



(72) DRÖSCHER, Michael, DE

(72) SCHMIDT, Friedrich Georg, DE

(71) HÜLS AKTIENGESELLSCHAFT, DE

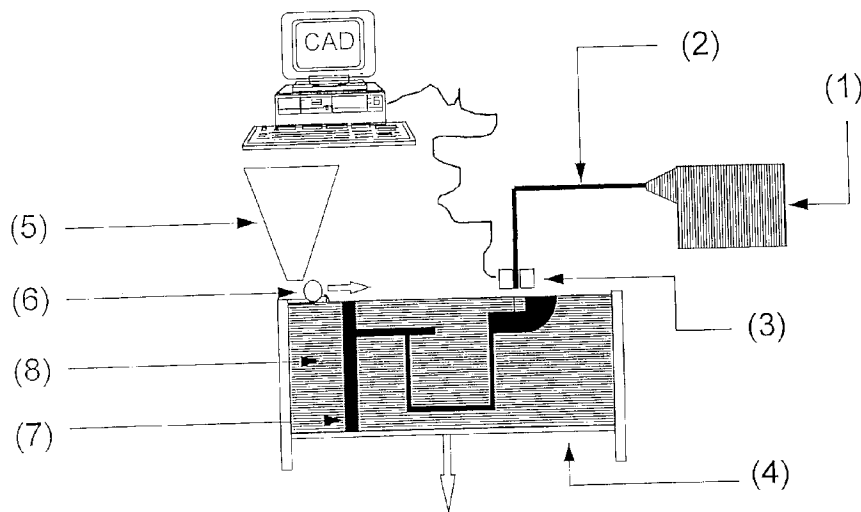
(51) Int.Cl.⁶ B29C 41/32

(30) 1997/06/30 (197 27 677.6) DE

(54) **METHODE DE PRODUCTION D'OBJETS**

TRIDIMENSIONNELS ET APPAREIL CORRESPONDANT

(54) **METHOD AND DEVICE FOR PRODUCING THREE-
DIMENSIONAL OBJECTS**



(57) Cette invention concerne une méthode de production d'un objet tridimensionnel et l'appareil correspondant. Une couche de matériau pulvérulent formé, par exemple, de particules d'un polymère ou d'un monomère polymérisable est irradiée par une source hyperfréquence. L'appareil comprend un générateur d'ondes hyperfréquences et, au choix, un plateau où disposer la couche de matériau à traiter. Il comprend aussi un dispositif servant à déposer la couche à traiter sur le plateau et un émetteur d'ondes hyperfréquences mobile selon l'axe des x et l'axe des y, ou dans toutes les directions, le plateau étant mobile selon l'axe des z ou fixe. L'utilisation d'ondes hyperfréquences au lieu d'autres sources d'énergie, le laser par exemple, permet d'éviter les surchauffes localisées.

(57) Disclosed are a method and an apparatus for producing a three-dimensional object. A pulverulent substrate, such as particular polymer or polymerizable monomer is treated by means of microwave radiation. The apparatus includes a microwave generator, and optionally a table for disposing the pulverulent substrate, a device for applying the pulverulent substrate and a transmitting unit for radiating microwave. The transmitting unit is movable in the x, y-plane or in all directions and the table is movable in the z-axis or is stationary. Because microwave is used as opposed to other energy source such as laser, local overheating may be avoided.

ABSTRACT OF THE DISCLOSURE

Disclosed are a method and an apparatus for producing a three-dimensional object. A pulverulent substrate, such as particular polymer or polymerizable monomer is treated by means of microwave radiation. The apparatus includes a microwave generator, and optionally a table for disposing the pulverulent substrate, a device for applying the pulverulent substrate and a transmitting unit for radiating microwave. The transmitting unit is movable in the x,y-plane or in all directions and the table is movable in the z-axis or is stationary. Because microwave is used as opposed to other energy source such as laser, local overheating may be avoided.

METHOD AND DEVICE FOR PRODUCING THREE-DIMENSIONAL OBJECTSField of the Invention

The invention relates to a method and an apparatus for producing three-dimensional objects.

