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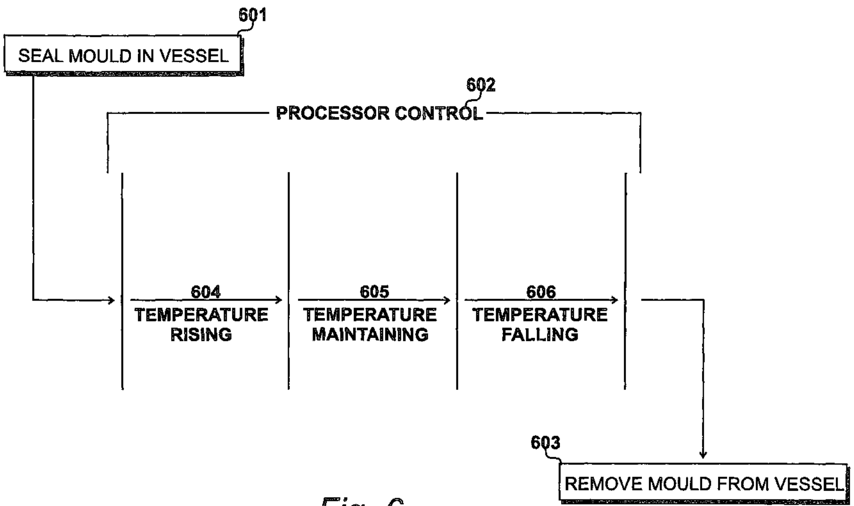

Fig. 6

(57) **Abstract**: Metal component forming is shown, in which heat is applied to a mould containing a metal in particulate form. The mould containing metal particles is placed in a sealed vessel. The temperature inside the vessel is increased to a first temperature range above the liquidus temperature of the metal during a temperature-raising interval (604). The temperature of the vessel is maintained during a temperature-maintaining interval (605). The temperature of the vessel is then reduced during a temperature-falling interval (606).

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Metal Component Forming

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority from United Kingdom Patent Application No. 13 13 849.0, filed August 02, 2013, and United Kingdom Patent Application No. 13 20 170.2, filed November 15, 2013 the entire disclosures of which are incorporated herein by reference in their entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a method of forming a metal component from a particulate feed material. The present invention also relates to an apparatus for forming a metal component from a particulate feed material.

2. Description of the Related Art

Powder metallurgy is a known method for forming a metal component, from a powdered feed material. In a known hot isostatic pressing (HIP) process, powder is shaped in a mould to which both pressure and temperature are applied. Typically, argon gas is used to provide the isostatic pressure which may range from 50 megapascal to 300 megapascal. During this process, the temperature of the material is raised so as to sinter the powder and cause the particles to fuse together. However, known powder metallurgy is limited in terms of the size of products that can be produced and also in terms of the complexity of their shape. Furthermore, it is a costly and time consuming process. It is difficult to scale and often impossible to produce products having the required size and complexity when competing against products produced by a more conventional casting process.

A method of forming a metal component, in which a feed material is initially in a powdered state and a solid component is formed by the application of heat, is disclosed in the present applicant's co-pending patent application (App No. GB 13 20 168.6), the whole content of which is included herein by way of reference. A sacrificial positive model is created of a component and a negative mould is built around the positive model from a material having a melting point higher than the melting point (liquidus point) of the metal from which the component is to be formed. The sacrificial positive model is removed from the negative mould and the feed material of metal powder is deployed into the mould. The metal powder is heated to a temperature higher than the liquidus point (melting point) of the metal powder so as to cause the metal powder to melt within the mould.

BRIEF SUMMARY OF THE INVENTION

According to an aspect of the present invention, there is provided a method of forming a metal component from a particulate feed material, comprising the steps of: placing a mould containing a feed material of metal particles in a vessel; increasing the temperature inside said vessel to within a first temperature range above a liquidus temperature of said metal during a temperature-rising interval; reducing the temperature of the vessel to a second temperature within a freezing range that is greater than the solidus temperature and less than the liquidus temperature of the metal; and maintaining the temperature of the vessel within said freezing range during a temperature maintaining interval.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a method of forming a metal component;

Figure 2 shows procedures for the creation of a positive model;

Figure 3 shows the addition of layers of slurry to produce a mould;

Figure 4 shows a deployment of feed material into the mould;

Figure 5 shows an apparatus for forming a metal component;

Figure 6 shows a method of operating the apparatus of Figure 5 to form a metal component;

Figure 7 shows a control process performed by the controller identified in Figure 5;

Figure 8 illustrates changes in temperature and pressure for a first embodiment of the invention;

Figure 9 illustrates changes in temperature and pressure for a second embodiment of the invention;

Figure 10 illustrates changes in temperature and pressure for a third embodiment of the invention;

Figure 11 shows an alternative control process performed by the controller of Figure 5; and

Figure 12 illustrates changes in temperature and pressure of a fourth embodiment in accordance with the control process performed as shown in Figure 11.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

Figure 1

A method of forming a metal component from a powdered feed material is illustrated in Figure 1. A feed material is initially in a powdered state (detailed in Figure 4) and a solid component is formed by the application of heat (detailed in Figure 5). At step **101** a sacrificial positive model **102** of a component is created. At step **103**, a negative mould **104** is built around the positive model from a material having a melting point higher than the liquidus temperature (melting point) of the material from which the component is to be formed (as detailed in Figure 3).

At step **105** the sacrificial positive model is removed so as to leave a void **106** within the negative mould. At step **107**, feed material of metal powder **108** is deployed into the mould. At step **109** heat **110** is applied to the mould to a temperature higher than the liquidus temperature (melting point) of the metal powder so as to cause the metal powder to melt within the mould, thereby establishing molten metal **111** within the mould **104**.

The metal powder **108** used herein to form a metal component is, in a first embodiment, a powder consisting particles of pure metal. However, in an alternative embodiment metal powder **108** is a powder comprising particles of an alloy. It should be appreciated therefore, that metal components formed from the said metal powder may be comprised either of a pure metal or an alloy compound.

Whereas metal powder need to be graded to specific size ranges for known powder metallurgy techniques, such as HIPping, powder metallurgy, and metal injection moulding, etc, the method described herein is relatively insensitive to the size range of the powder particles. The only requirement is that the metal powder flows readily into the ceramic moulds. Where the mould defines sections having diameters as a little as 0.5 millimetres, spherical powders produced by gas atomisation, for example, would be more appropriate. With larger mould sections, even angular powders produced by crushing and milling would enable the mould to be filled, especially when the flow of powder is aided by vibration, as will be described further with reference to Figure 4.

Figure 2

Procedures for the creation of the positive sacrificial model are illustrated in Figure 2. Operations are performed upon a source material **201** in order to produce the positive model **102**. It is possible to perform a machining operation **202** upon an appropriate material in order to define the shape of the positive model. However, it should be appreciated that the material used must be of a type such that it is possible to remove the sacrificial material in order to define the negative mould.

As an alternative, it is possible to perform a wax injection process **203**. Having created a mould around the wax positive, it is possible to remove the wax by the application of heat. Such an approach is known in conventional casting systems where the heating of the mould is also desirable prior to the application of molten metal. However, in an embodiment, the mould would be allowed to cool and the particulates would be added at room temperature.

As an alternative, it is also possible to produce the positive mould by a process of additive manufacturing **204**, with an appropriate rapid prototyping material for example. The material may be removed by the application of heat and/or the application of an appropriate solvent.

Figure 3

The negative mould, having a melting point higher than the melting point of the metal from which the component is to be formed, may be a ceramic shell that is relatively porous to air. In an embodiment the ceramic mould is produced by adding a plurality of layers, as illustrated in Figure 3. The layers are added as an alternating wet slurry layer followed by a substantially dry stucco layer.

Slurry **301** is applied to the model **102**. Dry stucco **302** is then applied that attaches itself to the wet slurry in order to build a layer.

This process is repeated, as shown generally at **303**, resulting in the build up of layers **304**. Thus, further repetitions are made until the negative mould **104** has been built to the required thickness. Ceramic mould **104** should ideally have relatively thin wall sections so as to allow the conduction of radiant heat from a radiant heating system therein, to enable to the metal powder to be melted. However, the wall sections must be sufficiently thick to prevent cracks or fracturing during processing, and therefore a compromise must be reached in creating a mould that has a high thermal conductivity, but is sufficiently strong.

In an embodiment a primary refractory slurry is applied that is inert to the metal being used. A dry sand of similar or different material is then applied and further slurries are applied, followed by sand, stucco and so on.

A number of suitable ceramic materials for forming the ceramic shell are known, such as silica and alumina. It has been found during testing that a silica shell does not have a sufficiently high thermal conductivity to allow the powder metal charge to be melted in a suitable time-period using a radiant heating system, as opposed to an induction heating system that heats the powdered metal directly. Therefore, in a preferred embodiment, a negative mould comprised of an alumina material having a high thermal conductivity may be used. Other types of shell material having a high thermal conductivity may be used, however they must not be susceptible to dissolution in the molten metal, as can be experienced by graphite based moulds when using certain metals.

Figure 4

Step **107** for the deployment of feed material is detailed in Figure 4. The positive sacrificial model **102** has been removed as illustrated by step **105**. The negative mould **104** is placed upon a vibrating table **401**, itself supported by a stable base **402**. In this way, as the feed material **108** is deployed into the mould **104**, or after deployment, a degree of vibration is introduced, as illustrated by arrows **403** and **404**, to facilitate the dispersal and densification of the feed material within the mould. High frequency vibration, e.g. 40-60 hertz, with low amplitude displacement of, say 0.10-0.15 millimetres enables moulds for large and complex metal components to be filled easily.

