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Dual cure epoxy formulations for 3D printing applications

Abstract

The present invention lies in the field of 3D printing methods. In particular, the invention relates to 3D printing methods for the production of a 3D part in a layer-by-layer manner, wherein the printable composition is a pasty epoxy composition comprising at least one epoxy resin, at least one monomer and/or prepolymer that is polymerizable by exposure to radiation and at least one photoinitiator, wherein the pasty epoxy composition has a viscosity factor (1.5/15) of at least 2 at application temperature.

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Background/Summary

(1) The present invention lies in the field of 3D printing methods. In particular, the invention relates to 3D printing methods for the production of a 3D part in a layer-by-layer manner, wherein a pasty epoxy 3D printing composition is used.

(2) In 3D printing applications, also referred herein as additive manufacturing, a wide variety of polymeric materials are used. In various of these applications, three-dimensional objects are formed in a layer-by-layer manner, i.e. by repeatedly printing material layers on top of each other to form the desired object. Many of the existing polymeric compositions for 3D printing are liquid or are liquefied for the actual printing, for example by melting, and become solid after being printed, for example in form of filaments.

(3) In 3D printing applications that are used for forming objects in a layer-by-layer manner, one drawback is that after printing a layer on top of an already printed layer the adhesion between the layers is not sufficient. This problem is particularly pronounced for printing with filaments. Here the next layer is printed on top of a usually fully cooled and solidified layer, which might lead to an insufficient interlayer adhesion. In the event of reactive liquid printable compositions the build up of a 3D structure is often difficult due to the low viscosity of the composition, which might lead to a deformation of the printed part and/or a poor resolution.

(4) While it is desirable to provide polymeric 3D printing materials with elastomeric properties, the use of such materials has inter alia been hampered by the above problems.

(5) The present invention solves these issues by providing a method for additive manufacturing that uses a pasty epoxy material with a special viscosity factor as described below. By using the pasty epoxy compositions, which are at the same time radiation curable and heat curable, the thixotropic behaviour ensures that the printed layer is already dimensionally stable, which can be preferably supported by radiation curing, while at the same time a good wettability of the second layer is maintained due to the still uncured epoxy portion. The final heat cure would determine the final thermoset properties, like good mechanical strength and good chemical resistance. The finally cured part exhibits an outstanding smooth surface, showing virtually no interfaces between the applied layers any more, as a result of the viscosity properties of the printable composition and the dual cure thereof.

(6) In a first aspect, the present invention relates to a method for additive manufacturing a three-dimensional part in a layer-by-layer manner, wherein the method comprises (i) providing a carrier substrate to support the three-dimensional part and a print head connected to a reservoir of a printable composition; (ii) printing the printable composition with the print head in form of extrudate strands onto the carrier substrate to form a first layer; (iii) printing the printable composition with the print head in form of extrudate strand onto the first layer to form a second layer; (iv) optionally repeating step (iii) at least once to form a third or subsequent layer; (v) exposing the printable composition directly after printing and/or after each layer application and/or after application of multiple layer to radiation, preferably UV radiation; and (vi) curing the printed layers of the reactive curable printable composition by heating to obtain the three-dimensional part; wherein the printable composition is a pasty epoxy comprising at least one epoxy resin; at least one monomer and/or prepolymer that is polymerizable by exposure to radiation, preferably a poly(meth)acrylate; and at least one photoinitiator; wherein the epoxy composition has a viscosity factor (1.5/15) of at least 2 at application temperature.

(7) In another aspect, the invention also relates to the three-dimensional articles manufactured by

use of the methods described herein.

(8) In a further aspect, the invention also relates to the use a pasty epoxy composition as described above for 3D printing.

(9) “Additive manufacturing” and “3D printing” are used interchangeably herein to refer to methods for the formation of three-dimensional objects or parts in which material is joined or solidified, typically under computer control, with material being added together in a layer-by-layer manner.

(10) “Layer-by-layer”, as used herein, relates to a method of additive manufacturing in which an object is produced by printing separate layers on top of each other such that they form the desired shape. It is typically important to achieve sufficient inter-layer adhesion to produce a stable three-dimensional object.

(11) “Print head”, as used herein, relates to the part of an apparatus used for depositing the printing material in form of a layer onto a support or an already formed layer. The print head is typically freely movable to allow formation of layers in the desired shape on a substrate (typically by horizontal movement) and print layers on top of already existing layers (typically by retracting the print head in the vertical direction such that the distance to the substrate or printed layer is adjusted to be suitable for printing the next layer). Alternatively, the print head may be fixed and the substrate is moved relative to the print head or both are movable relative to each other. The print head has typically at least one orifice through which the printable material is deposited. Herein, the printable material is preferably in form of a pasty polymeric composition, so that the print head orifice can resemble an extruder die and the printed material be in form of an extrudate strand. Also reference is made herein to a “print head orifice”, it is understood that this term also includes embodiments where the print head has more than one opening/orifice.

(12) “Extrudate strand”, as used herein, relates to the form of the printed/extruded material once it leaves the print heads orifice and forms the layer. It is in form of a strand that extends in the direction of the movement of the print head. Strands printed next to each other, for example parallel to each other, can together form one layer (for this they may fuse to a certain extent), while strands printed on top of an existing strand form the next layer in the layer-by-layer manufacturing process.