Background Art

10 The traditional development process for a product involves the diagrammatic stages of drawing - model - model refinement - design - prototype - small-scale production - large-scale production. Such a process is too slow for the product cycles of industrial manufacture, which are becoming ever shorter.

Methods have therefore been developed in order to bring products on more quickly and with the avoidance of intermediate handcrafted stages from a design drawing to a prototype or to small-scale production. These methods are frequently summarized under the terms of "rapid prototyping" or "fast free form manufacturing".

20 By contrast with shaping methods, such as milling or casting, in rapid prototyping systems, three-dimensional objects are automatically manufactured without the use of means such as molds by controlled and locally limited chemical reactions (for example polymerization) or physical conversion (smelting/solidification) from preliminary stages of the respective material.

Some rapid prototyping systems are already in industrial use and may be briefly sketched. They may be roughly classified as follows.

1) Selective laser sintering

In the laser sintering method (A. Gebhardt, "Rapid prototyping: Werkzeug für Schnelle Produktentwicklung" ["Rapid prototyping: A tool for rapid product development"], Hauser Verlag, Munich, Vienna 1996), pulverulent materials, usually plastics, are fused in layers by a laser to form an object. The powders used are preheated to just below the melting point of the material. The powders are fused (sintered) with one another by the action of the laser beam. The layer produced is then lowered by means of a suitable device, and a new layer of powder is applied to the already hardened layer and is in turn processed by the laser to produce the next object layer. The advantage of this technique is that it can be applied widely since, at least theoretically, any meltable pulverulent materials can be used. A disadvantage is the very rough surface of the objects produced and the fact that it is difficult to set the energy output of the laser. High laser energies do not lead to a sintering operation but to undesired complete melting of the powder grains, that is to say to a far reaching loss of the shaping properties. Excessively low energies particularly have the effect of fusing the layers to one another inadequately, with the result that the mechanical stability of the product produced is defective.

2) Thermal stereolithography

U.S. Patents 5,121,329 and 5,141,680 disclose methods in which a thermoplastic material is applied in layers by means of a nozzle. The material is applied, in a fashion capable of being shaped as a liquid or at least plastically,

from the nozzle onto a support structure or onto already cooled layers, and solidifies in the desired shape. U.S. Patent 4,665,492 describes a similar method. Here, the liquified material is applied by means of at least two independent particle canons.

The extreme difficulty of controlling the resolution of detail is disadvantageous in these methods.

3) Stereolithography/photopolymerization

10 In methods of photopolymerization (A. Gebhardt, "Rapid prototyping: Werkzeug für Schnelle Produktentwicklung" ["Rapid prototyping: A tool for rapid product development"], Hauser Verlag, Munich, Vienna 1996), liquid monomers or oligomers are crosslinked to form a solid polymer under the action of UV radiation. The most free-radical polymerization can be initiated and terminated again by the decomposition of a photoinitiator. Use is made as monomers of acrylate mixtures or epoxy resins, and as light sources, UV lasers or UV lamps with a mask stop.

20 The object is also built up in layers. After one layer has been produced photochemically and polymerized out, new monomer is applied to the existing layer and induced to polymerize by radiation. The application of the new monomer layer can, for example, be performed by lowering the cured layer in a storage tank of the monomer. This method permits three-dimensional objects with complex cavities to be produced. Supplying energy by a laser is a problem, since the injected energy depends on the depth of penetration, that is to say the surface energy of the laser, the optical properties

of the monomer mixture and the wavelength of the laser radiation employed.

The rapid prototyping methods described in the prior art have the common disadvantage that it is difficult to control the supply of energy, whether for melting powder particles or for initiating chemical reactions. This control is particularly problematic in the case of relatively large layer thicknesses, since the local energy intensity depends strongly on the depth of penetration. Relatively large local energy intensities such as are required for relatively large depths of penetration are, however, only connected with a relatively high thermal loading, or loading due to radiation chemistry, of the material employed. Higher energy intensities or a corresponding lengthening of the time over which energy is supplied are frequently not desirable with regard to thermally unstable materials.