Thus, the feed material is deployed within the mould and then heated, as illustrated by step **109**. The heat may be applied without pressure and the mould is heated to a temperature that causes the feed material to melt. In this way, it is possible to obtain close to 100 percent density using a process that has less overall complexity compared to known systems. The heat is required not only to raise the temperature of the metal, but also to melt the metal completely. Consequently, it is typically heated to around 50 degrees Celsius above the melting point of the metal, in the case of a pure metal, or above the liquidus temperature in the case of an alloy.

In some known systems, contamination is often introduced from containers and this is a particular problem when using titanium. Processes using solid state diffusion result in the container experiencing a similar environment to the material contained inside. Thus, even after machining away, it is possible that a significant layer of a material mixture will remain. Consequently, additional processing is required in order to achieve the required result.

It has been recognised that the use of metal powder as a feed material may produce products having desirable properties. There is a tendency for the microstructure to be very uniform, which may improve strength and fatigue properties. Properties of this type may be provided by forging operations but, as is known, forging results in the production of significant levels of waste and therefore increases overall cost. Similarly, a casting process yield is typically 50 percent; again increasing cost, which becomes an important factor when expensive alloys are being used.

Figure 5

In an embodiment, the heating system includes a radiant heat source for producing radiant heat from an electrical supply, along with a control circuit for controlling the electrical supply in order to control temperature.

An embodiment further includes pressure reduction apparatus configured to reduce the pressure of a chamber or vessel to a pressure below atmospheric pressure. An example of this apparatus is shown in Figure 5. The apparatus, indicated generally at **501**, has a vacuum furnace **502**. The vacuum furnace has a vacuum-tight vessel **503**, with a refractory lining **504**, defining a vacuum chamber **505**. Vessel **503** is provided with a door **506**, for the purpose of providing access to the chamber **505**, thereby allowing the chamber to be loaded and unloaded with moulds, such as mould **501**.

In an embodiment, the vacuum furnace **502** has a resistance heating element **507** connected to a suitable electrical power supply **508**. Typically, resistance heating elements are formed of molybdenum or graphite, but the full specification of the vacuum furnace will depend upon the specific types of metals and alloys that are being used in the process. Furthermore, the specification will also depend upon the requirements of the metal objects that are being formed.

In an embodiment, the vacuum furnace and its heating element and power supply are selected such that the temperature of the chamber may be raised to a temperature in excess of 2000 degrees Celsius. Furnaces with these capabilities are commercially available, generally for the purpose of providing heat treatment operations.

Chamber **505** is connected to a vacuum system **509** for evacuating air from the chamber, such that pressures in the chamber may be reduced to levels substantially below atmospheric pressure. The chamber **505** has an inlet port **511** connected to a noble gas supply. In an embodiment, a tank **512** of compressed helium may be provided in combination with a tank **513** of compressed Argon.

The apparatus **501** also includes a fan **514**, having an inlet connected to outlet port **510** of chamber **505** and an outlet connected to the inlet port **511**. Helium gas may be supplied to chamber **505** up to a predetermined pressure and the gas may be circulated by a fan **514** to provide additional cooling.

Temperature sensor **515** is located within the chamber and is configured to provide signals indicative of an actual temperature of the powdered or molten metal in the moulds located within the chamber. The apparatus also includes a vacuum pressure gauge **516** configured to provide an indication of vacuum pressure within the chamber.

The pressure gauge **516** and the temperature sensor **515** are arranged to provide signals to a controller **517** indicative of the pressure and temperature of the chamber. The controller is arranged to operate the power supply **508** for the resistance heating element **507** and the vacuum system **509**, in response to the signals received from gauge **516** and sensor **515**.

Figure 6

A method for forming a metal component is illustrated in Figure 6, in which heat is applied to a mould containing a metal in a particulate form. A mould containing metal powder is placed in a vessel and the vessel or pressure chamber is sealed, as illustrated at **601**. Inside the vessel, the mould experiences changes in temperature and pressure under processor control **602**, whereafter the mould is removed from the vessel as illustrated at **603**.

While under processor control, the temperature inside the vessel is increased to within a first temperature range above a liquidus temperature of the metal, during a temperature-rising interval **604**. The temperature of the vessel is maintained, after the temperature rising interval **604**, during a temperature-maintaining interval **605**.

The temperature of the vessel is then reduced, after the temperature-maintaining interval **605**, during a temperature-falling interval **606**. Different results may be obtained by subtle changes occurring within each of intervals **604** to **606**, as will be described with reference to Figures 8 through 12.

Figure 7

Operations performed by controller **517**, to achieve processor control **602**, are detailed in Figure 7. In this example, prior to the temperature-rising interval **604**, pressure inside the vessel is reduced at step **701** and at step **702** a question is asked as to whether the required pressure has been achieved. If answered in the negative, further pressure reduction occurs and if answered in the affirmative the temperature-rising interval **604** is initiated.

The pressure inside the chamber is reduced in order to avoid contamination from the surrounding air. Thus, from a contamination reduction perspective, the pressure should be reduced as far as possible, effectively creating a near vacuum. However, at extremely low pressures, material metal would be lost through evaporation therefore there is a lower limit in terms of the pressure reduction. A range of pressures therefore exist defined by a lower limit, below which evaporation would take place and an upper limit, above which contamination would take place. The specific range will vary depending upon the actual constitution of the metal.

Step **703** represents the start of the temperature-rising interval **604**, during which the temperature within the vessel is increased. At step **704** a question is asked as to whether the required temperature has been reached and if answered in the negative, further heating occurs at step **703**. The temperature-rising interval **604** is completed when the question asked at step **704** is answered in the affirmative. Step **705** initiates the temperature-maintaining interval **605**. The control processor maintains the operating temperature, within specified limits, and at step **706** a question is asked as to whether the temperature has been maintained for the required duration. When answered in the negative, the temperature is maintained at step **605**, while an answer in the affirmative represents the end of the temperature-maintaining interval **605**.

The temperature of the chamber is raised and maintained such that the temperature within the metal itself will be above the melting point (or liquidus temperature) of the metal, to ensure that the metal is in a fully liquid state. In an example, the temperature of the chamber may be raised to a level that is fifty degrees higher than the actual melting point of the metal. This temperature is maintained sufficiently long enough for all of the metal in the mould to be taken above the melting point (liquidus temperature), such that all of the particles in the mould will have melted. As described in the applicant's co-pending British patent application (App. No. GB 13 20 168.6), measures are taken to compensate for shrinkage while melting and solidification take place.

In this example, the start of the temperature falling interval **606** is initiated with a pressure increase at step **707** followed by temperature reduction at step **708**. At step **709** a question is asked as to whether the required temperature has been reached and if answered in the negative, further temperature reduction continues at step **708**. When the question asked at step **709** is answered in the affirmative, a further increase in pressure occurs, returning the pressure in the vessel to atmospheric pressure. Further temperature reduction occurs at step

711 until the temperature-falling interval **606** is complete and the mould may be removed from the vessel.

Figure 8

When a pure metal is heated at constant pressure, say atmospheric pressure, the metal will melt at a specific melting point, below which the metal is completely solid and above which the metal is completely liquid. For mixtures, such as metal alloys (as will often be deployed within embodiments of this invention) a range of temperatures exist over which the material is not completely solid, nor is it completely liquid; even though the mixture is in thermodynamic equilibrium. This may be referred to as the freezing range, in which melting starts to occur at a solidus temperature, below which the substance is completely solid, until a liquidus temperature is reached, above which the material is completely liquid. Embodiments will be described in which the material within the mould experiences these states during the process of metal component forming.

In the example of Figure 8, a first graph of pressure **801** and the second graph of temperature **802** are plotted against a common time axis **803**. At time **804** the pressure in the chamber is reduced, in accordance with step **707**, until the pressure drops below an upper pressure limit **805** and is maintained above a lower pressure limit **806**, resulting in the question asked at step **702** being answered in the affirmative.

Electrical power is supplied to the resistive heating coils at time **807**, effectively starting the temperature-rising interval **604**. The end of the temperature-raising interval **604** occurs when the temperature goes above a lower predetermined temperature **808**, thereby entering the temperature-maintaining interval **605**. Thus, during the temperature-maintaining interval **605**, the temperature is held above lower limit **808** and below an upper temperature limit **809**.

The temperature in the vessel is maintained between temperature **808** and temperature **809** for a predetermined period of time, during the temperature-maintaining interval **605**, until the resistive heating elements are powered down.

Thus, the temperature-maintaining interval **605** occurs between time **810** and power down time **811**.

During the temperature falling interval **606**, pressure is increased and temperature is reduced as previously described. In an embodiment, a noble gas, such as argon or helium, is supplied into the vessel to assist with the cooling of the mould and the metal components contained therein. Furthermore, in this example, at time **812** when the temperature has dropped below temperature **813**, the pressure is returned to atmospheric pressure as indicated at **814**. Below temperature **813**, the objects may be removed from the vessel without experiencing excessive oxidation.

