherm peak at high temperature (190 °C) is observed. The third thermogram was conducted on a fully cured sample (typically representing a C-stage material) after heating the sample at 210 °C for 120 minutes. No exotherm was observed on this scan.

With reference to Figure 1 again, there is shown a thermogram *via* DSC of an example of the composition of the present invention starting with a mixture of DVBDO, DETA and DETDA. In the thermogram, the mixture is heated at a rate of 10 °C/minute from 30 °C to 275 °C. The thermogram shows two exotherms a distinct temperatures, the low temperature exotherm with a peak at T_1 = 111 °C and the high temperature exotherm with a peak at T_2 = 196 °C.

With reference to Figure 2, there is shown a thermogram *via* DSC of an example of the composition of the present invention starting with a mixture of DVBDO, DETA and DETDA which has been preheated to 110 °C for 1 hour (typically representing a B-stage material). Only one exotherm peak at high temperature (190 °C) is observed.

With reference to Figure 3 there is shown a thermogram *via* DSC of an example of the composition of the present invention starting with a mixture of DVBDO, DETA and DETDA which has been preheated to 110 °C for 1 hour and heated to 210 °C for 2 hours (typically representing a C-stage material). No exotherm was observed on this scan.

With reference to Figure 4, there is shown a thermogram *via* DSC of an example of the solventless composition of the present invention starting with a mixture of DVBDO, bisphenol A and DETDA. In the thermogram, the mixture is heated at a rate of 10 °C/minute from -5 °C to 295 °C. The thermogram shows two exotherms a distinct temperatures, the low temperature exotherm with a peak at T_1 = 131 °C and the high temperature exotherm with a peak at T_2 = 227 °C.

With reference to Figure 5, there is shown a thermogram *via* DSC of an example of the solventless composition of the present invention starting with a mixture of DVBDO, bisphenol A, DETA, and the catalyst 1-benzyl-2-methyl imidazole. In the thermogram, the mixture is heated at a rate of 10 °C/minute from -5 °C to 295 °C. The thermogram shows two exotherms a distinct temperatures, the low temperature exotherm with a peak at T_1 = 85 °C and the high temperature exotherm with a peak at T_2 = 135 °C.

With reference to Figure 6, there is shown a rheology curve of the viscosity at B-staging of an example of the composition of the present invention starting with a mixture of DVBDO, DETA and DETDA. Figure 6 shows the viscosity change as a function of time for the composition containing DVBDO, DETA and DETDA. The testing parameters consisted of ramping the sample at 30 °C/minute from 25 °C to 110 °C; holding isothermally at 110 °C for 30 minutes; cooling at 5 °C/minute to 25 °C with an isothermal time of 15 minutes followed by a ramp at 5 °C/minute until the composition gelled at 172 °C. Figure 7 is a portion of the rheology curve of Figure 6 showing the first 30 minutes of the curve.

With reference to Figure A, there is shown a rheology curve of the viscosity at B-staging of an example starting with a mixture of XZ92530, XZ92535 and 2-phenyl imidazole. Figure A shows the viscosity change as a function of time for the composition containing XZ92530, XZ92535 and 2-phenyl imidazole. The testing parameters consisted of ramping the sample at 30 °C/minute from 25 °C to 160 °C; next holding isothermally at 160 °C until the composition gelled after 3 minutes at 160 °C.

The thermoset product of the present invention, (i.e., the cross-linked product made from the solventless composition of the present invention), shows several improved properties over conventional epoxy cured resins. For example, the cured product of the present invention (i.e., the C-staged material) may have a glass transition temperature (Tg) generally from 50 °C to 300 °C in one embodiment; from 100 °C to 250 °C in another embodiment; from 120 °C to 230 °C in yet another embodiment; from 140 °C to 200 °C in still another embodiment; and from 160 °C to 180 °C in still one other embodiment. The Tg may be measured using a differential scanning calorimeter by scanning at 10 °C/minute. The Tg is determined by the inflection point of the 2nd order transition.

The solventless curable composition of the present invention may be used in thermoset systems where conventional curable epoxy resins are used. Some non-limiting examples of applications wherein the composition of present invention may be used include, for example, prepregs, electrical laminates, composites, films, underfills (capillary underfills), coatings, castings, civil engineering materials, adhesives, or elastomers. For example, the composition may be used in composites for aerospace, infrastructure, sporting goods, transportation vehicles including car, trucks, boats and ships, liquid and gas containers. In another example, prepregs prepared using the solventless curable compositions of the present invention are also suitable for field repairs (such as military vehicles) where storage life under ambient conditions is needed.

In one embodiment, prepregs, electrical laminates, and composites may include additives such as fillers, dyes, pigments, adhesion promoters, wetting agents, flow-aids, anti-gloss or gloss additives, toughening agents, flame retardants, and mixtures thereof, can be used for making composite compositions which in turn are used for manufacturing a cured composite article. In another embodiment, underfills may include additives such as fillers, pigments, adhesion promoters, wetting agents, toughening agents, and mixtures thereof can be used for making underfill compositions which in turn are used for manufacturing a cured underfill article.

EXAMPLES

The following examples further illustrate the present invention in detail but are not to be construed to limit the scope thereof.

Various terms and designations used in the following examples are explained herein below:

"DVBDO" stands for divinylbenzene dioxide;

"DETA" stands for diethylene triamine;

"DETDA" stands for diethyltoluenediamine;

"2-PI" stands for 2-phenyl imidazole; and "FR-4" stands for Flame Retardant Class 4.