Summary of the Invention

A primary object of the present invention is to provide a rapid prototyping method for producing three-dimensional objects, using energy for shaping which is largely independent of thermal loading and/or loading due to radiation chemistry of a substrate.

Surprisingly, it has been found that the energy required to produce three-dimensional objects in layers in rapid prototyping systems can be supplied by microwave radiation.

The present invention therefore provides a method for producing a three-dimensional object in layers, wherein

energy required to produce the three-dimensional object is supplied by microwave radiation.

The method according to the invention permits a three-dimensional object to be built up in layers automatically by microwave irradiation of a suitable substrate.

Furthermore, the present invention provides an apparatus for producing a three-dimensional object made up of layers, which comprises a microwave generator which supplies
10 the energy required to produce the three-dimensional object.

In an embodiment of the apparatus according to the invention, the energy required to produce the three-dimensional object is directed in the form of microwave radiation onto a substrate via a device which can move in all directions in space.

In another embodiment of the apparatus according to the invention, the energy required to produce the three-dimensional object is directed, via a device which can move in the x,y-plane, in the form of microwave radiation onto a
20 substrate which is located on or in a device which can move in the z-direction.

The method according to the invention is preferably designed such that the layers generated in the production of the three-dimensional object are interconnected.

This can be performed, for example, by partially fusing the layers, by simple adhesion of the layers with one another or by graft polymerization.

Brief Description of the Drawings

Fig. 1 is a schematic diagram showing a preferred embodiment of the method according to the present invention.

Description of Preferred Embodiments

The first step in the method according to the invention is to provide geometrical information of the required three-dimensional object to be produced. This can be performed by computer-aided compilation of a design plan or by measuring an object to be reproduced and subsequently
10 processing the data thus obtained with the aid of CAD (Computer Aided Design) programs which are often commercially available such as, for example, AUTOCAD. This information must now be converted, preferably using the same CAD program, into a layer model with a layer thickness which depends on the desired precision of the object to be produced ("slicing"). This process is not limited only to generating mathematical layers, but may also comprise introducing support functions for structurally weak components or compounds found in
cavities, because of the method. The layers thus produced are
20 normally 0.1 to 3 mm thick and represent the actual structural information for the manufactured unit.

One preferred embodiment of the present invention is described with reference to Figure 1.

A microwave generator (1) supplies the microwave radiation via a guidance system (2) to an arm, which can be moved in the x,y-plane and supports a transmitting unit (3) for the microwave radiation. The transmitting unit (3), constructed as a microwave probe, can (optionally) include

means for focusing of the microwave radiation. A table (4) (typically a horizontal table), which can move on the z-axis, can be lowered in accordance with the desired layer thickness calculated in the slicing process, while the movable arm (3) coordinates the distribution of the microwave radiation in the plane of the table. A pulverulent substrate taken from a storage tank (5) is applied in a defined layer thickness in the plane of the table by means of a doctor knife (6). The microwave probe (3) then transmits the microwave radiation and thereby generates in layers the three-dimensional object (7), which is surrounded by the non-converted pulverulent substrate (8). The substrate (8) not required can be reused, optionally after preparation (for example screening).

In another variant of the present invention, the table is of stationary design, while the arm supporting the transmitting unit for the microwave radiation can move in all directions in space.

The movable parts of the device (microwave probe (3) and table (4)) are preferably controlled by the CAD program or an additional program, which converts the CAD data into an appropriate industrial robot technique.

The microwave radiation required for the method according to the invention may be generated by an external microwave generator and may be in the frequency range of 300 MHz to 300 GHz. The frequencies used in industrial processes and requiring government clearance are usually 430 to 6800 MHz (Encyclopedia of Chemical Processing and Design, Vol. 30, p. 202 ff, Marcel Dekker, N.Y. -Basel, 1989). The radiation

emanating from the external microwave transmitter is possibly polarized and/or filtered and supplied to the substrate via the movable arm. Metal tubes or glass or plastic tubes metal-vapor-deposited inside and/or outside (Encyclopedia of Science & Technology, McGraw-Hill, vol. II, p. 159 ff., 6th Edition 1987) are especially suited for the transport of microwave radiation. The transport of the microwave radiation is preferably performed in flexible pipes. However, box-shaped guidance systems may also be used. The diameter of the tubes should be selected such that the circumference is larger than the wavelength of the microwave radiation employed. The movable arm thus functions as the microwave probe and may optionally have devices for focusing the microwave radiation.