(13) The term “curable” is to be understood to mean that, under the influence of external conditions, in particular under the influence of radiation and/or heat present in the environment and/or supplied for the purpose, the composition can pass from a relatively flexible state, optionally possessing plastic ductility, to a harder state. In general, the crosslinking can take place by means of chemical and/or physical influences, for example, by the supply of energy in the form of heat, light or other electromagnetic radiation, but also by simply bringing the composition into contact with air, atmospheric moisture, water, or a reactive component. “Radiation curable”, as used herein, thus relates to curing under the influence, e.g. exposure, to radiation, such as electromagnetic radiation, in particular UV radiation or visible light. UV radiation is in the range of 100 to 400 nanometers (nm). Visible light is in the range of 400 to 780 nanometers (nm). “heat-curable”, as used herein, thus relates to curing under the influence of heat, typically by heating the three-dimensional part in an oven to temperatures above 100° C.

(14) Provided reference is made to molecular weights of oligomers or polymers in the present application, the quantities, unless otherwise stated, refer to the number average, i.e., the $M_{sub.n}$ value, and not to the weight average molecular weight. The number average molecular weight $M_{sub.n}$, as well as the weight average molecular weight $M_{sub.w}$, is determined according to the present invention by gel permeation chromatography (GPC, also known as SEC) at 23° C. using a styrene standard. The molecular weight can be determined by gel permeation chromatography (GPC) with tetrahydrofuran (THF) as the eluent according to DIN 55672-1:2007-08, preferably at 23° C. or 35° C. Molecular weights of monomeric compounds are calculated based on the respective molecular formula and the known molecular weights of the individual atoms. These methods are known to one skilled in the art.

(15) "At least one," as used herein, refers to 1 or more, i.e., 1, 2, 3, 4, 5, 6, 7, 8, 9, or more. In regard to an ingredient, the term relates to the type of ingredient and not to the absolute number of molecules. "At least one polymer" thus means, for example, at least one type of polymer, i.e., that a type of polymer or a mixture of a number of different polymers can be used. Together with weight data, the term refers to all compounds of the given type, contained in a composition/mixture, i.e., that the composition contains no other compounds of this type beyond the given amount of the relevant compounds.

(16) All percentage data, provided in connection with the compositions described herein, refer to % by weight, based in each case on the relevant mixture, unless explicitly indicated otherwise.

(17) The invention relates to methods for additive manufacturing a three-dimensional part in a layer-by-layer manner, wherein the method comprises, in a first step, providing a carrier substrate to support the three-dimensional part and a print head connected to a reservoir of a printable composition. The carrier substrate may be any suitable substrate. It may be a printing bed that may be flat, essentially flat or curved. It can be made of any suitable material and can also be in form of a tray. In various embodiments, it can be made of metal, glass or plastic. It is preferably designed such that it allows easy release of the layers printed thereon, e.g. being inert towards the printed material and any potential curing process used.

(18) In various embodiments, the print head forms part of a printing apparatus and is connected to at least one reservoir of at least one printable composition. While the print head may, in various embodiments, be connected to multiple reservoirs of different printable compositions, it is herein preferred that the print head is connected to one reservoir of one printable composition. The print head is that part of the printing apparatus that deposits the printing material onto the substrate or an already formed layer in the desired pattern. To achieve this, it is connected to a feeding means through which the print head is fed with the printable composition, such as a pump, conveyor and the like, via tubing/pipes. The print head has an orifice or nozzle through which the printable composition leaves the print head and is deposited on a surface. The orifice/nozzle may have any desired shape, but is typically an essentially circular opening. The shape of the print head and the print head orifice may define the shape of the printed material strand. In various embodiments, the print head and/or its orifice are designed such that due to the shear forces that act on the printable composition during transport and extrusion/printing, the viscosity is lowered to such a degree that the composition is printable with the selected device but increases viscosity once the layer has been formed such that the formed object retains its form even before curing is completed. The printing method may include heating the composition and/or the printhead. Typical application temperatures for printing/extrusion range from about 10° C. to about 120° C., typically from about 15° C. to about 80° C. In some embodiments, application temperatures are preferably in the range of 15° C. to 40° C., preferably 20° C. to 30° C., more preferably the application temperature is about 25° C. In some embodiments, application temperatures are preferably in the range of 40° C. to 80° C., preferably 45° C. to 60° C., more preferably the application temperature is about 55° C.

(19) The reservoir may be a cartridge, tank or similar storage container in which the printable composition is stored and which is connected to the print head with a suitable feeding line, tubing or the like. The transport of the printable material may be facilitated by a transporting device, such as a pump or conveyor screw, all of which are known in the field.

(20) The print head is designed such that it allows printing the printable composition with the print head in form of extrudate strands onto the carrier substrate to form a first layer in the next step of the inventive method. For this, as already described above, the print head, the carrier substrate or both may be movable. Typically, the print head is moved over the carrier substrate and extrudate strands are deposited onto the substrate in the desired pattern. The layers are formed by depositing strands next to each other. Once the first layer is formed, the method continues by printing the printable composition with the print head in form of extrudate strand onto the first layer to form a second layer. The second layer may be similar to or different in shape relative to the first layer but

is formed on top of the first layer. To form the three-dimensional object, the steps of forming a layer on top of the already formed layers may be repeated to form a third, fourth, fifth and subsequent layer. Computer programs exist that allow to devise a layer-by-layer printing process for a given shape or object.