Figure 9

A substantially similar process to that shown in Figure 8 is shown in Figure 9. The temperature-rising interval starts at time **901** and a temperature-maintaining interval starts at time **902**, with a temperature falling interval then following at time **903**. At time **903**, representing the start of the temperature-falling interval **606**, noble gas is supplied into the vessel and blown through the vessel by fan **514** in order to provide an increased rate of cooling. In an embodiment, helium gas is used to improve heat transfer. However, although the pressure in the vessel increases at time **903**, it remains below ambient pressure, as indicated by pressure **904**, whereafter the pressure is increased to ambient pressure at time **905**.

Figure 10

A similar example is shown in Figure 10, again showing plots of pressure and temperature against a common time axis. Again, the temperature-rising interval **604** is initiated at time **1001**, the temperature-maintaining interval **605** is initiated at time **1002** and the temperature-falling interval **606** is initiated at time **1003**. However, in this example, helium gas is supplied into the vessel at increased pressure, indicated by pressure **1004**, that may be several times atmospheric pressure and is maintained until time **1005**. During this period, helium gas is supplied and blown through the vessel in order to increase the rate of cooling. This approach is taken in order to obtain crystals of reduced size within the metal component.

The apparatus of Figure 5 is therefore configured to form a metal component in which heat is applied to a mould containing metal in particulate form. The apparatus includes a pressure vessel **503**, a heating device **507** for heating the contents of the pressure vessel, a pressure adjustment device **509** for adjusting pressure within the pressure vessel and a control system for controlling the heating device and the pressure adjusting device over controlled intervals.

A control system is configured to increase the temperature inside the vessel to within a first temperature range above the liquidus temperature of the metal during the temperature-rising interval. Thus, in this way, the metal particles become liquid and as such run into the features of the mould, thereby adopting the shape of the mould. This situation is encouraged by maintaining the temperature of the vessel during a temperature-maintaining interval in order to ensure that all of the material within the mould has become liquid and that the form of the mould has been taken fully.

The temperature of a vessel is then reduced during a temperature falling interval and this is carefully controlled to obtain required attributes, as described with reference to Figures 8 to 10. In an embodiment, the control system also controls the pressure adjustment device; thereby reducing pressure inside the vessel during a pressure reduction interval, prior to the temperature-rising interval.

Figure 11

An alternative procedure for the processor **517**, in order to perform processor control **602**, is detailed in Figure 11. During the temperature maintaining interval **605**, process steps **705** and **706** are replaced with process steps **1101** to **1106**. Furthermore, a first portion **1109**, a second portion **1110** and a third portion **1111** are established within the temperature-maintaining interval **605**.

During the first portion **1109**, the temperature is maintained at step **1101** and at step **1102** a question is asked as to whether the temperature has been maintained for the required duration. This duration may be substantially similar in duration to the entire temperature-maintaining interval **605** in Figure 7.

At step **1103**, representing the start of the second portion **1110**, the temperature is reduced while the reduced pressure is maintained and a question is asked at step **1104** as to whether the required temperature has been reached. When answered in the negative, further temperature reduction occurs at step **1103**, again while maintaining reduced pressure.

The end of the second portion **1110** and the start of the third portion **1111** is identified by the question asked at question **1104** being answered in the affirmative, in that the required temperature has been reached; this being a second specified temperature within the temperature maintaining interval **605**. A question is then asked at step **1106** as to whether the temperature has been maintained for the required duration, during portion **1111** and when answered in the negative the temperature is maintained at step **1105**.

When the question asked at step **1106** is answered in the affirmative, temperature reduction is initiated at step **1107**, representing the start of the temperature-falling interval **606**. At step **1108** a question is asked as to whether a required temperature has been reached and when answered in the negative further temperature reduction occurs at step **1107**, while still at reduced pressure. Eventually, the question asked at step **1108** will be answered in the affirmative, resulting in a pressure increase at step **710** and further temperature reduction at step **711**.

Figure 12

Operational conditions within the pressure vessel **503** resulting from the operations performed under the control of the process indentified in Figure 11, are detailed in Figure 12. Initial pressure reduction, in accordance with step **701**, occurs at time **1201**, resulting in the pressure falling from pressure **1202** to pressure **1203**, between a predetermined upper pressure bound **1204** and a predetermined lower pressure bound **1205**.

The temperature-rising interval **604** starts at time **1206** and the interface between the temperature-rising interval **604** and the temperature-maintaining interval **605** occurs at time **1207**.

On the temperature plot shown in Figure 12, the solidus temperature **1208** is shown, above which there is the liquidus temperature **1209**; the interval between these being dependent upon the particular material being used to form the component. Above this there is a lower predetermined temperature **1210** and an upper predetermined temperature **1211**. During the first portion **1109** of the temperature maintaining interval **605**, the temperature is held between the lower predetermined level **1210** and the upper predetermined level **1211**, both above the liquidus temperature **1209**.

During the second portion **1110**, the temperature is reduced at time **1212** until, at time **1213**, it is has fallen below the liquidus temperature **1209** but above the solidus temperature **1208**.

During a third portion **1111**, the temperature is maintained at temperature **1214** to encourage the formation of large crystals. Thus, in this example, crystallisation occurs during the third portion of the temperature-maintaining interval **605**, with complete solidification occurring after time **1215**. Thereafter, at time **1216** the vessel is returned to atmospheric pressure **1217**.

It can be appreciated that some of the temperature ranges required during the temperature maintaining interval **607** may be relatively small. Thus, to achieve the required level of accuracy, a requirement exists to identify the temperature of the metal itself, which may differ from the temperature of gas contained within the vessel at a distance displaced from the metal itself. In an embodiment, the temperature inside the sealed chamber is measured and this measured temperature is processed to produce an indication of the temperature in the metal itself. Heat introduced into the chamber is then adjusted to maintain the temperature of the metal. This approach facilitates the maintenance of temperature **1214** between the liquidus temperature and the solidus temperature. The processing step may be achieved by means of a lookup table, programmed in response to empirical data. As illustrated in Figure 12, the temperature-falling interval **606** has been divided into a fourth portion **1218** and a fifth portion **1219**. During the fourth portion, the metal is cooled below the solidus temperature at reduced pressure and during the fifth portion, further cooling is achieved at increased pressure, possibly with forced cooling.

Claims

What we claim is:

1. A method of forming a metal component from a particulate feed material, comprising the steps of:

placing a mould containing a feed material of metal particles in a vessel;

increasing the temperature inside said vessel to within a first temperature range above a liquidus temperature of said metal during a temperature-rising interval;

reducing the temperature of the vessel to a second temperature within a freezing range that is greater than the solidus temperature and less than the liquidus temperature of the metal; and

maintaining the temperature of the vessel within said freezing range during a temperature maintaining interval.

2. The method of claim 1, further comprising the step of maintaining the temperature in the vessel within said freezing range for a period to enable the formation of large crystal structures in the metal.

3. The method of claim 1, further comprising the step of maintaining the first temperature in the vessel in a range that is greater than the liquidus temperature of the metal to ensure that the form of the mould has been taken fully and all particles have been melted.

4. The method of claim 1, further comprising the step of reducing the temperature of said vessel during a temperature falling interval.

5. The method of claim 1, further comprising the step of reducing the pressure inside said vessel during a pressure-reduction interval prior to said temperature-rising interval to within a first reduced pressure range.

6. The method of claim 1 to 5, further comprising the step of maintaining the pressure inside said vessel within said reduced pressure range

during said temperature maintaining-interval.

7. The method of claim 4, further comprising the step of increasing the pressure within the vessel during said temperature-falling interval.

8. The method of any of claim 3, further comprising the step of blowing a noble gas through the vessel during said temperature-falling interval.

9. The method of any of claim 4, further comprising the step of increasing the pressure within the vessel to a level above atmospheric pressure during said temperature-falling interval.

10. The method of claim 1, wherein the temperature of the vessel is maintained by the steps of:

measuring the temperature inside the sealed chamber to produce a measured temperature;

processing said measured temperature to produce an indication of the temperature of the metal; and

adjusting heat output to maintain the temperature of the metal between the liquidus temperature and the solidus temperature.

11. The method of claims 7, further comprising the steps of:

dividing said temperature falling interval into a fourth portion and a fifth portion;

cooling the metal to below the solidus temperature during said fourth portion while maintaining said reduced pressure; and

cooling said metal further during said fifth portion by increasing pressure within the vessel and applying forced cooling.

12. The method of any of claims 1, wherein said mould is built around a sacrificial positive model to produce a negative mould having a melting point higher than the liquidus point of the metal from which the component is to be formed.

13. The method of claim 12, wherein said negative mould is built using a substance comprising a porous ceramic material.

14. An apparatus for forming a metal component from a particulate feed material, comprising:

a mould containing a feed material of metal powder;

a vessel for controlling the temperature of the mould;

a heating system for increasing the temperature within the vessel; and

a control system for controlling said heating system over controlled intervals, wherein said control system is configured to:

increase the temperature inside said vessel to within a first temperature range above a liquidus temperature of said metal during a temperature-rising interval;

reduce the temperature inside the vessel to a second temperature within a freezing range that is greater than the solidus temperature and less than the liquidus temperature of the metal; and

maintain the temperature inside said vessel within said freezing range during a temperature maintaining interval.

15. The apparatus of claim 14, further comprising a pressure adjustment device for adjusting pressure within the pressure vessel.