A microwave radiation in the frequency range of 430 to 6800 MHz is preferably used in the method according to the invention.

The microwave radiation is preferably focused onto a beam width of 0.1 to 3 mm, particularly preferably 0.3 to 1 mm.

The beam width simultaneously fixes the minimum web widths of the three-dimensional objects.

In an embodiment of the method of the present invention, the three-dimensional objects are produced by microwave-induced fusion of a pulverulent substrate.

This method according to the invention may be carried out using an apparatus by means of which the three-dimensional objects are produced by microwave-induced fusion of a pulverulent substrate.

The pulverulent substrate preferably has a grain size of 50 to 100 μm , and is preferably made of a polymer.

In addition to the table and the movable arm which is designed as a microwave probe, the apparatus according to the invention may have a device for applying a defined quantity of the substrate powder to the object plane. This can be performed for example, by means of an application roller, a doctor knife and/or a movable storage tank (see Figure 1). The application of a uniform layer thickness is
10 important for the quality of the object produced.

In the method according to the invention, it is possible to use any pulverulent substrate which is fusible by heat generated by microwave radiation, that is to say, having a dipolar basic structure. This includes polymers such as polyesters, polycarbonates, polyamides, polyurethanes and/or ABS copolymers (acrylonitrile-butadiene-styrene copolymers), but also ceramic or metal powders coated with these polymers. Polyolefins or polystyrene are less suitable.

The pulverulent substrates used preferably have an
20 adequate flowability in the heated state and a monomodal or bimodal grain size distribution. Nylon 12 powder commercial available under the trademark VESTOSINT® (Hüls AG, Marl), for example, is particularly desirable.

Preferably, the method according to the invention contains the following steps, which are repeated cyclically until a predetermined number of layers are formed,

- application of a defined layer of substrate powder,
- microwave irradiation to a desired area of this layer

by means of the microwave probe to fuse the substrate in the desired area, thereby producing a layer of the object which is firmly connected to an object layer which optionally has already been produced, and

- lowering of the table by one layer thickness.

If the movable arm, which is designed as a microwave probe, can move in all directions in space, the table can be permanently installed. This method contains the following cycle:

- 10 - application of a defined layer of substrate powder,
- microwave irradiation to a desired area of this layer by means of the microwave probe to produce a layer of the object which is optionally firmly connected to an already produced object layer, and
- raising of the microwave probe by one layer thickness.

20 In order to avoid possible undesired chemical reactions, the operation is preferably carried out in an atmosphere of an inert gas such as argon or nitrogen while excluding oxygen and water. When the used substrates are not attacked by water, water adhering can act as a thermal transmitter and thus further improve the heat flow.

The energy injection required to fuse the pulverulent substrate can be minimized by preheating the powder to a few degrees (i.e., 2 to 5°C) below the melting point or glass transition temperature of the substrate.

In a further embodiment of the method of the present invention, the material of a three-dimensional object is obtained by a microwave-induced polymerization. This

embodiment of the present invention is carried out by using an apparatus by means of which the material of the three-dimensional object is obtained by microwave-induced polymerization. In this embodiment, a monomer or suitable prepolymer is polymerized locally in layers, optionally using an initiator, by microwave radiation. The layers obtained in this way are polymerized with one another to form a strong bond, and thus build up the three-dimensional object.

10 In this embodiment, the table of the apparatus according to the invention is preferably constructed inside a monomer reservoir so that the layer thickness produced is a function of a level of the monomer mixture above the plane of the table.

This embodiment of the method according to the invention includes the following steps, which are repeated cyclically:

- lowering the table by a defined measure below the surface of the monomer, and

20 - microwave irradiation of this layer by means of the microwave probe to a desired area of the layer to polymerize, thereby producing a layer of the object which is strongly bonded to an object layer which has optionally been produced in a similar manner.