"XZ92530" is a solution of a polyglycidyl ether resin containing a phosphorous moiety, commercially available from The Dow Chemical Company; and "XZ92535" is a solution of a multi-functional phenol novolac hardener, commercially available from The Dow Chemical Company.

The following standard analytical equipment and methods are used in the Examples:

Analytical

Differential scanning calorimetry (DSC) is performed using the following instruments: TA Instrument DSC Q200, DSC Q2000, DSC 2920 and using the following process:

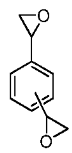
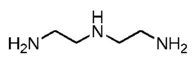
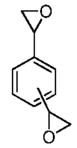
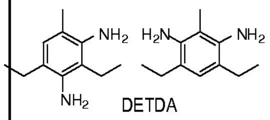
DSC is carried out using ASTM E 1269 Standard Test Method for determining specific heat capacity, and ASTM E 1356 standard test method for assignment of the glass transitions temperatures by differential scanning calorimetry. The samples are run in a TA Instrument DSC Q2000.

Samples of approximately 10 mg are cut from cured plaques; or in the case of liquid samples, aliquots of the samples are drawn and loaded into aluminum pans that were hermetically sealed. The pans are loaded into an auto sampler on a TA Instruments Q2000 DSC. The samples are cooled to -20 °C, ramped at 10 °C/minute to 200 °C, equilibrated again at -10 °C, then ramped a second time to 250 °C at a rate of 10 °C/minute.

Minimum melt viscosity data and dynamic mechanic analysis (DMA) tests are performed using a TA Instrument ARES Rheometer; and using the following process: Sample viscosity is tested using parallel plate fixtures on a TA Instruments ARES Rheometer. A 40 mm top and 50 mm bottom plate are installed on the rheometer to test the samples. One example of the testing parameters consists of ramping the sample at 5 °C/minute from ambient temperature to 80 °C, ramping again at 5 °C/minute to 25 °C with an isothermal time of 15 minutes followed by a third ramp at 5 °C/minute until the composition gells using the oven control and attached liquid nitrogen supply. The gap is set at 1.000 mm and all samples are run at a strain of 100 % and frequency of 1 Hertz.

Example 1

A solvent-free dual-cure composition containing DVBDO, DETA and DETDA was prepared. In this Example 1, the two separate reactions taking place at different temperatures are (1) the reaction between DVBDO and DETA, which takes place upon applying a low temperature; and (2) the reaction between DVBDO and DETDA which occurs at high temperature.

Low Temperature Reaction		High Temperature Reaction	
Epoxide	Hardener 1	Epoxide	Hardener 2
	 DETA		

General Preparation Procedure

A solventless composition containing DETA, DETDA and DVBDO was prepared according to the following general procedure: Since all the materials were completely soluble at ambient temperature (20 °C to 30 °C), no heating of the composition was necessary to obtain a homogeneous mixture. A total of 5 g of composition were prepared in a 4 mL glass vial by first adding 1.47 g (33 mmol) of DETDA, and then adding 3.35 g (41 mmol) of DVBDO to the glass vial. The resulting mixture was stirred to mix thoroughly. Then, 0.17 g (8 mmol) of DETA was added to the mixture in the glass vial and the resulting mixture was stirred to obtain a low viscosity composition having a viscosity of 0.1 Pa-s.

General Curing Procedure

In order to B-stage the solventless low viscosity composition prepared above, 2 g of the low viscosity composition were placed in an aluminum 2 inches in diameter (5 centimeters (cm)) disposable pan. The 2 g sample of the composition was B-staged in an oven at 110 °C for 1 hour.

Next, the resultant B-staged material was fully cured utilizing the following curing schedule: 160 °C for 30 minutes, 200 °C for 40 minutes and 210 °C for 40 minutes.

Characterization of the Composition Sample

Each stage of the process of this Example 1 was characterized by DSC. The DSC scan of the A-stage material (measured right after mixing of all components at ambient temperature), showed the marked partition of the reaction exotherms corresponding to the decoupling of reactions of each hardener with DVBDO. An exotherm peak with a maximum at 111 °C corresponding to the reaction of DETA and DVBDO was found. A second exotherm peak at 196 °C corresponding to the reaction of DETDA with DVBDO was also found.

To confirm the decoupling of reactions, the solventless composition was placed in the oven at 110 °C for 1 hour to perform the A-to-B stage. A DSC scan obtained after B-staging the composition showed that the reaction of DETA and DVBDO had gone to completion which was evidenced by the complete disappearance of the first peak. On the other hand, the second peak was still present and unchanged in the spectrum supporting the presence of unreacted DETDA and DVBDO in the B-staged material.

The B-staged material prepared above was then cured in an oven at a curing schedule of 160 °C, 200 °C and 210 °C to perform the B-stage-to-C-stage. A DSC scan of the resulting C-stage thermoset was obtained and a high Tg of the fully cured thermoset was determined by DMTA analysis. The Tg of the C-stage thermoset was found to be 225 °C.