(21) In one embodiment of the invention, the distance of the print head orifice to the carrier substrate or the already formed layers is equal to or greater than the thickness of the printed extrudate strand. In preferred embodiments, it is greater than the thickness of the printed extrudate strand. In various embodiments, the ratio of the distance of the print head orifice to the carrier substrate or the already formed layers during printing to the thickness of the printed extrudate strand ranges from 1.0 to 3.0, preferably 1.0 to 2.0, more preferably 1.1 to 1.8. Keeping said distance of the print head to the substrate or already printed layer ensures that shear stress on the already formed layers is minimized. As a result, deformation of the formed layers can be avoided.

(22) The printable composition is exposed directly after printing and/or after each layer application and/or after application of multiple layer to radiation, preferably UV radiation. Therefore, radiation curing of the epoxy composition may occur directly after printing, for example in that the printed extrudate strands are exposed to radiation directly after they left the print head orifice or once they have been deposited on the substrate or an underlying layer, separately for each strand/layer application and/or after more than one layer application or after the complete object has been formed or a combination of these. In one embodiment, the printable composition is exposed to radiation directly after printing. This is of special advantage, since due to the radiation curing directly after application the strands directly gain additional stability on top of the stability according to the thixotropic/paste behaviour and bridging parts could be printed without a support structure. In such an embodiment, it might also be beneficial that the printed composition is again exposed to radiation at a later stage, preferably the printed composition is exposed again to radiation after the complete object has been formed.

(23) In one preferred embodiment, the method comprises (i) providing a carrier substrate to support the three-dimensional part and a print head connected to a reservoir of a printable composition; (ii) printing the printable composition with the print head in form of extrudate strands onto the carrier substrate to form a first layer, wherein the printable composition is exposed to radiation directly after printing and/or after application of this layer, preferably directly after printing; (iii) printing the printable composition with the print head in form of extrudate strand onto the first layer to form a second layer; wherein the printable composition is exposed to radiation directly after printing and/or after application of this layer, preferably directly after printing; (iv) optionally repeating step (iii) at least once to form a third or subsequent layer; (v) optionally exposing the printable composition again to radiation after application of multiple layers or after the complete object has been formed; and (vi) curing the printed layers of the reactive curable printable composition by heating to obtain the three-dimensional part.

(24) The printable composition is a pasty epoxy reactive composition comprising at least one epoxy resin; at least one monomer and/or prepolymer that is polymerizable by exposure to radiation, preferably a poly(meth)acrylate; and at least one photoinitiator; wherein the epoxy composition has a viscosity factor (1.5/15) of at least 2 at application temperature.

(25) The printable epoxy compositions are in form of a printable paste. "Paste" and "pasty", as used herein, relate to liquid compositions as described in more detail herein. The pastes are shear-thinning and/or thixotropic liquids, which means their viscosity is decreased when subjected to shear forces. The decrease in viscosity upon application of shear stress is such that the printable compositions are printable/extrudable by 3D printing apparatuses and print heads, as described herein, but at the same time are stable enough to maintain the form until the first radiation curing, usually UV curing, is completed. The printable epoxy compositions have therefore a viscosity factor (1.5/15) at application temperature of at least 2.0, preferably at least 3.0, more preferably 4.0

or more. Such a viscosity factor (1.5/15) ensures that the material once extruded to form a 3D object is stable enough to maintain the form until curing is completed. The viscosity factor (x/y) is the viscosity ratio of the viscosity of the composition at a shear rate of x/s to the viscosity at a shear rate of y/s at application temperature. Therefore, the viscosity factor (1.5/15) is the viscosity of the composition at a shear rate of 1.5/s divided by the viscosity at a shear rate of 15/s. Viscosities as described herein if not explicitly indicated otherwise, are determined using MCR302 rheometer from Anton-Paar GmbH using the method as set forth in BS EN ISO 3219:1995. Specifically, the measuring conditions are as follows: Geometry: 25 mm plate/plate geometry; Gap: 0.2 mm, F=0N, under nitrogen, 25° C., Shear rate 0.3 to 40 1/s. To determine the viscosity factor (1.5/15) the formulation is kept for 30 sec under constant shear of 1.5 s⁻¹, followed by 30 sec of constant shear with 15 s⁻¹, both in rotation mode. The viscosity factor (1.5/15) is determined by dividing the two plateau values of the viscosities at the two shear rates. The other viscosity factors can be determined accordingly.

(26) In various embodiments, the printable compositions have a viscosity factor (1.5/15) at a temperature in the range of 15° C. to 40° C., preferably 20° C. to 30° C., more preferably at 25° C. of at least 2.0, preferably at least 3.0, more preferably 4.0 or more. In other embodiments, the printable compositions have a viscosity factor (1.5/15) at a temperature in the range of 40° C. to 80° C., preferably 45° C. to 60° C., more preferably at 55° C. of at least 2.0, preferably at least 3.0, more preferably 4.0 or more.

(27) In other embodiments, the pasty epoxy composition has also a viscosity factor (5/50) at application temperature, preferably at 25° C. or 55° C., of at least 1.5, preferably at least 2.0, more preferably at least 3.0. Pasty epoxy compositions which have the desired value of this additional second viscosity factor (5/50) show a beneficial thixotropic behaviour. Especially preferred are compositions with a viscosity factor (1.5/15) greater than the viscosity factor (5/50) at application temperature, preferably at 25° C. or at 55° C.

(28) While there is principally no upper limit, it may be preferred that the viscosity factor (1.5/15) and/or the viscosity factor (5/50) at the mentioned application temperature do not exceed 100, preferably 50, more preferably 30.