A possible alternative method consists in abandoning a movable table and using a microwave probe which can be moved in all directions in space. The monomer is supplied so as to produce a layer of the monomer over the object to be produced which corresponds to the desired layer thickness.

This method includes the following cycle:

- application of a defined layer of a monomer,
- microwave irradiation of this layer by means of the microwave probe, in order to produce a layer of the object which is strongly bonded to an object layer which has optionally already been produced, and
- raising the microwave probe by one layer thickness.

The monomers used for the microwave-induced polymerization can, for example, contain the following monomers: acrylates, vinyl ethers and epoxy resins as well as suitable initiators such as, for example, azobisisobutyronitrile, benzoyl peroxide and other initiators, which have a decomposition half life period in the range of seconds under the operating temperatures.

Furthermore, instead of the monomer mixture, polymerizable oligomers or prepolymers made from these monomers may be employed.

In the case of free-radical polymerizations, in particular, work should be done under an inert gas such as nitrogen or argon, or with the exclusion of oxygen and water.

The complete curing of the object can be carried out optionally after conclusion of the shaping steps under UV radiation.

The method of microwave radiation according to the invention has the following advantages by comparison with, for example, laser irradiation.

(1) The substrate is heated by direct absorption of the radiation ("internal friction") and not purely thermally.

Local overheating can thus be avoided.

(2) The depth of penetration of the microwaves is a function only of the dielectric properties and not of optical characteristics of the substrate. Fillers can thus be added without a problem. It is also possible to realize larger depths of penetration than in the case of laser methods.

(3) Lasers of sufficient power (e.g., CO₂ lasers or YAG lasers) are very expensive. Their power output can be regulated only in narrow frequency ranges and intensities.

10 Microwave generators are of simple design, and are therefore cost-effective and their power output can be regulated over wide ranges by duplexers or amplifiers.

To the person skilled in the art, knowledge of the concept of the invention opens up further embodiments of the method according to the invention and of the apparatus according to the invention.

The invention is explained in more detail by the following example, without being limited thereto.

EXAMPLE

20 A beaker-shaped sample with the dimensions of diameter 5 cm, height 10 cm and wall thickness 2 mm and made of nylon-12 powder (VESTOSINT®, Hüls Company, Marl) was produced in the apparatus described in Figure 1.

A 2 mm thick plastic tubelet (wall thickness 0.2 mm), which is metallized on the inner side and positioned in the x/y-plane, was used as wave guide. The apparatus was purged with dry nitrogen, and had an operating temperature of 160°C. The frequency of the microwave generator was 2450 MHz.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method for producing a three-dimensional object in layers, wherein energy required to produce the three-dimensional object is supplied by microwave radiation.

2. The method as claimed in claim 1, wherein the layers generated in the production of the three-dimensional objects are interconnected.

3. The method as claimed in claim 1 or 2, wherein the three-dimensional object is produced by microwave-induced fusing of a pulverulent substrate.

4. A method for producing a three-dimensional object made up of a predetermined number of layers, the method comprising:

(a) applying a layer of desired thickness of a pulverulent substrate which is fusible by microwave radiation;

(b) supplying microwave radiation to a desired area of the layer to fuse the pulverulent substrate within the desired area; and

(c) repeating steps (a) and (b) until the three dimensional object has the predetermined number of fused layers.

5. The method of claim 4 wherein the layers are fused to one another.

6. The method as claimed in any one of claims 3 to 5, wherein the pulverulent substrate has a grain size of 50 to 100 μm .
7. The method as claimed in any one of claims 3 to 6, wherein the pulverulent substrate comprises a polymer.
8. The method as claimed in any one of claims 3 to 7 wherein the pulverulent substrate comprises polyesters, polycarbonates, polyamides, polyurethanes and/or acrylonitrile-butadiene-styrene copolymers.
9. The method of any one of claims 3 to 8 wherein the pulverulent substrate comprises nylon-12 powder.
10. The method of any one of claims 3 to 9 wherein the pulverulent substrate is preheated to about 2 to 5°C below its melting point or glass transition temperature prior to exposure to microwave radiation.
11. The method as claimed in claim 1 or 2, wherein the material of the three-dimensional object is obtained by microwave-induced polymerization of a polymerizable material.
12. A method for producing a three-dimensional object made up of a predetermined number of layers, the method comprising:
- (a) apply a layer of desired thickness of a

polymerizable monomer or prepolymer which is polymerizable by microwave radiation;