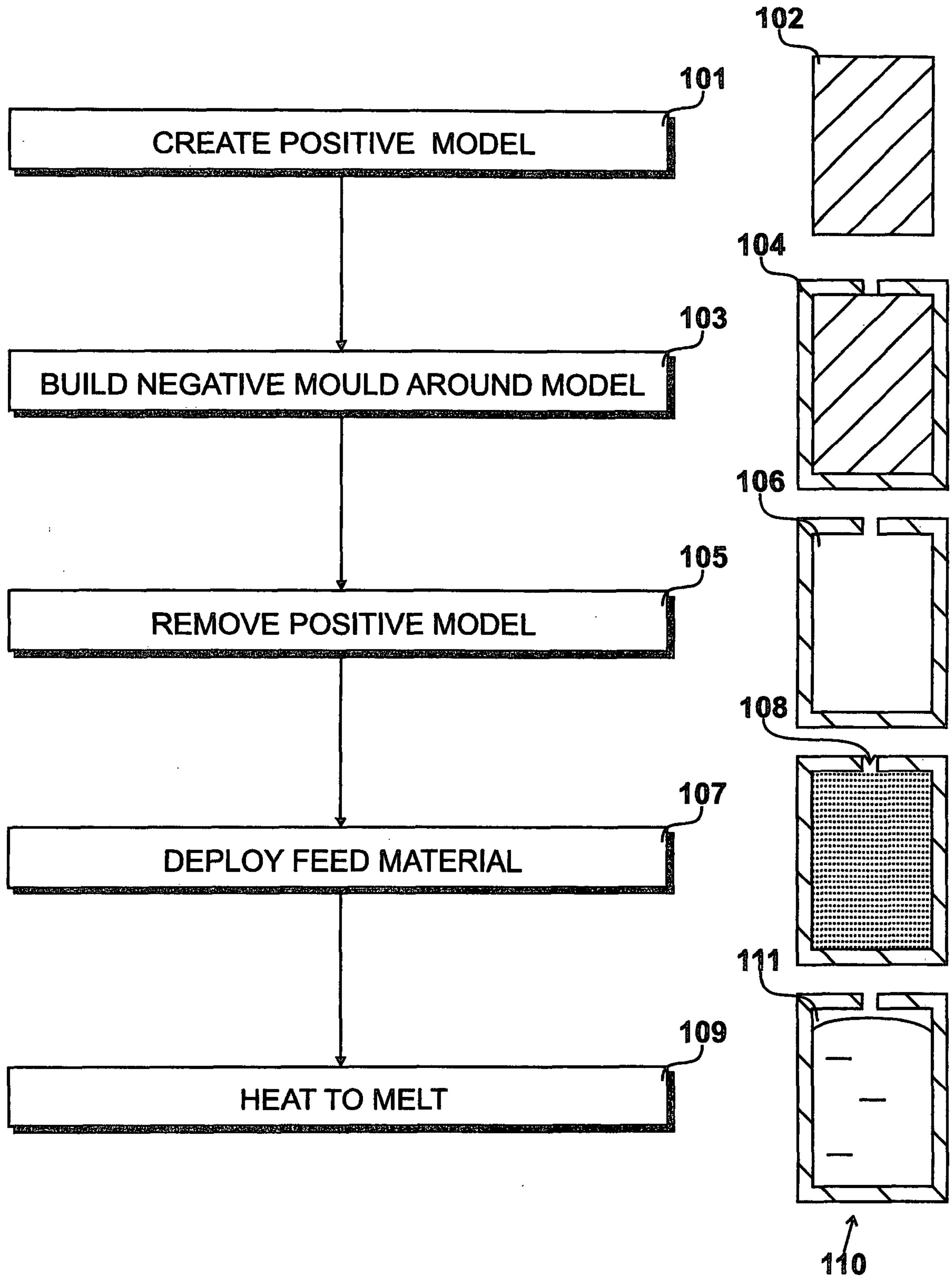

101
CREATE POSITIVE MODEL
103
BUILD NEGATIVE MOULD AROUND MODEL
105
REMOVE POSITIVE MODEL
107
DEPLOY FEED MATERIAL
109
HEAT TO MELT
102
104
106
108
111
110