(29) In preferred embodiments, the pasty epoxy composition has a viscosity at a shear rate of 1.5/s of at least 10 Pas, preferably at least 20 Pas, more preferably at least 30 Pas. In other embodiments, the pasty epoxy composition has a viscosity at a shear rate of 1.5/s of at most 2000 Pas, preferably at most 1500 Pas, more preferably at most 1300 Pas. Preferably the pasty epoxy composition has a viscosity at a shear rate of 1.5/s in the range from 10 to 2000 Pas, preferably from 20 to 1500 Pas, more preferably from 30 to 1300 Pas.

(30) As first component the pasty epoxy reactive composition comprises at least one epoxy resin. A large number of polyepoxides which have at least two 1,2-epoxy groups per molecule are suitable as epoxy resins. The epoxy equivalent of said polyepoxides may vary between 100 g/mol and 50000 g/mol, preferably between 110 g/mol and 5000 g/mol, more preferably between 130 g/mol and 2000 g/mol. The epoxy equivalent can be determined according to DIN 16945. The polyepoxides may in principle be saturated, unsaturated, cyclic or acyclic, aliphatic, alicyclic, aromatic or heterocyclic polyepoxide compounds. Examples of suitable polyepoxides include the polyglycidyl ethers, which are prepared by reacting epichlorohydrin or epibromohydrin with a polyol, like polyphenol in the presence of alkali. Polyphenols suitable for this are for example resorcinol, catechol, hydroquinone, bisphenol A (bis-(4-hydroxyphenyl)-2,2-propane)), bisphenol F (bis-(4-hydroxyphenyl)methane), bis-(4-hydroxyphenyl)-1,1-isobutane, 4,4'-dihydroxybenzophenone, bis-(4-hydroxyphenyl)-1,1-ethane, 1,5-hydroxynaphthalene. Other suitable polyphenols as a basis for the polyglycidyl ethers are the known condensation products of phenol and formaldehyde or acetaldehyde of the novolac resin type. Further polyepoxides which are suitable in principle are the polyglycidyl ethers of polyalcohols or diamines. These polyglycidyl ethers are derived from polyalcohols such as ethylene glycol, diethylene glycol, triethylene glycol,

1,2-propylene glycol, 1,4-butylene glycol, triethylene glycol, 1,5-pentanediol, 1,6-hexanediol or trimethylolpropane. Further polyepoxides are polyglycidyl esters of polycarboxylic acids, for example reaction products of glycidol or epichlorohydrin with aliphatic or aromatic polycarboxylic acids such as oxalic acid, succinic acid, glutaric acid, terephthalic acid or dimer fatty acid. Further epoxies are derived from the epoxidation products of olefinically unsaturated cycloaliphatic compounds or from natural oils and fats.

(31) In one embodiment, aliphatic epoxy resins, especially cycloaliphatic epoxy resins are preferred. Aliphatic epoxy resin, which include cyclic or acyclic resins, are especially preferred for application temperatures in the range of 15 to 40° C., while the cycloaliphatic epoxy resins are in particular preferred. In preferred embodiments, the pasty epoxy composition comprise at least one epoxy resin containing at least two 3,4-epoxycyclohexane groups, like (3',4'-epoxycyclohexane)methyl-3,4-epoxycyclohexylcarboxylate and (3',4'-epoxycyclohexane)methyl-3,4-epoxycyclohexylcarboxylate modified epsilon-caprolactone.

(32) In another embodiment, the printable composition contains at least one aromatic epoxy resin, preferably selected from epoxy resins based on Bisphenol or epoxy resins based on Novolac resins, in particular phenol-formaldehyde resins, or mixtures thereof. In a preferred embodiment the pasty composition includes at least one epoxy resin based on Bisphenol A and/or Bisphenol F. These aromatic epoxy resins are especially preferred for application temperatures in the range from 40 to 80° C.

(33) Typically the amount of the at least one epoxy resin is in the range from 2 to 50% by weight of the entire printable composition, preferably 5 to 45% by weight, in particular 10 to 40% by weight, particularly preferably 15 to 35% by weight.

(34) Additionally, the printable composition contains at least one monomer and/or prepolymer that is polymerizable by exposure to radiation. The monomers and/or prepolymers polymerizable by exposure to radiation are those comprising reactive end groups selected from the group consisting of acrylates, methacrylates, alpha-olefins, N-vinyls, acrylamides, methacrylamides, styrenics, 1,3-dienes, vinyl halides, acrylonitriles, vinyl esters, maleimides, and vinyl ethers. Preferably the monomers and/or prepolymers polymerizable by exposure to radiation contain a carbon-carbon double bond. In the most preferred embodiment the monomer and/or prepolymer that is polymerizable by exposure to radiation is selected acrylates and/or methacrylates (herein also described as (meth)acrylates), especially poly(meth)acrylates, more preferably low-molecular-weight poly(meth)acrylates. "Poly(meth)acrylate" shall be understood to mean a compound that comprises at least two acrylate groups. "low-molecular-weight" shall be understood to mean a compound that has a molecular weight of less than 2400 g/mol, and preferably less than 800 g/mol. In particular monomers and/or prepolymers polymerizable by exposure to radiation comprising two, three or more acrylate groups per molecule have proven to be advantageous, especially a combination of di- and tri(meth)acrylates.