The solventless composition of Example 1 is characterized in Figure 1, Figure 2 and Figure 3. Figure 1 shows a graphical illustration of the characterization of the stages of the present invention *via* DSC. The first thermogram shown in Figure 1 was conducted on the composition of Example 1 (which represents a typical mixture in the A-stage) that is heated at a rate of 10 °C/minute from 30 °C to 275 °C. The thermogram shows two exotherms at distinct temperatures, the low temperature exotherm with a peak at T_1 = 111 °C and the high temperature exotherm with a peak at T_2 = 196 °C. The second thermogram shown in Figure 2 is a similar temperature ramp scan, but the sample has been preheated at 110 °C for 60 minutes to represent a typical B-stage material. Only one exotherm peak at high temperature (190 °C) is observed. The third thermogram shown in Figure 3 was conducted on a fully cured sample (typically representing a C-stage material) after heating the sample at 210 °C for 120 minutes. No exotherm was observed on this DSC scan.

Example 2

The following is a detailed description of the preparation of 80 g of composition for "hand paint"-technique laminate. First, 40 g (0.50 mol) of DVBDO were warmed up to 55 °C, and 28 g (0.25 mol) of powdered bisphenol A were added in multiple portions over 40 minutes. During the addition of bisphenol A, the temperature was gradually increased to 95 °C to help dissolve the phenolic hardener in the epoxide. The reaction mixture was vigorously stirred using a mechanical stirrer to obtain a homogeneous mixture. The resulting mixture was then cooled to ambient temperature, and 11 g (0.25 mol) of DETDA were added to the mixture.

The solventless composition was applied using a brush onto 12 inches by 12 inches (30 cm x 30 cm) sheets of glass cloth. The composition was B-staged in an oven at 80 °C for 60 minutes. Next, the prepregged glass sheets were stacked on top of each other, and pressed according to the following cycle: At 25 °C at 8 psi (800 lbs/sq inch), followed by a heating ramp rate of 5 °C per minute up to 160 °C. At 160 °C, the pressure is increased to 20 psi (2,000 lbs). The heating rate is increased to 20 degrees per minute from 160 °C up to 200 °C. The pressure is held at 200 °C until full cure of the resin is achieved.

The solventless composition of this Example 2 is characterized in Figure 4. Figure 4 shows a graphical illustration of the characterization of the stages of the present invention *via* DSC. The thermogram shown in Figure 4 was conducted on the composition of Example 2 (which represents a typical mixture in the A-stage) that is heated at a rate of 10 °C/minute from -5 °C to 295 °C. The thermogram shows two exotherms at distinct temperatures, the low temperature exotherm with a peak at T_1 = 131 °C and the high temperature exotherm with a peak at T_2 = 227 °C.

Example 3

This Example 3 was carried out utilizing two different epoxy resins and two different amine hardeners. The solventless composition investigated contained the epoxy resins D.E.R 383 and DVBDO; and two different amine hardeners DETA and DETDA.

The composition was mixed and prepared at ambient temperature. 2.2 g (12 mmol) of DER 383 were mixed with 1 g (12 mmol) of DVBDO at ambient temperature. Next, 0.88 g (20 mmol) of DETDA was added to the mixture followed by 0.1 g (5 mmol) of DETA. The resulting formulation was mixed until homogeneous.

Example 4

A solventless composition containing the hardeners DETA and DETDA, DVBDO and silica filler was prepared as follows. A total of 80 g of composition were prepared in a 1 L beaker by first adding 24 g (0.53 mol) of DETDA. Next 54 g (0.66 mol) of DVBDO were added. The mixture was stirred to mix thoroughly. Next, 3.7 g (0.13 mol) of DETA were added followed by the remaining amount of DVBDO. The resulting mixture was stirred. 6 % of fumed silica filler was added last. 4.8 g (6 % by weight) of fumed silica were added in small portions. The addition was accompanied by vigorous stirring utilizing an overhead mechanical stirrer to obtain a uniform dispersion of the filler in the composition. The resulting composition, containing filler was immediately subjected to B-staging.

Example 5

A solventless composition containing the hardeners, DETA and bisphenol A, the epoxy resin DVBDO and the catalyst 1-benzyl-2-methyl imidazole was prepared. First, 1.09 g (13.5 mmol) of DVBDO was warmed up to 55 °C, and 0.77 g (6.75 mmol) of powdered bisphenol A was added in small portions over 40 minutes. During the addition of bisphenol A, the temperature was gradually increased to 95 °C to help dissolve the phenolic hardener in the epoxide. The mixture was then cooled to ambient temperature, and 0.14 g (6.80 mmol) of DETA was added; followed by addition of 0.08 g (4 wt %) of 1-benzyl-2-methyl imidazole catalyst at ambient temperature. For B-staging, the composition was poured into an aluminum 2 inches in diameter (5 centimeters (cm)) disposable pan and placed in the oven at 80 °C for 40 minutes.

The composition of Example 5 is characterized in Figure 5. Figure 5 shows a graphical illustration of the characterization of the stages of the present invention *via* DSC.

The thermogram in Figure 5 was conducted on the Example 5 composition (which represents a typical mixture in the A-stage) that is heated at a rate of 10 °C/minute from --15 °C to 240 °C. The thermogram shows two exotherms a distinct temperatures, the low temperature exotherm with a peak at $T_1 = 81$ °C and the high temperature exotherm with a peak at $T_2 = 133$ °C.

Example A

In this Example A, a typical solvent-containing composition for FR-4 laminate production was investigated. A solvent-containing composition was made up of XZ92530, a resin solution, and cured with XZ92535, a phenolic novolac hardener solution. This composition contained an accelerator, 2-PI. The ratio of XZ92530:XZ92535:2-PI was 77.1:22.9:0.4. The actual amounts of materials employed in the preparation of the compositions were 314.9 g of XZ92530, 128.7 g of XZ92535 and 6.31 g of 2-PI.