Fig. 1

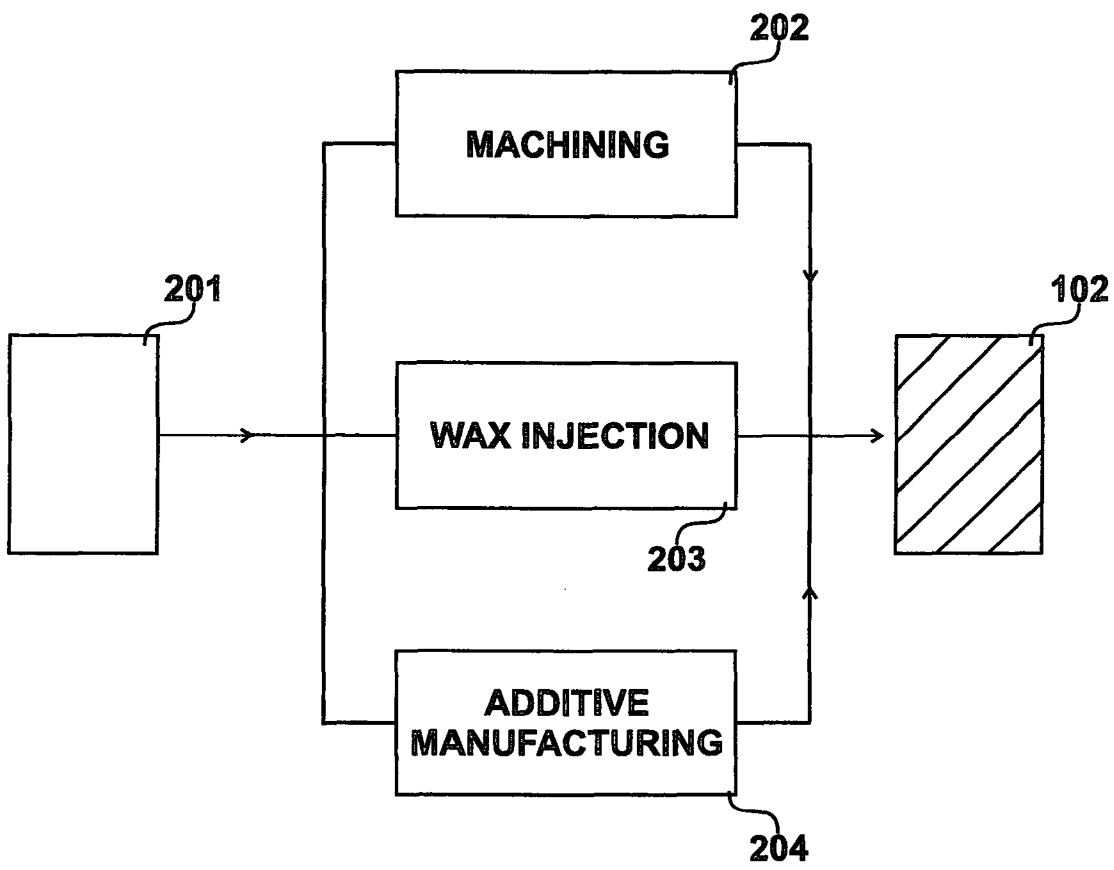

202
MACHINING
201
102
WAX INJECTION
203
ADDITIVE MANUFACTURING
204

Fig. 2

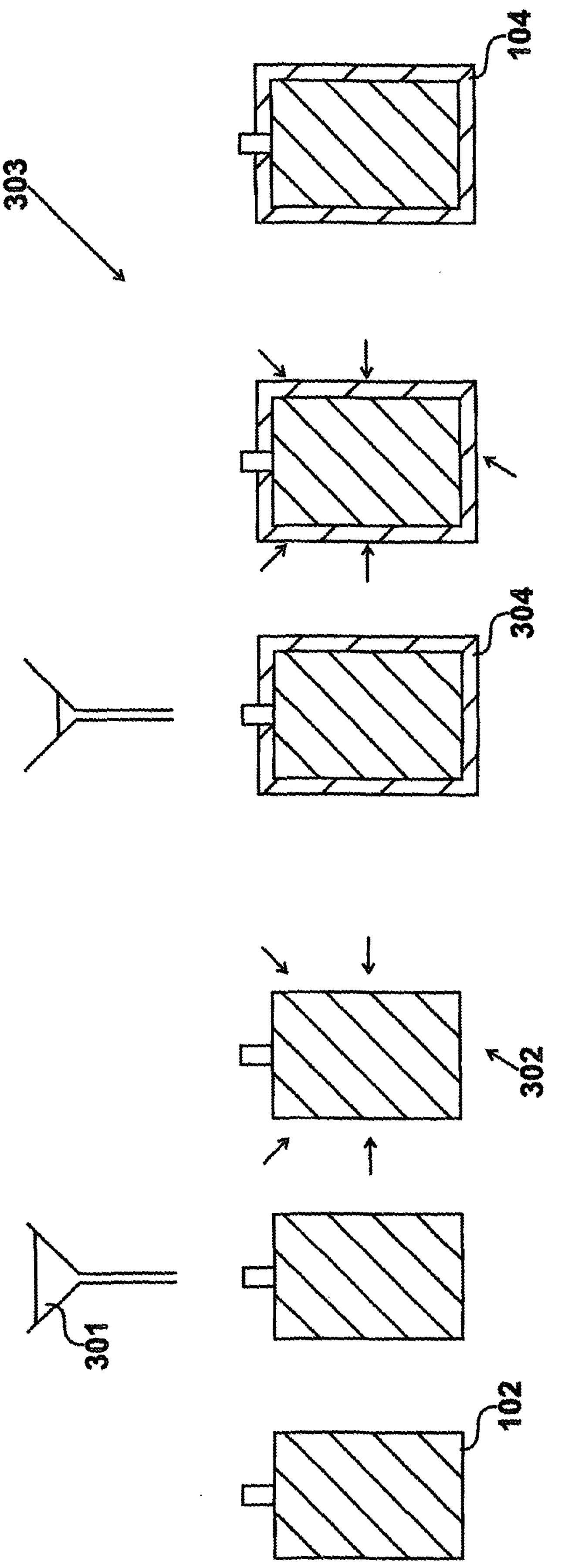


Fig. 3

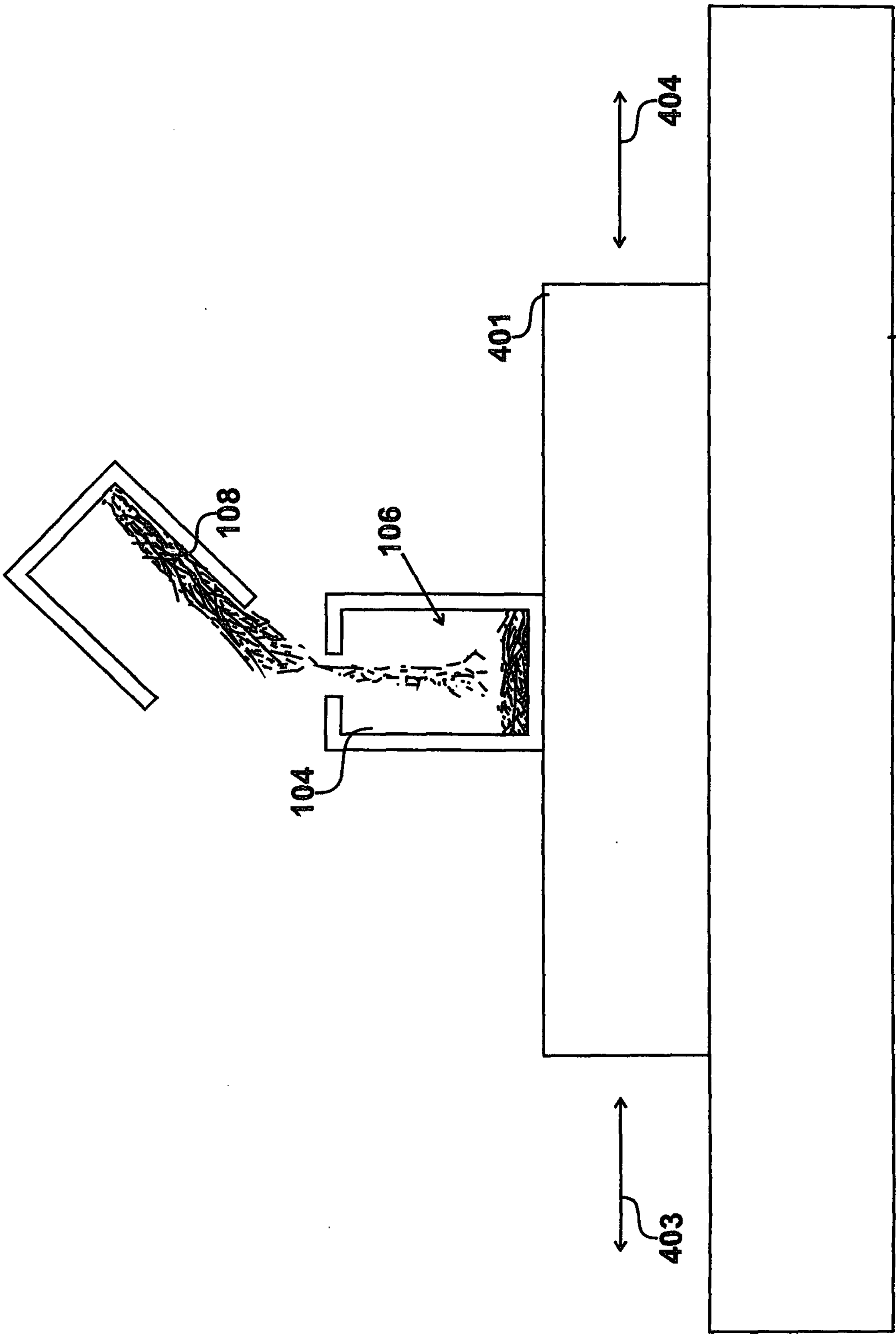
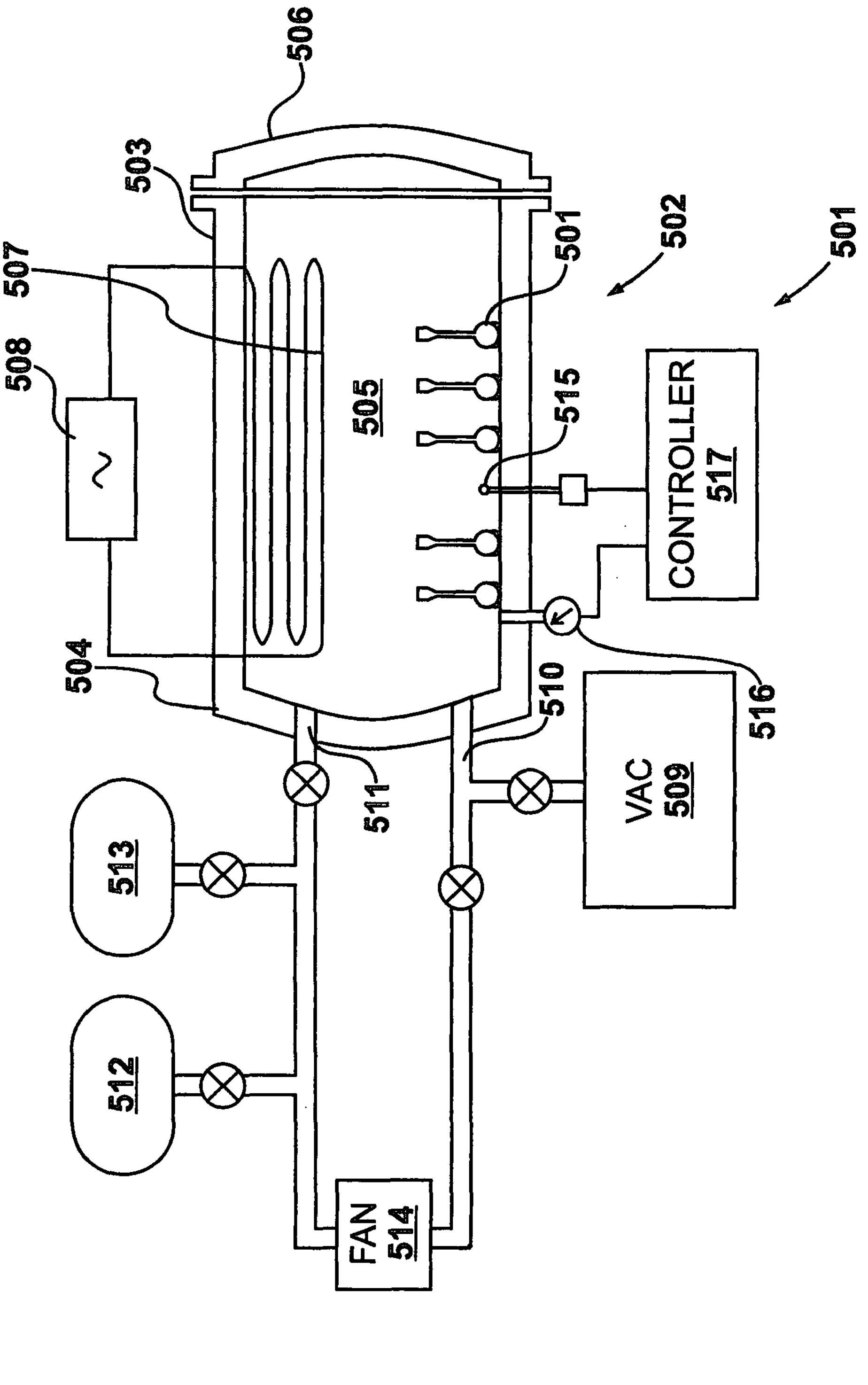