(35) Preferred difunctional (meth)acrylates are ethylene glycol dimethacrylate, diethylene glycol dimethacrylate, triethylene glycol dimethacrylate, triethylene glycol diacrylate, tripropylene glycol dimethacrylate, 1,4-butanediol dimethacrylate, 1,3-butylene glycol dimethacrylate, 1,3-butanediol dimethacrylate, tricyclodecane dimethanol dimethacrylate, 1,10-dodecanediol dimethacrylate, 1,6-hexanediol dimethacrylate, 2-methyl-1,8-octanediol dimethacrylate, 1,9-nonanediol dimethacrylate, neopentyl glycol dimethacrylate and polybutylene glycol dimethacrylate. Also difunctional (meth)acrylate based on a phenol structure, like bisphenol, are suitable. Especially preferred are epoxylated bisphenol A and/or F di(meth)acrylates.

(36) Preferred (meth)acrylates comprising three or more acrylate groups are glycerol triacrylate, dipentaerythritol hexaacrylate, pentaerythritol triacrylate (TMM), tetramethylolmethane tetraacrylate (TMMT), trimethylolpropane triacrylate (TMPTA), pentaerythritol tetraacrylate, di(trimethylolpropane) tetraacrylate (TPMA), pentaerythritol tetraacrylate, trimethylolpropane trimethacrylate (TMPTMA), tri(2-acryloxyethyl) isocyanurate and tri(2-methacryloxyethyl)

trimellitate.

(37) Printable compositions comprising at least one poly(meth)acrylate selected from triethylene glycol diacrylate, triethylene glycol dimethacrylate, difunctional (meth)acrylate based on a phenol structure, especially epoxylated bisphenol A diacrylate, trimethylolpropane triacrylate (TMPTA) and trimethylolpropane trimethacrylate (TMPTMA), pentaerythritol triacrylate (TMM), tetramethylolmethane tetraacrylate (TMMT), pentaerythritol trimethacrylate, di(trimethylolpropane) tetraacrylate (TPMA) and pentaerythritol tetraacrylate are especially particularly preferred according to the invention.

(38) In a preferred embodiment, the at least one monomer and/or prepolymer that is polymerizable by exposure to radiation, preferably a poly(meth)acrylate, is comprised in an amount of 1 to 30 wt. %, preferably 5 to 20 wt. %, based on the total weight of the printable composition.

(39) Furthermore, pasty epoxy reactive composition comprising at least one photoinitiator.

Photoinitiators may be radical or cationic photoinitiators. Suitable compounds are well-known in the art and include, without limitation, benzoin ethers, such as benzoin methyl ether and benzoin isopropyl ether, substituted acetophenones, such as 2,2-diethoxyacetophenone, 2,2-dimethoxy-2-phenyl-1-phenylethanone, dimethoxyhydroxyacetophenone, substituted alpha-ketols, such as 2-methoxy-2-hydroxypropiophenone, aromatic sulfonylchlorides, such as 2-naphthyl sulfonyl chloride, and photoactive oximes, such as 1-phenyl-1,2-propandion-2-(O-ethoxycarbonyl)oxime. The mentioned and further suitable photoinitiators can comprise the following residues:

benzophenone-, acetophenone-, benzile-, benzoin-, hydroxyalkylphenone-, phenylcyclohexylketone-, anthrachinon-, trimethylbenzoylphosphin oxide-, methylthiophenylmorpholinketone-, aminoketone-, azobenzoin-, thioxanthone-, hexarylbisimidazole-, triazin-, or Fluorenone, wherein each of these residues may additionally be substituted with one or more halogen atoms and/or one or more alkoxy groups and/or one or more amino or hydroxy groups. Two preferred examples of a suitable photoinitiators are an oxyphenyl acetic acid ester based initiator and bis (2, 4, 6-trimethylbenzoyl)-phenyl-phosphinate.

(40) The compositions contain the photoinitiators preferably in an amount of from about 0.01 to 5.0% by weight, preferably 0.1 to 4.0% by weight, more preferably 0.5 to 3% by weight, based in each case on the total weight of the composition. If a mixture of different photoinitiators is used, the amounts refer to the total amount in the composition.

(41) In preferred embodiments, the printable epoxy composition may comprise further to the photoinitiator an epoxy curing catalyst. Suitable epoxy curing catalysts are well-known in the art and include cationic curing catalysts and latent curing catalysts.

(42) The cationic curing catalysts may be one of the commonly used for the cationic polymerizations including onium salts with anions of low nucleophilicity, such as ammonium salts, halonium salts, iodonium salts, sulfonium salts, sulfoxonium salts or diazonium salts. Suitable anions include for example hexafluoroantimonate, hexafluorophosphate or tetrakis(pentafluorophenyl) borate. Preferred are sulfonium and iodonium salts, wherein the counter ion is selected from hexafluoroantimonate, hexafluorophosphate and tetrakis(penta fluoro aryl) borates, especially triaryl sulfonium and bis(alkylphenyl) iodonium salts with hexafluoroantimonate as a counter ion, particularly preferably Triarylsulfonium hexafluoroantimonate salts. Especially preferred are cationic curing catalysts based on hexafluoroantimonate. These cationic curing catalysts are preferably combined with an aliphatic, especially cycloaliphatic epoxy resin.

(43) The compositions contain the cationic curing catalyst preferably in an amount of from about 0.01 to 5.0% by weight, preferably 0.1 to 4.0% by weight, more preferably 0.5 to 2% by weight, based in each case on the total weight of the composition.