Typical processing conditions for this type of solvent-containing composition include B-staging at 177 °C for 3 minutes.

As a comparison, the solvent-free composition described in Example 1 of the present invention, containing DVBDO, DETA and DETDA was B-staged at 110 °C for 30 minutes. The compositions from Example 1 and Example A were tested in an ARES rheometer to evaluate the increase in viscosity as a function of time at the B-staging temperature of each of the compositions.

Even though the processing conditions for the solvent-containing composition and the solvent-free composition are different, the viscosities of both samples at the B-staging temperature were tested in the ARES rheometer using the following methods:

For the composition containing DVBDO, DETA and DETDA the testing parameters consisted of ramping the sample at 30 °C/minute from ambient temperature to 110 °C; isothermal at 110 °C for 30 minutes; cooling at 5 °C/minute to 25 °C with an isothermal time of 15 minutes followed by a ramp at 5 °C/minute until the composition gelled at 172 °C (Figure 6).

For the composition containing XZ92530, XZ92535 and 2-PI the testing parameters consisted of ramping the sample at 30 °C/minute from ambient temperature to 160 °C; isothermal at 160 °C until the composition gelled after 3 minutes at 160 °C (Figure A).

The results for the viscosity change as a function of time at the B-staging temperature for DVBDO, DETA and DETDA and for XZ92530, XZ92535 and 2-PI are also summarized in Table I.

Table I

	Example A		Example 1	
Amount of B-staging Time (minutes)	Viscosity (Pa-s)	Temperature* (°C)	Viscosity (Pa-s)	Temperature* (°C)
0	9.22	25.3	2.1	25.0
1	2.30	37.7	0.96	37.9
2	0.13	71.7	0.38	63.4
3	0.047	106	0.11	108.6
4	0.057	127	0.13	112.6
5	0.12	160	0.20	109.7
6	0.29	161	0.31	109.5
7	1.1	160	0.46	110
8	Gel	160	0.62	110
9	Gel	160	0.77	110
10			0.92	110
15			1.41	110
20			1.61	110
25			1.82	110
30			2.17	110

*Reading in the ARES Rheometer

According to Table I, upon B-staging the composition containing XZ92530, XZ92535, 2-PI (Example A) at 160 °C, the solvent-containing composition undergoes a large increase in viscosity and quickly gels after only 3 minutes at 160 °C (Figure A) . On the other hand, the solvent-free composition containing DVBDO, DETA and DETDA (Example 1), was B-staged for up to 30 minutes at 110 °C. The composition of Example 1 does not gel after 30 minutes isothermally at 110 °C (Figure 6).

CLAIMS:

1. A solventless curable epoxy resin composition comprising (a) at least one divinylarene dioxide; and (b) at least one hardener; wherein the solventless curable epoxy resin composition is solvent-free; wherein the solventless curable epoxy resin composition has at least two exotherm peaks; and wherein the exothermic peak difference of the two exotherm peaks is sufficient to allow the solventless curable epoxy resin composition of being B-staged.

2. The composition of claim 1, wherein the divinylarene dioxide is divinylbenzene dioxide.

3. The composition of claim 1, wherein the at least one hardener (b) comprises (b1) at least a first hardener, and (b2) at least a second hardener different from the first hardener.

4. The composition of claim 3, wherein the molar ratio of the first hardener to the second hardener is from 0.001 to 1000.

5. The composition of claim 3, wherein each of the first and second hardeners contain reactive amine hydrogens; and wherein the composition contains an exotherm peak difference when measured by differential scanning calorimetry with a heating rate of 10 °C/minute of at least greater than or equal to 20 °C.

6. The composition of claim 3, wherein the first hardener contains reactive amine hydrogens and the second hardener contains reactive phenol hydrogens; and wherein the composition contains an exotherm peak difference when measured by differential scanning calorimetry with a heating rate of 10 °C/minute of at least greater than or equal to 20 °C.

7. The composition of claim 3, wherein the first and second hardeners each separately and individually comprise aliphatic amines, aromatic amines, cycloaliphatic amines, carbodiimides, ureas, guanidines, phenols, aliphatic alcohols, mercaptans, anhydrides, and mixtures thereof.

8. The composition of claim 1, wherein the exotherm peak difference when measured by differential scanning calorimetry with a heating rate of 10 °C/minute is at least greater than or equal to 20 °C.

9. The composition of claim 1, including (c) an epoxy resin different from the at least one divinylarene dioxide.

10. The composition of claim 1, wherein a solvent is present in the composition in a concentration of less than 10 percent by weight.

11. The composition of claim 1, wherein the composition has a viscosity of less than 50,000 mPa-s under processing conditions of the B-stageable composition.

12. The composition of claim 1, wherein the composition is capable of undergoing a B-staging reaction and a C-staging reaction; wherein the B-staging reaction and the C-staging reaction are two distinct chemical reactions; and wherein the B-staging reaction takes place at a first temperature, T_1; and the C-staging reaction takes place at a second temperature, T_2; wherein T_2 is different from T_1; and wherein T_2 is a higher temperature than T_1.