Fig. 4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508
~
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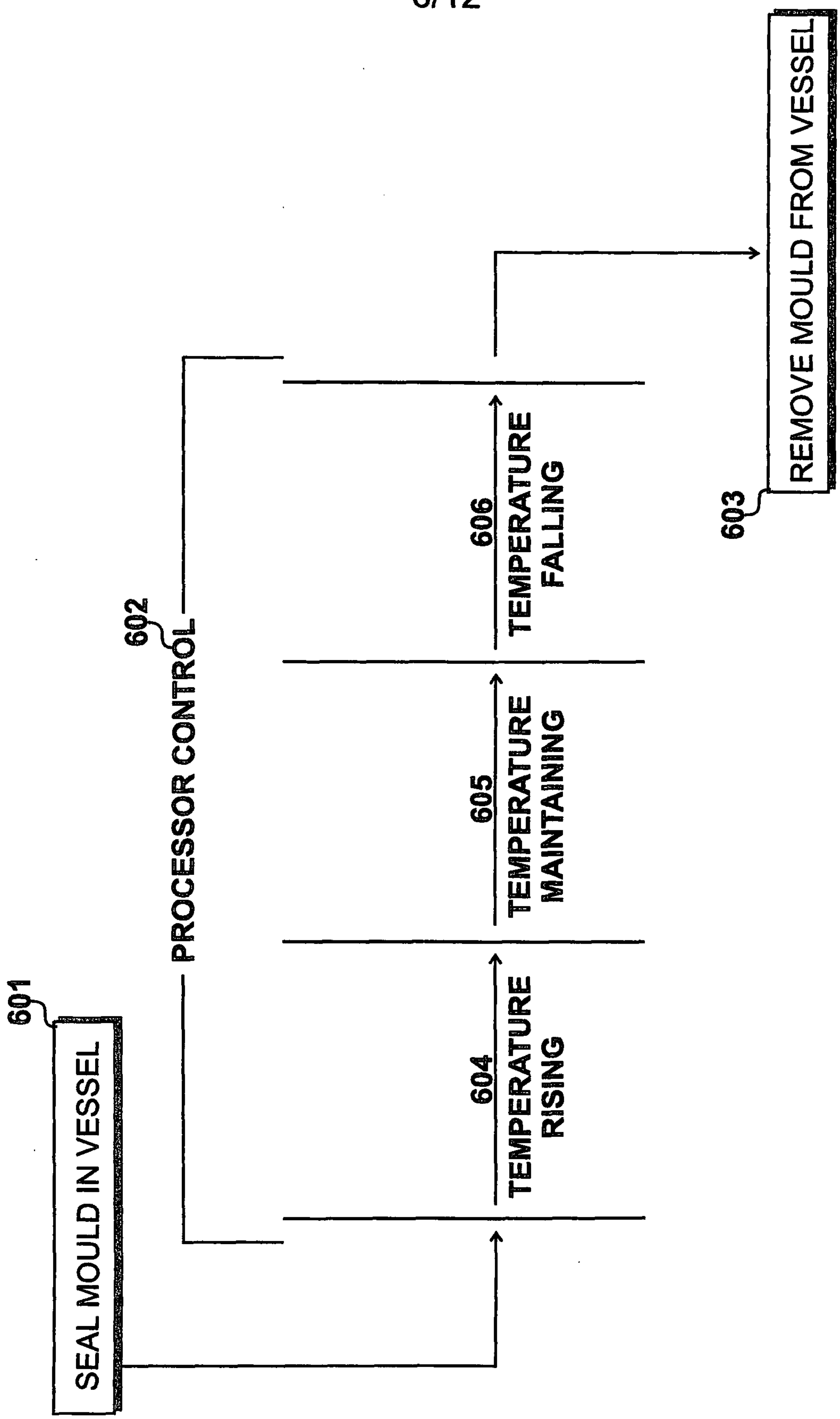
515
CONTROLLER
517
504
516
510
511
VAC
509
513
512
FAN
514

Fig. 5


SEAL MOULD IN VESSEL
601
PROCESSOR CONTROL
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604
TEMPERATURE RISING
605
TEMPERATURE MAINTAINING
606
TEMPERATURE FALLING
REMOVE MOULD FROM VESSEL
603

Fig. 6

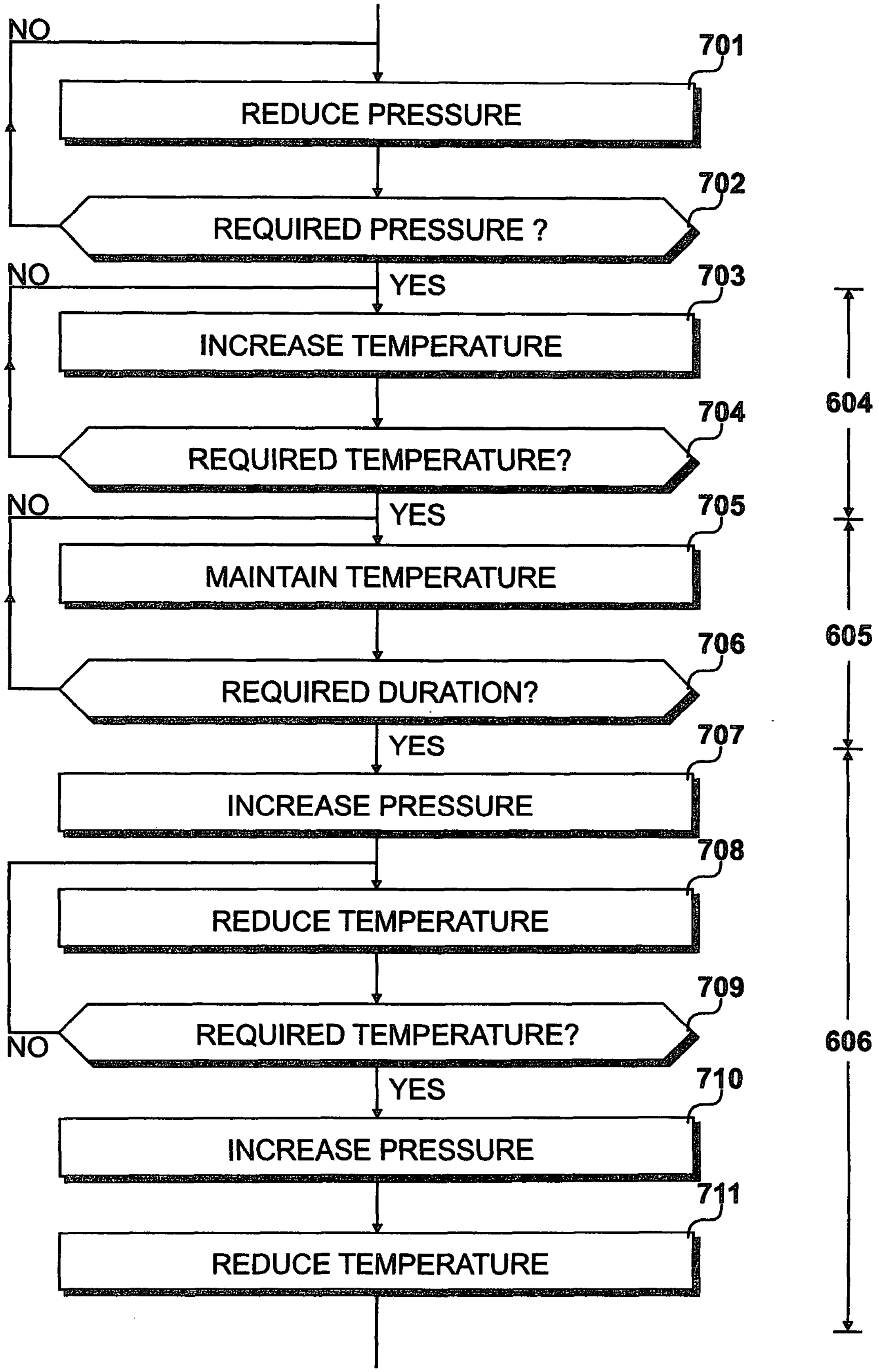
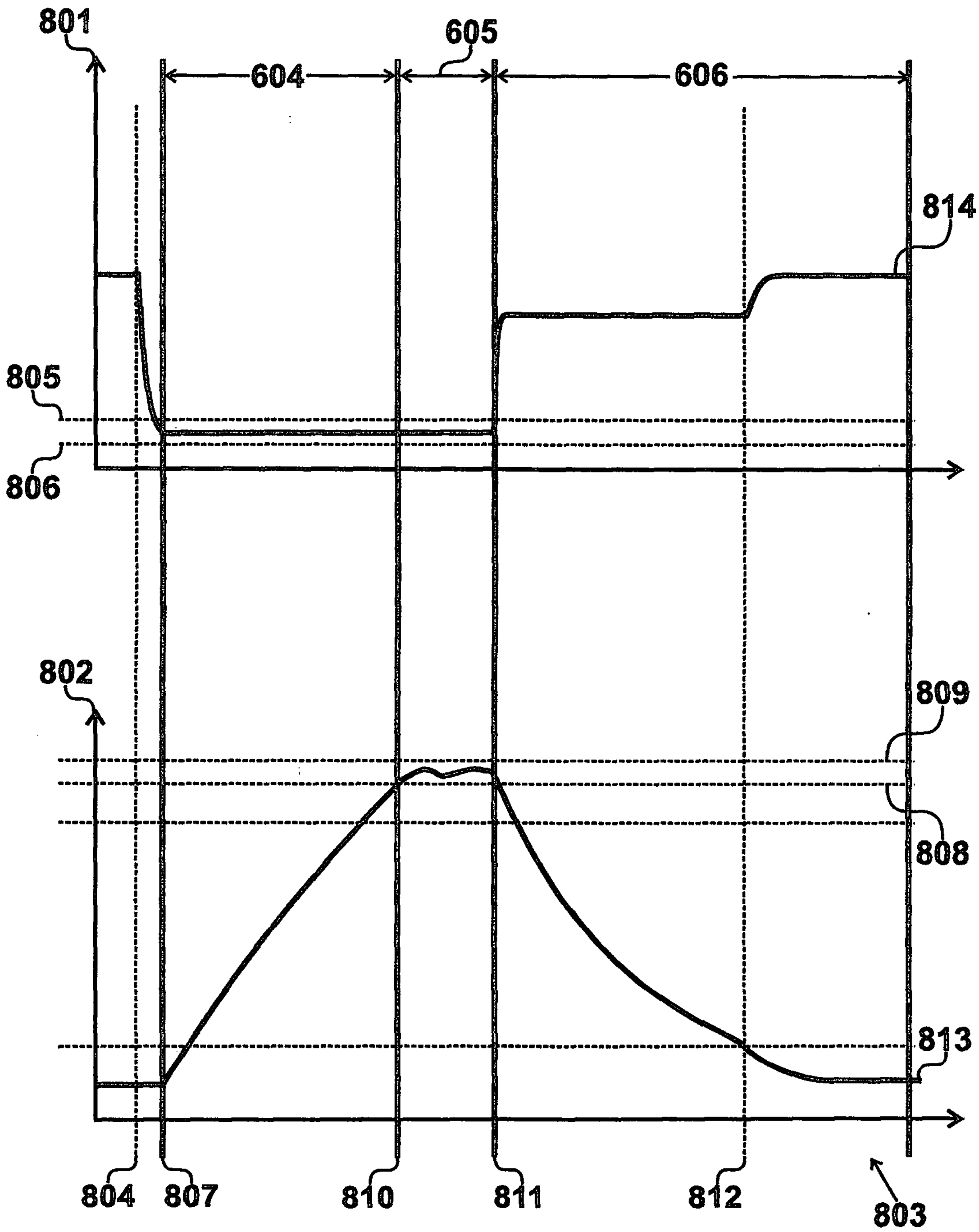