(44) In some embodiments, the epoxy composition comprises a latent hardener as epoxy curing catalyst, especially in combination with aromatic epoxy resins. As heat-activatable or latent curing catalyst for the epoxy resin use may be made of guanidines, substituted guanidines, substituted

ureas, melamine resins, guanamine derivatives, cyclic tertiary amines, aromatic amines and/or mixtures thereof. The curing agents may be stoichiometrically included in the curing reaction. However, they may also be catalytically active. Examples of substituted guanidines are methyl guanidine, dimethyl guanidine, trimethyl guanidine, tetramethyl guanidine, methyl isobiguanidine, dimethyl isobiguanidine, tetramethyl isobiguanidine, hexamethyl isobiguanidine, heptamethyl isobiguanidine and, most particularly, cyanoguanidine (dicyanodiamide). As representatives of suitable guanamine derivatives, mention may be made of alkylated benzoguanamine resins, benzoguanamine resins or methoxymethyl ethoxymethyl benzoguanamine. Dicyandiamide is particularly suitable.

(45) The compositions contain the latent curing catalyst preferably in an amount of from about 0.01 to 10% by weight, preferably 1 to 8% by weight, more preferably 2 to 7% by weight, based in each case on the total weight of the composition.

(46) In addition to or instead of the aforementioned curing catalyst, use may be made of catalytically active substituted ureas. These are, in particular, p-chlorophenyl-N,N-dimethyl urea (Monuron), 3-phenyl-1,1-dimethyl urea (Fenuron) or 3,4-dichlorophenyl-N,N-dimethyl urea (Diuron). In principle, use may also be made of catalytically active tertiary acryl- or alkylamines, such as for example benzyl dimethyl amine, tris(dimethylamino)phenol, piperidine or piperidine derivatives. Furthermore, use may also be made of various, preferably solid, imidazole derivatives as catalytically active accelerators. As representatives, mention may be made of 2-ethyl-2-methylimidazole, N-butylimidazole, benzimidazole and N—C1-12-alkylimidazoles or N-arylimidazoles. Particular preference is given to the use of a combination of curing agent and accelerator in the form of so-called accelerated dicyandiamides in finely ground form. Especially preferred is a combination of dicyandiamide and fenuron.

(47) In some embodiments, the printable composition may contain additionally a dual reactive compound. In general, such a dual reactive compound comprises: (i) a first reactive group reactive with the monomers and/or prepolymers that are polymerizable by exposure to radiation, and (ii) a second reactive group reactive with the epoxy resin. One or more of each reactive group may be included.

(48) Examples of suitable first reactive groups include, but are not limited to, acrylates, methacrylates, alpha-olefins, N-vinyls, acrylamides, methacrylamides, styrenics, thiols, 1,3-dienes, vinyl halides, acrylonitriles, vinyl esters, maleimides and vinyl ethers. Examples of suitable second reactive groups include, but are not limited to, epoxy, amine, isocyanate, alcohol and anhydride groups.

(49) Thus, particular examples of suitable dual reactive compounds include compounds of the general formula $(X)_nR(X')_m$, wherein: X is the first reactive group, X' is the second reactive group, n and m are each integers of from 1 or 2 to 10 or 20, and R is a hydrocarbyl or organic group (e.g., an aromatic, aliphatic, or mixed aromatic and aliphatic group, such as bisphenol A). Particular examples include but are not limited to epoxy acrylates and epoxy methacrylates. In a preferred embodiment, the dual reactive compound, preferably an epoxy (meth)acrylate, is comprised in an amount of 1 to 20 wt. %, preferably 5 to 15 wt. %, based on the total weight of the printable composition.

(50) In various embodiments, the composition comprises at least one compound having at least one oxetane group, preferably 1 to 4, in particular 1 to 2, particularly preferably exactly two oxetane groups per molecule. "Oxetane group" as used herein refers to a four-membered ring having an oxygen atom. In addition to the oxetane group, these compounds may also have at least one hydroxyl group, preferably 1 to 4, in particular 1 to 2, particularly preferably exactly one hydroxyl group per molecule. The compound having at least one oxetane group is preferably a monomeric compound. The at least one compound having at least one oxetane group preferably has a molecular weight of less than 1000 g/mol, preferably less than 500 g/mol, preferably less than 400 g/mol. Preferred examples of such compounds include tetraphthalate-bisoxetane, and biphenylene-

bisoxetane.

(51) In a preferred embodiment, the oxetane is comprised in an amount of 1 to 20 wt. %, preferably 5 to 15 wt. %. based on the total weight of the printable composition.

(52) In a preferred embodiment, the pasty epoxy composition contains at least one organic hardener co-polymerizable with said epoxy resin. Any suitable hardener for epoxy resins may be used. In some embodiments, the hardener is selected from an amine, a polyamine (e.g., an aromatic amine or polyamine, a cycloaliphatic amine or polyamine, an aliphatic amine or polyamine such as a polyether amine), an acid, polyacid (i.e. polycarboxylic acids), an anhydride, an alcohol, an polyol, a thiol or a polythiol. Especially preferred are alcohols and polyols, in particular containing primary hydroxyl groups. These preferably have a functionality of at least 1, preferably at least 2, are preferably free from groups that can inhibit the curing reaction and preferably only contain OH groups as reactive groups. The alcohol can be aliphatic or aromatic compounds. Examples are polyester polyols, polyether polyols and polyester/polyether polyols, hydroxyl-functionalized polybutadienes, polycaprolactone diols or triols, and ethylene/butylene polyols. The used alcohols, preferably polyols used as hardener may have a number-average molecular weight of 200 to 5000, preferably 300 to 2500 g/mol (determinable by means of GPC against a polystyrene standard).

(53) In a preferred embodiment, the organic hardener, preferably a polyol, is comprised in an amount of 1 to 20 wt. %, preferably 5 to 15 wt. %. based on the total weight of the printable composition.