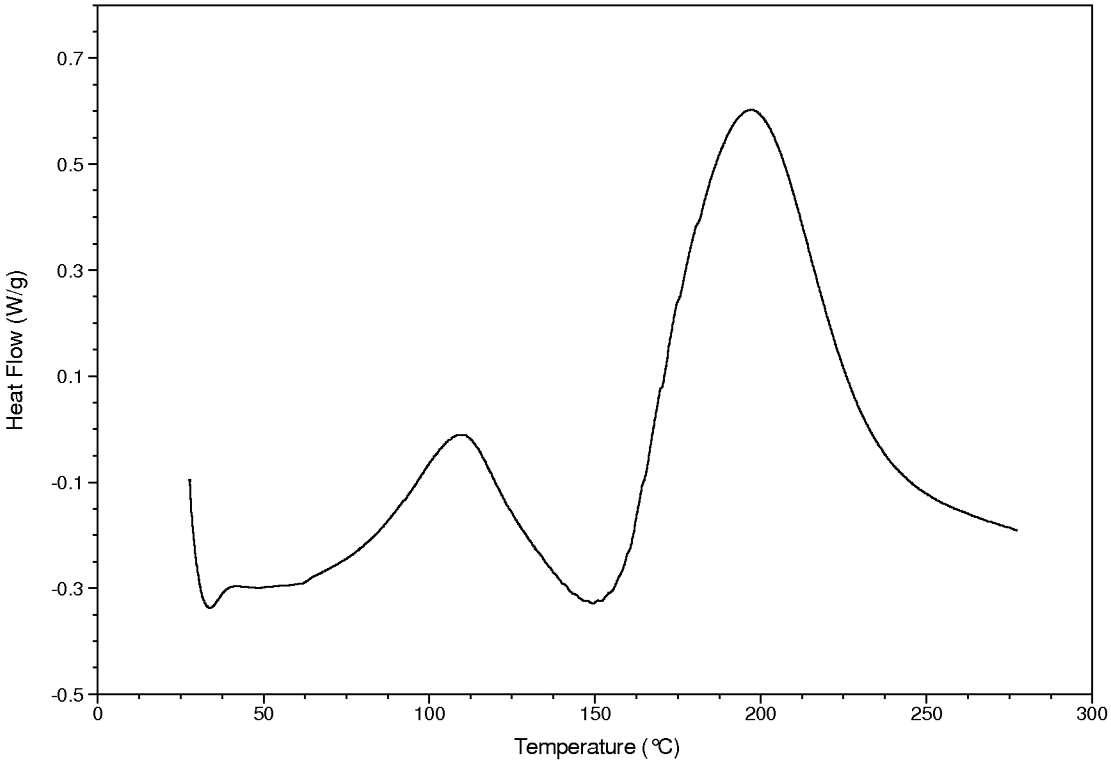
13. The composition of claim 12, wherein T_1 is greater than or equal to 20 °C and T_2 is greater than 20 °C but less than 300 °C.

14. An article made by curing the composition of claim 1.

15. The article of claim 14 wherein the article is a prepreg or a laminate.

16. A process comprising (i) coating reinforcing fibers with a curable epoxy resin composition of claim 1, and (ii) partially curing the composition coating the reinforcing fibers of step (i) to form a prepreg.