(b) supplying microwave radiation to a desired area of the layer to polymerize the polymerizable material within the desired area; and

(c) repeating steps (a) and (b) until the three-dimensional object has the predetermined number of polymerized layers.

13. The method of claim 12 wherein the layers are chemically bonded to one another.

14. The method as claimed in claim 11, 12 or 13, wherein the polymerizable material comprises monomers selected from acrylates, vinyl ethers, epoxy resins, and mixtures thereof.

15. The method as claimed in any one of claims 11 to 14, wherein the polymerizable material also comprises a free radical initiator.

16. The method as claimed in any one of claims 1 to 15, wherein the microwave radiation is in the frequency range of 430 to 6800 MHz.

17. The method as claimed in any one of claims 1 to 16, wherein the microwave radiation is focused onto a beam width of 0.1 to 3 mm.

18. The method as claimed in claim 17, wherein the microwave radiation is focused onto a beam width of 0.3 to 1 mm.

19. The method of any one of claims 1 to 18, wherein an inert gas blanket is supplied to the layers.

20. An apparatus for producing a three-dimensional object in layers, which comprises a microwave generator for supplying energy in the form of microwave radiation required to produce the three-dimensional object.

21. The apparatus as claimed in claim 20, further comprising a device through which the microwave radiation is directed onto a substrate and which can move in all directions in space.

22. The apparatus as claimed in claim 20, further comprising a device which can move in the x,y-plane and through which the microwave radiation is directed onto a substrate that is located on or in a device which can move in the z-direction.

23. The apparatus as claimed in any one of claims 20 to 22, wherein the three-dimensional object is produced by microwave-induced fusing of a pulverulent substrate.

24. The apparatus as claimed in any one of claims 20 to 22, wherein the material of the three-dimensional object is obtained by microwave-induced polymerization.

25. An apparatus for producing a three-dimensional object made up of layers, comprising:

(a) a horizontal table for disposing a layer of a substrate which is a pulverulent polymer fusible by microwave radiation or is a monomer or prepolymer polymerizable by microwave radiation;

(b) a device for applying a defined quantity of the substrate on the table;

(c) a microwave generator;

(d) a transmitting unit for radiating microwave to the substrate layer on the table,

wherein either (i) the transmitting unit is movable in the x,y-plane and the table is movable in the z-axis or (ii) the transmitting unit is movable in all directions in space and the table is stationary.

26. The apparatus according to claim 25, which further comprises an arm constituting a guidance system connecting the microwave generator to the transmitting unit.

27. The apparatus according to claim 25 or 26, wherein the table sits within a reservoir of the monomer or prepolymer.

28. The apparatus according to any one of claims 25 to 27, wherein the device for applying the substrate comprises an application roller, a doctor knife or a movable storage tank.

29. The apparatus according to any one of claims 25 to 28, wherein the transmitting unit can move only in the x,y-plane, and the table can move only in the z-axis.

30. The apparatus according to any one of claims 25 to 28, wherein the transmitting unit can move in all directions in space, and the table is stationary.

31. The apparatus according to any one of claims 25 to 30, provided with means for focusing microwave radiation to a beam of about 0.1 to 3 mm.

32. The apparatus according to any one of claims 25 to 30, provided with means for focusing the microwave radiation to a beam of about 0.3 to 1 mm.

33. The apparatus according to any one of claims 25 to 32, wherein the microwave radiation has a frequency of 430 to 6800 MHz.

34. The apparatus according to any one of claims 25 to 33 further provided with a means for supplying an inert gas blanket to the table.

FETHERSTONHAUGH & CO.
OTTAWA, CANADA

PATENT AGENTS