(54) In some embodiments, the printable composition may further comprise core-shell particles, especially core-shell rubbers (CSRs). These core-shell particles can be used to improve the mechanical properties of the printed part, especially the toughness. In principle all known core-shell particles could be used. In various embodiments of the invention the core-shell rubbers can be dispersed in a resin matrix, in particular an epoxy resin matrix. The epoxy resin matrix can be chosen from the above described epoxy resins, in particularly preferred embodiments, the epoxy resin matrix for the CSR is similar to the used epoxy resin for the printable composition, e.g. a cycloaliphatic epoxy resin as matrix resin in case the printable compositions contains a cycloaliphatic epoxy resin. If the core-shell rubbers are present in an epoxy resin matrix, the amount of epoxy resin counts towards the proportion of the total epoxy resins in the composition. In various embodiments the polymer, which forms the shell of the core-shell rubber, has a sufficient affinity for the epoxy resin used as matrix and/or base resin, such that the core-shell rubber particles are present in the epoxy resin as primary particles, dispersed in a stable manner.

(55) In preferred embodiments, both the core and the shell of the core-shell rubber consists of a polymer having glass transition temperatures preferably less than 0° C., preferably -30° C. or lower. The glass transition temperature can be determined by means of DSC (in accordance with DIN EN ISO 11357 at a heating rate of 10° C./min). The core-shell rubber particles preferably have a size of 0.03 to 50 µm, particularly preferably 1 to 20 µm, even more particularly preferably of less than 5 µm. A core-shell rubber particle usually even has an average diameter of just 500 nm or less than 200 nm, i.e. approximately 25 to 22 nm or 50 to 150 nm.

(56) The core material of a CSR preferably consists of a diene homopolymer or a copolymer having elastomeric properties, such as a homopolymer of butadiene or isoprene, a copolymer of butadiene or isoprene with one or more ethylenically unsaturated monomer(s), such as vinyl aromatic monomer(s), (meth)acrylonitrile and/or (meth)acrylate. Preferred polymers as core material are selected from polybutadiene, polybutyl acrylate, polydimethylsiloxane, polyacrylates, polymethacrylates, poly(meth)acrylic acids and poly(meth)acrylic esters and co- or terpolymers thereof with polystyrene, polyacrylonitrile or polysulfide, more particularly preferably from polybutadiene, polydimethylsiloxane or polybutyl acrylate. Elastomeric polysiloxanes, such as polydimethylsiloxane or crosslinked polydimethylsiloxane, are also suitable as core material. The diene homo- and copolymers already disclosed above as core material are preferably also used as shell material.

(57) If a polymer or a copolymer not having elastomeric properties (preferably a thermoplastic or thermoset/crosslinking polymer) is to be used as shell material, polymers of this type are selected for example from polystyrene, poly(meth)acrylamide, polyacrylonitrile, polyacrylate mono-, co- or terpolymers, polymethacrylate mono-, co- or terpolymers or styrene/acrylonitrile/glycidyl methacrylate terpolymers, or from a polymer or a copolymer from among one or more monomers of unsaturated acids and anhydrides (for example acrylic acid).

(58) The core-shell rubber particles can consist of a number of layers, for example more than two layers. A CSR of this type preferably has a central core, which consists of a first diene homopolymer or copolymer having elastomeric properties, which is enclosed by a second core formed from a second (different) diene homopolymer or copolymer, likewise having elastomeric properties.

(59) In various embodiments of the present invention the used CSRs have a core and at least two concentric shells having different chemical compositions and/or properties. Particles which have a core formed from polybutadiene and a shell formed from polybutadiene, polystyrene or a polybutadiene-polystyrene copolymer are preferred. Suitable CSRs are commercially obtainable for example from Kaneka and are present in the form of phase-separated particles dispersed in epoxy resins. These particles have a core formed from a copolymer of (meth)acrylate-butadiene-styrene, wherein butadiene is the primary component of the copolymer. Further commercially obtainable masterbatches of core-shell rubber particles dispersed in epoxy resins are, for example, the product Genioperl M23A from Wacker (a dispersion of 30 wt % CSR in an aromatic epoxy resin based on bisphenol A diglycidyl ether; the CSRs have an average diameter of approximately 100 nm and contain a core formed from elastomeric crosslinked silicone, onto which an epoxy-functional acrylate copolymer has been grafted).

(60) In various embodiments, the printable composition preferably contains 1 to 15 wt. %, preferably 2 to 10 wt. %, based on the total weight of the printable composition, of at least one of the above-described core-shell rubbers.

(61) All printable compositions described herein may comprise at least one filler. The at least one filler, may, without limitation, be selected from chalk, powdered limestone, silica, such as precipitated and/or fumed silica, zeolites, bentonites, magnesium carbonate, kieselguhr, alumina, clay, tallow, titanium oxide, iron oxide, zinc oxide, sand, quartz, flint, mica, powdered glass and other ground minerals. In preferred embodiments, the filler(s) are precipitated and/or fumed silica. Furthermore, organic fillers can also be used, in particular carbon black, graphite, wood fibers, wood flour, sawdust, cellulose, cotton, pulp, wood chips, chopped straw, chaff, ground walnut shells and other short-cut fibers. Furthermore, short fibers such as glass fibers, glass filament, polyacrylonitrile, carbon fibers, Kevlar fibers or polyethylene fibers can also be added. Aluminum powder is also suitable as a filler. In addition, hollow spheres with a mineral shell or a plastic shell are suitable as fillers. These can be e.g. hollow glass spheres which are commercially available with the trade names Glass Bubbles®. Plastic-based hollow spheres are commercially available, e.g. with the names Expancel® or Dualite®. These are composed of inorganic or organic substances, each with a diameter of 1 mm or less, preferably of 500 µm or less. Generally, fillers which make the preparations thixotropic are preferred. These fillers are also described as rheological auxiliaries.