NO
701
REDUCE PRESSURE
702
REQUIRED PRESSURE ?
NO
YES
703
INCREASE TEMPERATURE
604
704
REQUIRED TEMPERATURE?
NO
YES
705
MAINTAIN TEMPERATURE
605
706
REQUIRED DURATION?
YES
707
INCREASE PRESSURE
708
REDUCE TEMPERATURE
709
REQUIRED TEMPERATURE?
NO
606
YES
710
INCREASE PRESSURE
711
REDUCE TEMPERATURE

Fig. 7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813
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811
812
803

Fig. 8

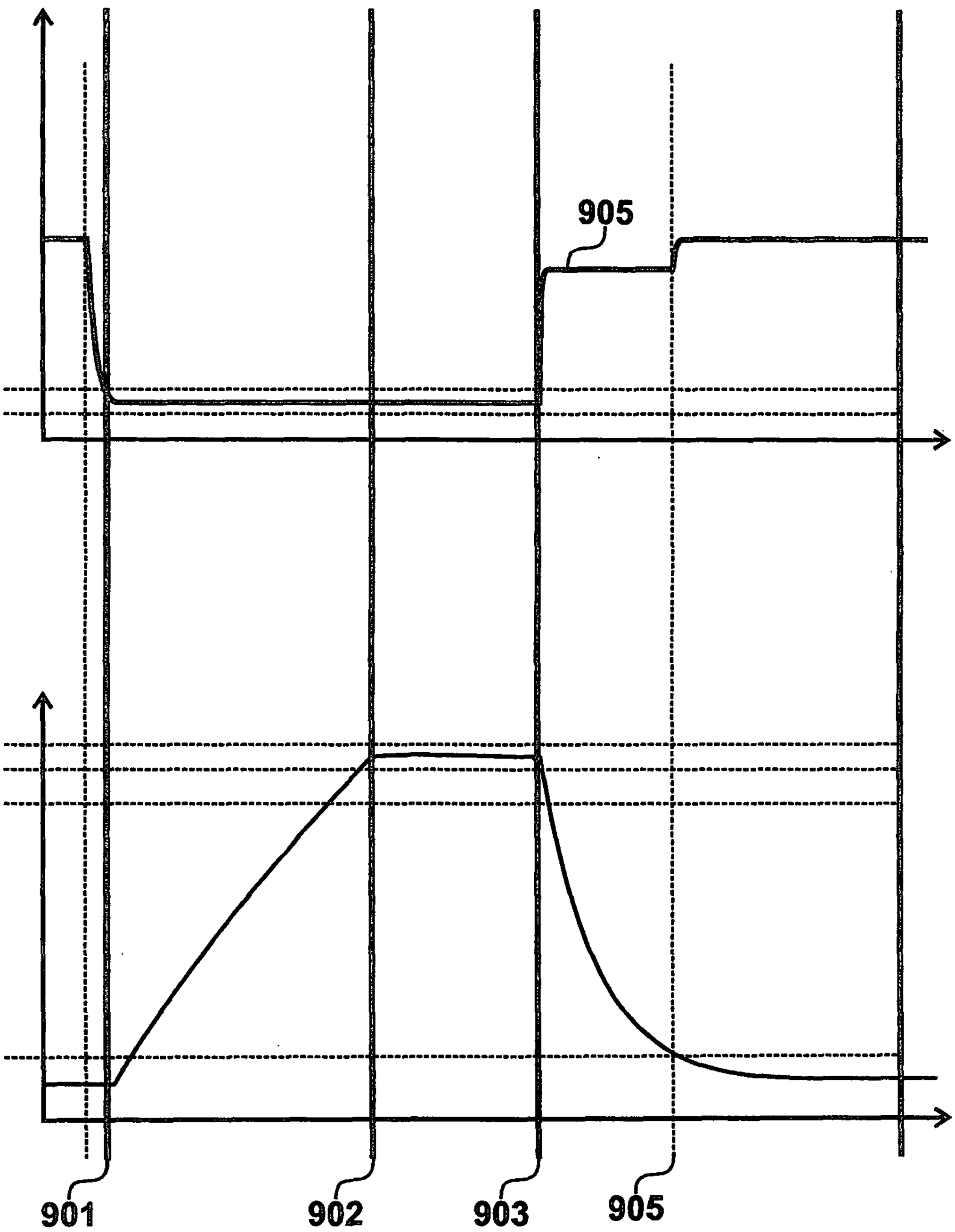

Fig. 9

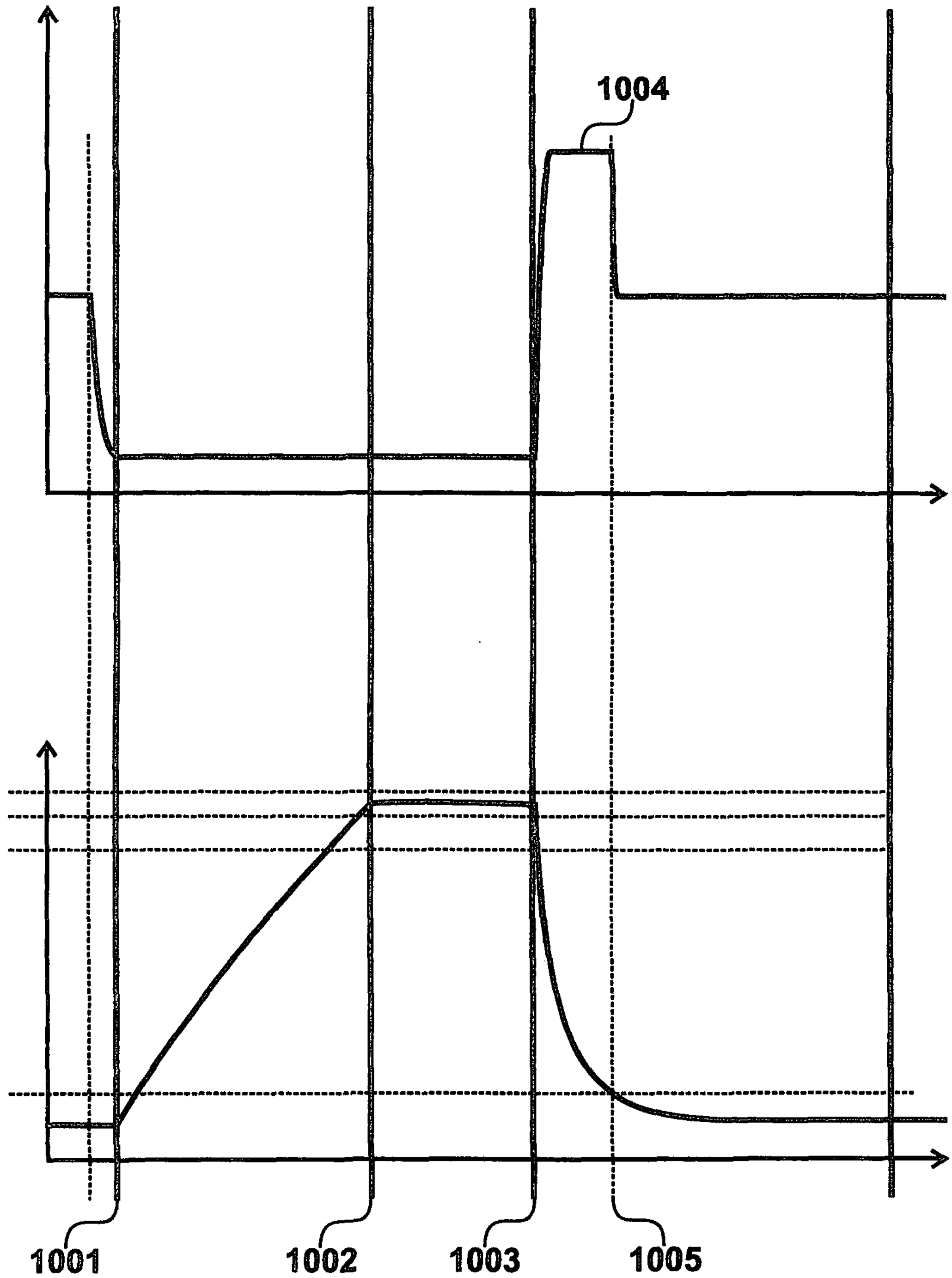

Fig. 10

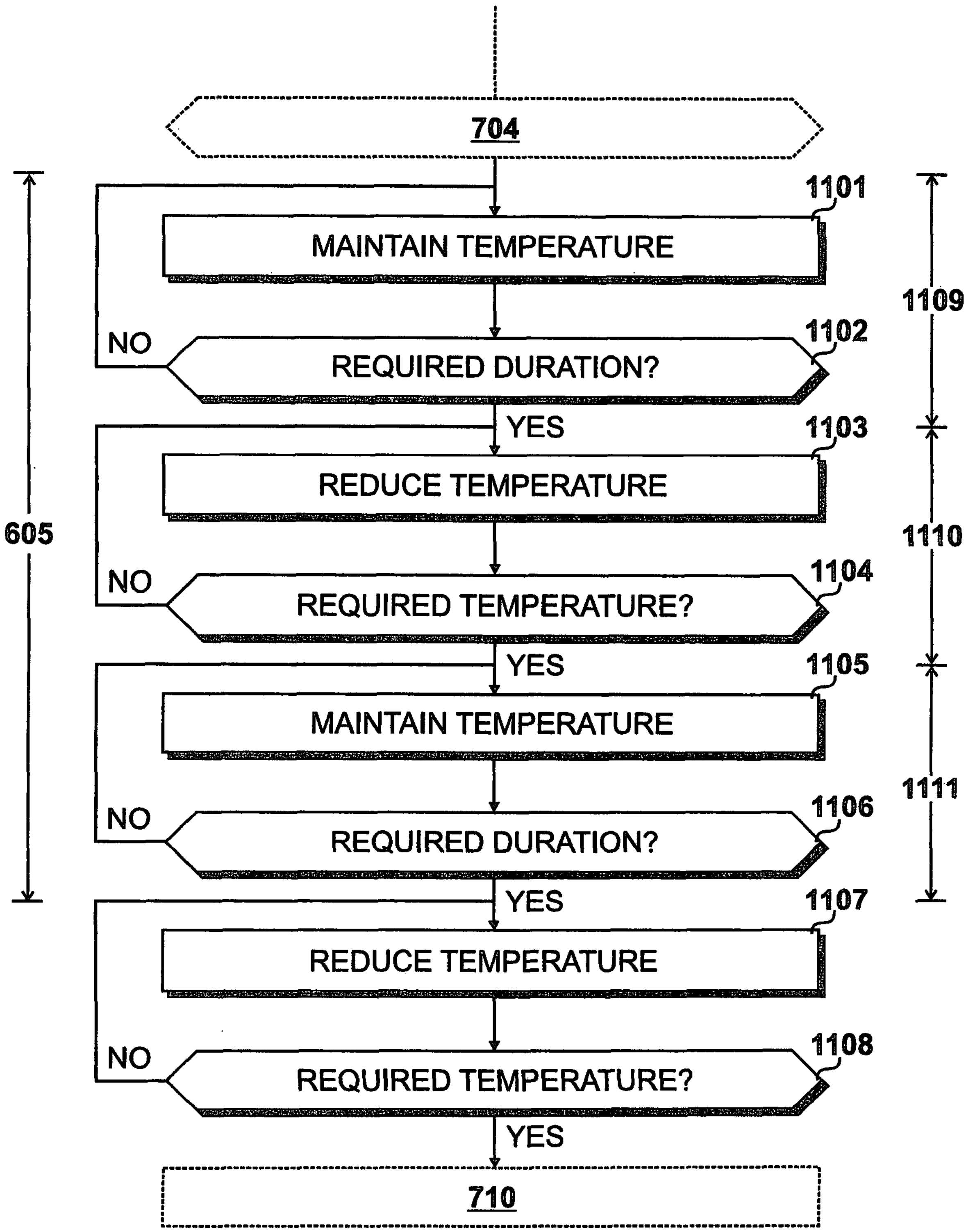
704
1101
MAINTAIN TEMPERATURE
1109
NO
1102
REQUIRED DURATION?
YES
1103
REDUCE TEMPERATURE
605
1110
NO
1104
REQUIRED TEMPERATURE?
YES
1105
MAINTAIN TEMPERATURE
1111
NO
1106
REQUIRED DURATION?
YES
1107
REDUCE TEMPERATURE
NO
1108
REQUIRED TEMPERATURE?
YES
710

Fig. 11

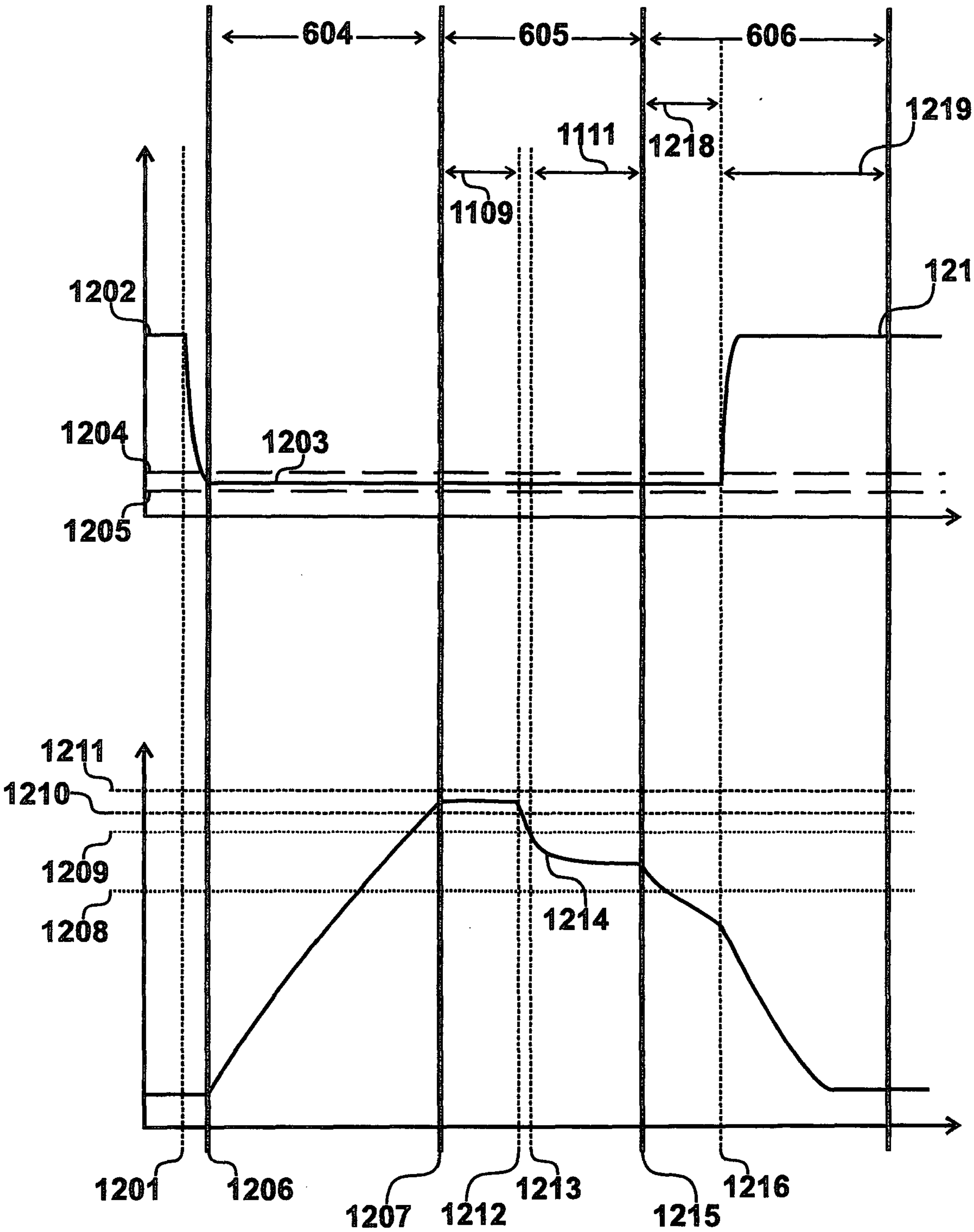
604
605
606
1218
1111
1219
1109
1217
1202
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Fig. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2014/000301

A. CLASSIFICATION OF SUBJECT MATTER
INV. B22D23/06 B22D27/04
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B22D C30B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	EP 2 436 461 A2 (GEN ELECTRIC [US]) 4 April 2012 (2012-04-04) abstract paragraph [0017] -----	14,15 1-13
X	US 5 197 531 A (HUGO FRANZ [DE] ET AL) 30 March 1993 (1993-03-30) abstract column 2, lines 28-36 -----	14,15
X,P A,P	WO 2013/166103 A1 (UNITED TECHNOLOGIES CORP [US]) 7 November 2013 (2013-11-07) the whole document -----	14,15 1-13

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
9 October 2014	16/10/2014

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Scheid, Michael

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2014/000301

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 2436461	A2	04-04-2012	CN	102441658	A	09-05-2012
			EP	2436461	A2	04-04-2012
			US	2012080158	A1	05-04-2012
US 5197531	A	30-03-1993	NONE			
WO 2013166103	A1	07-11-2013	US	2013294901	A1	07-11-2013
			WO	2013166103	A1	07-11-2013