17. The process of claim 17, including step (iii) fully curing the prepreg of step (ii) to form a laminate.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0.1
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100
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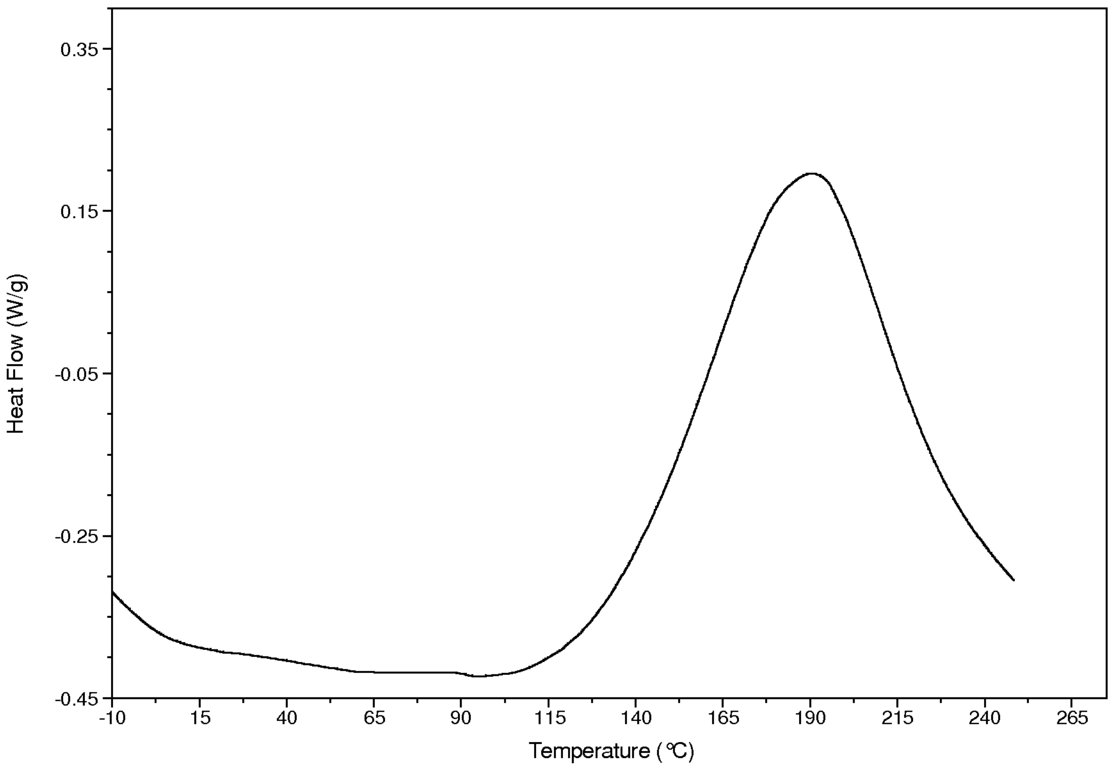
200
250
300
Temperature (℃)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240
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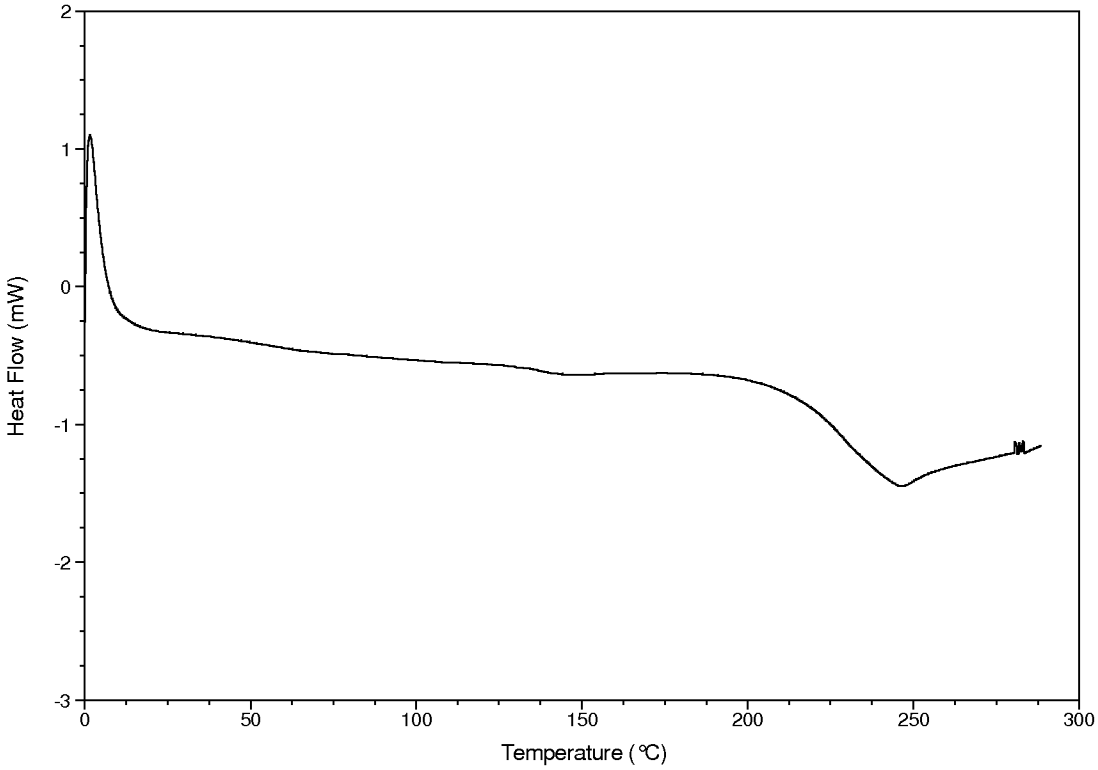
Temperature (℃)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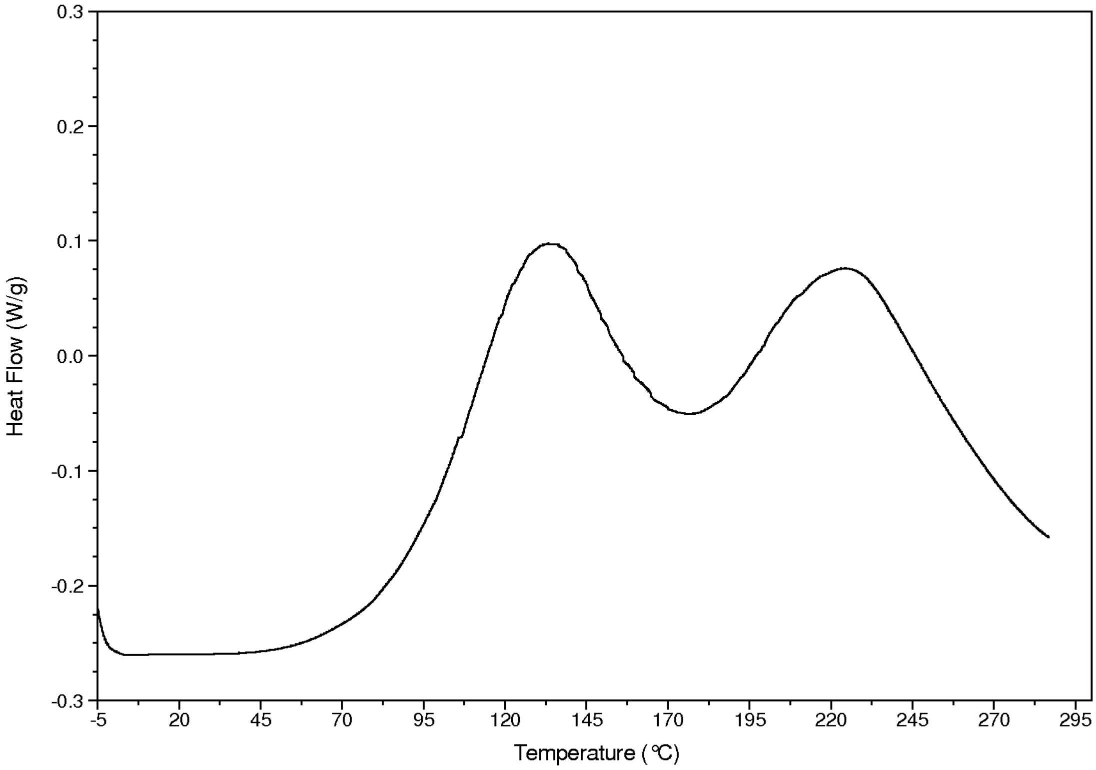