(62) The filler(s) are preferably used in a quantity of 1 to 90 wt. %, preferably 5 to 30 wt. %, based on the total weight of the composition according to the invention. An individual filler or a combination of several fillers can be used.

(63) In various embodiments, the filler comprises silica. For example, a highly disperse silica with a BET surface area (DIN ISO 9277; DIN 66132) of 10 to 500 m²/g can be used as a filler. The use of such a silica may contribute to reinforcing the hardened preparation. By means of this reinforcement, for example the initial strengths and tensile shear strengths of the hardened composition may be improved. Preferably, coated silicas with a BET surface area of 100 to 400,

liquid, Epoxy Equivalent 187 g/eq Oxetane Bis(3-ethyl-3-oxethanyl)methoxymethyl)biphenyl CSR 1 30% CSR (vinyl acrylic copolymer) in liquid cycloaliphatic epoxy resin CSR 2 methacrylate-butadiene-styrene core-shell CSR 3 40% CSR in unmodified liquid epoxy resin based on bisphenol A Polyol 1 Polyethylene glycol, molecular weight 400 g/mol Polyol 2 Polyol, OH value 1-1.15 eq/kg GLYMO 3-Glycidyloxypropyltrimethoxysilan Epoxy Liquid epoxy methacrylate resin based Acrylate 1 on bisphenol A diglycidylether Epoxy Liquid EPOXY ACRYLATE OLIGOMER Acrylate 2 Triacrylate TRIMETHYLOLPROPANE TRIACRYLATE (TMPTA) Diacrylate ETHOXYLATED BISPHENOL A DIACRYLATE Cationic curing Catalyst based on hexafluoroantimonate catalyst Photoinitiator 1 Mixture of Oxyphenyl-acetic acid 2-(2-oxo-2-phenyl-acetoxy-ethoxy)- and Oxyphenyl-acetic acid 2-[2-hydroxy-ethoxy]-ethyl ester Photoinitiator 2 Bis(2,4,6-Trimethylbenzoyl)phenylphosphine oxide

Claims

1. A method for additive manufacturing a three-dimensional part in a layer-by-layer manner, the method comprising: (i) providing a carrier substrate to support the three-dimensional part and a print head connected to a reservoir of a printable composition; (ii) printing the printable composition with the print head in the form of extrudate strands onto the carrier substrate to form a first layer; (iii) printing the printable composition with the print head in the form of extrudate strands onto the first layer to form a second layer; (iv) optionally repeating step (iii) one or more times to form a third layer or the third layer and subsequent layer(s); (v) exposing the formed layers to radiation directly after forming each layer and/or after forming all of the layers; and (vi) curing the formed layers of the printable composition by heating to obtain the three-dimensional part, wherein the printable composition is a pasty epoxy composition comprising: at least one epoxy resin; at least one monomer and/or prepolymer that is polymerizable by exposure to radiation; at least one photoinitiator; and at least one adhesion promoter, wherein: the pasty epoxy composition has a first viscosity factor (1.5/15) of at least 4 and a second viscosity factor (5/50) at an application temperature, the pasty epoxy composition has a viscosity at a shear rate of 1.5/s of at least 10 Pas, and the first viscosity factor (1.5/15) is greater than the second viscosity factor (5/50).
2. The method of claim 1, wherein the distance of the print head to the carrier substrate or an already formed layer is equal to or greater than the thickness of the printed extrudate strands.
3. The method of claim 1, wherein the second viscosity factor (5/50) at the application temperature is at least 3.
4. The method of claim 1, wherein the application temperature is in a range of from 15° C. to 80° C.
5. The method of claim 1, wherein the viscosity at the shear rate of 1.5/s is at least 20 Pas.
6. The method of claim 1, wherein the at least one epoxy resin comprises an aliphatic epoxy resin.
7. The method of claim 1, wherein the at least one monomer and/or prepolymer that is polymerizable by exposure to radiation is selected from the group consisting of di-acrylates, tri-acrylates and mixtures thereof.
8. The method of claim 1, wherein the printable composition further comprises an epoxy curing catalyst.
9. The method of claim 1, wherein the printable composition further comprises a dual reactive compound.
10. The method of claim 1, wherein the printable composition further comprises at least one compound having at least one oxetane group.
11. The method of claim 1, wherein the pasty epoxy composition further comprises at least one organic hardener co-polymerizable with the at least one epoxy resin.
12. The method of claim 1, wherein the pasty epoxy composition further comprises core-shell particles.

13. The method of claim 1, wherein the radiation is ultraviolet (UV) radiation.
 14. The method of claim 5, wherein the viscosity at the shear rate of 1.5/s is at least 30 Pas.
 15. The method of claim 1, wherein the at least one epoxy resin is a polyepoxide having an epoxy equivalent of between 110 g/mol and 5000 g/mol.
 16. The method of claim 1, wherein the at least one epoxy resin is a polyepoxide having an epoxy equivalent of between 130 g/mol and 2000 g/mol.
 17. The method of claim 4, wherein the application temperature is 25° C.
 18. The method of claim 4, wherein the application temperature is 55° C.
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