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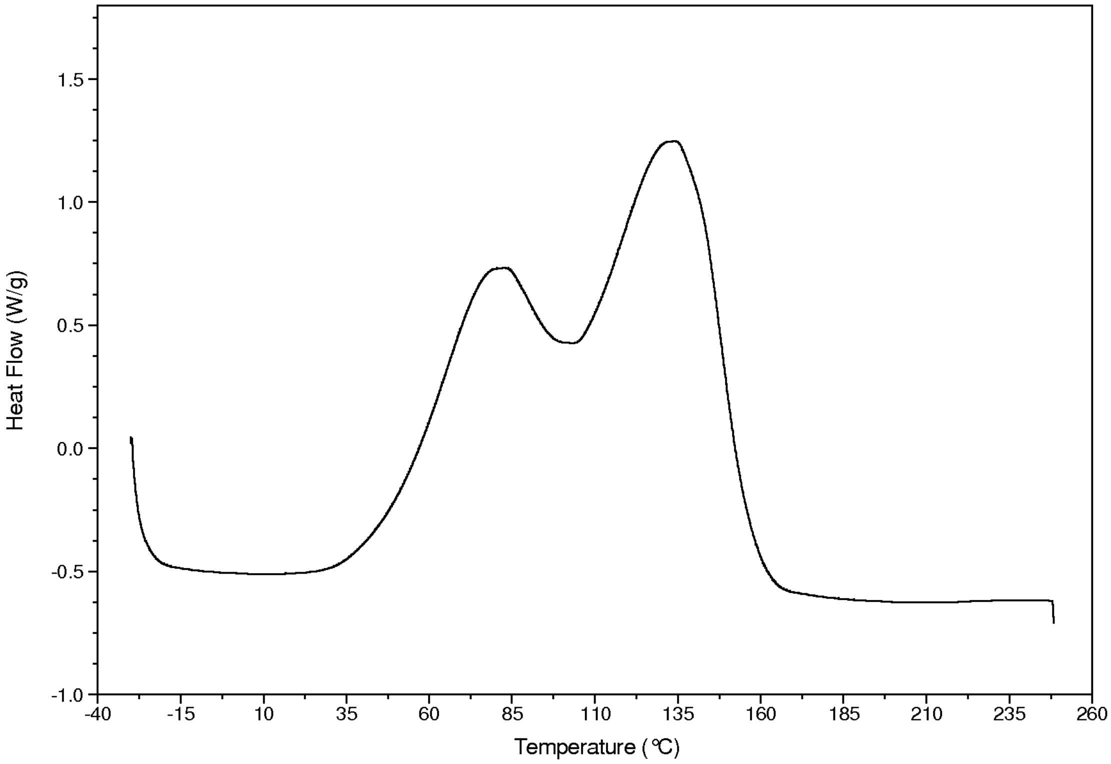
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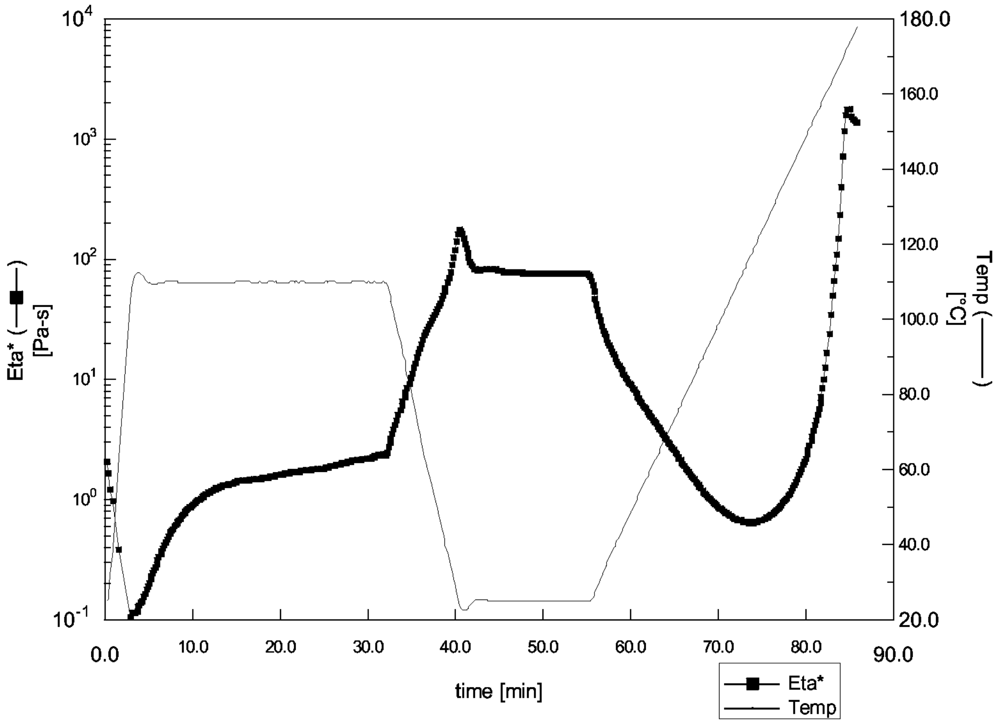
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10^0
10^{-1}
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140.0
120.0
100.0
80.0
60.0
40.0
20.0
Temp (———) [°C]
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10.0
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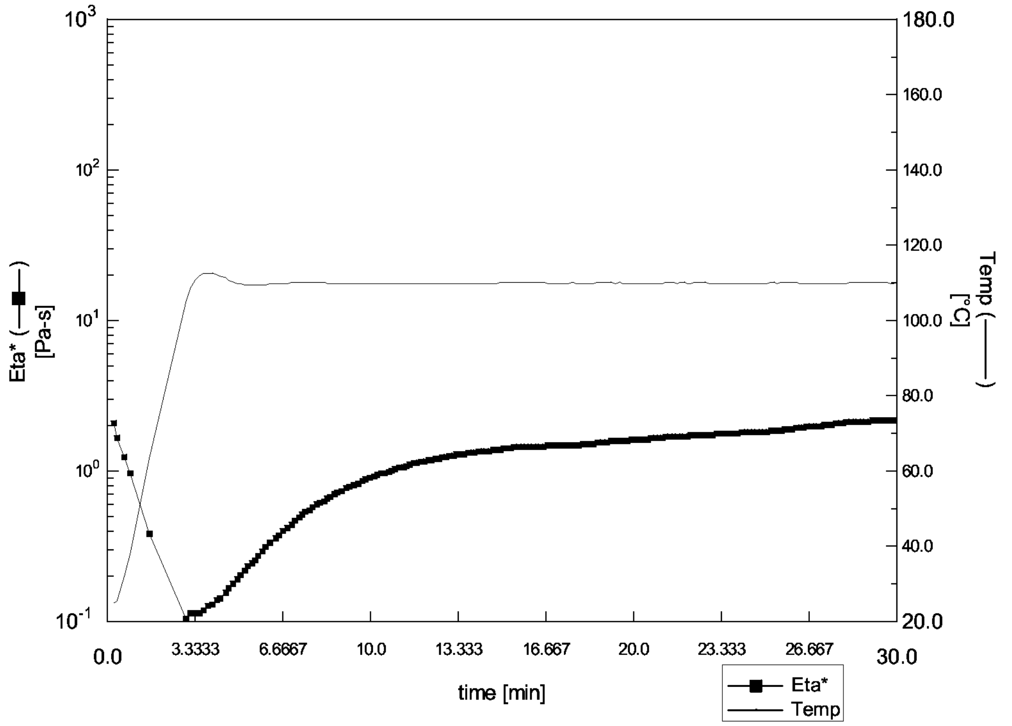
time [min]
—■— Eta*
——— Temp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Eta* (—■—)
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100.0
80.0
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40.0
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Temp (———)
[°C]
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10.0
13.333
16.667
20.0
23.333
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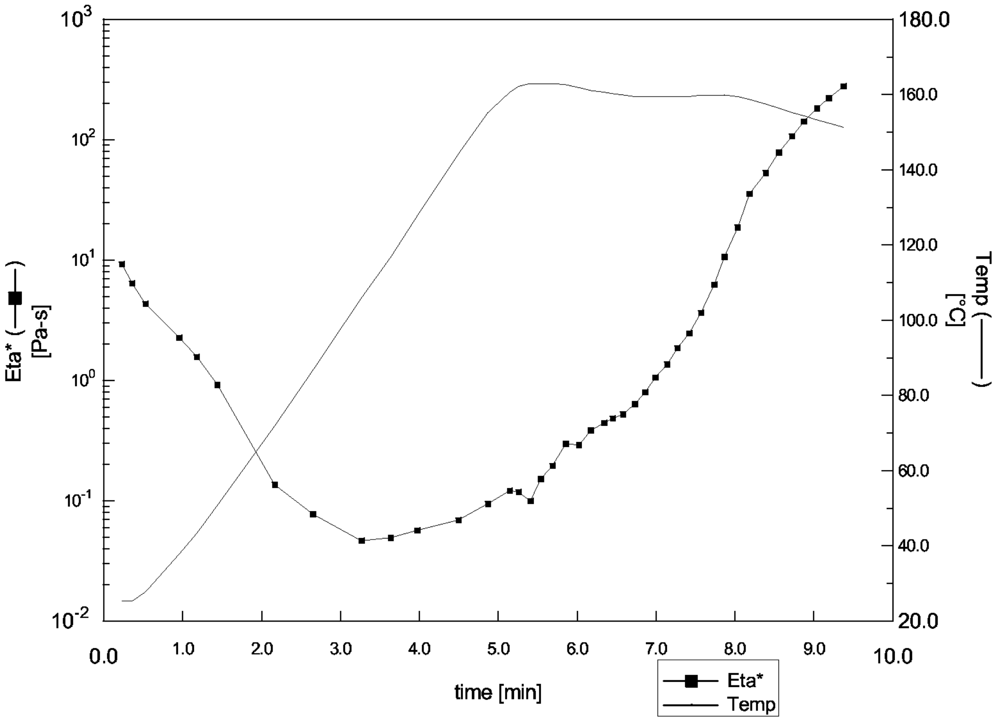
—■— Eta*
——— Temp


10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Eta* (—■—)
[Pa-s]
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
Temp (———)
[°C]
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
time [min]
—■— Eta*
——— Temp